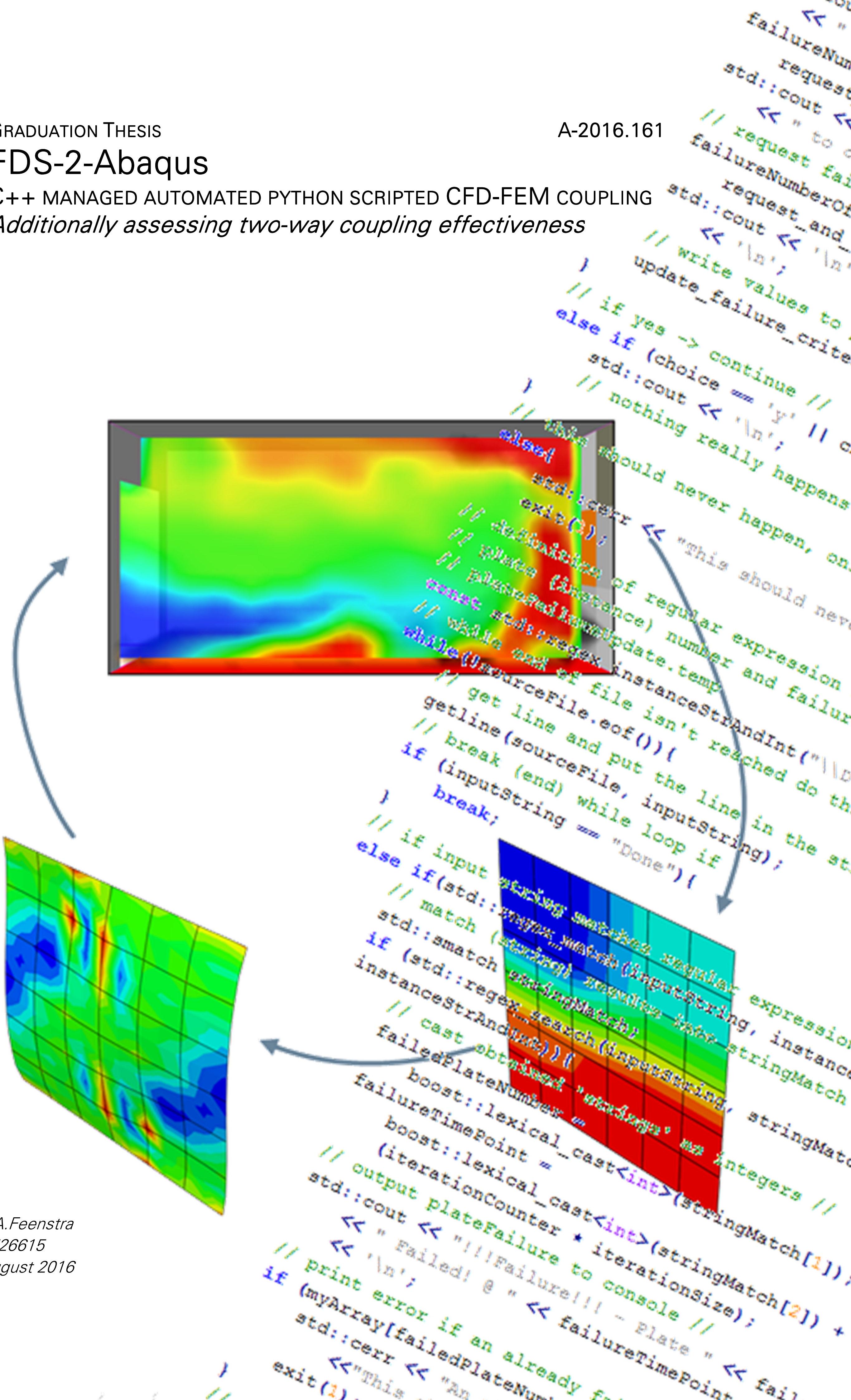
Graduation Thesis A-2016.161

FDS-2-Abaqus

C++ managed automated python scripted CFD-FEM coupling

Additionally assessing two-way coupling effectiveness



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PREFACE

Before you lies my graduation thesis for my master Structural Design at Eindhoven University of Technology. Within this thesis a program called `FDS-2-Abaqus` was developed which can be used to perform one and two-way coupled CFD-FEM analyses. `FDS-2-Abaqus` was used to study the feasibility and effectiveness of a two-way coupled of CFD-FEM analysis.

In the past year I was able to develop numerous skills. Most notably my ability to read and write code. The core process of coding is to continuously subdivide a problem until you can solve one with a simple line of code. I think this process is widely applicable in any project. Looking back there are numerous things that I, in retrospect, would like to do or approach differently. Actually illustrating the numerous skills I developed over the course of this project.

This thesis would not have been a success without the support and encouragement of my environment. Therefore I would like to thank my supervisors for their guidance throughout this project. I am very grateful for their encouragement, explanations, and enthusiasm. It helped me keep motivated and were vital to the successful completion of this project. Thank you Herm Hofmeyer for our in depth discussion in which we always seemed to run out of time. Thank you Ruud van Herpen for your clear explanations on fire. Also thanks to prof. Mahen Mahendran of Queensland University of Technology for his interest in my project and his feedback on my writing.

In addition I would like to thank my family and friends for their support and interest throughout this project. You guys really never seemed bored. A special shout out to my parents who have always encouraged and supported me.

Jelmer Auke Feenstra

Utrecht, August 2016

ABSTRACT

Coupling of CFD fire simulations to thermo-mechanical FE models is a relative new area of research. A distinction is made between one and two way coupling where in a two way coupled analysis the effect of the structural response on the fire propagation is taken into account. The effect of mechanical behaviour on the fire has only been studied in a very limited number of cases.

The aim of this thesis is to study the feasibility of the two-way coupling of CFD fire simulations to FE heat transfer and structural response analyses. More specifically to compare the difference in failure propagation of a thin walled steel façade subjected to fire for a one and two-way coupled analysis.

Coupled CFD-FEM fire to thermomechanical analysis can be split into three separate types of analysis (a1) fire simulations, (a2) heat transfer analysis, and (a3) structural response analysis. These Analysis steps and their mutual coupling steps, have been studied separately. For the fire simulation the CFD software Fire Dynamic Simulator (FDS) by NIST is used. Both the heat transfer (HT) and the structural response (SR) analyses are modelled using FE software Abaqus.

`FDS-2-Abaqus` is a managing program developed during this thesis to facilitate the one and two-way coupling of a CFD-FEM analysis. `FDS-2-Abaqus` was used to perform one and two way coupled analyses of an office space comprising a twelve plate thin walled steel façade. The results were used to assess the effectiveness of two-way coupling. Concluding that the significant difference in failure progression illustrates both the feasibility and the effectiveness of two-way coupling. Although additional research, using more advanced fire and structural models, is required for an all conclusive answer.

ABBREVIATIONS AND SYMBOLS

Overview of abbreviations and symbols used throughout this thesis.

ABBREVIATIONS

AST	Adiabatic Surface Temperature
CFD	Computational Fluid Dynamics
DOF	Degree of Freedom
FDS	Fire Dynamic Simulator
FEA	Finite Element Analysis
FEM	Finite Element Method
HRR	Heat Release Rate
HT	Heat Transfer
OWC	One-Way Coupled / One-Way Coupling
SR	Structural Response
TWC	Two-Way Coupled / Two-Way Coupling

SYMBOLS - GREEK

α	Coefficient of thermal expansion	$[\mathrm{K}^{-1}]$
ε	Emissivity	-
ε_{long}	Longitudinal strain	-
ε_{trans}	Transverse strain	-
ν	Poisson's ratio	-
σ_{th}	Thermal Stress	$[\mathrm{N}\cdot\mathrm{m}^{-2}]$
σ_{boltz}	Stefan Boltzmann Constant	$5{,}5703\cdot10^{-8}\ [\mathrm{W}\cdot\mathrm{m}^{-2}\mathrm{K}^{-4}]$

SYMBOLS – LATIN

A_{fi}	Total fire surface	$[\mathrm{m}^2]$
A_{ht}	Heat transfer surface	$[\mathrm{m}^2]$
c	Specific heat	$[\mathrm{J}\cdot\mathrm{kg}^{-1}\mathrm{K}^{-1}]$
E	Young's modulus	$[\mathrm{N}\cdot\mathrm{m}^{-2}]$
F	View factor	-
HRR_f	Heat release rate	$[\mathrm{W}\cdot\mathrm{m}^{-2}]$
h_c	Convective heat transfer coefficient	$[\mathrm{W}\cdot\mathrm{m}^{-2}\mathrm{K}^{-1}]$
k	Thermal conductivity	$[\mathrm{W}\cdot\mathrm{m}^{-2}\mathrm{K}^{-1}]$
ΔL	Elongation	$[\mathrm{m}]$
L_0	Original length	$[\mathrm{m}]$
m	Unit mass	$[\mathrm{kg}]$
Q	Thermal energy	$[\mathrm{J}]$
Q_{fi}	Net heat of combustion	$[\mathrm{J}]$

q	Heat rate	$[\mathrm{W}]$
q''	Heat flux	$[\mathrm{W \cdot m^{-2}}]$
q_{cd}	Conductive heat rate	$[\mathrm{W}]$
q_{cv}	Conductive heat rate	$[\mathrm{W}]$
q_{fi}	Fire load density	$[\mathrm{J \cdot m^{-2}}]$
q_{rad}	Radiative heat rate	$[\mathrm{W}]$
q''_{inc}	Incident radiation flux	$[\mathrm{W \cdot m^{-2}}]$
T_{amb}	Absolute ambient temperature	$[\mathrm{K}]$
T_{AST}	Adiabatic Surface Temperature	$[\mathrm{K}]$
T_{gas}	Absolute temperature of fluid	$[\mathrm{K}]$
T_{surf}	Absolute surface temperature	$[\mathrm{K}]$
t	Duration	$[\mathrm{s}]$
t_0	Duration flashover phase	$[\mathrm{s}]$
t_1	Duration fully-developed phase	$[\mathrm{s}]$
t_2	Duration decay phase	$[\mathrm{s}]$
t_{fi}	Total fire duration	$[\mathrm{s}]$

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1. INTRODUCTION

The traditional approach of structural response to fire is by imposing prescriptive time temperature curves on the structure. This approach is widely used in standards and codes, for example the ISO cellulosic fire curve included in EC1 1-2 [1]. Fire safety design thereby revolves around meeting fire resistance times for the separate structural components. Advanced numerical models based on the Finite Element Method (FEM) are used nowadays to predict local and global structural behaviour. In addition these methods have been applied to predict structural response to fire. However the use of the simplified time-temperature curves do not take into account the randomness of fire and therefore cannot accurately represent the fire. Fire evolution is governed by fuel distribution, oxygen supply, and the geometric boundary conditions of the compartment. More advanced numerical models based on Computational Fluid Dynamics (CFD) are capable of modelling the three dimensional fire propagation more accurately.

The Coupling of CFD fire simulations to thermo-mechanical FE models is a relative new area of research. Challenges are found in their underlying differences, e.g. discretization and time scales. A coupled CFD-FEM analysis can be split into three separate steps a (a) fire simulation, (b) heat transfer analysis, and (c) structural response analysis. These steps are mutually coupled by coupling steps. Distinction is made between a one-way coupled (OWC) and a two-way coupled (TWC) analysis. In a two way coupled analysis the effect of the structural response on the fire propagation is taken into account. For instance, failure of a window or local element result in openings which change the fire behaviour, and consequently influence the fire load on the structural elements. This effect of mechanical behaviour on the fire has only been studied in a very limited number of cases and therefore this two-way interaction between fire and mechanical behaviour needs to be studied.

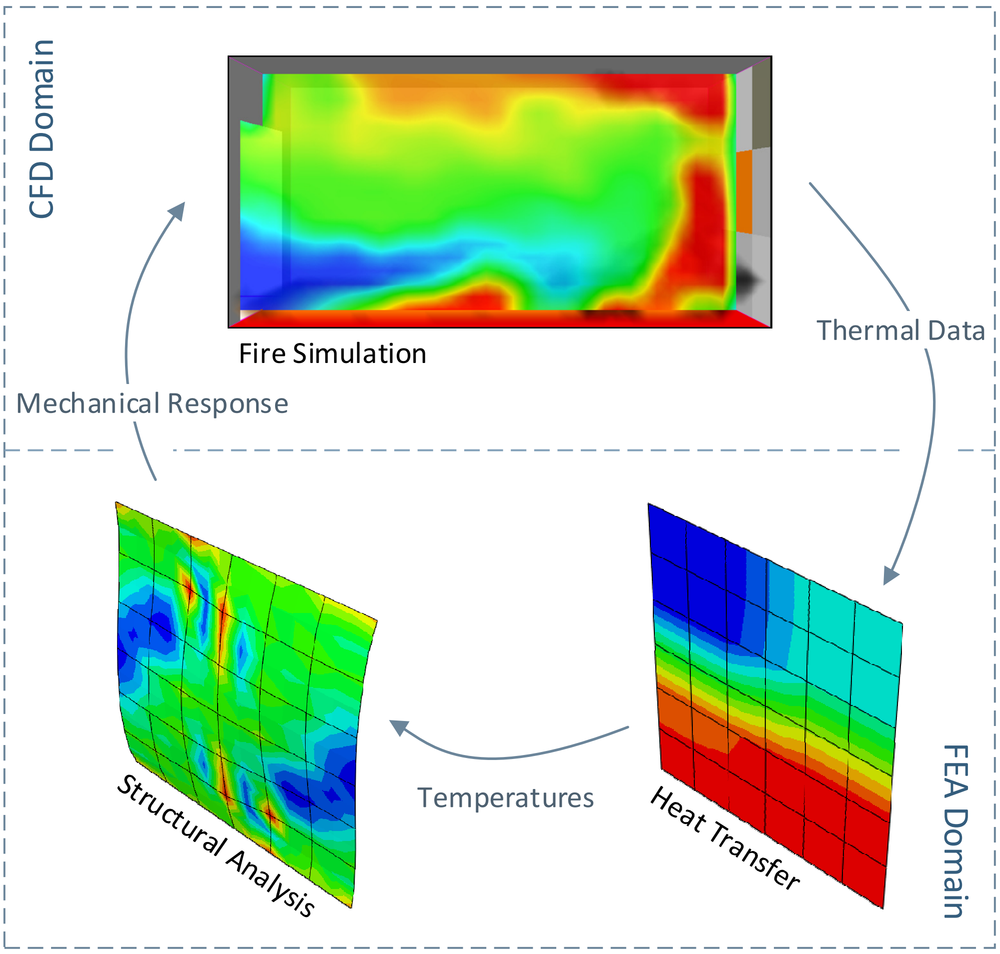


Figure 1.1 - Two way coupling of CFD fire simulations and finite element analyses

The aim of this thesis is to study the feasibility of the two-way coupling of CFD fire simulations to FE heat transfer and structural response analyses, as illustrated in Figure 1.1. Several programs and scripts were developed to facilitate and automate both one- and two-way CFD-FEM coupling. The developed managing program `FDS-2-Abaqus` was used to perform one and two way coupled analyses on an office space comprising a twelve plate thin walled steel façade. The results were used to assess the effectiveness of two-way coupling.

This thesis is structured as follows. Chapter 2 contains a selection of relevant literature topics where, among others, heat transfer is discussed. Chapter 3 discusses the approach to the coupling, the methodology. A model room, and fire scenario, to act as a starting point for the coupling procedure is developed in chapter 4. Chapter 5 discusses fire simulation using the software Fire Dynamic Simulater (FDS) by NIST. The subsequent thermal and structural response analysis are performed using finite element software Abaqus, and discussed in chapter 6. The development of the various coupling programs and scripts are discussed chapter 7. The assessment on the effectiveness of two way coupling is presented as part of the results in chapter 8. Lastly, the conclusions and recommendations are presented in chapter 9.

RESEARCH QUESTIONS

The main question for this thesis is presented below:

> *"Is the two-way coupling of CFD fire simulations to finite heat transfer and structural response analysis a feasible technique for use in structural fire safety design?"*

This main question has been elaborated in various sub questions as follows:

> *"How does a two-way coupling perform compared to a one-way coupled CFD-FEM? "*
>
> *"What separate analysis steps can be identified and how to perform and implement these in a coupled analysis?"*
>
> *"What coupling steps can be identified and what data exchange occurs between the analysis steps?"*
>
> *"What tools are required to facilitate and automate the coupling procedure?"*

In a sense these questions loosely translate to a can, how and should question. Can we do it? Should we do it? And How to do it? The questions have been answered throughout this report by first investigating the separate analyses and coupling steps. Subsequently programs and scripts have been developed to facilitate one and two way CFD-FEM coupling.

SOCIAL RELEVANCE

The thesis focusses on the feasibility of coupling fire simulation to finite element analysis. In a sense this is very specific, but in the long run it could contribute to a better understanding of fire and its behaviour. Fire often results in the loss of human life. Therefore, understanding fire and its effects could contribute to fire safety and structural performance. In addition it is important to note that the majority of the victims of an earthquake are due to resulting fires in the aftermath of the earthquake. Again underlining the importance of fire safety. This research could also be relevant to the field of engineering. Large projects often take advantage of BIM models. BIM models incorporate aspects of all different professions into one big model. This study could contribute to such models by integrating fire analyses with structural analyses possibly resulting in more efficient and safe solutions.

2. Theory

Several relevant topics to this research are explained. First the coupling of fire simulations to structural analysis is explored. Followed by fire, fire load, heat transfer and the concept of adiabatic surface temperature.

2.1 Coupling of Fire Simulations and Structural Analysis

Coupling of CFD fire simulations and structural finite element analyses is a relatively new area of research. One of the reasons for the resurgence of interest in thermo-mechanical response to fire was due to the attacks on the World Trade Centre (WTC) towers in 2001. In the aftermath of the collapse Prasad and Baum (2005) [2] developed an interface model to couple the gas phase energy release and fluid movements with the stress analysis in the load bearing materials. Their procedure, used in the analysis of the collapse of the WTC towers, couples CFD with FEA based on heat transfer by radiation and conduction. The resulting method, called Fire Structural Interface (FSI) can be used to generate realistic thermal boundary conditions for use in solutions to the heating of complex structures. Later work by Baum (2011) [3] discusses the fire-thermomechanical coupling. Specifically it discusses the role of uncertainty in input parameters and provides a context to illustrate the strengths and weaknesses of employed coupling methodologies.

The European research project FIRESTRUC analysed coupling methodologies for predicting thermo-mechanical behaviour. The FIRESTRUC paper by Welch et al (2006) [4] shows a broad examination of approaches to coupling CFD and FEM codes, while taking into account the implications for accuracy and computational requirements. Each of the analysis and coupling steps are discussed separately in the paper and multiple methods are proposed for both one and two-way coupling.

Luo et al. [5] developed an Fire Interface Simulator Toolkit (AFIST) by integrating CFD software Fire Dynamic Simulator (FDS) with a customized Abaqus structural analyser through a two-way coupling. A two-way coupling exchange of heat and mass flow is integrated on the incremental level. In addition various demonstration and validation methods are presented to illustrate the capability of the tool.

The concept of adiabatic surface temperature (AST) was introduced by Wickström et al. in 2007 [6]. Adiabatic surface temperature is a practical tool to express the thermal exposure of a surface to fire in a single quantity, thereby reducing the data flow. The AST concept and associated equations are discussed in more detail in paragraph 2.5. Duthinh et al (2008) [7] utilized AST to developed an interface between fire simulation software FDS and FEA software ANSYS. They applied their interface to a trussed beam and verified it using a real life fire test by NIST. Another example of utilizing AST to couple CFD and FEA analyses is found in a paper by Banerjee et al (2009) [8]. Banerjee et al. created an Immersive Visualization Environment (IVE) to visualize, and study, in real time the structural and thermal behaviour of a chosen structural element under fire. For the initial study a beam was selected as structural element. The software Fire Dynamic Simulator (FDS) was used to simulate the onset and development of fire in a typical room. Subsequently the resulting gas temperatures were imposed on a simulated beam using finite element software Abaqus. Finally Abaqus was used to compute the deformation over time as a result of the thermal and mechanical loads.

Silva et al (2014) [9] developed a computational interface model, the Fire- Thermomechanical Interface (FTMI), to provide an interface for fire-thermomechanical performance based analysis of structures under fire. The interface allows for coupling of the fire-driven fluid model FDS and structural thermomechanical analysis via ANSYS. The coupling allows for both convective and radiative heat transfer to the exposed surface by utilizing the AST concept. In the paper the methodology is described and applied to a simple case for verification. In addition the code has been added to the FDS repository under the name FDS2FTMI allowing for one-way coupling of FDS and finite element software ANSYS [10]. Additional validation of FDS2FTMI was carried out by Zhang et al (2015) [11].

The transfer of data between analysis models can get rather complicated because of difference in discretization and time scale. Banerjee (2014) [12] discusses software independent mapping tools to assist in both types of data transfer for one-way coupling. More specifically, the transfer from fire model to heat transfer model, and subsequently from the heat transfer model to the structural analysis model.

2.2 FIRE

According to the encyclopedia of Natural Hazards fire can be defined as the combustion (a series of chemical reactions) between a fuel (an organic compound) and an oxidant (oxygen source) producing heat, light, and often sound [13]. Chemically speaking is fire a rapid exothermic oxidation of a combustible material accompanied by the evolution of heated gaseous products of combustion. The previous description hint at the conditions needed for the onset, and continuation of fire. The requirements for fire are oxygen, fuel, heat, and chemical chain reaction. The first three elements are required to trigger the fire. The oxidizing agent (oxygen) sustains combustion, heat is needed to raise the material to its ignition temperature, and a combustible material (fuel) acts as the reducing agent. Once triggered the fire is sustained by a chemical chain reaction and keeps burning until one of the conditions is removed or blocked. These requirements are commonly symbolized by the fire tetrahedron (or triangle, excluding the chain reaction) as shown in Figure 2.1.

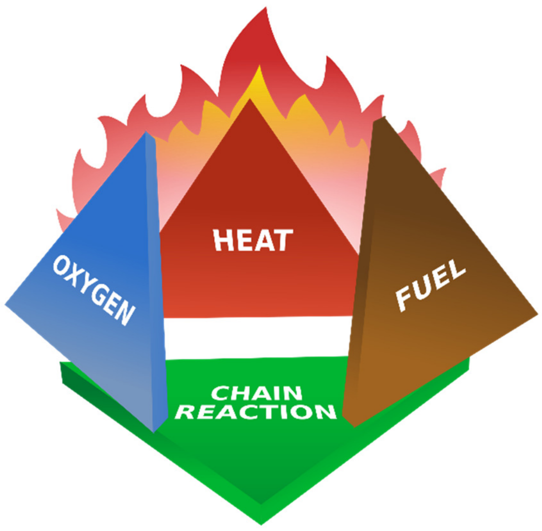


Figure 2.1 - The Fire Tetrahedron

STAGES OF A FIRE

Both the trigger and development of a compartment fire are random and vary greatly for specific situations. Despite this randomness a general behaviour can be explained and understood. Given a compartment fire four stages can be recognized: the initial, flashover, fully developed, and cooling phase. These stages are illustrated in Figure 2.2 and discussed in more detail below.

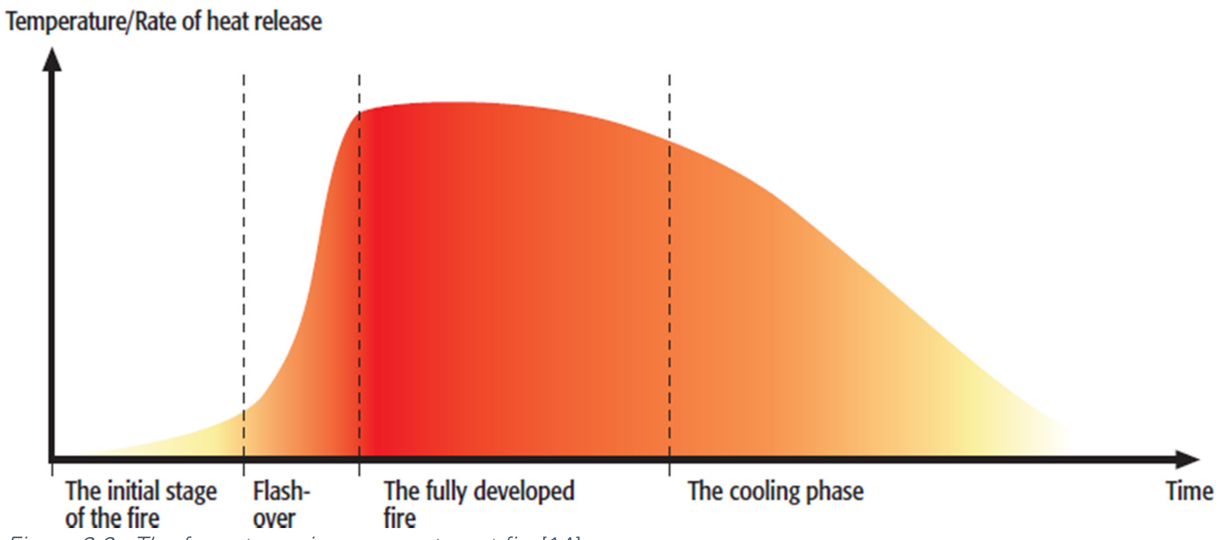


Figure 2.2 - The four stages in a compartment fire [14]

Initial Stage of the Fire

The first stage of the fire, also called incipient, is characterized by ignition. Heat, fuel and oxygen combine and form a chemical chain reaction resulting in a fire. During this stage the fire is *fuel controlled*, there is sufficient oxygen for all (currently burning) fuel to combust. Once triggered the gaseous products, generated by the fire, form a hot layer of gases close to the ceiling. The fire gradually heats its surroundings due to the overall temperature increase from the continuing generating of heated gases. The increase in temperature combined with the availability of both oxygen and fuel will cause the fire to grow in size at an increasing rate [14], [15].

.

Flashover

With the growth of the fire the temperatures of its surroundings keep increasing. The fire can develop to such an extent that the compartment and its interior can reach a certain temperature that allows for flashover to occur. Flashover is a rapid transition resulting in total surface involvement of all combustible materials in the compartment. In other words all combustible material reach their ignition temperature resulting in a fully developed fire. However, this can only occur when sufficient oxygen is available, if oxygen is limited the fire's intensity will decrease which results in the fire burning out or devolve into a smouldering fire. Generally flashover occurs at temperatures ranging from 600 - 700 °C [14], [15].

Fully Developed

After flashover the fire is fully developed when all combustible material is ignited. Flames rush out through openings and the heat of the surrounding structures greatly increases. This poses a great threat for spreading to adjoining rooms or buildings. The heat release is at its greatest, although limited by ventilation (availability of oxygen). The average gas temperatures within the compartment range from 700 - 1200 °C [14], [15].

Cooling Phase

The cooling phase is initiated as a result of limited availability of fuel or oxygen, in the end resulting in the end of the fire. Simply put, the cooling phase is the dying out of the fire due to lack of resources. When insufficient oxygen is available the end stage results in hot pyrolized fuel and flammable gaseous products of combustion. These products present a threat since they could re-ignite when introduced to a source of oxygen, so called *backdraft*. Backdraft is the burning of heated gaseous products of combustion when oxygen is introduced into an environment that has a depleted supply of oxygen due to fire. This burning often occurs with explosive force [14], [15].

2.3 Fire Load and Heat Release Rate

The most basic way to simulate a fire is by simulating a time temperature curve. The increase in temperature, due to a fire, is the result of the release of energy by combustion of available combustible materials. The temperature development in a compartment depends strongly on the availability of combustible materials. The total energy release is expressed in the fire load. The fire load is the quantity of energy which is released by the complete combustion of all combustible material in a fire compartment. The fire load is often subdivided in a permanent and variable part. The permanent fire load is the energy stored in the combustible components of the structural elements. The variable fire load is all combustible material stored in furniture and equipment. The fire load density is the fire load per unit floor area or volume. The fire load density, in combination with the availability of oxygen and the combustion properties of the material, determine the heat release rate (HRR) of a fire. Basically the fire load determines 'how much' energy is released and the heat release rates determines 'how fast' this energy is released. The fire load is greatly depended on the interior and occupancy class of the room/building and the heat release rate depends on either the (rate of) oxygen supply or the rate at which the combustible material can be released. These burning regimes are referred to as, respectively, ventilation or fuel controlled fires as illustrated in Figure 2.3 [16].

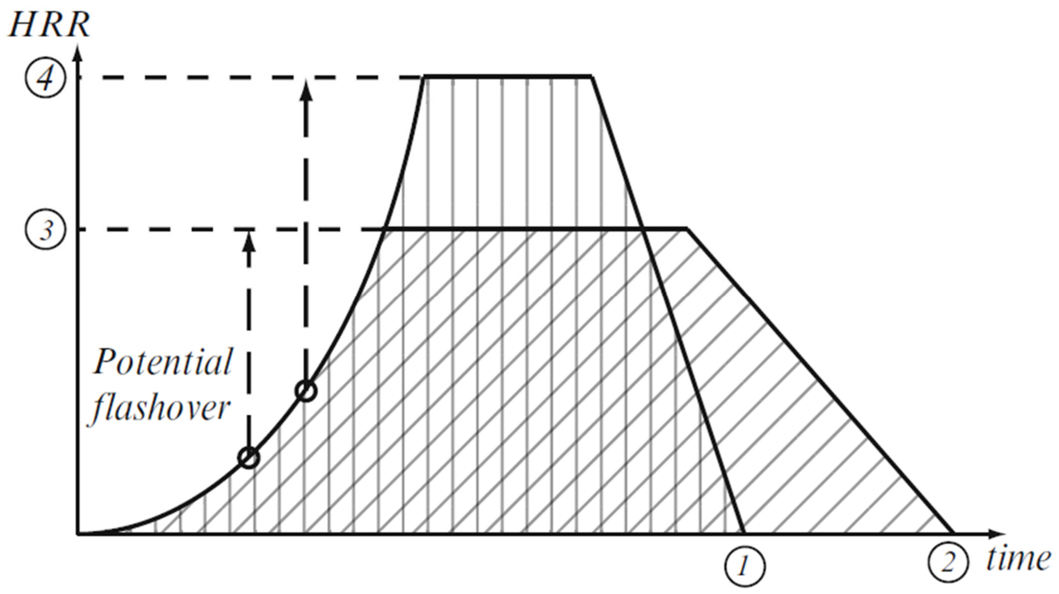


Figure 2.3 - Schematic Representation of Heat Release Rate and Fire Duration for Fuel or Ventilation Controlled Fires with (1) Duration of Fuel Controlled Fire (2) Duration of Ventilation Controlled Fire (3) HRR of Ventilation Controlled Fire (4) HRR of Fuel Controlled Fire. The total fire load (hatching) is equal for both burning regimes.

The furniture and equipment in a room or compartment differs from room to room or is still unknown, for instance during the design phase. Therefore when calculating the fire load it is often estimated by a deterministic or statistic approach. In the deterministic approach a calculation is made based on the expected combustible materials in the room or construction. The statistic approach is based on statistical data of research on similar building types with similar functions. The permanent fire load can be estimated with a deterministic approach with an in-situ survey or based on the design, since both materials and dimensions are known. For estimating the variable fire load both approaches can be used. For specific situations the deterministic approach could be applied. In general the statistic approach is used since extensive data is available for different occupancy classes like residential buildings, offices, hotels, schools, or hospitals. An advantages of these occupancy classes is that it allows for future rearrangements, as long as the occupancy class remains unaltered. The occupancy classes and their appropriate fire load density values will be discussed in more detail below [16].

Both architecture and interior can be considered a cultural characteristics. Therefore no universal values for the different occupancy classes can be provided. For Europe, mean and fractile values for common occupancy classes are defined in Appendix E of Eurocode 1 part 1-2 [1]. Appendix E is informative only, meaning national Appendixes are allowed to define different values. Outside of Europe, the International Fire Engineering Guidelines (IFEG) [17] are considered for information concerning fire load densities for both specific and common occupancy classes. Both standards refer to the CIB W14, an international overview on fire load surveys conducted before 1986. It is important to note that the present-day furnishing and construction materials are different from what was customary several decades ago. A more recent overview on fire load densities in office buildings is found in a paper by Khorasani et al. (2013) [18]. The paper discusses that recent surveys indicate a large range of fire load density values, and show strong correlation between fire load density, compartment area, and use. These variables are not account for in current codes (like Eurocode). Showing, for instance, that Eurocode is conservative for 'lightweight' (general, clerical, lobby, and conference) and non-conservative on 'heavyweight' (file, storage, and library) compartment use. In addition new fire load density and maximum temperature models are proposed by Khorasani et al. for application in probabilistic performance-based fire design, taking into consideration the area and compartment use.

The fire load density data, for a 'general' office function, from the previously discussed (sub)sources are combined into Table 2.1. The percent fractile is the value that is not exceeded in that percentile of the rooms or occupancies.

Table 2.1 – Fire loads for 'general' office spaces.

REFERENCE		MEAN $[\mathbf{MJ/m^2}]$	ST DEV $[\mathbf{MJ/m^2}]$	PERCENT FRACTILE 80% $[\mathbf{MJ/m^2}]$	90% $[\mathbf{MJ/m^2}]$	95% $[\mathbf{MJ/m^2}]$	TYPE OF FIRE LOAD[1)]
EN 1991-1-2	[1]	420	126	511	-	-	V
EN 1991-1-2/NB (NL)	[19]	420	-	570	-	-	V
IFEG	[17]	420	-	570	670	760	V
Bryl (1)	[20]	420	370	570	740	950	V
Bryl (2)	[21]	410	330	520	770	920	V
E. Zalok	[22]	557	286	-	-	-	U
VKF - AEAI	[23]	300-900	-	-	-	-	U
NFPA 557	[24]	730	502	-	-	-	U
Khorasani et al.	[18]	364-782	224-487	-	-	-	U

1) Type – V is variable, T is total, U is unknown

2.4 HEAT TRANSFER

The transfer of energy from fire to structural elements increases their temperature and structural performance. An exothermic fire heats surrounding air and yields hot gaseous by-products. Heat energy is transferred to surrounding objects by a combination of different heat transfer modes. There are three fundamental heat transfer modes, namely conduction, convection and radiation. Conduction is the transfer of energy between substances that are in direct contact with each other. Convection is the transfer of energy between an object and its environment, convection occurs when warmer areas of a liquid or gas rise to cooler areas. Thermal radiation is a method of heat transfer involving electromagnetic radiation and does not rely upon any contact between the heat source and the heated object. Heat transfer always occurs from a region of high temperature to a region of lower temperature. The process of heat transfer will continue up until all involved bodies reach the same temperature and thermal equilibrium is reached. The different modes of heat transfer, and related parameters, will be discussed in more detail below [25]. For completeness, all discussed parameters, symbols and units for heat transfer measurements and calculations are listed in Table 2.2.

Table 2.2 – Parameters, symbols and units for heat transfer measurements and calculations

PARAMETER	SYMBOL	UNITS
Specific Heat	c	$\mathrm{J \cdot kg^{-1} K^{-1}}$
Thermal Energy	Q	J
Heat Rate	q	W
Heat Flux	q''	$\mathrm{W \cdot m^{-2}}$
Thermal Conductivity	k	$\mathrm{W \cdot m^{-2} K^{-1}}$
Convective Heat Transfer coefficient	h_c	$\mathrm{W \cdot m^{-2} K^{-1}}$
Stefan Boltzmann Constant ($5{,}6703 \cdot 10^{-8}$)	σ	$\mathrm{W \cdot m^{-2} K^{-4}}$
Emissivity	ε	-
View Factor	F	-

SPECIFIC HEAT

Energy and temperature are linked by the so called specific heat. The specific heat c is the required amount of heat per unit mass m to raise the temperature T by one degree Celsius. The specific heat for steel at room temperature and atmospheric pressure equals $c_{steel} = 452\,\mathrm{J \cdot kg^{-1} K^{-1}}$. Expressed in an equation:

$$dQ = m \cdot c \cdot dT \qquad 2.1$$

With:

dQ	Required energy	$[\mathrm{J}]$
m	Unit mass	$[\mathrm{kg}]$
c	Specific heat	$[\mathrm{J \cdot kg^{-1} K^{-1}}]$
dT	Temperature difference	$[\mathrm{K}]$

HEAT RATE AND HEAT FLUX

An increase in thermal energy results in increased temperature as previously discussed. This transfer of heat is commonly expressed in the so called heat rate or heat flux. The difference being that heat rate is a scalar quantity which describes the heat transfer through a given surface, while heat flux is a vectorial quantity describing the heat rate per unit area. Thermal energy can be expressed in terms of heat rate and duration as:

$$Q = q \cdot t \qquad 2.2$$

With:

Q	Thermal Energy	$[\mathrm{J}]$
q	heat rate per unit time	$[\mathrm{W}]$
t	duration of heat transfer	$[s]$

In turn, heat rate can be expressed in terms of heat flux and surface area.

$$q = q'' \cdot A_{ht} \tag{2.3}$$

With:

A_{ht}	Heat transfer area of the surface	$[\mathrm{m}^2]$
q''	Heat Flux	$[\mathrm{W} \cdot \mathrm{m}^{-2}]$

CONDUCTION

Conduction is the flow of heath through solids and liquids by vibration and collision of molecules. Heat is transferred from high energetic to less energetic molecules through collision. Since high temperature is associated with high molecular energy heat energy transfers in direction of the lower temperatures. Conduction occurs if there is a temperature gradient within a solid or fluid medium.

Thermal conductivity k is the property of a material to conduct heat. The thermal conductivity for (carbon) steel at room temperature equals $k = 53{,}3\ \mathrm{W} \cdot \mathrm{m}^{-1}\mathrm{K}^{-1}$ and drops linearly to $k = 27{,}3\ \mathrm{W} \cdot \mathrm{m}^{-1}\mathrm{K}^{-1}$ at $T = 800\ °\mathrm{C}$. The total conductive heat transfer to a surface can be expressed as:

$$q_{cd} = k \cdot A_{ht} \frac{dT}{ds} \tag{2.4}$$

With:

q_{cd}	Conductive heat transfer per unit time	$[\mathrm{W}]$
k	Thermal conductivity	$[\mathrm{W} \cdot \mathrm{m}^{-2}\mathrm{K}^{-1}]$
$\frac{dT}{ds}$	Temperature gradient over distance s	$[\mathrm{K} \cdot \mathrm{m}^{-1}]$

CONVECTION

Convection is the transfer of heat energy between a surface and a moving fluid (liquid or gas) at different temperatures. A distinction is made between forced and natural convection. Forced convection, also known as assisted convection, occurs when an external force induces a fluid flow. For instance a pump, mixer or fan. Natural convection, also known as free convection, is caused by buoyant forces resulting from density variations due to variations in temperature in the fluid. At the interface layer between fluid and surface the hot fluid transfers heat and, as a result of its increase in density, sinks. Therefore this cooled fluid is replaced by hot fluid, which in turn transfers heat, sinks, and is replaced by hot fluid. This continuous process is known as natural or free convection [25].

Convective heat transfer depends on the area of the surface, the temperature difference, and the so called convective heat transfer coefficient. The convective heat gain of a surface can be expresses as:

$$q_{cv} = h_c \cdot A_{ht} \left(T_{gas} - T_{surf} \right) \tag{2.5}$$

With:

q_{cv}	Convective heat transfer per unit time	$[\mathrm{W}]$
h_c	Convective heat transfer coefficient	$[\mathrm{W} \cdot \mathrm{m}^{-2}\mathrm{K}^{-1}]$
T_{gas}	Temperature of fluid (gas)	$[\mathrm{K}]$
T_{surf}	Surface temperature	$[\mathrm{K}]$

The convective heat transfer coefficient of air depends on the relative speed of the surface through the air and can be approximated using the equation 2.6 or the graph in Figure 2.4. It is important to note that it concerns an empirical equation and can only be used for velocities from $2 < v \leq 20\ \mathrm{m \cdot s^{-1}}$ [25].

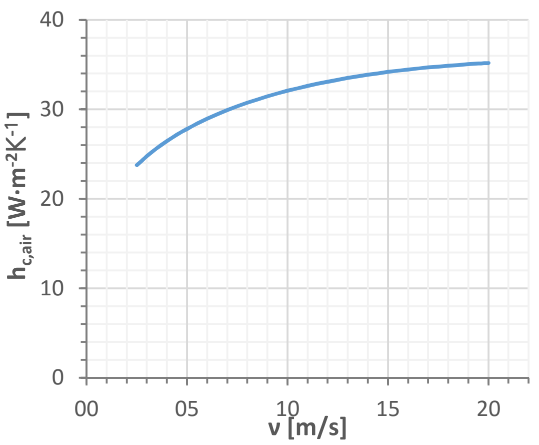


Figure 2.4 – Convective heat transfer coefficient (air)

$$h_{c,air} = 10.45 - v + 10 \cdot v^{0,5} \tag{2.6}$$

With:

v	The relative speed of the object through the air	$[\mathrm{m \cdot s^{-1}}]$

RADIATION

Heat transfer through radiation is the increase in temperature due to absorbing electromagnetic waves. Radiation heat transfer can be described by reference to a black body. A black body is an idealized object that absorbs all electromagnetic radiation that falls on its surface. By absorbing this energy its inner building blocks are agitated, resulting in an increased temperature of the object in comparison to its surroundings. This heat is then emitted in the form of electromagnetic radiation. Theoretically a black body will emit radiation on all wavelengths, although at low temperatures the amount of visible light is negligible and the radiation mainly comprises infrared radiation. The emission spectrum of such a black body was first fully described by Max Planck [25].

The radiation energy per unit time from a black body is proportional to the fourth power of the absolute temperature and can be expressed with Stefan-Boltzmann Law as:

$$q_{rad} = \sigma \cdot T^4 \cdot A \tag{2.7}$$

With:

q_{rad}	Radiative heat loss per unit time	$[\mathrm{W}]$
σ_{boltz}	Stefan Boltzmann Constant (5,6703·10^{-8})	$[\mathrm{W \cdot m^{-2} K^{-4}}]$
T	Absolute temperature	$[\mathrm{K}]$
A	Area of the emitting body	$[\mathrm{m^2}]$

Since black bodies don't exist in nature the Stefan-Boltzmann Law for other objects, so called 'grey bodies', includes a factor ε describing the emissivity of the object. The emissivity coefficient ε indicates the radiation of heat from a grey body compared to the radiation of heat form an ideal black body $\varepsilon = 1{,}0$. The emissivity depends on the type of material and its surface finishing as illustrated in Table 2.3 for steel [25]. In most cases of structural materials being exposed to fire, it can be assumed equal to 0.8 [6].

Table 2.3 – Emissivity of steel

MATERIAL	EMISSIVITY ε
Steel Oxidized	0,79
Steel Polished	0,07
Stainless Steel, weathered	0,85
Stainless Steel, polished	0,075
Steel Galvanized (Old)	0,88
Steel Galvanized (New)	0,23

$$q_{rad} = \varepsilon \cdot \sigma \cdot T^4 \tag{2.8}$$

With:

ε	Emissivity of the object	$[-]$

Above formulation describes heat loss by radiation. The net radiation heat received by a surface is the difference between the absorbed incident radiation and the radiation emitted from the surface. Both heat transfer through the surface and the influence of various wavelengths are neglected. Resulting in equal values for absorptivity and emissivity. The net heat received by a surface can be written as:

$$q_{rad} = \varepsilon \left(q''_{inc} - \sigma T_{surf}{}^4 \right) A \tag{2.9}$$

With:

q''_{inc}	Incident radiation flux	$[\mathrm{W \cdot m^{-2}}]$
T_{surf}	Absolute surface temperature	$[\mathrm{K}]$

Fires show non-homogeneous temperature distributions. The incident radiation heat flux should include contribution from all nearby flames, hot gases, and surfaces. Radiation exchange between two or more surfaces depends strongly on the surface geometries and orientations, as well as on their radiative properties and temperature. The incident radiation flux can be written as the sum of all contributing radiating sources [6]:

$$q''_{inc} = \sum_i \varepsilon_i F_i \sigma T_i^4 \tag{2.10}$$

With:

ε_i	Emissivity of the ith flame/surface	$[-]$
F_i	View factor of the ith flame/surface	$[\mathrm{W \cdot m^{-2}}]$
T_i	Absolute temperature of the ith flame/surface	$[\mathrm{K}]$

The view factor F_i is defined as the fraction of the radiation leaving a surface i that is intercepted by the surface under consideration. If a cold object is receiving radiation energy from its hot surroundings the net heat gain decreases as its temperature equalizes. For this basic case the view factor can be neglected and the net radiation heat only depends on the difference between the object and ambient temperature. The net radiation heat gain can be expressed as:

$$q_{rad} = \varepsilon \cdot \sigma \left(T_{amb}{}^4 - T_{surf}{}^4 \right) A \tag{2.11}$$

With:

T_{amb}	Absolute ambient temperature	$[\mathrm{K}]$
T_{surf}	Absolute surface temperature	$[\mathrm{K}]$

2.5 ADIABATIC SURFACE TEMPERATURE

Adiabatic surface temperature is a practical tool to express the thermal exposure of a surface to fire. The concept of adiabatic surface temperature (AST) was introduced by Wickström et al. in 2007 [6]. AST is the temperature of an imaginary perfect insulator exposed to the same heating (fire) conditions as the real surface and can be used for transferring data from fire models to thermal/structural models. Utilizing AST reduces the data flow to the structural model by eliminating the dependency of the surface temperature on the net heat flux. A simple way to describe adiabatic surface temperature is as an imaginary temperature being used commonly for calculating both convective and radiative heat transfer to a Structural Model.

AST provides an interface between fire and a structural model. A fire model is defined as a calculation method to predict temperature and species concentrations of the fire-driven flow. CFD fire models often approximate bounding solid as thick slabs to estimate surface temperatures. A detailed thermal study requires an interface to transfer the required thermal data. The most obvious quantity is heat flux but this has two problems. First, the net heat flux to a surface computed by the fire model is dependent on the corresponding surface temperature computed by the same fire model. Secondly, many commonly used heat transfer programs incorporate heat flux by prescribing a boundary gas temperature and a surface temperature. Adiabatic Surface Temperature can be used as intermediary to solve both aforementioned problems. The main advantage for utilizing AST is that only one quantity needs to be transferred from fire model to structural model.

Below the basic theory for this fairly new concept, as proposed by Wickström et al. [6] is explained. For further reading and verification, using real life fire test, is referred to the full paper.

BASIC THEORY

Heat transfer from flames and hot gases to surrounding solid surfaces occurs via radiation and convection. The net total heat flux q''_{tot} to a surface can be expressed as:

$$q''_{tot} = q''_{rad} + q''_{cv} \tag{2.12}$$

Both modes of heat transfer are discussed in the previous paragraph. Combining equations 2.3, 2.5 and 2.9 result in a net total heat flux to a surface of:

$$q''_{tot} = \varepsilon\left(q''_{inc} - \sigma T_{surf}{}^{4}\right) + h_c\left(T_{gas} - T_{surf}\right) \tag{2.13}$$

Consider a surface of a perfect insulator exposed to the same heating conditions as the real surface. The temperature of this surface is referred to as the adiabatic surface temperature (AST). The net total heat flux to this ideal surface is by definition zero, thus:

$$\varepsilon\left(q''_{inc} - \sigma T_{AST}{}^{4}\right) + h_c\left(T_{gas} - T_{AST}\right) = 0 \tag{2.14}$$

At every surface point under consideration the fire model (FM) computes a radiation heat flux and a corresponding gas temperature adjacent to the surface. Solving the implicit equation below will result in the AST of that specific surface point.

$$\varepsilon\left(q''_{inc,FM} - \sigma T_{AST}{}^{4}\right) + h_c\left(T_{gas,FM} - T_{AST}\right) = 0 \tag{2.15}$$

With:

$q''_{inc,FM}$	Incident radiation heat flux (Fire Model)	$[\mathrm{W \cdot m^{-2}}]$
$T_{gas,FM}$	Gas temperature adjacent to surface (Fire Model)	$[\mathrm{K}]$
T_{AST}	Adiabatic Surface Temperature	$[\mathrm{K}]$

For the structural model (SM) the heat flux is computed based on the fire conditions predicted by the fire model and the surface temperature as predicted by the structural model.

$$q''_{tot,SM} = \varepsilon\left(q''_{inc,FM} - \sigma T_{surf,SM}{}^{4}\right) + h_c\left(T_{gas,FM} - T_{surf,SM}\right) \qquad 2.16$$

With:

$q''_{tot,SM}$	Total heat flux (Structural Model)	$[\mathrm{W \cdot m^{-2}}]$
$q''_{inc,FM}$	Incident radiation heat flux (Fire Model)	$[\mathrm{W \cdot m^{-2}}]$
ε	Emissivity	$[-]$
σ	Stefan Boltzmann Constant	$[\mathrm{W \cdot m^{-2} \cdot K^{-4}}]$
h_c	Heat transfer coefficient	$[\mathrm{W \cdot m^{-2} \cdot K^{-1}}]$
$T_{gas,FM}$	Gas temperature adjacent to surface (Fire Model)	$[\mathrm{K}]$
$T_{surf,SM}$	Absolute Surface Temperature (Structural Model)	$[\mathrm{K}]$

Subtracting equation 2.16 from equation 2.15 results in a total net heat flux to the surface of:

$$q''_{tot,SM} = \varepsilon\sigma\left(T_{AST}{}^{4} - T_{surf,SM}{}^{4}\right) + h_c\left(T_{AST} - T_{surf,SM}\right) \qquad 2.17$$

3. APPROACH

The main goal of this thesis is to study the effectiveness (and feasibility) of the two way coupling of CFD fire simulations to FE heat transfer and structural response analyses. In this chapter the general approach to this topic will be clarified. Additionally it aims to explain the 'what' and the 'how' question, as in what separate steps can be identified and how to address these steps.

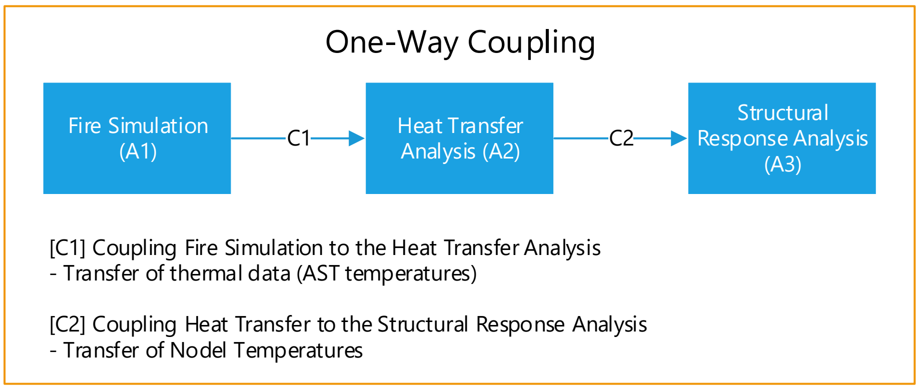

One-Way Coupling
Fire Simulation (A1)
C1
Heat Transfer Analysis (A2)
C2
Structural Response Analysis (A3)
[C1] Coupling Fire Simulation to the Heat Transfer Analysis
- Transfer of thermal data (AST temperatures)
[C2] Coupling Heat Transfer to the Structural Response Analysis
- Transfer of Nodel Temperatures

Figure 3.1 – Flowchart for one-way coupling [simplified]

As previously mentioned coupled thermomechanical fire analysis can be split into three separate types of analysis (a1) fire simulations, (a2) heat transfer analysis, and (a3) structural response analysis. These analysis steps are mutually coupled by three coupling steps. (c1) Coupling of the fire simulations to heat transfer analysis, (c2) coupling heat transfer to structural analysis, and (c3) the coupling of the structural response to the (original) fire simulation. In which the latter is exclusive to the two-way coupling procedure. In other words, a distinction is made between one and two-way coupling procedures where for one-way coupling the influence of structural changes on the fire model is neglected. This sounds as a relative small difference but actually has a large influence on their implementation. The reason being that one-way coupling is a linear process while two-way coupling is a circular or iterative process. A one-way coupled analysis consist of a fire simulation for the full duration of the intended analysis and then continues sequentially with the heat transfer and structural response analysis, again for the full duration. In the two-way coupled analysis one needs to verify, during the initial fire simulation, if (some part of) the structural model has failed and if so update the fire model. Basically one should simulate a fire for small time increment then verify, using a heat transfer and structural response analysis, if structural integrity is still met. Ideally the time increment size approaches single calculations steps. In other words a two way coupling is a combination of a limited number of one-way coupled thermomechanical simulations. Where after each one-way-coupled increment the geometric changes are updated in the fire and structural models. Simplified flowcharts for the one and two-way coupling methodologies are illustrated in Figure 3.1 and Figure 3.2 respectively. Detailed flowcharts for the one and two-way coupled procedures are included in Appendix A1 and Appendix A2.

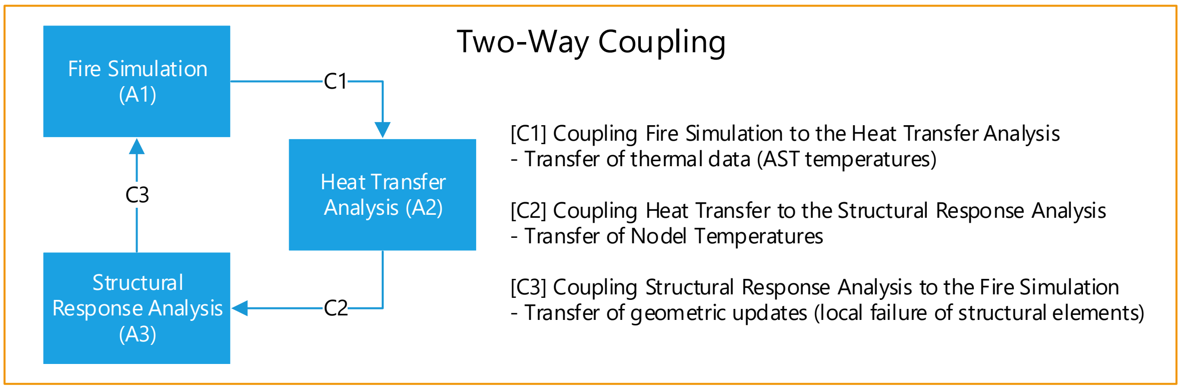

Two-Way Coupling
Fire Simulation (A1)
C1
Heat Transfer Analysis (A2)
C2
Structural Response Analysis (A3)
C3
[C1] Coupling Fire Simulation to the Heat Transfer Analysis
- Transfer of thermal data (AST temperatures)
[C2] Coupling Heat Transfer to the Structural Response Analysis
- Transfer of Nodel Temperatures
[C3] Coupling Structural Response Analysis to the Fire Simulation
- Transfer of geometric updates (local failure of structural elements)

Figure 3.2 – Flowchart for two-way coupling [simplified]

Based on the idea of a two-way coupling as a combination of multiple one-way coupling procedures. The various steps in a one way coupling procedure are studied and later expended to two way coupling. Basically it draws down to study the separate steps and then design coupling tools (scripts and programs) to facilitate this one and two way coupling. But before these procedures can be modelled a room should be designed as 'case study' for the coupling procedure. Therefore the first step comprises the design of a model room and fire scenario. All steps are discussed separately in the remainder of this chapter including references to chapters containing the information.

MODEL ROOM

A standard room model is developed to act as a starting point for the successive one- and two-way coupling analyses. The design of the room is based on an office building comprising a thin-walled steel structural façade. Both its geometric design and a corresponding fire scenario, based on its occupancy class, are discussed in chapter 4.

FIRE SIMULATION (A1)

For the fire simulation the software Fire Dynamic Simulator (FDS) and its accompanying visualization tool SmokeView are used. Using FDS the time and spatial varying thermal data is obtained for later use in the heat transfer analysis. More specifically the obtained thermal data consist of the adiabatic surface temperature of the structural elements under consideration. The concept of AST, as discussed in section 2.5, is used to limit the data transfer from fire simulation to heat transfer model. A detailed discussion on the fire simulation is included in chapter 5.

COUPLING FIRE SIMULATION TO THE HEAT TRANSFER ANALYSIS (C1)

The AST data from the fire simulation needs to be transferred to the subsequent heat transfer analysis. The output from FDS cannot be input directly and should be pre-processed for use in the FE software. It is important to note that the coupling from FDS to the HT simulation is assumed one-way, meaning the resulting structural temperature is not fed back to the fire model. Since the structural system under consideration is assumed adiabatic it will have constant temperature (room temperature) throughout the duration of the simulation. Thereby influencing the temperature generation in the model. The overall temperatures will be lower, compared to non-adiabatic behaviour, due to the constant temperature of the studied structural system. The coupling of the fire simulation to the heat transfer is discussed in section 6.3, the program developed to automate this coupling is discussed in section 7.3.

HEAT TRANSFER ANALYSIS (A2)

Finite Element software Abaqus is used to predict the thermal response of the structural system to the thermal load from the fire. All three modes of heat transfer, as discussed in section 2.4 are taken into account. The AST data is used to model convection and radiation to the structural model. Conduction is accounted for as a material property. The assumed steel quality is S355 and all required material properties comply with this selection. The heat transfer analysis is discussed in section 6.3.

COUPLING HEAT TRANSFER ANALYSIS TO THE STRUCTURAL RESPONSE ANALYSIS (C2)

The nodal temperature from the heat transfer analysis need to be transferred to the subsequent thermal response analysis to model the response, and possible failure, of the structural system to the increase in temperature. Both the heat transfer and structural response analysis are modelled using Finite Element software Abaqus thereby simplifying this coupling. The output from the HT analysis can be input directly in the SR analysis. Abaqus even allows the use of dissimilar meshes between the two analyses. So no additional mapping tools are required. It is important to note that the coupling is sequential, a one-way coupling. Both the heat generation due to rapid deformation and the disturbance of the conductance flow field, due to occurrence of gaps, are neglected since both are assumed negligible for the utilized time and structural scale. This coupling is discussed in more detail in section 6.4.

STRUCTURAL RESPONSE ANALYSIS (A3)

Finite Element software Abaqus is used to predict the structural response to the temperature increase. The nodal temperatures from the time varying nodal temperature data from the HT analysis is applied as a boundary condition on the structural response model. Due to the temperature increase the steel elements, assuming elastic plastic material behaviour, expand. This expansion is restricted thereby generating thermal stresses to allow (some of) this expansion the structural elements could bend and are therefore susceptible to buckling. This structural response could result in partial failure of the structural system thereby influencing the fire propagation. It is important to note that for this initial study the temperature dependency of the material properties are neglected. The structural response analysis is discussed in section 6.4.

COUPLING STRUCTURAL RESPONSE ANALYSIS TO THE FIRE SIMULATION (C3)

This initial study focusses on the effect of (partial) failure of the structural system on the propagation of the fire. It is not possible to model and study the effect of the relative small deformations (expansion and buckling) since the precision of the fire model is limited to its discretization. A failure criteria is required to determine if the structural system failed or not. For this study a simplified approach to failure is assumed which checks if the von Mises Stress in the structural system exceeds the yield stress. Geometric changes, based on aforementioned stress criterion, are then updated in the Fire, HT and SR models. The failure criteria and the script to predict (plate) failure are discussed in section 7.7 .The programs to automatically update the geometric changes in Fire Simulation, Heat Transfer, and Structural Response analysis are discussed in sections 7.4 - 7.6 respectively.

PROGRAMS AND SCRIPTS

Given the multiple simulations and coupling steps the coupling procedure quickly becomes a tedious, time consuming task. Not only because of the various iterations in the two-way coupled procedure but also because of the 'trial-and-error' throughout the development. Therefore scripts and programs, using programming language C++ and python, are developed to both facilitate the coupling steps and manage the complete coupling procedure. A brief overview of the various programs and scripts is listed below. For a detailed discussion on the scripts and programs is referred to chapter 7.

`FDS-2-Abaqus`	Master program managing the two-way coupling.
`reWriteAST2Py`	Program to rewrite FDS AST output for input in HT analysis.
`upGeomFDS`	Program to update the FDS model.
`upGeomHT`	Program to update the Heat Transfer model.
`upGeomSR`	Program to update the Structural Response model.
`PlateFailureCheck`	Script to check plate failure.

4. EXPERIMENTAL SETUP: MODEL ROOM

A standard room model is developed to act as a starting point for the successive one- and two-way coupling analyses. This room comprises thin-walled steel structural elements and acts as basis to proof the principle of two way coupling. The design and function (occupancy class), thin-walled steel façade, and fire scenario will be discussed consecutively in this chapter.

4.1 DESIGN

Thin walled steel façade systems are often applied in office buildings and industrial buildings. Therefore during the initial phase of this project an office function was selected as model room by association of thin walled steel structural systems with industrial/office like types of buildings

The traditional office building in the Netherlands is highly standardized and established according to fixed dimensions, modules, and building grids. Industrial manufactured prefabricated elements follow this principle. The conventional module in an office building comprises a module of 1,8 x 5,4 meters; a corridor of 1,8 meter with rooms of 5,4 meters in depth on both sides, as illustrated in Figure 4.1. The width of the module was either 1,8 or 2,4 meters. Flexibility is of primary importance in these types of office buildings and therefore the structural elements are often located along the façade and the corridor. Allowing a flexible layout for the space on both sides of the corridor using non-bearing partition walls. Due to the high vacancy rate (15%) these traditional office buildings are often repurposed to various function among which student rooms [26].

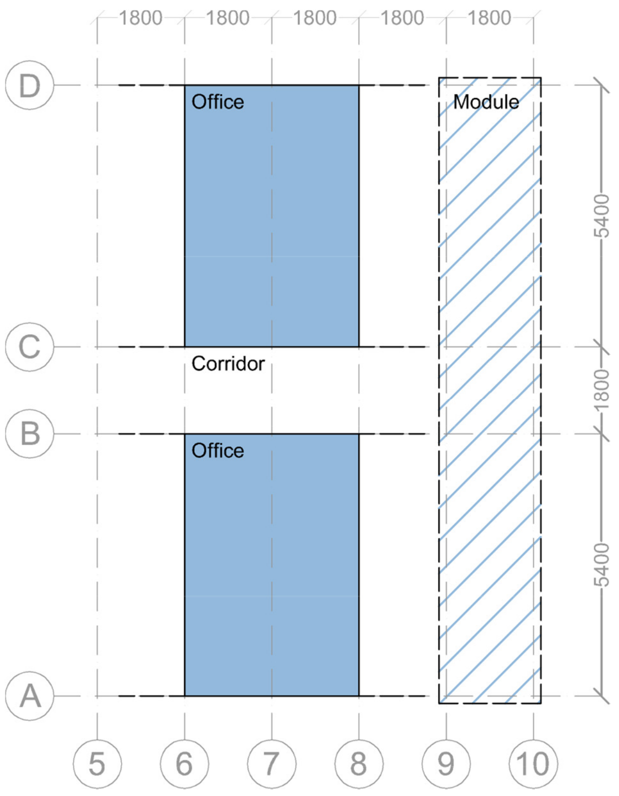


Figure 4.1 – Traditional Office Layout and Model Room Floor Plan

An office space of two modules is selected as model room, as illustrated in Figure 4.1. For this initial study the office space is isolated from the floor plan and modelled as a single room. Neighbouring rooms and the corridor will not be modelled. Meaning sufficient 'fresh' air can be drawn from the corridor into the office space and, if partial façade failure occurs, from the outside. Although this is still limited by the size of the openings. The façade will be constructed out of a thin walled steel structural system discussed in the next section. The remainder of the structural elements, walls and floors, consist of concrete. Therefore the non-bearing partition walls are, for simplicity, not modelled but assumed concrete. In later research a model can be developed to include a more detailed structural system and even represent a real life scenario. A sketch of the model room is included in Figure 4.2.

MODEL ROOM

- Width: 3,6 meters
- Depth: 5,4 meters
- Height: 2,7 meters
- Thin-Walled Steel Façade (1)
- Concrete Walls/Floors (2)
- (door) Opening to control air flow (3)

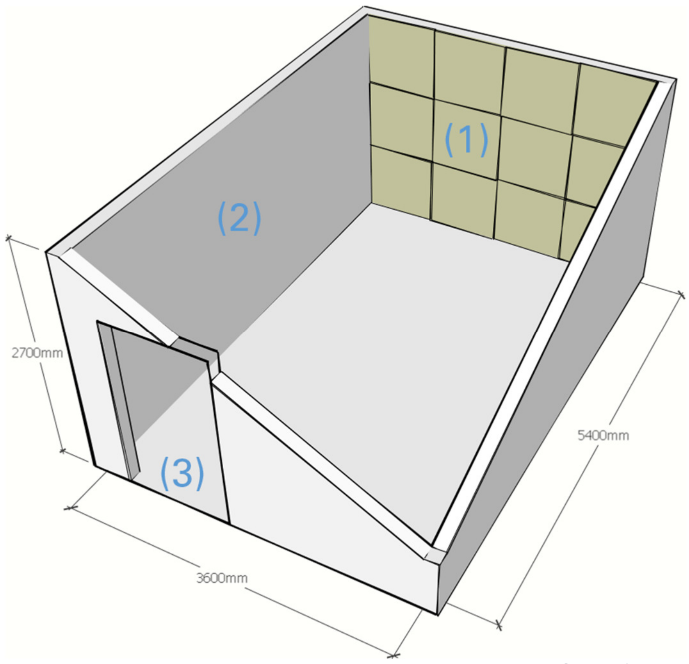


Figure 4.2 – Model Room design with Thin walled Steel façade (1), Concrete walls/floors (2) and (door) opening to allow air into the room (3)

4.2 THIN WALLED STEEL FAÇADE SYSTEMS

This section briefly discusses the various types of thin walled steel façade systems and the simplified structural approach for use in this initial research.

TYPES OF THIN WALLED STEEL FAÇADE SYSTEMS

Currently applied types of wall, cladding and roofing systems can be subdivided into three types as illustrated below in Figure 4.3 - Figure 4.5. In the first type steel sandwich panels, made of an insulation core between two face sheets, are supported by a steel frame of horizontal beams and vertical struts. The second type removes the requirement for a supporting frame by utilizing self-supporting sandwich panels. This type is also used to build complete units or buildings. The third type is a system consisting of liner tray-sheeting and insulation. Liner tray, also referred to as cassettes, span horizontally between the columns. Their open C-shaped cross-sections provide space for insulation material. Corrugated or trapezoidal sheeting, connected vertically to the liner tray lips, protect the insulation and complete the system. All three types can be referred to as thin walled steel façade systems utilizing thin walled steel and insulation materials.

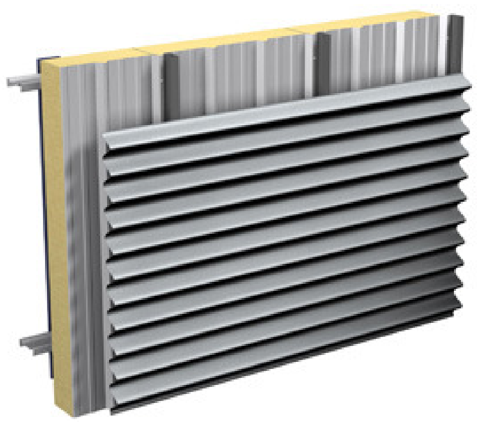


Figure 4.3 – Sandwich Panels on Steel Frame

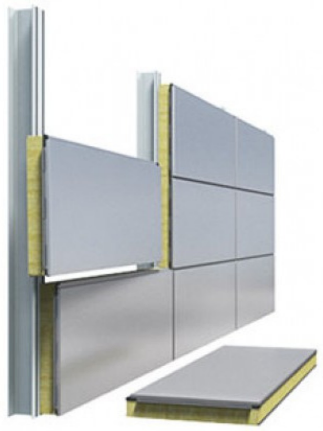


Figure 4.4 – Self-Supporting Sandwich Panels.

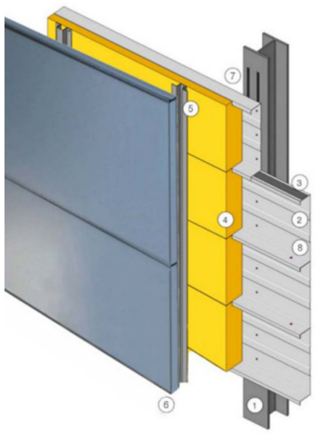


Figure 4.5 – Cassettes with insulation and External Sheeting

SIMPLIFYING THE THIN WALLED FAÇADE

The detailed modelling of thin walled steel façade systems is outside the scope of this initial research. But rather focusses on the effectiveness of two way coupling compared to one-way coupling and other types of fire simulations. A thin walled steel façade system of sandwich panels on a steel frame is selected as structural system. The panels are simplified to a single steel plate. Failure of a panel results in a direct connection to the outside (and thereby influencing the fire). The second simplification step is modelling the steel frame as boundary conditions, thereby omitting its modelled geometry from the calculations. The simplification procedure is illustrated in Figure 4.6 below, the full wall can be modelled as twelve separate panels.

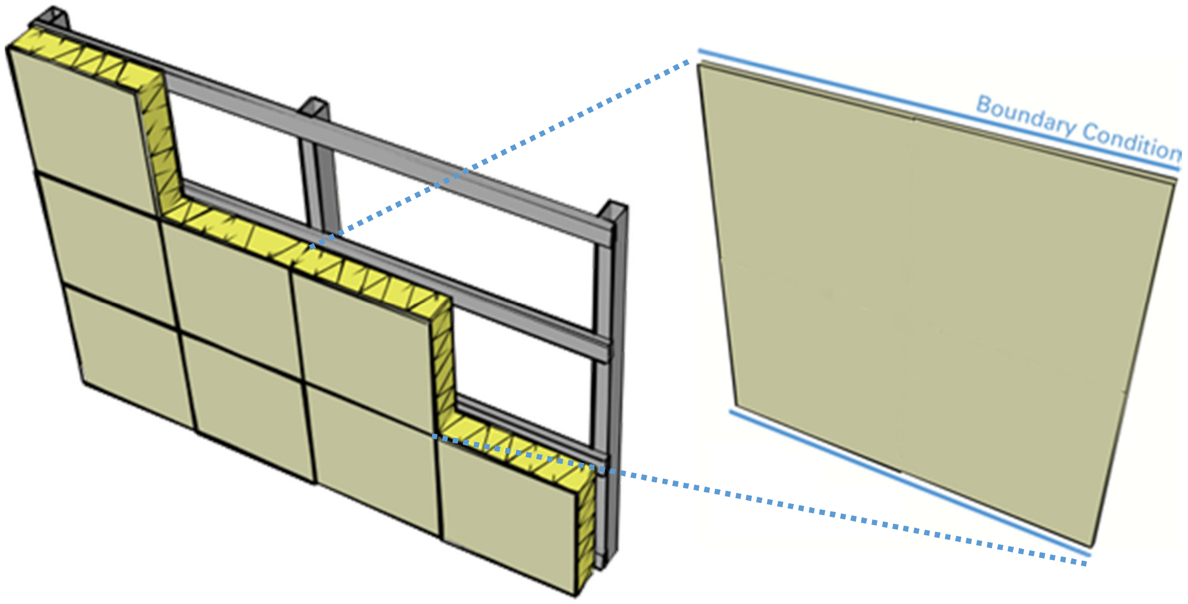


Figure 4.6 - Simplification of sandwich panels on thin walled steel frame

4.3 FIRE SCENARIO

In this section a fire scenario is designed based on literature and regulations as previously discussed in section 2.2. Based on Table 2.1 a fire load density of $q_{fi} = 700\ \mathrm{MJ/m^2}$ is selected for the office function (average of ~90% fractile). Based on the floor plan of the model room the net heat of combustion Q_{fi} can be expressed as

$$\begin{aligned} Q_{fi} &= q_{fi} \cdot A_{fi} \\ &= 700 \cdot 3{,}6 \cdot 5{,}4 \\ &= 1{,}36 \cdot 10^4\,\mathrm{MJ} \end{aligned}$$

The limit value for the heat release rate for an office function is $250\ \mathrm{kW/m^2}$. A fully developed fire is assumed with a linear decreasing decay phase initialized when 70% of the combustibles have been consumed [19]. The corresponding durations for these fully developed and decay phase can be expressed with equation 2.18. The fire scenario is summarized below in Figure 4.7.

$$\begin{aligned} t_1 \cdot A_{fi} \cdot HRR_f &= 0{,}7 \cdot Q_{fi} \\ \tfrac{1}{2} \cdot t_2 \cdot A_{fi} \cdot HRR_f &= 0{,}3 \cdot Q_{fi} \end{aligned} \qquad 2.18$$

FIRE SCENARIO

- $q_{fi} = 700\ \mathrm{MJ/m^2}$
- $Q_{fi} = 13600\ \mathrm{MJ}$
- $t_{fi} = 3650\ \mathrm{s}$
- $t_0 = 10\ \mathrm{s}$
  Duration flashover phase
- $t_1 = 1960\ \mathrm{s}$
  Duration fully-developed phase
- $t_2 = 1680\ \mathrm{s}$
  Duration decay phase

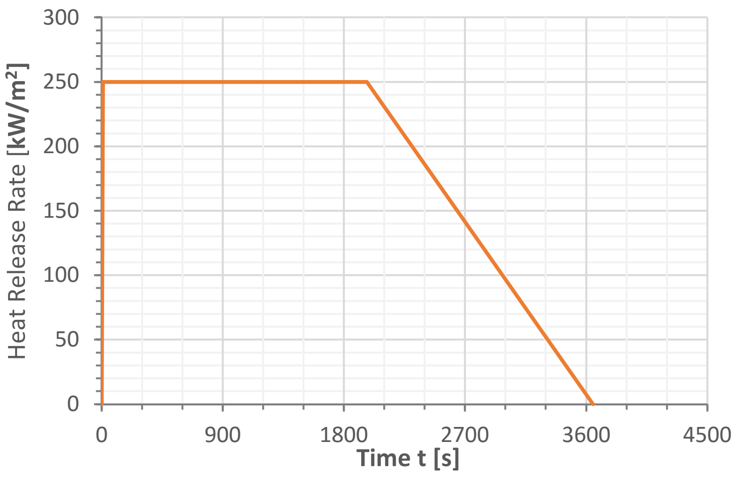


Figure 4.7 – Fire Scenario for Model Room

5. SIMULATING FIRE WITH FIRE DYNAMIC SIMULATOR

This chapter discusses the fire simulation using Fire Dynamic Simulator (FDS). The first section describe briefly the fire dynamic simulator software and its accompanying visualization tool SmokeView. In the subsequent sections both the coding and running of an FDS simulation are discussed in detail. The last section discusses the modification of the fire model during the simulation.

5.1 FIRE DYNAMIC SIMULATOR (FDS)

Fire Dynamics Simulator (FDS), is a computational fluid dynamics (CFD) program that describes the propagation of fire by numerically modelling the fire-driven fluid flow. FDS solves a Large Eddy Simulation (LES) form of the Navier-Stokes equation with an emphasis on smoke and heat transport. FDS is freeware developed by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce, in cooperation with VTT Technical Research Centre of Finland [27]. Detailed information on the mathematical model discussing the numerical algorithm is discussed in the FDS Technical Reference Guide [28]. For Verification and validation of the model is revered to the FDS verification [29] and validation [30] guide respectively. Smokeview is accompanying visualization software that is used to display the results of an FDS simulation. For a detailed description of Smokeview is referred to the Smokeview User's Guide [31]. Figure 5.1 shows the Smokeview visualization of the room fire simulation included in the FDS code at 150s into the simulation.

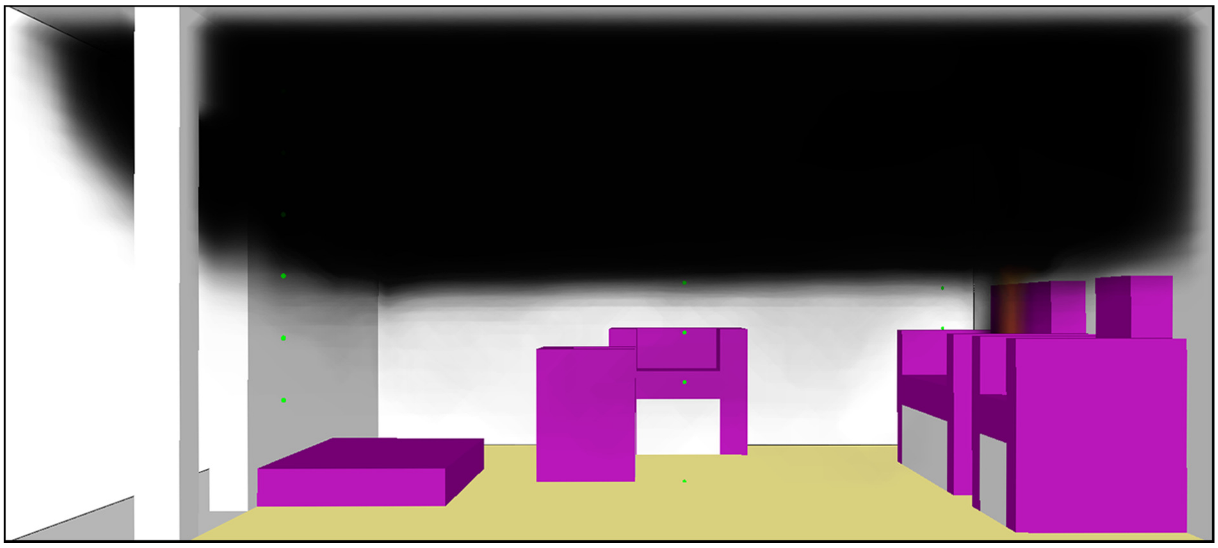


Figure 5.1 – Smokeview snapshot at 150s into the room fire simulation

FDS is based on the programming language Fortran. An ASCII text input file is needed to supply FDS with the necessary information to describe the fire scenario. The commands listed in the input file are organized into namelist groups. The name of the namelist group, and its comma-delimited list of input parameters is put between an ampersand character, &, at the beginning and a forward slash, /, at the end. An example is the following namelist group that describes the global dimensions and the resolution, the domain and its mesh, of the simulation. Input files will be discussed in more detail in the following section.

```
&MESH IJK=80,40,20, XB=0.0,16.0,0.0,8.0,0.0,4.0 /
```

The aim of FDS is to solve practical fire problems in fire engineering and to provide a tool for studying fire dynamics and propagation. Its first version was released to the public in February 2000. Its main applications comprise the design of smoke handling systems and sprinkler/detector activation studies and the reconstruction of industrial and residential fires.

FDS version 6.1.12 is used throughout this report.

5.2 WRITING AN FDS INPUT FILE

This paragraph discussed the writing (and running) of an FDS input file. Complete FDS input file with detailed explanation are included in Appendix X. For additional information on writing and running FDS input files and all possible namelist groups and attributes, is referred to the FDS User's Guide [27] .

FILE STRUCTURE

An FDS Input File (*.fds) is written from `&HEAD` to `&TAIL`. In between its `&HEAD` and `&TAIL` the namelist records can be included in any order in the input file. Typically the namelist records are organized in a systematic way with general information near the top while detailed information, like obstructions and devices are listed towards the end. Each time FDS processes a namelist group it scans the whole input file. It is advised to liberally include comments to increase the (re)readability of the input files. Ensure that these comments do not fall within the namelist records by preceding them with one (or more) forward slash characters.

The namelist group `&HEAD` contains two attributes: `CHID` and `TITLE`. `CHID` is a string of up to 30 characters used to tag output files. The `TITLE` attribute is a string of up to 60 characters describing the simulation. These attributes are of great importance in organizing various simulations. The `&TAIL` namelist record ensures that FDS reads the entire file. The `&HEAD` is often followed by the `&TIME` namelist group describing the initiation (`T_BEGIN`) and duration (`T_END`) of the simulation. If `T_BEGIN` and `T_END` are equal to each other FDS only generates the model set-up allowing one to check the model set-up before running the simulation.

For illustrative purposes a (very) generalized input file is listed below.

```
&HEAD CHID='FirstFDS', TITLE='My First FDS Simulation' /
&TIME T_END=300 /
// General Information
// Detailed Information
&TAIL /
```

GEOMETRY

The FDS calculations are performed within a domain that is made of rectilinear volumes called meshes. Each mesh is divided into rectangular cells. Increasing the number of cells increases the resolution and required computational time of the simulation. This computational domain is defined using the `&MESH` namelist group.

A mesh is a rectangular box with a coordinate system that conforms to the right hand rule. Its dimensions are defined by the attribute `XB`, containing a string of six numbers describing the origin and opposite corner of the domain. The first, third and fifth value define the origin point and the second, fourth, and sixth the opposite corner. The attribute `IJK` describes the number of cells within the mesh in respectively the x, y, and z direction. For instance the input line listed below creates a domain of $xyz = 9.0 \cdot 3.6 \cdot 2.7 \text{ m}^3$ subdivided into cells of $xyz = 0.3 \cdot 0.3 \cdot 0.3 \text{ m}^3$

```
&MESH IJK=30,12,9, XB=0.0,9.0,0.0,3.6,0.0,2.7 /
```

The envelope of the domain consist of external walls. Additional obstructions describing the geometry of the model can be introduced with the `&OBST` namelist group. Each `&OBST` line describes a rectangular solid in the flow domain. Like the domain it is defined using the attribute `XB` containing a string of six numbers defining the origin and opposite corner of the rectangular obstruction. The (surface) boundary conditions of the obstruction can be specified with the attribute `SURF_ID`, which refers to a corresponding `&SURF` line. The `&SURF` namelist group is discussed in more detail below. The level of detail of the model and its obstructions is limited by cell size. In other words: the dimensions of obstructions are scaled and fitted to nearby cells.

It is self-evident that when one wants to model a wall containing a door or window it would be a tedious task to split this wall in separate rectangular components. The `&HOLE` namelist group can be used to carve a hole out of an existing obstruction or set of obstructions. As with `&OBST` the attribute `XB` is used to define the size and location of the `&HOLE` object. Any solid mesh cells intersecting with the object are removed.

The `&SURF` namelist group is used to define attributes for all solid surfaces or openings within the flow domain. The default boundary condition is that of an inert wall at fixed temperature. Each `&SURF` line is identified with an identification string `ID='<name>'`. This string is used to reference to the `&SURF` line by the `&OBST` and `&VENT` namelist groups using the character string `SURF_ID='…'`. If a `SURF_ID` is omitted from an `&OBST` or `&VENT` line the default surface properties are applied. One can overwrite the boundary condition by including `DEFAULT=.TRUE.` on the `&SURF` line.

Material properties can be prescribed using the `&MATL` namelist group. Various material properties like density, conductivity, specific heat, and emissivity can be prescribed. The `&MATL` line is identified with an identification string `ID='<name>'`. This string is used to reference to the `&MATL` line by the `&SURF` line (which in turn is referred to by a `&VENT` or `&OBST` line).

The `&VENT` namelist group is used to apply a particular boundary condition to a rectangular patch on a solid surface. Historically the `&VENT` attribute allowed for air to be blown into or sucked out of the computational domain but has since evolved well beyond its initial role. The attribute `XB` is used to describe the dimension and location of the patch. Since a plane is described two of the six coordinates must be the same within the `XB` attribute. Alternatively, the attribute `MB` (Mesh Boundary) can be used to easily select limiting planes of the mesh. As previously discussed each `&VENT` includes a character string `SURF_ID` referring to a set of boundary conditions described on the corresponding `&SURF` line. A special type of (reserved) `SURF_ID` is `'OPEN'` denoting a passive opening to the outside and can only be used if the `&VENT` is applied to an exterior boundary of the computational domain.

Combining the namelist groups discussed in this section, the input lines below create a concrete box with a large opening in direct contact with the outside. The Smokeview visualization is shown in Figure 5.2.

```
…
&MESH IJK=30,12,9, XB=0.0,9.0,0.0,3.6,0.0,2.7 /
&SURF   ID='CONCRETE_S',
        MATL_ID='CONCRETE_M',
        THICKNESS=0.3,
        COLOR='GRAY',
        DEFAULT=.TRUE. /
&MATL   ID='CONCRETE_M',
        DENSITY=1800,
        CONDUCTIVITY=1.15,
        SPECIFIC_HEAT=1.00,
        EMISSIVITY=0.80,    /
&OBST XB=1.8,1.8,0.0,3.6,0,2.7 /
&HOLE XB=1.6,2.0,0.6,3.0,0.0,2.1 /
&VENT XB=0.0,1.8,0.0,3.6,0.0,0.0, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,0.0,3.6,2.7,2.7, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,0.0,0.0,0.0,2.7, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,3.6,3.6,0.0,2.7, SURF_ID='OPEN' /
&VENT MB='XMIN', SURF_ID='OPEN' /
...
```

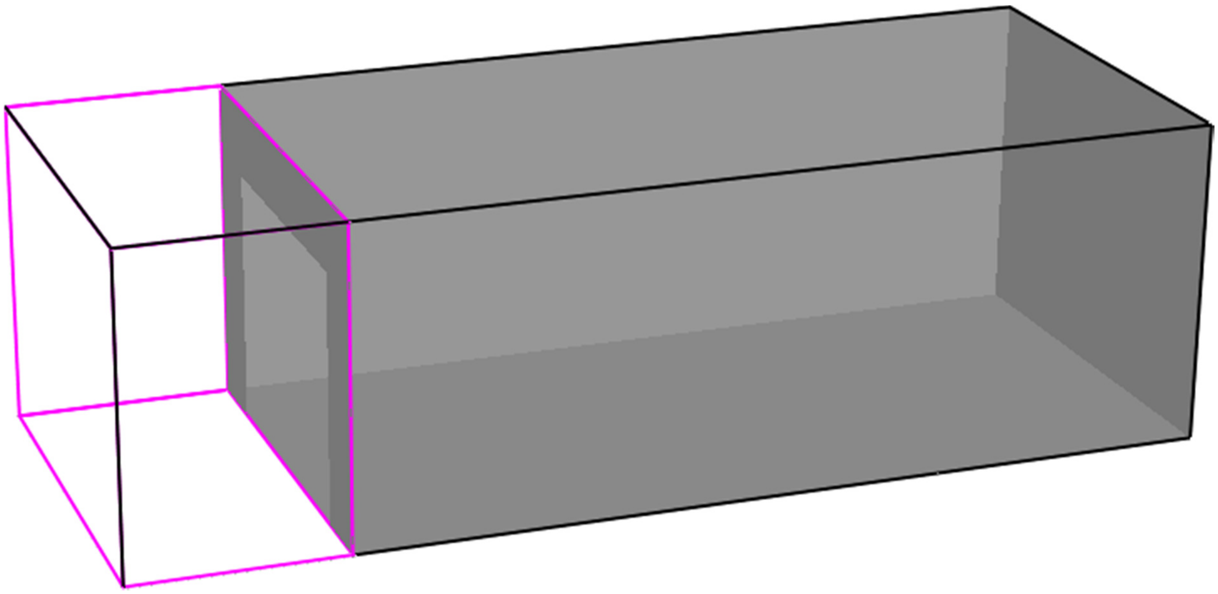


Figure 5.2 – Basic FDS Model Utilizing Geometry Namelist Groups

SIMULATING FIRE

In section 4.3 a fire scenario was developed. This fire scenario needs to be modelled in FDS. For example

```
…
&SURF ID='fire',HRRPUA=250 ,TMP_FRONT=20,COLOR='RED' /
&VENT XB=1.8,7.2,0.0,3.6,0.0,0.0, SURF_ID='fire' /
...
```

generates a fully developed fire on the entire surface area of the office floor. To accurately model the fire scenario discussed previously the `&RAMP` namelist group is used. The input lines

```
…
&SURF ID='fire',HRRPUA=250,RAMP_Q='fire_r',TMP_FRONT=20,COLOR='RED' /
&RAMP ID='fire_r',T=   0,F=0. /
&RAMP ID='fire_r',T=  10,F=1. /
&RAMP ID='fire_r',T=1970,F=1. /
&RAMP ID='fire_r',T=3650,F=0. /
&VENT XB=1.8,7.2,0.0,3.6,0.0,0.0, SURF_ID='fire' /
...
```

accurately describe the fire scenario. The heat release increases linearly from 0 to 250 kW/m² in the first 10 seconds of the simulation and remains constant for 1960 seconds. After that it drops linearly to 0 kW/m² over the course of 1680 seconds. If the simulation duration would be increased the heat release would remain constant at 0 kW/m², the last defined value.

The heat released by the aforementioned input lines cannot be generated out of thin air but need to be generated by a combustion reaction. This combustion reaction has been discussed in detail in 4.3 but needs to be included in the input file. Combustion reactions are prescribed in FDS using the `&REAC` namelist group.

The default combustion model in FDS is that of single-step mixing controlled combustion, in which the reaction of fuel and oxygen is infinitely fast and only controlled by mixing, hence the label. This approach is referred to as the 'simple chemistry' combustion model. FDS considers a single fuel species that is composed primary of Carbon (C), Hydrogen (H), Oxygen (O), and Nitrogen (N) reacting with oxygen (O_2) to form Water (H_2O), Soot (mainly C), Carbon dioxide (CO_2), Carbon monoxide (CO), and Nitrogen (N_2). This 'simple chemistry' approach can be expressed in a chemical equation as shown in equation 2.19

$$\mathrm{C_xH_yO_zN_v} + v_{O_2}\mathrm{O_2} \rightarrow v_{CO_2}\mathrm{CO_2} + v_{H_2O}\mathrm{H_2O} + v_{CO}\mathrm{CO} + v_S\mathrm{Soot} + v_{N_2}\mathrm{N_2} \qquad 2.19$$

The stoichiometric coefficients are automatically calculated by FDS. To accurately calculate these values from the chemical formula the post combustion yields of CO, soot and volume fraction of Hydrogen in the soot, need to be defined. The default values for the post combustion yields are 0. The total energy released by the combustion can be computed by taking the sum of the net change in mass for each species multiplied by the species enthalpy of formation. Various enthalpy of formations values are included in FDS and listed in table 11.1 in the FDS User's Guide [27]. If the fuel species is not included in table 11.1 of the FDS User's Guide there are various options to specify the missing enthalpies. In the first option one can specify the unknown enthalpy on a separate species, `&SPEC`, line in kJ/mol. Secondly, if only the enthalpy of formation of the fuel is missing, the heat of combustion can be directly specified on the `&REAC` line in kJ/kg. Lastly, if enthalpies are missing and no heat of combustion is specified, the heat of combustion is computed based on the amount of energy released per unit mass of oxygen consumed.

The combustion reaction discussed in section 4.3 can be included by defining both a `&REAC` line and defining the enthalpy of formation of cellulose on a `&SPEC` line as listed below. Alternatively the heat of combustion could be directly specified on the `&REAC` line.

```
…
&SPEC    ID = 'CELLULOSE',
         FORMULA = 'C4H6O3',
         MW = 102.0886
         ENTHALPY_OF_FORMATION=-5.13E2 /
&REAC    FUEL = 'CELLULOSE' /
...
```

Combining the namelist groups discussed in this section a (ramp based) fire can be simulated as illustrated with the Smokeview visualization in Figure 5.3.

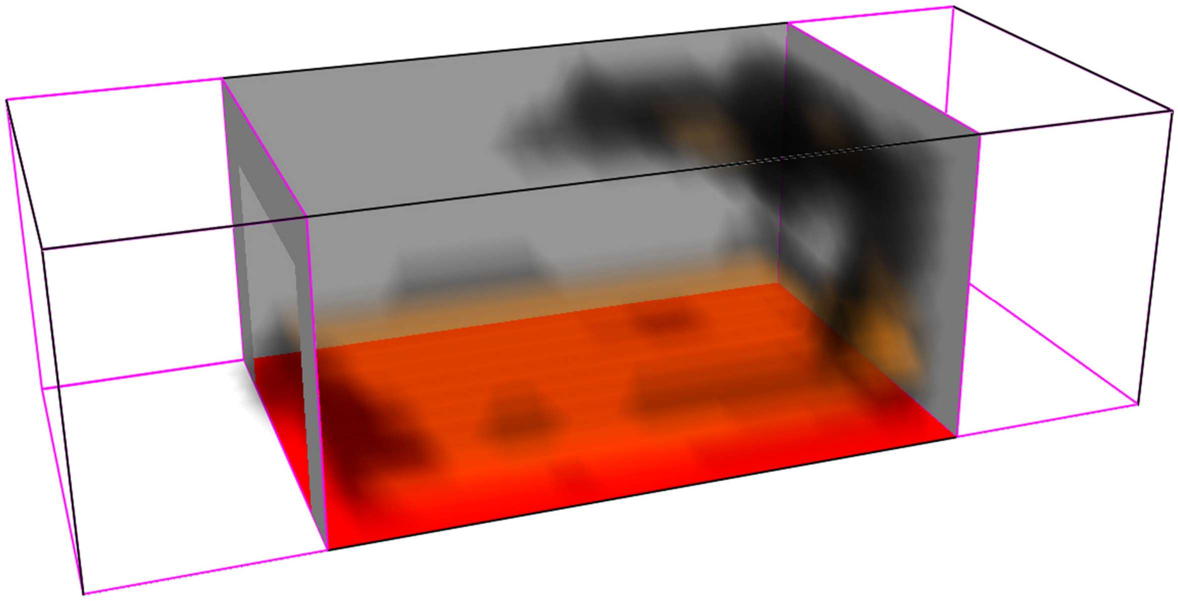


Figure 5.3 – Basic FDS Fire Simulation with Cellulose Combustion Reaction

Alternatively one can model an interior using `&OBST` and assigning calorific values in the `&MATL` namelist group. This allows one to accurately model a fire compartment, its interior and its encompassed calorific energy. This will not be discussed further but a good example is found in the room_fire model included in the FDS installation.

SPECIFYING OUTPUT

To effectively couple the fire simulation to a subsequent heat transfer analysis AST data needs to be extracted at specific locations in the fire model. By default FDS outputs the total Heat Release and related quantities to an output file called `CHID_hrr.csv`. Additional data can be requested using devices designated via the `&DEVC` namelist group. Devices can be used to record some location dependent quantity of the simulated environment or to trigger events. This section will focus on obtaining specific data using devices. As an example the line

```
…
&DEVC XYZ=7.2,2.475,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
      ID='AST_1A', IOR=-1 /
...
```

creates a device at position `XYZ` that records the `QUANTITY` adiabatic surface temperature. A device is characterized with an unique character string `ID`. This descriptive string is used to identify the device in the output files. `IOR` is an abbreviation of Index of Orientation and should be defined for any device placed on the surface of a solid. Its value depicts the direction the device points, where the values ±1, ±2, or ±3 correspond to respectively the positive or negative x,y, or z direction. The above device is actually positioned on the back wall of the fire model illustrated in Figure 5.3 hence the '-1' direction. Various AST output devices should be included in the input file to obtain sufficient temperature data for use in the subsequent thermomechanical analysis.

An overview of frequently used `QUANTITY` attributes is given in table 16.3 of the FDS User's Manual. For additional reading and information on defining more complex devices like smoke detectors and sprinklers is referred to chapter 15 of the FDS User's Manual [27].

RUNNING THE SIMULATION

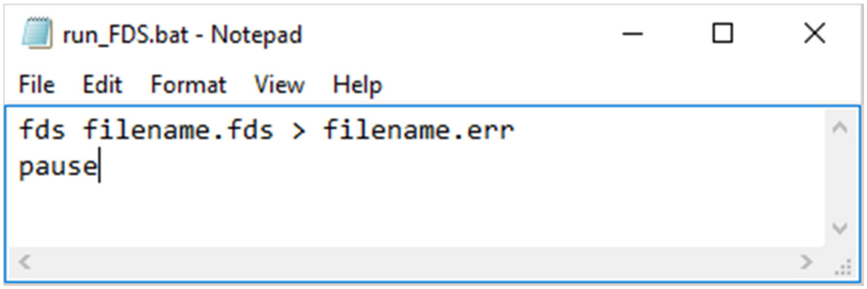
FDS is run from command prompt by first locating the correct path and then using the command:

```
fds inputfile.fds
```

The string contained in the `CHID` attribute in the `&HEAD` namelist group of the input file is associated with the ouput files generated by the simulation. Detailed diagnostic information is automatically written to a file `CHID.out`. Screen output can be redirected to a file by the command

```
fds inputfile.fds  > inputfile.err
```

Alternatively one can create a batch file (*.bat) in the folder of the input file and include the code above the directly run the simulation without the necessity to browse to the path using the command prompt. An example of such a batch script is listed below. The `pause` command interrupts closing of the cmd prompt until `'any key'` is pressed. This way one can check the simulation (or possible errors) before closing it.



```
fds filename.fds > filename.err
pause
```

It is also possible to associate the *.fds file extension with FDS, if associated one can run the simulation by double clicking the *.fds file (Windows 10 automatically associates *.fds files with FDS). Keep in mind that rerunning a simulation without changing the `CHID` attribute in the `&HEAD` namelist group will overwrite previous output.

5.3 MODIFYING THE FIRE MODEL DURING SIMULATION

In order to successfully perform the two way coupling of a fire model and a thermomechanical analysis one needs to iterate through the various analysis steps. So first simulate for x iterations and checking for plate failure in subsequent thermomechanical analysis. If failure occurs update the FDS model and continue with the next iteration. The ideal case being when x = 1. Independent of the iteration size one should be able to stop the calculation wait for the output of the thermomechanical analysis and possibly remove a panel based on this outcome and continue to the next iteration. These steps: stopping the simulation, restarting the simulation and changing the model during (or in between) simulations are required in order to be able to perform a two-way coupled thermomechanical analysis and will be discussed in the remainder of this paragraph.

INTERRUPTING A FDS SIMULATION

There are two ways to interrupt (or kill) a FDS simulation. The first possibility is by creating a dummy file `CHID.stop` in the simulation path. In which `CHID` refers to the tag string defined in the `&HEAD` namelist group that is used to name all output files. The second possibility is by using a device (`&DEVC`) to trigger a control function (`&CTRL`). As an example the following lines will interrupt the simulation when the simulation time reaches 300 seconds.

```
…
&DEVC XYZ=0.1,0.1,0.1, ID='Trigger', SETPOINT=300.0, QUANTITY='TIME' /
&CTRL ID='Stop_Simulation', FUNCTION_TYPE='KILL', INPUT_ID='Trigger' /
…
```

RESTARTING A FDS SIMULATION

FDS requires a restart file `CHID.restart` in order to restart a simulation after interruption. FDS can create restart files periodically by including the attribute `DT_RESTART='Seconds'` on the `&DUMP` line in the input file. This is especially valuable in very long simulations as a safety measure against random crashes or a power outage. As an example the following line should be included to create restart files every 300 seconds (simulation time, not real time).

```
…
&DUMP DT_RESTART=300.0 /
…
```

Alternatively a restart file can be generated with a `&CNTR` function and a corresponding `&DEVC` trigger, similar to the `KILL` function discussed previously. As an example the following lines will interrupt the simulation when the simulation time reaches 300 seconds, and at the same time, create a restart file.

```
…
&DEVC XYZ=0.1,0.1,0.1, ID='Trigger', SETPOINT=300.0, QUANTITY='TIME',
      LATCH=.FALSE. /
&CTRL ID='Stop_Simulation', FUNCTION_TYPE='KILL', INPUT_ID='Trigger',
      LATCH=.FALSE. /
&CTRL ID='Create_Restart', FUNCTION_TYPE='RESTART', INPUT_ID='Trigger',
      LATCH=.FALSE. /
…
```

Since multiple changes of state are required the attribute `LATCH=.FALSE.` is included. A latch can only change state a single time and therefore, if excluded, the simulation would not be interrupted and no restart file would be generated after the first iteration.

To restart a simulation from a restart file the line the attribute `RESTART=.TRUE.` should be included on the `&MISC` line. The output from the restarted simulation is appended to the output files from the original simulation. Alternatively the attribute `RESTART_CHID='some_name'` can be specified on the `&MISC` line to restart the simulation from a specific restart file and write the output to output files tagged with the `CHID` as defined in the `&HEAD` line.

The FDS user manual specifically states that between stops and restarts major changes cannot be made to the fire model. The changes are limited to those attributes that do not directly influence the existing flow field. The removal (or addition) of obstructions would directly influence the flow field and are therefore not allowed. Meaning it is impossible to simply delete the obstructions that, as a result of the subsequent thermos-mechanical analysis, have failed. A solution is discussed in the next section.

TIME-CONTROLLED OBJECT REMOVAL

Similar to the device trigger controlling the previously discussed `KILL` and `RESTART` function a device can be defined to (de)activate an obstruction. The following lines will deactivate the obstruction `Plate_08` after 300 seconds.

```
…
&OBST XB=7.2,7.2,0.9,1.8,0.9,1.8, DEVC_ID='Plate_08' /
&DEVC XYZ=0.1,0.1,0.1, ID='Plate_08', SETPOINT=300.0, QUANTITY='TIME',
      INITIAL_STATE=.TRUE. /
…
```

Time-Controlled Object Removal can be utilized as a solution to the inability to remove obstruction between the stop and restart of a simulation. Initially a unique timed removal should be defined for all plates with a trigger time outside the simulation time. Given a simulation with a total simulation time of `T_END=3650`, the following lines define the deactivation of `Plate_08` after 3700 seconds. Since the simulation only last for 3650 seconds the plate will never be removed and will still be there at the end of the simulation.

```
…
&TIME T_END=3650 /
&OBST XB=7.2,7.2,0.9,1.8,0.9,1.8, DEVC_ID='Plate_08' /
&DEVC XYZ=0.1,0.1,0.1, ID='Plate_08', SETPOINT=3700.0, QUANTITY='TIME',
      INITIAL_STATE=.TRUE. /
...
```

Assuming above lines are used in a two-way coupled thermo-mechanical simulation. After a couple of iteration steps at, for instance, 1200 seconds the mechanical analysis returns failure of `Plate_08`. Before restarting the FDS simulation the `SETPOINT` attribute should be changed to remove the plate from the simulation. The removal can occur directly at the restart of the simulation since FDS ‘knows’, due to the time controlled object removal device, that the obstruction will be removed at some point. Thereby invalidating the non-altering for the existing flow field. The following lines show the updated lines for the next iteration of the input file incorporating the removal of the plate after the mechanical analysis returned failure of `Plate_08`.

```
…
&TIME T_END=3650 /
&OBST XB=7.2,7.2,0.9,1.8,0.9,1.8, DEVC_ID='Plate_08' /
&DEVC XYZ=0.1,0.1,0.1, ID='Plate_08', SETPOINT=1200.0, QUANTITY='TIME',
      INITIAL_STATE=.TRUE. /
...
```

With the namelist groups and corresponding attributes discussed in this chapter it is possible to create, run, interrupt and restart FDS simulations. In addition obstructions can be removed at a moment in time slightly after obstruction failure is measured by the subsequent mechanical analysis. This removal is governed by time-controlled object removal. It is self-evident that the increase in iterations (coupling cycles) limits the time difference between the measured failure time and the moment in time at which the panel is removed from the simulation. For a few iterations this is possible to do by hand but soon this becomes a tedious task. Therefore this process should be automated. For additional reading on the coupling programs used in the two-way coupling of fire simulations to the thermomechanical analysis is referred to chapter 7.

6. ABAQUS ANALYSIS

The finite element code used throughout this study is Abaqus. This software will be discussed briefly in the following section. In the remainder of the chapter the basic model setup, the heat transfer model and analysis, the structural response model and analysis, multiple plate models, restart analysis, and plate removal will be discussed sequentially.

6.1 ABAQUS CAE

The Abaqus Complete Abaqus Environment (CAE) is part of the Abaqus product suite for finite element analysis and computer aided design. The full suite offers powerful and complete solutions for both routine and sophisticated engineering problems covering a vast spectrum of industrial applications. The first version of Abaqus was released in 1978 by a company called HKS, renamed to Abaqus inc. in 2002 and acquired by Dassault Systèmes in 2005 [32].

The finite element method is a numerical method for solving systems of differential equations to predict structural response. The finite-element method divides a structural model in a limited, hence the name finite, number of elements. These elements are interconnected through nodes and governed by boundary conditions. The connected nodes, for instance, should displace equally. By dividing the structural model in a finite number of elements the complex differential equations can be approximated by matrix calculations. By increasing the number of elements the solution converges to the analytical solution.

The approach to a finite element problem can be split in three consecutive steps as illustrated in Figure 6.1. The first step is pre-processing, a representative model is defined and subjected to boundary conditions describing the problem at hand. In the simulation a Finite element solver is used to obtain numerical solutions to the given problem. During post-processing the previously obtained results are used to interpret the response of the model to the boundary conditions. Abaqus CAE is used for the pre-processing and post-processing of the finite element analysis. For the simulation either the Abaqus/Standard or Abaqus/Explicit finite element solver is used. In which the former employs an implicit and the latter an explicit integration scheme.

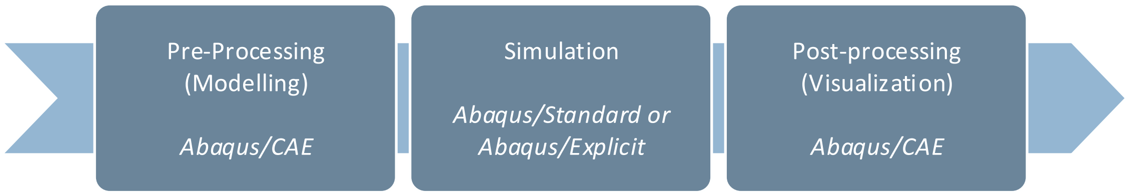


Figure 6.1 – Approach to a finite element problem.

Each step in the above approach is challenging on its own. One could state that a basic understanding of the modelling, simulation and visualization process is required to obtain valid results. The extensive documentation included in Abaqus CAE, and available online, could be of help in this process. This documentation consist of guides on modelling and visualization, analysis, examples, benchmarks and basic tutorials. In addition reference guides on theory, verification and scripting are available [33].

Abaqus is based on program language Fortran. In the pre-processing phase one either inputs all parameters directly in the GUI, or by using scripts based on the Python language. Some tasks would be practically impossible or very time consuming when only using the GUI. Abaqus uses programing language C for writing the output database. A basic understanding of these different programming languages helps in efficiently using Abaqus to solve problems.

Abaqus CAE version 6.14 is used throughout this report.

6.2 BASIC MODEL

This paragraph discusses the basic model setup and explains some basic Abaqus terminology. It is assumed that the reader has basic knowledge on finite element modelling in Abaqus, if not, there are countless tutorials available online. The modelling process in Abaqus consist of the following steps: geometry definition, material properties, mesh generation and element selection, creating boundary conditions, and the analysis step. These steps are discussed separately in the remainder of this section.

GEOMETRY

A physical structural model is typically created by assembling various components, Abaqus mimics this physical process. In an Abaqus model the separate components are called *part-instances*, assembled into one structural model called the *assembly*. As an example the steel frame from Figure 6.2 consist of respectively three plate, three girts, and two column *part-instances* combined into one steel frame *assembly*.

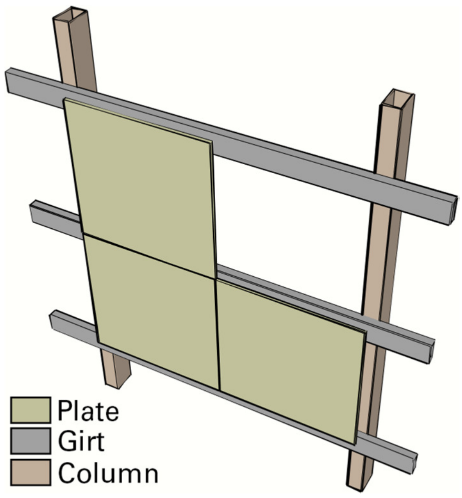


Figure 6.2 – Steel Frame Assembly Consisting of Plate, Girt, and Column Part-Instances

The structural model from Figure 6.2 can be further simplified by omitting the steel frame. The connection of the plate to the girts can be modelled with a simple (hinged) boundary condition. In addition each plate is subdivided into four *temperature partitions*. With these temperature partitions the surface of the plate is subdivided into four sub-surfaces allowing heat transfer to be defined for each of those *temperature partitions*. The single plate model is included in Figure 6.3.

For the initial study four temperature partitions are selected to allow for conductive heat transfer within the plate due to temperature differences in between the different partitions. The heat transfer analysis for a single plate is discussed in detail in the next paragraph.

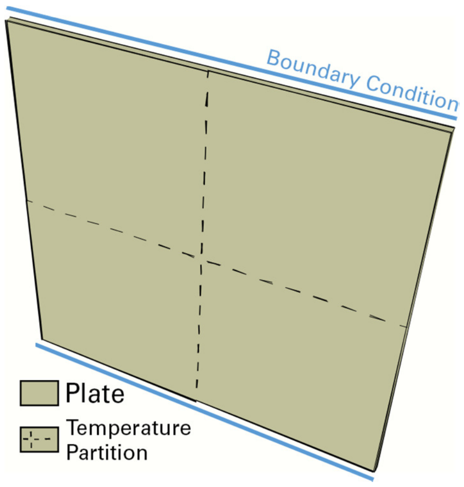


Figure 6.3 – Single Plate Sketch of Abaqus Model including Temperature Partitions and Boundary conditions.

MATERIAL PROPERTIES

Various material properties can be described using the material module in Abaqus. Steel S355 is selected as material for the plates. For this initial study material properties are assumed to be independent of temperature. The required material properties for the heat transfer and subsequent structural response analysis are discussed in their corresponding sections.

MESH GENERATION

As previously discussed in finite element analysis the model is divided in a finite number of elements for which the complex differential equations can be approximated by matrix calculations. The subdivision into separate elements is called the mesh. Each element in the mesh is then assigned an element type with corresponding element properties. There are a wide range of element types available in Abaqus for which is referred to the Abaqus Analysis User's Guide chapters 27 – 33 [33].

Shell elements are often used when the thickness of the shell is small compared to the typical dimensions in the shell surface. With shell elements a three dimensional continuum is approximated using a, more economical, two-dimensional theory. Shell elements will be used throughout this study since the nature of the model 'plates on a frame', have a relative small thickness compared to its surface dimensions.

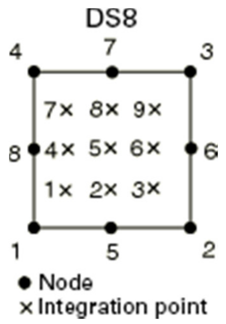


Figure 6.4 – DS8 Heat Transfer Element

The element type DS8 will be used for the heat transfer analysis and the element type S8R for the sequentially coupled stress/displacement analysis. These elements are illustrated in Figure 6.4 and Figure 6.5. In Abaqus the element name identifies its primary element characteristics. Element DS8 is an 8-node quadrilateral Heat Transfer Shell Element and element S8R is an 8-node doubly curved Stress/displacement shell element with reduced integration. Reduced-order integration allow for fast and cheap calculation of the element matrices but may have significant effect on the accuracy of the element.

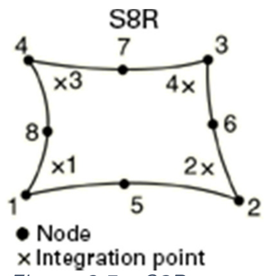


Figure 6.5 – S8R Stress/Displacement Element

Stresses (and temperatures) are accurately calculated in the *integration* (Gauss) *points* using Gaussian quadrature method to numerically approximate the integrals. The locations of the shell elements are illustrated in Figure 6.4 and Figure 6.5. *Section Points* are the equally spaced integration points over the thickness of the shell. The typical number of *section points* is five.

BOUNDARY CONDITIONS

The step module controls the incrementation and duration of the simulation. Boundary conditions (and loads) are applied during the initial step or a newly defined step. The heat transfer analysis is independent of support boundary conditions since no displacement is involved. For the structural response analysis hinged (line) supports are imposed on the top and bottom edge of the plate to simulate the connection of the plate to the girts (see also Figure 6.4 and Figure 6.5). The load in the heat transfer analysis is controlled by the convective and radiative flux as result of the adiabatic surface temperature from the corresponding FDS fire simulation. The load step in the structural response analysis are governed by the nodal temperatures from the heat transfer analysis inducing thermal expansion resulting in thermal stresses and displacements due to bending.

ANALYSIS

An Abaqus analysis is run by first creating a job and then submitting this job for analysis. The result of this analysis are stored in an output database file called `jobname.odb`. This output database contains both the model data and the result data. The temperature, stress and displacement result in the result data can then be analysed (post-processed) to predict plate failure. The variables stored, and the frequency with which they are stored, are controlled through the field output module. The number of section points for which field output is stored is also controlled through the field output interface. For additional information on the `jobname.odb` data structure is referred to section 7.7.

6.3 HEAT TRANSFER ANALYSIS

The temperate field does not depend on the stress/displacement solution and can therefore be obtained separately. This section discussed the pure heat transfer analysis based on the adiabatic surface temperature (AST) results obtained from the FDS fire simulation discussed in previous chapter. Sequentially the heat transfer (HT) model setup, the approach to heat transfer in Abaqus, and importing AST data are discussed. The python script for the Heat Transfer analysis is included in Appendix C1.

MODEL SETUP: HEAT TRANSFER – SINGLE PLATE

The model setup for the single plate heat transfer with four temperature partitions is summarized at the end of this sub-section and illustrated in Figure 6.6. This model includes all three heat transfer modes. Convection and radiative heat transfer are governed by the AST results from the FDS simulation and, over time, heat the *temperature partitions*. Conductive heat flux occurs as a result of the temperature differences in these *partitions*. Defining convective and radiative heat transfer is discussed in the next sub-section. To correctly predict the structural response the material properties density, specific heat, and conductivity should be defined. As an example the following lines define the required thermal material properties for steel.

```
…
mdb.models['Model-1'].Material(name='Steel')
modMat = mdb.models['Model'].materials['Steel']
modMat.Density(table=((7850.0, ), ))
modMat.SpecificHeat(table=((452.0, ), ))
modMat.Conductivity(table=((53.3, ), ))
…
```

The required results from this simulation are the nodal temperature field over time to be used in the subsequent structural response analysis. A resulting temperature field is illustrated in Figure 6.6.

SINGLE PLATE HEAT TRANSFER ANALYSIS

- Abaqus Standard Analyis
- Step: Implicit Heat Transfer
- Transient Heat Transfer
- 1 Plate (0,9 x 0,9 m^2)
- 4 Temperature Partitions (blue square)
- Steel S355
- 36 Shell Elements
- 3 mm thickness
- DS8 Element Type
- DS8: 8 nodes, 9 Integration Points
- AST data from FDS fire Simulation
- 3650 seconds
- Result: Nodal Temperature Field

Python script for the heat transfer analysis is included in Appendix C1

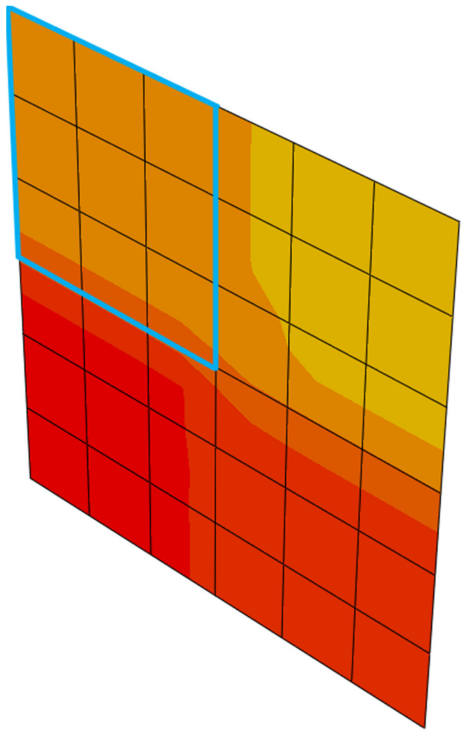


Figure 6.6 – Single Plate Heat Transfer Analysis – Temperature Field

Defining Heat Transfer

In Abaqus convection can be accounted for using the interaction module. In the interaction module a surface film condition can be defined describing a Film coefficient (convective heat transfer coefficient) and a sink (AST or ambient) temperature. In Abaqus the convective heat flux to the surface is governed by equation 6.1. The convective heat transfer equation 2.5 and equation 6.1 as implemented in Abaqus are of the same form, their only difference being that the former describes heat rate $[\mathrm{W}]$ and the latter heat flux $[\mathrm{W}\cdot\mathrm{m}^{-2}]$. For additional information is revered to the Abaqus/CAE User's Guide section 15.13.22 and the Abaqus Analysis User's Guide section 34.4.4 [33]. The convective heat transfer to a simply supported plate is illustrated in Figure 6.7.

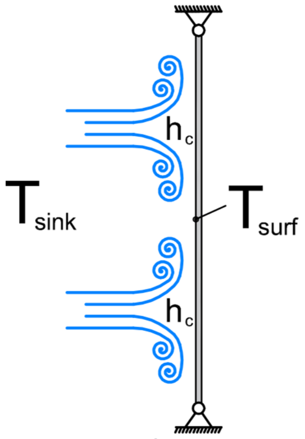


Figure 6.7 – Convective Heat Transfer [Abaqus]

$$q''_{\mathrm{cv}} = -h_c\left(T_{surf} - T_{sink}\right) \tag{6.1}$$

With:

q''_{cv}	Convective heat flux to surface	$[\mathrm{W}\cdot\mathrm{m}^{-2}]$
h_c	Reference sink coefficient	$[\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{K}^{-1}]$
T_{surf}	Surface Temperature	$[\mathrm{K}]$ or $[^{\circ}\mathrm{C}]$
T_{sink}	Absolute Surface Temperature (Structural Model)	$[\mathrm{K}]$ or $[^{\circ}\mathrm{C}]$

In Abaqus radiation can be accounted for using the interaction module. In the interaction module a surface radiation to the environment can be defined describing the emissivity and an ambient temperature. The heat flux on a surface due to radiation is governed by equation 6.2. This expression of the same form as equation 2.11 in chapter 2.3, the former describing heat flux and the latter heat rate. It is important to note that equation equation 6.2 describes the radiative heat flux to the environment, hence the difference in sign compared to equation 2.11. Radiative heat transfer to a simply supported plate is illustrated in Figure 6.8

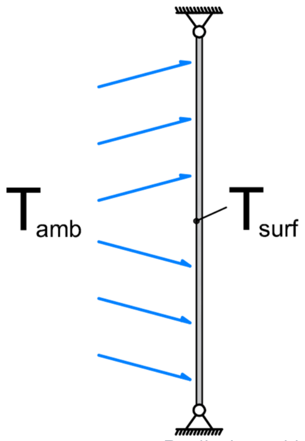


Figure 6.8 – Radiative Heat Transfer [Abaqus]

$$q''_{rad,env} = \varepsilon\cdot\sigma\left(\left(T_{surf} - T_{abs}\right)^4 - \left(T_{amb} - T_{abs}\right)^4\right) \tag{6.2}$$

With:

$q''_{rad,env}$	Radiative heat flux to the environment	$[\mathrm{W}\cdot\mathrm{m}^{-2}]$
ε	Emissivity (0,8)	$[-]$
σ	Stefan Boltzmann Constant	$[\mathrm{W}\cdot\mathrm{m}^{-2}\cdot\mathrm{K}^{-4}]$
T_{amb}	Surface Temperature	$[\mathrm{K}]$ or $[^{\circ}\mathrm{C}]$
T_{surf}	Absolute Surface Temperature	$[\mathrm{K}]$ or $[^{\circ}\mathrm{C}]$
T_{amb}	Value of absolute zero	$[\mathrm{K}]$ or $[^{\circ}\mathrm{C}]$

In order to correctly model radiation in Abaqus the Stefan Boltzmann Constant and the temperature value for absolute zero should be defined. Since FDS utilizes the Celsius temperature scale the following line should be included to correctly model radiative heat transfer.

```
…
mdb.models['Model-1'].setValues(absoluteZero=-273,
    stefanBoltzmann=5.67e-08)
...
```

Combining equations 6.1 and 6.2 to obtain the total heat flux to the structural model results in equation 6.3.

$$q''_{tot,SM} = \varepsilon\sigma\left(\left(T_{amb} - T_{abs}\right)^4 - \left(T_{surf,SM} - T_{abs}\right)^4\right) + h_c\left(T_{\text{sink}} - T_{surf,SM}\right) \qquad 6.3$$

Now by rewriting the ambient temperature T_{amb} and the sink temperature T_{sink} to the adiabatic surface temperature T_{AST} equation 6.4 is obtained which is identical to the expression for expression obtained in equation 2.17. Where the latter is only defined for the Kelvin scale and the former alsow works with the Celcius scale. Therefore by utilizing both conductive and convective heat transfer in Abaqus the total heat flux, based on the concept of adiabatic surface temperature, is obtained.

$$q''_{tot,SM} = \varepsilon\sigma\left(\left(T_{\text{AST}} - T_{abs}\right)^4 - \left(T_{surf,SM} - T_{abs}\right)^4\right) + h_c\left(T_{\text{AST}} - T_{surf,SM}\right) \qquad 6.4$$

As previously mentioned both convective and radiative heat transfer can be defined directly using the interaction module in the interactive Abaqus CAE environment. Alternatively the lines listed below can be added to define respectively conductive and radiative heat transfer to a single temperature partition. Both lines refer to AST amplitude data, `'AST_TabAMP'`. This imported amplitude data will be discussed in more detail in the next section.

```
…
mod = mdb.models['Model-1']
mod.FilmCondition(createStepName='HeatTransfer', definition=
    EMBEDDED_COEFF, filmCoeff=25.0, filmCoeffAmplitude='', name='Conv',
    sinkAmplitude='AST_TabAMP', sinkDistributionType=UNIFORM,
    sinkFieldName='', sinkTemperature=1.0, surface=
    mod.rootAssembly.instances['Plate'].surfaces['Surf-1'])
mod.RadiationToAmbient(ambientTemperature=1.0,
    ambientTemperatureAmp='AST_TabAMP', createStepName='HeatTransfer',
    distributionType=UNIFORM, emissivity=0.8, field='', name='Rad',
    radiationType=AMBIENT, surface=
    mod.rootAssembly.instances['Plate'].surfaces['Surf-1'])
...
```

Defining convective and radiative heat transfer for all plates and all temperature partitions is a tedious task. Therefore a program was developed using object orientated programming language C++. This program, `upGeomHT`, automatically updates a basic Heat Transfer script for the next iteration and appends the conduction and radiation python code, illustrated above, for all plates and temperature sections. For a detailed description of this program is referred to section 7.5.

Importing Adiabatic Surface Temperature Data

The AST data from the FDS fire simulation is stored in a comma separated (csv) file. This file cannot be input directly in Abaqus and should be pre-processed to obtain the tabular time/temperature amplitude data required for modelling convective and radiative heat transfer. The most basic way is by manipulating the csv data with typical spreadsheet software to obtain separate time/temperature data for each separate temperature surface. This data can then be copied and pasted directly in the create amplitude module in the interactive Abaqus CAE environment. Alternatively amplitude data can be created using python code. For example the following lines generate amplitude data for use in a heat transfer analysis. Abaqus automatically interpolates (linearly) between specified time/temperature coordinates.

```
…
mdb.models['Model-1'].TabularAmplitude(timeSpan=TOTAL, name='AST_TabAMP',
    data=((0, 20), (1500, 500), (3000, 600), (3600, 20),))
…
```

With increasing number of plates and temperature surfaces both previously described methods quickly become tedious, time consuming tasks. Therefore a program was developed using object orientated programming language C++. This program, `ReWriteAST2py`, automatically rewrites the FDS csv output data into an Abaqus python script, similar to the lines illustrated above. For a detailed description of this script is referred to section 7.3.

6.4 Structural Response Analysis

In response to heating materials tend to expand. The temperature distribution from the HT analysis will induce thermal expansion, and due to restricted movement, thermal stresses and buckling (bending stresses). The basic SR model setup, thermal stresses, imperfections and importing nodal temperatures are discussed successively in this section. The python script for the single plate Heat Transfer analysis is included in Appendix C4.

Model Setup: Structural Response – Single Plate

The model setup for the single plate structural response analysis is summarized at the end of this sub-section and illustrated in Figure 6.6. The resulting stress/displacement field is a result of the expansion due to the temperature increase. The occurrence of thermal stresses are explained in detail in the next sub-section. To correctly predict the structural response the elastic and plastic material properties and the thermal expansion coefficient should be defined. As an example the following lines define the required material properties for the structural response analysis.

```
…
mdb.models['Model-1'].Material(name='Steel')
modMat = mdb.models['Model'].materials['Steel']
modMat.Elastic(table=((210000000000.0, 0.29),))
modMat.Expansion(table=((12e-06, ), ))
modMat.Plastic(table=((320000000.0, 0.0), (357000000.0, 0.002),
     (366100000.0, 0.0157), (541600000.0, 0.1351)))
…
```

Initially the plate is perfectly flat and will remain flat for the duration of the simulation. Therefore an imperfection should be introduced, allowing the plate to bend out-of-plane. This imperfection is implemented as a linear superposition of the first buckling eigenmode obtained from a separate buckling analysis and will be discussed in detail later in this chapter.

The required results for this simulation are the stresses and displacements which can be post processed to predict plate failure. A resulting stress field is illustrated in Figure 6.9.

SINGLE PLATE STRUCTURAL RESPONSE ANALYSIS

- Abaqus Standard (Implicit) Analyis
- Step: Dynamic Implicit (quasi static)
- Geometric Non-linear
- 1 Plate (0,9 x 0,9 m^2)
- 36 Shell Elements
- 3 mm thickness
- Imperfection from first buckling mode
- Steel S355
- Elastic-plastic material behaviour
- S8R Element Type
- S8R: 8 nodes, 4 Integration Points, Reduced Integration
- Nodal Temperature Field from previous Heat Transfer Analysis
- 3650 seconds
- Result: Stress/displacement field

Python script for a single plate structural response analysis is included in Appendix C4

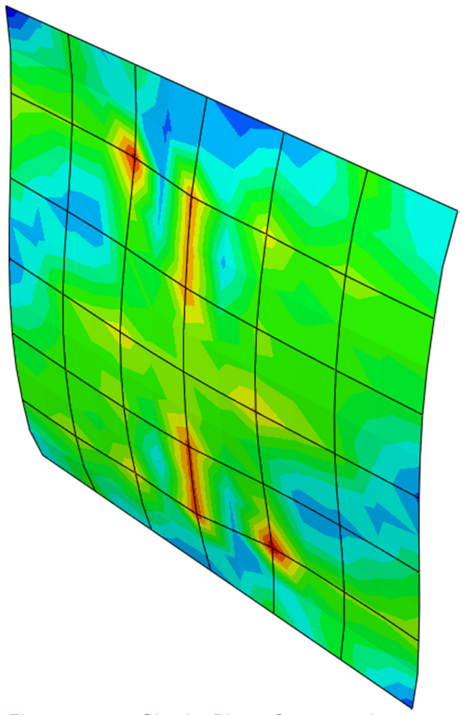


Figure 6.9 – Single Plate Structural Response Analysis – Stress Field

THERMAL STRESSES

The stress generation in the structural response analysis is governed by the thermal expansion of the steel. Solid materials expand in response to heating and contract when cooled. This expansion is proportional to its original length and the temperature difference. The response to temperature can be predicted with the so called coefficient of thermal expansion α as expressed in equation 6.5. It is important to note that α itself varies with temperature and also depends on the composition of the material, e.g. the type of steel. For now it is assumed constant.

$$\frac{\Delta L}{L_0} = \alpha \Delta T \tag{6.5}$$

With:

ΔL	is the elongation	$[\mathrm{m}]$
L_0	is the original length	$[\mathrm{m}]$
α	is the coefficient of thermal expansion	$[^\circ\mathrm{C}^{-1}]$
ΔT	is the temperature difference	$[^\circ\mathrm{C}]$

Restricting thermal expansion results in the occurrence of stresses, so called thermal stresses. These stresses can be estimated by combining above equation 6.5 with Hooke’s law into equation 6.6. Combining these equations results in the expression for thermal stresses below.

$$\sigma_{th} = -\alpha \cdot \Delta T \cdot E \tag{6.6}$$

With:

σ_{th}	is the (thermal) stress	$[\mathrm{N} \cdot \mathrm{m}^{-2}]$
E	is the tensile modulus	$[\mathrm{N} \cdot \mathrm{m}^{-2}]$

For steel S355 $\alpha = 12 \cdot 10^{-6}\ °\mathrm{C}^{-1}$, $\Delta T = 500\ °\mathrm{C}$, and $E = 210 \cdot 10^{9}\ \mathrm{N} \cdot \mathrm{m}^{-2}$. The thermal stresses for the one-dimensional case increase with $2{,}52\ \mathrm{N} \cdot \mathrm{mm}^{-2} °\mathrm{C}^{-1}$. To relax these thermal stresses the structure tends to buckle (bend), effectively exchanging compressive thermal stresses for some bending stresses.

When a material is compressed in one direction it often tends to expand in the other two directions. This behaviour can be predicted using the so called Poisson's ratio ν. The Poisson's ratio is the ratio of transverse contraction strain to longitudinal extension strain in the direction of the stretching force. Imagine a plate fixed on its top and bottom edge (Figure 6.3). If subjected to a fire the plate expands in both directions, due to its boundary condition it cant expand to the top or bottom generating thermal stresses. Restriction of (thermal) expansion in one direction will result in additional expansion in the other direction (out-of-plane neglected). This additional expansion could, for instance when partly restricted, generate additional (Poisson) stresses. Long story short: the relation between different strain directions influence the stress behaviour.

$$\nu = -\frac{\varepsilon_{trans}}{\varepsilon_{longitudinal}} \tag{6.7}$$

With:

ν	is the Poisson's ratio
ε_{trans}	is transverse strain
$\varepsilon_{long.}$	is longitudinal strain

INTRODUCING IMPERFECTIONS

To accurately predict the structural response to the temperature increase an imperfection should be introduced in the perfectly flat plate to allow out-of-plane bending. This imperfection is implemented as a linear superposition of the first buckling eigenmode obtained from a separate buckling analyses. The separate buckling analysis consist of the same structural model applying a linear perturbation buckle step combined with a uniform normalized temperature field as the unit load. To capture the buckling modes it is necessary to export result file (`jobname.fil`) containing the nodal displacements. This file can be obtained by directly editing the input file (`'Model'` → `'Edit Keyword'`) and include the following lines after `**FIELD OUTPUT`.

```
…
*NODE FILE
U
…
```

To include it in a python script the following lines should be added.

```
…
modKey = mdb.models['Model-1'].keywordBlock
modKey.synchVersions(storeNodesAndElements=False)
modKey.insert(47, '\n*Node File\nU')
 …
```

It is important to note that the python script imports a string at a certain line number. Therefore if the model is developed further the required position for the additional lines requesting the result file could change, and should be checked.

To include the first eigenmode as imperfection in the structural response analysis the following lines should be included in the input file. It is mandatory to enter the lines after `**STEP`.

```
...
*IMPERFECTION, FILE=jobname, STEP=1
1, 0.005
...
```

The corresponding python commands are

```
...
modKey = mdb.models['Model-1'].keywordBlock
modKey.synchVersions(storeNodesAndElements=False)
modKey.insert(33,'\n*Imperfection, file=jobname, step=1\n1, 0.005')
 ...
```

Where `jobname` refers to the requested result file from the buckling analysis (tagged with the name of the job in the buckling analysis). The values on the second line correspond to respectively the buckling mode and the scale factor for the deflections. The eigenvector buckling modes are normalised to give a maximum deflection of 1 unit.

An alternative method to introduce an imperfection is by drawing a slightly curved plate in the initial creation of the part. For additional information on implementing a geometrical imperfection is referred to the Abaqus Analyses User's Guide 11.3.1 [34].

Importing Nodal Temperature Data

The output data from the Heat Transfer analysis can be directly read into the structural response analysis. Nodal temperatures (NT) are stored as function of time in the heat transfer analyses output database file. The temperature distributions can be input directly into the stress analysis as a predefined field, at the nodes, and interpolated to the calculations points within the elements as needed. Abaqus even allows the use of dissimilar meshes for both analyses. The temperature values will be interpolated based on element interpolators evaluated at nodes of the thermal-stress model. To import the temperature data from the `HeatTranfer.odb` file into the structural response analysis the following lines should be added.

```
...
mdb.models['Model-1'].Temperature(absoluteExteriorTolerance=0.0,
    beginIncrement=None, beginStep=None, createStepName='i0-SR-Step',
    distributionType=FROM_FILE, endIncrement=None, endStep=None,
    exteriorTolerance=0.05, fileName='path\HeatTranfer.odb',
    interpolate=ON, name='Temp-From-HT')
...
```

For additional reading on the (sequentially) coupled thermal-stress analyses in Abaqus is referred to the Abaqus Analysis User's Guide sections 16.1.2 [33].

6.5 MULTIPLE PLATE MODELS

This section discusses how to extend the previous models to include multiple instances of a single part. Additionally the use of thermal and structural tie constraints between the plate-instances is addressed. The numbering convention for both plates and temperature partitions is from bottom to top first and from left to right second. This numbering convention is illustrated in the typical SR output in Figure 6.10.

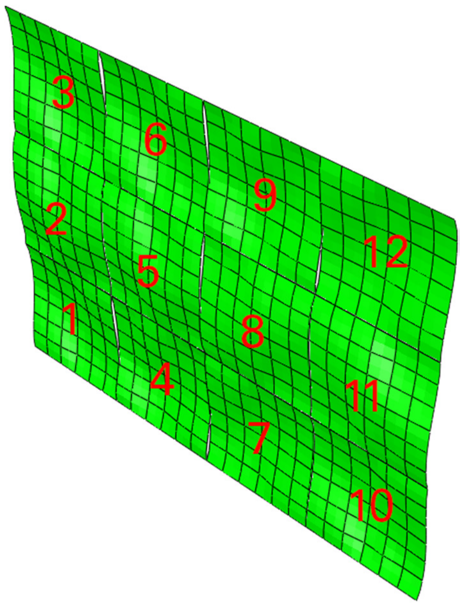


Figure 6.10 – Numbering convention overlay on a 12 (untied) plate-instance Abaqus SR model with each plate subdivided into 36 finite elements

MULTIPLE PLATE-INSTANCES MODEL

As previously discussed in section 6.2 an Abaqus model consist of one assembly consisting of a single or multiple instance(s) of one or several parts. Therefore the single plate-instance model, as discussed in the previous sections, can be easily expanded to include multiple plate-instances of the same part. Various geometric operations for instances are included in Abaqus like translation, rotation and linear and radial patterns. As an example the following lines create a 2x2 plate-pattern.

```
...
modRa = mdb.models['Model-1'].rootAssembly
modRa.LinearInstancePattern(instanceList=('Plate-1', ),
    direction1=(1.0, 0.0, 0.0), direction2=(0.0, 1.0, 0.0),
    number1=2, number2=2, spacing1=0.9, spacing2=0.9)
...
```

Abaqus automatically assigns names to the newly generated plate-instances based on their original name and their location in the pattern. To rename these instances the following lines should be added.

```
...
modRaFe = modRa.features
modRaFe.changeKey(fromName='Plate-1-lin-1-2', toName='Plate-2')
modRaFe.changeKey(fromName='Plate-1-lin-2-1', toName='Plate-3')
modRaFe.changeKey(fromName='Plate-1-lin-2-2', toName='Plate-4')
...
```

Since Abaqus generates multiple instances of the same part all previous and possible newly assigned `SETS` and `SURFACES` in the part are automatically created for all instances. The plate-instances are structurally and thermally independent. Depending on the modelled structural system, structural and/or thermal ties could be implemented. The tying of instances is discussed in the next section.

TYING PLATES

Plate-instances can be tied using `TIE` constraints. A `TIE` constraint ties two separate surfaces together so that there is no relative motion between them, effectively fusing them together. To define a TIE constraint a master and slave surface should be selected. As an example the following lines tie together `Plate-1` and `Plate-2`.

```
...
mod = mdb.models['Model-1']
mod.Tie(name='Tie_P1-P2',
    master=modRa.instances['Plate-1'].surfaces['Surf-0'],
    slave=modRa.instances['Plate-2'].surfaces['Surf-0'])
...
```

Alternatively the plates can be tied by selecting edges or node regions. Although this does not work for the Heat Transfer Analysis which has to use the `surface` method listed above. Specific edges can be tied using the following lines.

```
...
mod.Tie(name='Tie_P1-P2',
    master=modRa.instances['Plate-1'].sets['Edge-Top'],
    slave=modRa.instances['Plate-2'].sets['Edge-Bot'])
...
```

The slave nodes degrees of freedom (dof) are written as a linear combination of master dofs in a constraint equation. If slave nodes are defined in more than one constraint equation this can result in over-constrained nodes thereby obtaining questionable results. Abaqus does warn for, and often deactivates, over-constrained nodes.

The combination of ties with the restart analysis and plate removal has proved challenging for additional reading on this challenge is referred to section 8.2. For additional information on `TIE` constraints is referred to the Abaqus/CAE User's Guide 15.15.1 [33].

SINGLE PART INSTANCE MODEL

An alternative approach to a structural system consisting of multiple plates is to define the system as a single part and assign subsection as plate-area's. Either by redrawing the complete system as a single plate or, alternatively, by merging the meshes of the plate-instances of the 'multiple-plate-instances' approach. When using this method Abaqus will supress all part-instances and create a new part instance with all instances combined. The major drawback of this method is that all `SET` and `SURFACE` information is lost and needs to be reassigned.

The major advantage for this approach is, given only a single 'full-wall' part is defined, that all plates are automatically tied and no additional `TIE`-constraints need to be defined. The major drawback for this approach is that for every plate all plate `SETS` and (temperature partition) `SURFACES` need to be defined individually.

6.6 RESTART ANALYSIS

In order to restart or continue any simulation a restart file `*.fil` should be requested in the step module. One can either define a frequency n or interval m to control restart file creation. For frequency n restart data is written every n'th increment (and the last). For interval m, the step is divided into m intervals and restart data is written at the end of every interval, if time marks is checked restart data will be written for the increment closest to this interval. The Boolean argument `overlay` specifies that restart data should be overwritten, thereby minimizing the size of the restart file. As an example the following lines request a restart file at the end of the step (single interval).

```
...
mod = mdb.models['Model-1']
mod.steps['i0_SR-Step'].Restart(frequency=0, numberIntervals=1,
    overlay=ON, timeMarks=OFF)
...
```

In the subsequent analysis this restart data should be specified to allow Abaqus to restart from the previous simulation. As illustrated in the following lines.

```
...
mod = mdb.models['Model-1']
mod.setValues(restartJob='i0_SR-Job', restartStep='i0_SR-Step')
...
```

In addition the job type needs to be set to restart, compared to the standard full analysis. The restart job type is automatically selected when creating a job in Abaqus CAE but needs to be specified when using python script input. An example is found in the following line.

```
...
mdb.Job(name='i1_SR-Job', model='Model-1', type=RESTART)
...
```

For additional information on restart simulations is referred to the Abaqus Analysis Guide section 9.1.1 [33].

6.7 REMOVING PLATES

Plates can be removed from the simulation by a model change interaction from the interaction module. The model change interaction can be used to deactivate, or reactivate) a region in the model. Both geometry and element regions can be deactivated. A model change interaction can only be defined at the beginning of a (restart) step. As an example the following lines deactivate the geometry region `Plate-Area` for instance `Plate-2` at the beginning of step `i1_SR-Step`.

```
...
mod = mdb.models['Model-1']
thisPlate = mod.rootAssembly.instances['Plate-2'].sets['Plate-Area']
mod.ModelChange(activeInStep=False, createStepName='i1_SR-Step',
    includeStrain=False, name='deActPlate-2', region=thisPlate)
...
```

Using a model change interaction in a restart analysis is only possible if a model change interaction was defined in the original model. To include the model change interaction in the initial model the following lines should be included.

```
...
mod.ModelChange(name='ModelChange', createStepName='i0_SR-Step',
    isRestart=True)
...
```

For additional information on the model change interaction is referred to the Abaqus/CAE User's Guide section 15.3.3 [33].

7. PROGRAMS AND SCRIPTS

Performing a two-way coupled CFD-FEM analysis manually would quickly become a tedious task, since it is both an iterative and multi-step procedure. Therefore programs and scripts were developed, using code languages C++ and python to facilitate this coupling. In this chapter the two-way coupling methodology and the programs and scripts to facilitate the coupling are discussed sequentially.

7.1 COUPLING METHODOLOGY

Over the course of the previous chapters a one-way coupled CFD-FEM analysis was performed. A fire was simulated using Fire Dynamic Simulator (chapter 5) and then sequentially coupled to an Abaqus Heat Transfer and Structural Response analysis (chapter 1). In addition the methods to update the geometries of the different models were discussed. Chapter 3 discussed the approach to a two-way coupling as a combination of a limited number of one-way coupled thermomechanical simulations that, after each one-way-coupled increment, update the geometric changes in the fire, heat transfer and structural response models. The separate steps involved in a two-way coupling procedure can be explained as follows. First a fire is simulated using fire dynamic simulator. From this simulation an output file is obtained containing the AST data for the structural system. This data needs to be manipulated for use in the subsequent heat transfer analysis which in turn generates output containing the nodal temperatures of the structural elements. These temperatures are input directly into the structural response analysis. The resulting geometric changes, local failure, are updated in the fire model and a new iteration starts where, before every simulation step, the model is updated based on the geometric changes of the previous iteration. These steps are illustrated in Figure 7.1 below.

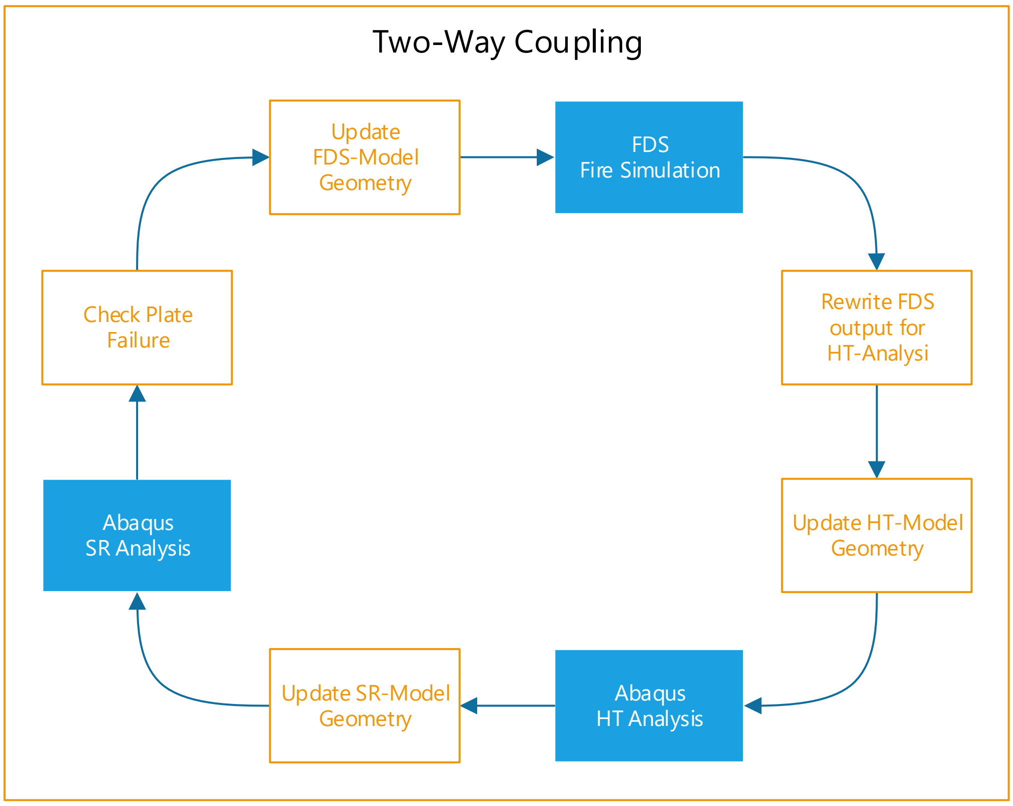


Figure 7.1 – Steps in a Two-Way Coupled CFD-FEM Analysis

The steps illustrated above and discussed previously identify the functions the programs and scripts should effectuate to facilitate a two-way coupling procedure. In addition, Figure 7.1 in itself represents a program, the master program `FDS-2-Abaqus` that manages the whole coupling procedure. These programs and scripts are discussed in the remainder of this chapter. An overview of the various programs and scripts is given in Table 7.1 and an updated illustration for the coupling process, representing `FDS-2-Abaqus`, is shown in Figure 7.2.

Table 7.1 – Overview of programs and scripts to facilitate two-way coupling procedure

PROGRAMME / SCRIPT	DESCRIPTION
`FDS-2-Abaqus`	Master Programme – managing two-way coupling procedure
`upGeomFDS`	Updates FDS input file for current iteration
`reWriteAST2py`	Rewrites AST data for use in subsequent HT analysis
`upGeomHT`	Updates HT script for current iteration
`upGeomSR`	Updates SR script for current iteration
`PlateFailureCheck`	Checks SR output for possible plate failure

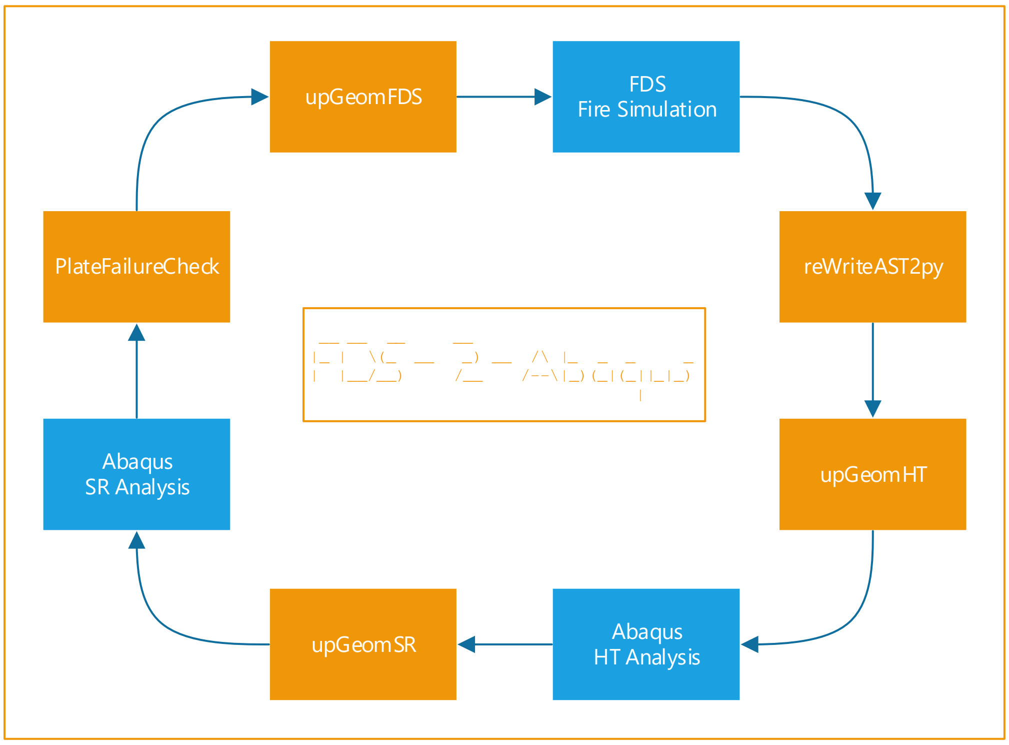


Figure 7.2 – Core process of coupling methodology as managed by Master programme FDS-2-Abaqus

7.2 FDS-2-ABAQUS

The flowchart for this program and its sub-processes is included in Appendix A5 and its C++ source code is included in Appendix D1.

`FDS-2-Abaqus` is a console based program developed in C++ to manage the two-way coupling of a CFD Fire Dynamic Simulator (FDS) fire simulation and a sequential coupled FE Abagus Heat Transfer (HT) and Structural Response (SR) analysis. Currently the coupling is limited to analysing structures consisting of multiple plates-instances using a stress-based failure criteria. A detailed summary of the program is included in Table 7.2.

Table 7.2 – Summary of FDS-2-Abaqus.cpp

NAME	`FDS-2-Abaqus`
DESCRIPTION	`FDS-2-Abaqus` is a program developed in C++ that manages the two-way coupling of a CFD Fire Dynamic Simulator (FDS) fire simulation and a sequential coupled FE Abaqus Heat Transfer (HT) and Structural Response (SR) analysis. In its current state `FDS-2-Abaqus` is limited to analysing structures consisting of multiple plate-instances using a stress-based failure criteria. The number of plates, temperature partitions, simulation duration, iteration size, and failure criteria can be varied freely (as long as required FDS and Abaqus basic model setups are supplied). Basically the programs iterates through various one way coupled CFD-FEM analyses. After every iteration the program checks plate failure based on user-defined stress failure criteria. If failure occurs the plates are removed from the models (FDS and Abaqus) for the next iteration. The overview of plate failure and failure time points is written to `_plateFailure.log`.
INPUT	`plateFailureUpdate.temp`

OUTPUT	`_plateFailure.log`
	`_iterationCounter.temp`
	`_platePartitionInfo.temp`
	`_runIterationTemp.bat`
	`plateFailureInputVariables.py`

REQUIRED PARAMETERS	`numberOfPlates`[1)] `numberOfPartitions`[1)] `totalSimulationDuration`[2)] `iterationSize`[2)] `failureStress`[3)] `failureNumberOfPoints`[3)] `failureNumberOfElements`[3)] `failedPlateNumber`[4)] `failureTimePoint`[4)]

1) User input, written to `_platePartitionInfo.temp`

2) User input, written to `_iterationCounter.temp`

3) User input, written to `plateFailureInputVariables.py`

4) Read from `plateFailureUpdate.temp`, managed by `PlateFailureCheck.py`.

PROCESS DESCRIPTION

The core-process of `FDS-2-Abaqus`, as illustrated in Figure 7.2, has been discussed previously in section 7.1. Basically `FDS-2-Abaqus` performs a two-way coupling as a combination of a limited number of one-way coupled thermomechanical simulations that, after each one-way-coupled increment, updates the geometric changes in the fire, heat transfer and structural response models. A more detailed description is listed below. An adequate flowchart, including the data exchange between the various programs and scripts, is included in appendix A5.

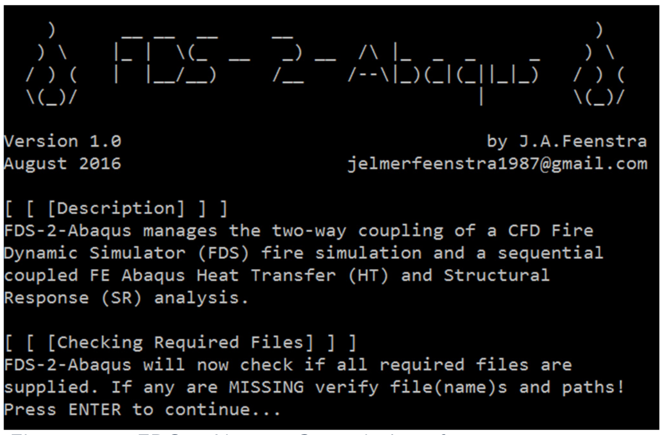
- Check existence of required files.
- Request basic variables (console input)
- Create `plateFailureArray` to log plate failure progression.
- Create data files `_plateFailure.log`, `platePartitionInfo.temp`.
- Create iteration batch file `_runIterationTemp.bat` containing the actual coupling sequence as listed (see Figure 7.2):
    - Run `upGeomFDS.exe`
    - Run FDS_Simulation
    - Run `reWriteAST2py.exe`
    - Run `upGeomHT.exe`
    - Run Abaqus HT simulation
    - Run `upGeomSR.exe`
    - Run Abaqus SR simulation
    - Run `PlateFailureCheck.py`
- While loop consisting of the following sequence (continues running till `totalSimulationDuration` is reached):
    - Write/update current iteration info to data file `_iterationCounter.temp`.
    - Write/update failure criteria and paths to data script `plateFailureInputVariables.py`.
    - Run `_runIterationTemp.bat` (see above).
    - Update `plateFailureArray` based on `plateFailureUpdate.temp`.
    - Next iteration
- Output completion info and summarize results

The C++ source code for this program is included in Appendix D1. This source code includes extensive comments for code clarification.

USING FDS-2-ABAQUS

In order to perform a two-way coupled analysis using `FDS-2-Abaqus` the following steps should be followed.

- Run FDS-2-Abaqus
- Supply necessary files
- Specify basic variables
- Specify failure Criteria
- Verify input and run simulation
- Check output for possible errors



```
Version 1.0                                         by J.A.Feenstra
August 2016                             jelmerfeenstra1987@gmail.com

[ [ [Description] ] ]
FDS-2-Abaqus manages the two-way coupling of a CFD Fire
Dynamic Simulator (FDS) fire simulation and a sequential
coupled FE Abaqus Heat Transfer (HT) and Structural
Response (SR) analysis.

[ [ [Checking Required Files] ] ]
FDS-2-Abaqus will now check if all required files are
supplied. If any are MISSING verify file(name)s and paths!
Press ENTER to continue...
```

Figure 7.3 - FDS-2-Abaqus Console Interface

The `FDS-2-Abaqus` interface, as illustrated in Figure 7.3, will guide the user through the above process. For the sake of completeness an overview of all necessary files and folders is included in Table 7.3.

Both FDS and Abaqus need to be installed on the computer before running `FDS-2-Abaqus`. A detailed installation guide is included in appendix E1. In addition a worked example is included in appendix E2. Lastly a debug guide is included in appendix E3.

Table 7.3 – Overview of required files for a two-way coupled CFD-FEM analysis managed by FDS-2-Abaqus

PROGRAMME / SCRIPT	DESCRIPTION
`FDS_BasicSetup.fds`	Basic Setup input for FDS simulation.
`upGeomFDS.exe`	Updates FDS input file for current iteration
`reWriteAst2py.exe`	Rewrites AST data for use in subsequent HT analysis
`HT_basicModel.py`	Basic Model script for HT analysis
`upGeomHT.exe`	Updates HT script for current iteration
`SR_basicModel.fds`	Basic Model script for SR analysis
`upGeomSR.exe`	Updates SR script for current iteration
`PlateFailureCheck.py`	Checks SR output for possible plate failure
`_outputHT [folder]`	Folder to store HT output
`_outputSR [folder]`	Folder to store imperfection files and SR output
`i0_buc-Job.fil`[1)]	Imperfection *node* file
`i0_buc-Job.prt`[1)]	Imperfection *part* file

[1)] in `_outputSR` folder

ALTERING FDS-2-ABAQUS

`FDS-2-Abaqus` and its subprograms and scripts are licensed as shareware and can be freely used, altered and improved upon. `FDS-2-Abaqus` is sub structured into multiple programs each with a distinct task. These subprograms can be altered independently as long as the new or upgraded program requires and generates the same input and/or output files. All scripts, input files and C++ source codes can be modified using a simple text editor. It is advised to use notepad++ for editing python code as notepad++ recognizes the python language. The python code is automatically coloured for better readability. A C++ source code can be edited and compiled in an integrated development environment (IDE). The C++ programs in this thesis were developed in the IDE Code Blocks including Boost libraries. Extensive online documentation on programming languages is freely available for both (Abaqus) python and C++. A selection of online documentation, used extensively in the development of FDS-2-Abaqus and its subprograms and scripts, is listed below.

http://www.learncpp.com
http://stackoverflow.com/
http://www.boost.org/
https://www.python.org/doc/
http://abaqus.software.polimi.it/v6.14/books/cmd/default.htm

7.3 REWRITEAST2PY

The flowchart for this program and its sub-processes is included in Appendix A3 and its C++ source code is included in Appendix D2.

`ReWriteAST2py` is a program developed in C++ to automatically rewrite the comma separated device output data from FDS into an Abaqus python script that imports amplitude data for the heat transfer analysis. A detailed summary of the program is listed in Table 7.4.

Table 7.4 – Summary of reWriteAST2py.cpp

NAME	`reWriteAST2py.cpp` [rewrite Adiabatic Surface Temperature data to an Abaqus python script]
DESCRIPTION	`reWriteAST2py` is a tool developed in C++ to automatically rewrite the comma separated adiabatic surface temperature device data `FDS_Simulation_devc.csv` from a FDS fire simulation into an Abaqus python script `AST_Amp_data.py` that imports the tabular amplitude data required to model convective and radiative heat transfer in a coupled Heat Transfer analysis. Required plate and partition info is read from `_platePartitionInfo.temp` a temporary file created by `FDS-2-Abaqus`.
INPUT	`FDS_Simulation_devc.csv` `_platePartitionInfo.temp`
OUTPUT	`AST_Amp_Data.py`
REQUIRED PARAMETERS	`numberOfPlates`1) `numberOfPartitions`1)

1) Read from `_platePartitionInfo.temp`, created by `FDS-2-Abaqus`.

PROCESS DESCRIPTION

`reWriteAST2py` iterates through the input file line by line and writes the time/temperature amplitude data in the output file until the end of file is reached. The process can be described as follows:

- Writing initial code including an unique name, '`AST_plateNumber-partitionNumber`'
- Reading line from the input file and checking if it contains time/temp value's
- Subdividing lines in separate values (separated by the comma)
- Writing time/temperature data for the current column (plate-partition)
- Continue above three lines until end of file is reached
- Continue process for other columns (plate-partitions) until all data is rewritten

This overall process of rewriting the temperature data is illustrated in Table 7.5 below. The C++ source code for this program is included in Appendix D2. This source code includes extensive comments for code clarification.

Table 7.5 – input and output of reWriteAST2py

FDS_Simulation_devc.csv

```
s,C,C,C,C
Time,"AST_1-1","AST_1-2","AST_1-3","AST_1-4"
 0.0000000E+000, 1.9933111E+001, 1.9924704E+001, 1.9935541E+001, 1.9926727E+001
 5.0350356E+000, 1.2587006E+002, 9.5066795E+001, 1.2907686E+002, 9.6406448E+001
 1.0006359E+001, 4.5135278E+002, 3.6574329E+002, 4.6353320E+002, 3.8612912E+002
 1.5002146E+001, 6.5682263E+002, 6.0171484E+002, 6.7507477E+002, 6.0263403E+002
 2.0017225E+001, 7.3107379E+002, 7.0298578E+002, 7.4941260E+002, 7.2567188E+002
 […]
 3.6500249E+003, 2.3215961E+002, 2.4729654E+002, 2.2615050E+002, 2.4190033E+002
```

AST_Amp_Data.py

```
imp(timeSpan=TOTAL, name='AST_1-1', data=(( 0.0000000E+000, 1.9933111E+001), […],
    ( 3.6500249E+003, 2.3215961E+002),))
imp(timeSpan=TOTAL, name='AST_1-2', data=(( 0.0000000E+000, 1.9924704E+001), […],
    ( 3.6500249E+003, 2.4729654E+002),))
imp(timeSpan=TOTAL, name='AST_1-3', data=(( 0.0000000E+000, 1.9935541E+001), […],
    ( 3.6500249E+003, 2.2615050E+002),))
imp(timeSpan=TOTAL, name='AST_1-4', data=(( 0.0000000E+000, 1.9926727E+001), […],
    ( 3.6500249E+003, 2.4190033E+002),))
```

The resulting output script can be called from the heat transfer analysis by including the following lines in the python script for the heat transfer analysis.

```
...
imp = mdb.models['Model'].TabularAmplitude
execfile('path\AST_Amp_Data.py', __main__.__dict__)
...
```

7.4 UPGEOMFDS

The C++ source code for this program is included in Appendix D3.

`upGeomFDS` is a program developed in C++ to automatically update a basic FDS input file for the current iteration. A detailed summary of the program is listed in Table 7.6.

Table 7.6 – Summary of upGeomFDS.cpp

NAME	`upGeomFDS.cpp` [update Geometry Fire Dynamic Simulator (model)]
DESCRIPTION	`upGeomFDS` is a program developed in C++ that creates a FDS input file for the current iteration. Basically it copies the basicSetupFile, `FDS_BasicSetup.fds`, to a new input file, `FDS_Script.fds`, and appends input lines defining the next iteration and plate failure devices. The iteration parameters are read from temporary file `_iterationCounter.temp` and the plate failure parameters from `_plateFailure.log`. Both of which are managed by the 'Master program' `FDS-2-Abaqus`.

INPUT	`FDS_BasicSetup.fds`[3)]
	`_iterationCounter.temp`
	`_plateFailure.log`
	`_platePartitionInfo.temp`

OUTPUT	`FDS_Script.fds`
REQUIRED PARAMETERS	`iterationCounter`[1)] `iterationSize`[1)] `totalSimulationDuration`[1)] `failedPlateNumber`[2)] `failureTimePoint`[2)] `plateFailureBool`[2)]

1) Read from `_iterationCounter.temp`, managed by `FDS-2-Abaqus`.

2) Read from `_plateFailure.log`, managed by `FDS-2-Abaqus`.

3) Should be supplied by user!

PROCESS DESCRIPTION

`upGeomFDS` copies the basicSetupFile `FDS_BasicSetup.fds` to a new input file and appends additional input lines controlling the duration of the next iteration and the removal of failed plates. The process can be described as follows:

- Read current iteration from `_iterationCounter.temp`.
- Read number of plates and partitions from `_platePartitionInfo.temp`.
- Copy basic setup FDS input file `FDS_BasicSetup.fds` to new input file `FDS_Script.fds`.
- Append `RESTART` and `KILL` lines for current iteration (see section 5.3)
- Read plate(failure) info from `_plateFailure.log`.
- Append input lines controlling (possible) plate removal based on `_plateFailure.log` (see section 5.3).
- Write `&TAIL` input line and finalize script.

The C++ source code for this program is included in Appendix D3. This source code includes extensive comments for code clarification.

`upGeomFDS` is managed by master program FDS-2-Abaqus meaning its required parameters are read from the data files created by `FDS-2-Abaqus`. It is very important to note that a valid `FDS_BasicSetup.fds` input file should be supplied by the USER to create a functioning (updated) FDS input file and subsequently perform a coupled analysis. An example of an `FDS_BasicSetup.fds` input file for an office with a 12-plate façade is included in Appendix B2. An example of typical code appended by the `upGeomFDS` program is included in Appendix B3. The C++ source code for this program is included in Appendix D3. This source code includes extensive comments for code clarification.

7.5 UPGEOMHT

The C++ source code for this program is included in Appendix D4.

`upGeomHT` is a program developed in C++ to automatically update the basic Abaqus python script for the Heat Transfer analysis for the current iteration. A detailed summary of the program is listed in Table 7.7.

Table 7.7 – Summary of upGeomHT.cpp

NAME	`upGeomHT.cpp` [update Geometry Heat Transfer (Analysis)]
DESCRIPTION	`upGeomHT` is a program developed in C++ that creates an Abaqus Heat Transfer (HT) python script for the current iteration. Basically it copies the basic model setup, `HT_basicModel.py`, to a new python script, `HT_Script.py`, and appends additional python code to update step, restart, AST, heat transfer and geometry info for the current iteration. The AST amplitude script `AST_Amp_data.py`, which is generated by the `reWriteAST2py` program, is used to update the AST data. Required iteration parameters are read from temporary file `_iterationCounter.temp`, the plate and partition parameters are read from `_platePartitionInfo.temp`, and plate failure parameters from `_plateFailure.log`. All of which are managed by the 'Master program' `FDS-2-Abaqus`.

INPUT	`HT_basicModel.py`
	`_iterationCounter.temp`
	`_platePartitionInfo.temp`
	`_plateFailure.log`
	`AST_Amp_data.py`

OUTPUT	`HT_Script.py` `ix_Script.py`
REQUIRED PARAMETERS	`iterationCounter`[1)] `iterationSize`[1)] `totalSimulationDuration`[1)] `numberOfPlates`[2)] `numberOfPartitions`[2)] `failedPlateNumber`[3)] `failureTimePoint`[3)] `plateFailureBool`[3)]

1) Read from `_iterationCounter.temp`, managed by `FDS-2-Abaqus`.

2) Read from `_platePartitionInfo.temp`, managed by `FDS-2-Abaqus`.

3) Read from `_plateFailure.log`, managed by `FDS-2-Abaqus`.

PROCESS DESCRIPTION

`upGeomHT` copies the Abaqus basic HT model `HT_basicModel.py` to a new script and appends additional code to update the script for the current iteration. More specifically update the duration and job of the next iteration, requesting and loading restart data, and appending additional code to model convective and radiative heat transfer. The process can be described as follows:

- Read current iteration from `_iterationCounter.temp`.
- Read number of plates and partitions from `_platePartitionInfo.temp`.
- Copy basic HT model `HT_basicModel.py` to new script `HT_Script`.
- Append code to update steps and define new steps.
- Append code to read the restart file from previous iteration and request a new restart file for the current iteration.
- Append code to update AST tabular amplitude data and define convective and radiative heat transfer for all temperature partitions.
- Read plate(failure) info from `_plateFailure.log`.
- Append code to deactivate failed plates, based on `_plateFailure.log`.
- Append code to create and run job for the current iteration.
- Create a backup of completed script named `ix_HT_Script.py` where `x` equals the number of the current iteration.

`upGeomHT` is managed by master program `FDS-2-Abaqus` meaning its required parameters are read from the data files created by `FDS-2-Abaqus`. It is very important to note that a valid `HT_basicModel.py` script should be supplied by the USER to create a functioning Abaqus HT script for use in the coupled analysis. A basic model setup, `HT_basicModel.py`, for a 12-plate structural system is included in Appendix C2. An example of typical code appended by the `upGeomHT` program is included in Appendix C3. The C++ source code for this program is included in Appendix D4. This source code includes extensive comments for code clarification.

7.6 UPGEOMSR

The C++ source code for this program is included in Appendix D4.

`upGeomSR` is a program developed in C++ to automatically update the basic Abaqus python script for the Heat Transfer analysis for the current iteration. A detailed summary of the program is listed in Table 7.8.

Table 7.8 – Summary of upGeomSR.cpp

NAME	`upGeomSR.cpp` [update Geometry Structural Response (Analysis)]
DESCRIPTION	`upGeomSR` is a program developed in C++ that creates an Abaqus Structural Response (SR) python script for the current iteration. Basically it copies the basic model setup, `SR_basicModel.py`, to a new python script, `SR_Script.py`, and appends additional python code to update step, restart, temperature, and geometry info for the current iteration. Required iteration parameters are read from temporary file `_iterationCounter.temp`, the plate and partition parameters are read from `_platePartitionInfo.temp`, and plate failure parameters from `_plateFailure.log`. All of which are managed by the 'Master program' `FDS-2-Abaqus`.

INPUT	`SR_basicModel.py`
	`_iterationCounter.temp`
	`_platePartitionInfo.temp`
	`_plateFailure.log`

OUTPUT	`SR_Script.py`
REQUIRED PARAMETERS	`iterationCounter`1) `iterationSize`1) `totalSimulationDuration`1) `numberOfPlates`2) `numberOfPartitions`2) `failedPlateNumber`3) `failureTimePoint`3) `plateFailureBool`3)

1) Read from `_iterationCounter.temp`, managed by `FDS-2-Abaqus`.
2) Read from `_platePartitionInfo.temp`, managed by `FDS-2-Abaqus`.
3) Read from `_plateFailure.log`, managed by `FDS-2-Abaqus`.

PROCESS DESCRIPTION

`upGeomHT` copies the Abaqus basic HT model `HT_basicModel.py` to a new script and appends additional code to update the script for the current iteration. More specifically update the duration and job of the next iteration, requesting and loading restart data, and appending additional code to model convective and radiative heat transfer. The process can be described as follows:

- Read current iteration from `_iterationCounter.temp`.
- Read number of plates and partitions from `_platePartitionInfo.temp`.
- Copy basic SR model `SR_basicModel.py` to new script `SR_Script`.
- Append code to update steps and define new steps.
- Append code to read the restart file from previous iteration and request a new restart file for the current iteration.
- Append code to import nodal temperature data (from previous HT analysis).
- Read plate(failure) info from `_plateFailure.log`.
- Append code to deactivate failed plates, based on `_plateFailure.log`.
- If non initial iteration: remove imperfection (as defined in `SR_basicModel.py`).
- Append code to create and run job for the current iteration.
- Create a backup of completed script named `ix_SR_Script.py` where `x` equals the number of the current iteration.

`upGeomSR` is managed by master program `FDS-2-Abaqus` meaning its required parameters are read from the data files created by `FDS-2-Abaqus`. It is very important to note that a valid `SR_basicModel.py` script should be supplied by the USER to create a functioning Abaqus SR script for use in the coupling analysis. A basic model setup, `SR_basicModel.py`, for a 12-plate structural system is included in Appendix C5. An example of typical code appended by the `upGeomHT` program is included in Appendix C6. The C++ source code for this program is included in Appendix D5. This source code includes extensive comments for code clarification.

7.7 PLATEFAILURECHECK.PY

The flowchart for this python script and its sub-processes is included in Appendix A4 and the python script is included in Appendix C7

`PlateFailureCheck.py` is an Abaqus python script that checks the output of the Structural Response analysis for plate failure. The plate number and failure time for failed plates are written to a temporary update file used by managing program `FDS-2-Abaqus` for tracking and logging failure progression. A detailed summary of the script is listed in Table 7.9.

Table 7.9 – Summary of PlateFailureCheck.py

NAME	`PlateFailureCheck.py`
DESCRIPTION	`PlateFailureCheck` is an Abaqus python script that checks the `ix_SR-Job.odb` data from the Structural Response analysis for possible plate failure based on a predefined (stress) failure criteria. The failure criteria and `*.odb` path info are read from `plateFailureInputVariables.py` as controlled by `FDS-2-Abaqus`. Plate failure data is written to temporary update file `plateFailureUpdate.temp` which is used to update geometries. Additional info is written to log file `plateFailurePythonDebug.log`.
INPUT	`ix_SR-Job.odb` `plateFailureInputVariables.py`
OUTPUT	`plateFailureUpdate.temp` `plateFailurePythonDebug.log`
REQUIRED PARAMETERS	`myOdbPath`[1)] `failureStress`[1)] `failureNumberOfPoints`[1)] `failureNumberOfElements`[1)]

1) Read from `plateFailureInputVariables.py`, managed by `FDS2Abaqus`.

In the remainder of this section the failure criteria for plate failure, the output database file structure, requesting specific values, and the script process are discussed subsequently.

FAILURE CRITERIA

The structural response output needs to be checked for plate failure after each iteration in the two-way coupled thermomechanical analysis. A failure criteria is required to determine if a plate failed or not. A simplified approach to failure is assumed which checks if the von Mises Stress exceeds the yield stress in a certain amount of integration points to consider an element failed. In turn a plate is considered failed when a certain number of failed elements is reached.

- An integration point (or section point) fails if $\sigma_{Mises} > \sigma_y$
- An element fails when `numberOfFailedPoints ≥ maxNumberOfFailedPoints`
- The plate fails when `numberOfFailedElements ≥ maxNumberOfFailedElements`

OUTPUT DATABASE FILE STRUCTURE

Abaqus creates an output database in which it stores its model and results data. The `*.odb` file structure is illustrated in Figure 7.4. The structural variables are stored in the `fieldOutputs` container. As previously discussed specific output variables, and the frequency with which they are stored, can be requested in Abaqus via the Field Output module. The number of section points for which field output is stored is also controlled through the field output interface. The default output value is two, the section points on respectively the top and bottom surface of a plate element.

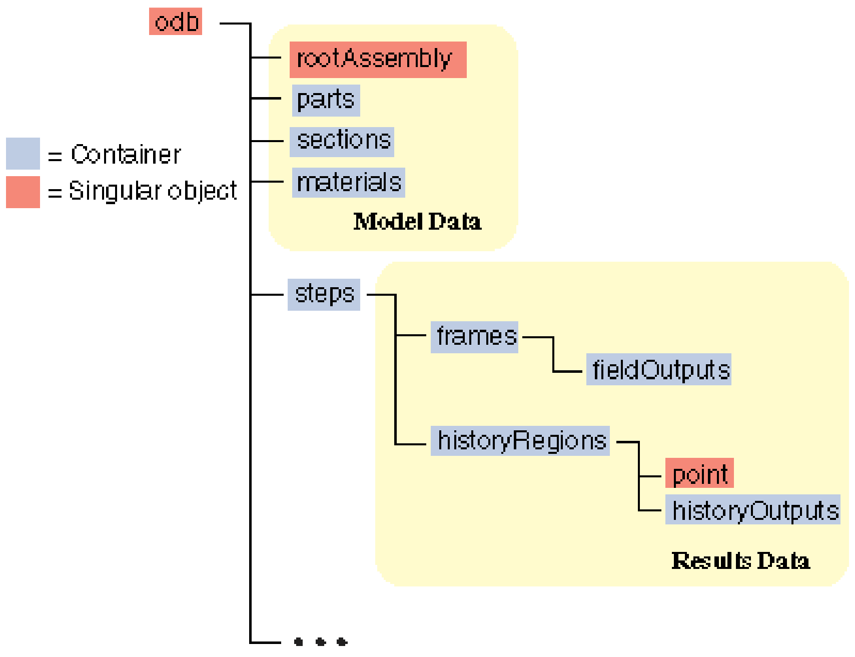


Figure 7.4 – Abaqus Output Database (.odb) File Structure*

Abaqus stores the field output for all steps and all frames separately. In other words, for each step and each frame there is a container, `fieldOutputs`, that contains all requested variables for every integration point. This means that all part-instances, elements, integration and section points are stored in a single container. These values are organized as follows: Part-Instance > Section Point > Element > Integration Point. This sub structuring is illustrated in Figure 7.5.

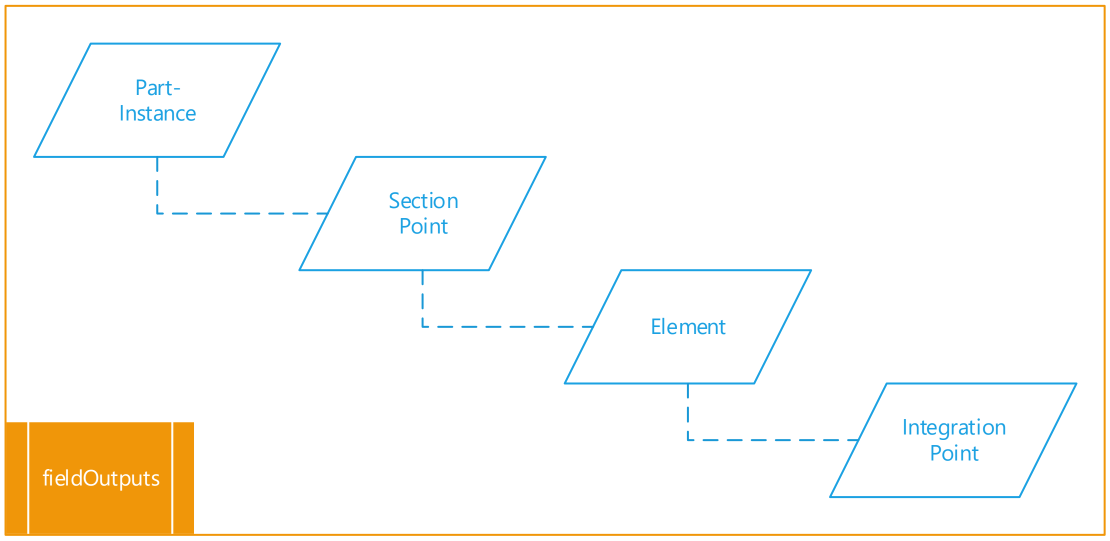


Figure 7.5 – Sub Structuring of fieldOutputs Container

As an example, given a model consisting of 4 part-instances (plates) with each having 36 elements with 4 integration points and 2 section points. The total number of values, for each variable, stored in the `fieldOutput` container equals 1.152. The first 4 values (position 0-3) are the four integration point values in section point 1 of element 1 for the first part-instance. The first 144 (36 x 4) values are all four integration point value's in section point 1 for all 36 elements for first part-instance. The next 144 values contain all values in section point 2 for all elements and integration points for the first part-instance. So all data for the first plate is stored in the first 288 values and after that iterates through the other part-instances.

REQUESTING OUTPUT VALUES

Specific values in the output database can be requested using python code. Assuming the same model from the previously discussed example (4 part-instances, 2 section points, 36 elements, 4 integration points). First we need to open our `example.odb` file:

```
…
from odbAccess import openOdb
odb = openOdb('path/example.odb')
…
```

It is important to note that in python a list starts with 0 and finish with N-1 where N is the number of elements in the list. The von Mises stress at position 478 (actually the 479th value) can be obtained as follows (the print command is used to actually output the value):

```
…
stress = odb.steps['stepname'].frames[-1].fieldOutputs['S']
print stress.values[478].mises
…
```

The corresponding part-instance (name), section point, element number and integration point for position 478 can be obtained respectively as follows:

```
…
print stress.values[478].instance.name
print stress.values[478].sectionPoint.number
print stress.values[478].elementLabel
print stress.values[478].integrationPoint
…
```

It is quite tedious to iterate through the whole `fieldOutput` container when only interested in the values for specific locations. To obtain values for a specific location, i.e. a plate-instance, element(set), or node(set), the `getSubset` command is used. As an example the following lines limit the return values from the `fieldOutput` container to only include the stresses for the first element of `Plate-1.`

```
…
### Select First Instance ###
instanceName = odb.rootAssembly.instances.keys()[0]
selectInstance = odb.rootAssembly.instances[instanceName]
### Select First Element ###
selectElement = selectInstance.elements[0]
### Subset Containing Stress Data For Element-1 of Plate-1 ###
elementStressField = stressField.getSubset(
    region = selectElement,
    position = INTEGRATION_POINT,
    elementType = 'S8R'
)
…
```

The brief discussion above covers the basic python commands to explore an `*.odb` output database. For extensive information on using the scripting interface to access and explore an output database is referred to the Abaqus Scripting User's Guide chapter 9 and the Abaqus Scripting Reference Guide chapter 34 [33].

PROCESS DESCRIPTION

`PlateFailureCheck.py` checks possible plate failure for each plate, based on the previously discussed stress based failure criteria. This script is coded in python, for which the output file exploration is covered in the previous section. The scripts checks every frame ('timestep') if failure occurred for the plate under consideration by iterating through all elements and checking if the failure criteria is met. If failure occurred the script writes plate number and failure time point to a temporary file `plateFailureUpdate.temp`. This temporary file is used by managing program `FDS-2-Abaqus` for tracking and logging failure progression. The script will continue with the next plate if failure occurred or the complete plate is checked. If a plate is deactivated the script automatically skips the failure check by verifying the number of values in the `fieldOutput` container (which is empty). The complete process can be described as follows:

- Read failure criteria and `*.odb` name and path from `plateFailureInputVariables.py`
- Select first plate-instance.
- Check if plate is deactivated (if so continue with next plate).
- Check plate failure for selected plate frame by frame ('timestep')
- If failure occurred write `failedPlateNumber` and `failureTimePoint` to the `plateFailureUpdate.temp` and `plateFailurePythonDebug.log` file and continue with next plate (interrupts frame loop)
- If failure did not occur write 'no-failure' info to the `plateFailurePythonDebug.log` file and continue with next plate.

Typical `plateFailureUpdate.temp` input and `plateFailurePythonDebug` output is listed in Table 7.10 below. The complete python code for this script is included in Appendix C7. This code includes extensive comments for code clarification.

Table 7.10 – PlateFailureCheck: Typical output for update and log file

`plateFailureUpdate.temp`

```
Plate-2 172
Plate-4 172
Done
```

`plateFailurePythonDebug.log`

```
18 Apr 2016 17:27:14 Script Running
18 Apr 2016 17:27:20 PLATE-1 did not fail, still going strong
18 Apr 2016 17:27:25 PLATE-2 failed at t=172 seconds since 13 elements failed
18 Apr 2016 17:27:30 PLATE-3 did not fail, still going strong
18 Apr 2016 17:27:35 PLATE-4 failed at t=172 seconds since 13 elements failed
18 Apr 2016 17:27:35 Completed
```

8. RESULTS AND DISCUSSION

Several coupled simulations were performed using `FDS-2-Abaqus`. This section presents the results for a twelve plate effectiveness study. In addition findings on the challenges associated with a coupling simulations comprising a multiple-plate-instance model combined with structural and/or thermal ties, a model change interaction (failure), and a restart analysis is discussed.

8.1 EFFECTIVENESS STUDY: TWELVE PLATES

The model room and its twelve plate thin walled steel façade, as designed in chapter 4, were modelled in FDS and Abaqus. The basic setup input file for the FDS simulation and the basic setup scripts for the HT, SR, and buckling analyses are included in appendices B2, C2, C5, and C8 respectively.

The fire scenario from section 4.3 was used in the FDS model with a cell size of 0,30 x 0,30 x 0,30 m^3. The total simulation duration was limited to 1800 seconds given that, during initial pilot studies, no plate failure occurred in the cooling phase of the fire scenario. Both the 'large' cell size and limitation of the fire duration limited the computational cost for the both analyses. The FDS model setup is summarized in Table 8.1.

Table 8.1 – Summary of FDS Fire Simulation Setup

FDS FIRE SIMULATION
▪ Mesh Cell Size: 0,30 x 0,30 x 0,30 m^3
▪ HRR: 250 kW/m^2
▪ Fuel Controlled Fire
▪ Fuel: Cellulose
▪ Concrete Walls
▪ Thin-Walled Steel Façade (Adiabatic)

* basicModel FDS input file is included in appendix B2

The model setup for both the HT and SR analyses were similar to the single-plate models discussed previously in sections 6.3 and 6.4. Their only difference being the number of modelled plates. The plates were assumed structurally and thermally independent and were therefore not tied. For tied simulations is referred to the next section. The buckling analysis, used for the initial imperfection in the SR model, was modelled as a tied plate since an untied system results in many buckling modes with identical eigenvalues and therefore in inconsistencies in the initial imperfection. The basic model setup parameters are summarized in table Table 8.2.

Table 8.2 – Summary of the Abaqus Heat Transfer and Structural Response Analysis Model Setups

HEAT TRANSFER ANALYSIS	STRUCTURAL RESPONSE ANALYSIS
▪ 12 Plates (untied)	▪ 12 Plates (untied)
▪ Step: Implicit Heat Transfer	▪ Step: Dynamic Implicit (quasi static)
▪ Transient Heat Transfer	▪ Geometric Non-linear
▪ 4 Temperature Partitions	▪ 36 Shell Elements
▪ Steel S355	▪ Imperfection from first buckling mode
▪ 36 Shell Elements	▪ Steel S355
▪ DS8 Element Type	▪ Elastic-plastic material behaviour
▪ DS8: 8 nodes, 9 Integration Points	▪ S8R Element Type
▪ AST data from FDS fire Simulation	▪ S8R: 8 nodes, 4 Integration Points,
▪ Result: Nodal Temperature Field	▪ Nodal Temperatures Field from HT analysis
	▪ Result: Stress/displacement field

* basicModel setup scripts are included in appendix C2 (HT) and C5 (SR)

The managing program `FDS-2-Abaqus` (section 0) was used to carry out multiple simulations of both the one and two-way coupled CFD-FEM analysis. The one-way coupled (OWC) simulation consisted of a single step iteration with a size of 1800 seconds. The two-way coupling (TWC) was subdivided in 150s iterations, for a total of 12 iteration steps, where after each iteration the model geometries were updated (automatically). The following failure criteria was selected: A finite element was assumed failed when the von Mises Stress exceeded the yield stress in 3 integration (or section) points (per element!). In turn a plate was considered failed when 13 finite elements were considered failed. The results and failure progression for the one and two-way coupled simulations are listed below.

ONE WAY COUPLED		TWO WAY COUPLED	
duration	1800 s	duration	1800 s
iteration size	1800 s	iteration size	150 s
iterations	1	iterations	12

RESULTS COUPLING ANALYSIS

Table 8.3 – Failure time [s] of plates for the one-way coupled analysis.

PLATE [#]	ONE WAY COUPLED SIMULATION [#] 1	2	3	4	5
01	680	830	955	714	655
02	765	715	745	714	680
03	610	620	590	639	605
04	405	360	450	664	655
05	0	0	0	0	0
06	675	595	615	0	0
07	0	0	0	0	0
08	0	0	0	0	0
09	0	0	0	0	0
10	0	0	0	0	0
11	1345	1525	1750	1789	1305
12	640	660	635	614	605

* failure time in seconds (if 0 s, plate did not fail)

Table 8.4 - Failure time [s] of plates for the two-way coupled analysis.

PLATE [#]	TWO WAY COUPLED SIMULATION [#] 1	2	3	4	5
01	0	0	0	0	0
02	0	0	0	0	0
03	0	0	0	0	0
04	330	310	440	402	402
05	0	0	0	0	0
06	0	0	0	0	0
07	0	0	0	0	0
08	0	0	0	0	0
09	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	1690	1690	1690	1752	0

* failure time in seconds (if 0 s, plate did not fail)

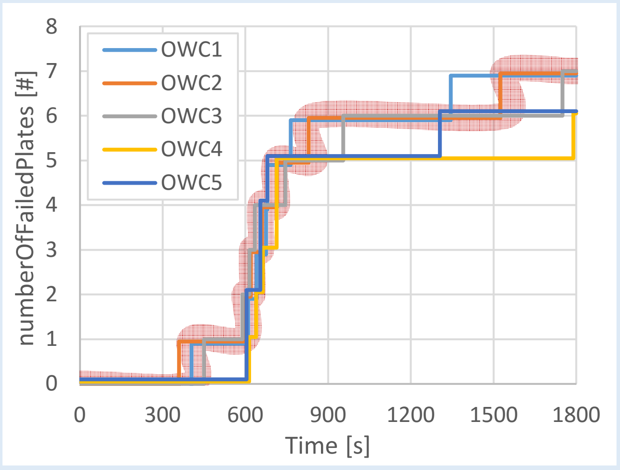


Figure 8.1 – Number of failed plates over time for the one-way coupled analysis

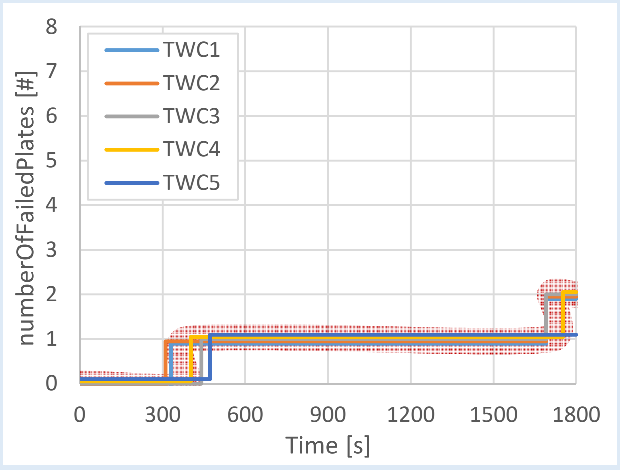


Figure 8.2 – Number of failed plates over time for the two-way coupled analysis

FAILURE PROGRESSION [PLATE #]:

ONE WAY COUPLED	TWO WAY COUPLED
4 – 3 – (6) – 12 – 2 – 1 – 11	**4 – (12)**

** continues on next page*

* *continued from previous page*

SMOKEVIEW VISUALIZATION

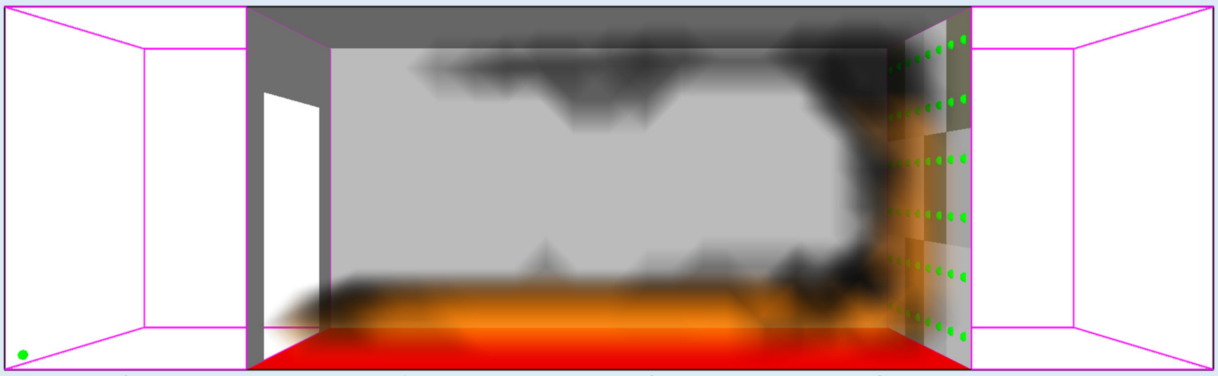


Figure 8.3 – Smokeview visualization of the one-way coupled CFD-FEM simulation @ 710 s.

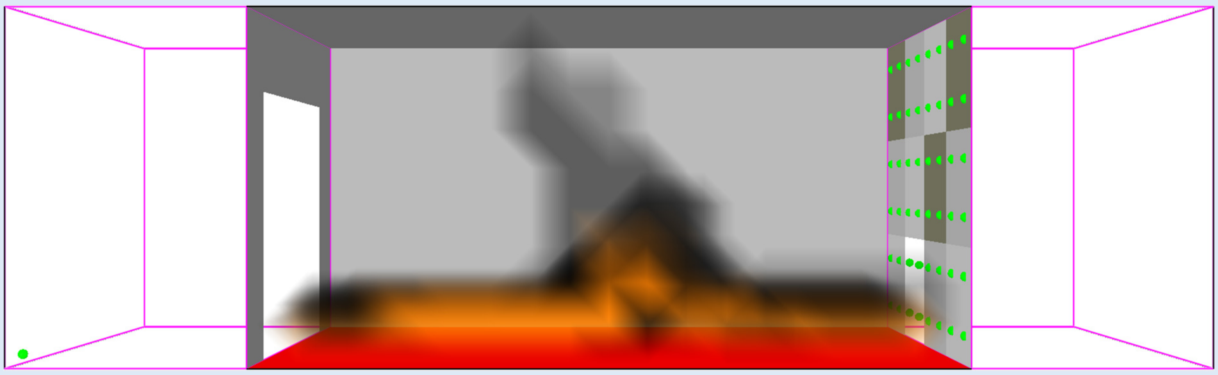


Figure 8.4 - Smokeview visualization of the one-way coupled CFD-FEM simulation @ 715 s.

The above results clearly show a significant difference in fire and failure behaviour between the one and two-way coupled simulations. Although the various simulations differ slightly in failure progression their overall trend is alike, as indicated by the red marker line in Figure 8.1 and Figure 8.2. From the Smokeview visualizations, in Figure 8.3 and Figure 8.4, it is clear that the additional airflow, due to plate failure, refocuses the fire to the middle of the compartment, away from the structural façade. Thereby greatly reducing the thermal load on the structural façade, and limiting its failure progression. Pilot experiments with smaller FDS mesh cell sizes (0,15 x 0,15 x 0,15 m^3) show similar results as illustrated in Figure 8.5. For this specific 'refined mesh' example plates 4 and 7 failed around the 300 s mark and no additional plate failure during the further 1800 s coupled simulation.

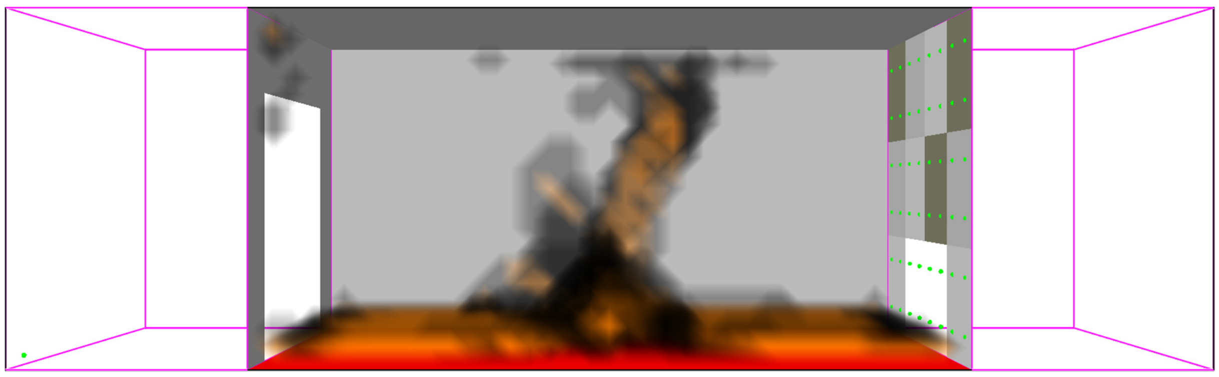


Figure 8.5 – Smokeview visualization of a two-way coupled 'refined mesh' CFD-FEM simulation.

In another pilot the bottom row of the plates was excluded from the simulation. The idea was, based on the failure progression of the twelve plate simulations, a top row panel would fail first given the bottom row failure in the twelve plate studies were soon followed by top row failures. These top row failures would then induce a different airflow resulting in a non-centrally located fire and thereby a different failure progression. Similar input parameters to those described in Table 8.1 and Table 8.2 for the FDS, HT, and SR models were used, their only difference being the use of eight plates compared to the twelve previously. The first panels failed around the 650 – 800 second mark for both the OWC and TWC analysis as listed in Table 8.5. No additional failure was recorded for the two-way coupling possibly due to energy release to the outside. The Smokeview visualization of the TWC analysis is included in Figure 8.6.

Table 8.5 – Failure time [s] and progression for 8-plate OWC and TWC Analysis.

PLATE [#]	OWC	TWC
01	1020	0
02	800	682
03	0	0
04	0	0
05	0	0
06	0	0
07	915	0
08	710	682
FAILURE PROGRESSIO	8 – 2 – 7 – 1	8 – 2

* failure time in seconds
(if 0 s, plate did not fail)

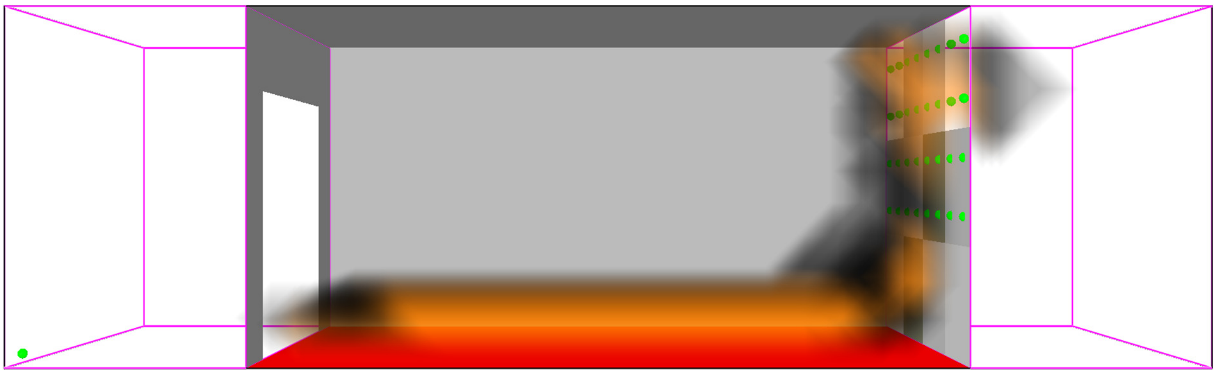


Figure 8.6 – Smokeview visualization of the two-way coupled CFD-FEM simulation @ 865 s.

An additional remark is that slightly varying the input variables influence the failure time and progression. Pilot experiments showed that changing the initial imperfections, interval of `fieldOutput` requests, and varying the coupling iteration size all affected the failure progression. A detailed parameter study, possibly verified using real life fire simulations, could help in both mapping and understanding these influences. Nevertheless the overall failure progression remained relatively identical.

The main drawback of above experiment is that a fuel controlled fire is assumed. Compartment fires in real life situations typically are, after flashover, ventilation controlled. Plate failure in a ventilation controlled fire would result in an additional oxygen source causing backdraft and an overall increase in HRR. Possibly accelerating the failure progression of a two-way coupled simulation compared to a one-way coupled one. Initial pilot experiments were conducted to include a ventilation controlled fire model in the simulations. These pilots showed that a fire cannot be defined as a prescriptive HRR curve, as discussed in section 5.2, to model a ventilation controlled fire. A more complex pyrolysis model needs to be developed to model a ventilation controlled fire in the simulation. For additional reading on defining a more complex pyrolysis model is referred to the FDS user's Guide section 8.5 [27].

All in all it is still too early to give an all conclusive answer on its effectiveness but is clear that the influence is of significant magnitude for further analysis. Especially considering the many possible improvements to the various models, scripts and simulations. For additional reading on possible improvements and recommendations for future research is referred to section 9.2.

8.2 TIED MULTI PLATE MODELS

In the effectiveness study the multiple plates were assumed structurally and thermally independent, in other words they were untied. Tying the plates influences the temperature and stress field of the model and subsequently its failure progression. However coupling simulations comprising a multiple-plate-instance model combined with structural and/or thermal ties, a model change interaction (failure), and a restart analysis, proofed difficult. This section will explore the findings of and discuss possible solutions to these challenges.

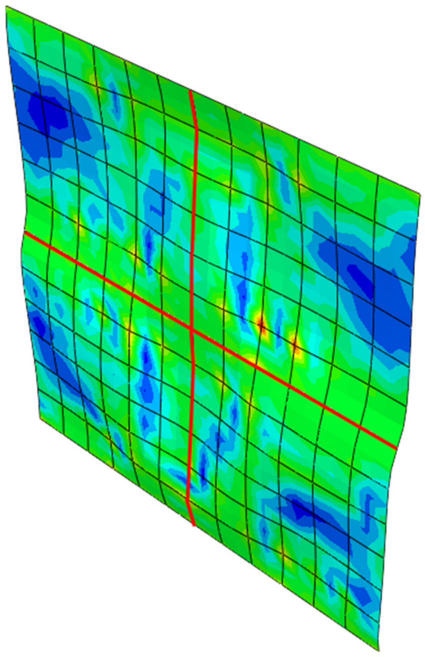


Figure 8.7 – Typical Stress Field for one-way coupled four plate model with structural and thermal TIE constraints.

Various pilot studies were carried out to study the two-way-coupling of a CFD fire simulation with a structurally and thermally tied multiple plate Heat Transfer and Structural response analysis. Tying plates in a one way coupled CFD-FEM analysis is pretty straight forward as illustrated in the resulting stress field of a one-way coupled four plate model with thermal and structural TIE constraints as shown in Figure 8.7. However it gets challenging when a model change and/or a restart analysis is introduced. When tying together nodes, a constraint is defined that describes the displacement (or temperature) of nodes from `plate-2` as a linear combination of the displacement of nodes from `plate-1`. Where the so called slave nodes depend on the master nodes. Therefore when defining tie constraints a master and a slave node set or surface is defined (see section 6.5) where the slaves depend on the masters. Consequently when introducing a model change in an analysis either a master or a slave plate is deactivated. In addition one could choose to also deactivate the TIEs between these plates. The last parameter is that the analysis is either an initial step or a restart step. Two plate pilot experiments were set up varying these parameters. A sketch of this pilot model is included in Figure 8.8 and the results are summarized in Table 8.6 for the HT analysis and Table 8.7 for the SR analysis. These results will be discussed in more detail in the following subsections.

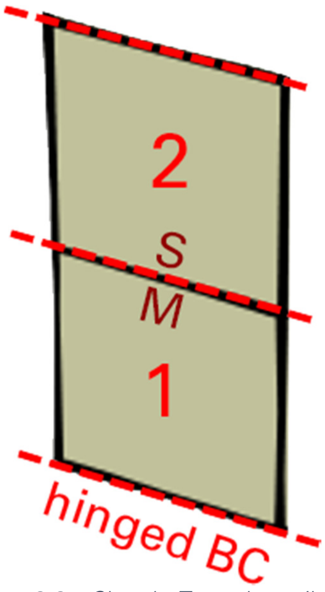


Figure 8.8 – Sketch: Two plate pilot model

HEAT TRANSFER TIE CONSTRAINTS

In the HT analysis the plates were tied using a master and slave surface definition. Deactivating the slave surface did not complicate the initial nor the restart analysis. This is pretty straight forward since the slave nodes depend on the master nodes in the TIE constraints and can be deactivated without deactivating variables in the constraint equations. However when deactivating a master surface the analysis aborts due to the occurrence of zero pivots. A zero pivot occurs when a term in the load vector corresponds to a dof that has no terms in the stiffness matrix. Basically the response of the slave nodes depends on master nodes that are no longer active, and therefore aborts. For the initial analysis (non restart) a possible work-around is to deactivate both the master surface and suppress the TIE constraints associated with this surface. Thereby omitting the dependencies and hence the analysis runs successfully. However this does not work for a restart analysis possibly due to the 'history' dependency of these nodes. A *possible* solution to this approach is to define a new 'initial' heat transfer analysis for every iteration in the two way coupling and importing the temperatures from the previous iteration as boundary condition. Basically just getting rid of the restart analysis. The main challenge here lies in redeveloping the `upGeomHT` program to supress TIE constraints when a corresponding master surface is deactivated. Another approach is to model the wall as an assembly of a single façade part containing multiple plate-area's that can be deactivated. Effectively removing the ties and therefore the challenges associated with the ties. Although this would work for this specific simplified 'wall-as-plate' approach it will not work for more detailed models, for instance a façade wall assembled from several column-, strut- and plate instances as previous shown in Figure 6.2. A third possible solution is to effectively remove the plate by increasing its conductance, more specifically to gradually adjust the material properties to effectively remove the plate. In absolute terms the plate is still there but the due to its adjusted material properties it is effectively removed. The main advantage of this approach is that no plate deactivations nor the suppression of TIE constraint need to be introduced in the model.

Table 8.6 – Results and possible errors for initial and restart HT analysis on a multiple plate model varying ties and model change interactions.

		INITIAL ANALYSIS (HT)		
TIE	MASTER	SLAVE	RESULT	ERROR
active	active	deactivated	Completed	-
active	deactivated	active	Aborted	Zero Pivot, Nodal temp below 0 K
supressed	deactivated	active	Completed	-
		RESTART ANALYSIS (HT)		
active	active	deactivated	Completed	-
active	deactivated	active	Aborted	Solver Problem Zero Pivot
supressed	deactivated	active	Aborted	Solver Problem Zero Pivot

In summary: Due to the dependency of slave nodes on master nodes deactivating these master nodes will cause a singularity in the constraint equations, thereby complicating and possibly crashing the analysis. Possible solutions are:

- Supress TIE constraints when deactivating master surface and omit restart analyses.
- Model façade as single part, effectively removing TIE constraints.
- Effectively remove plate by increasing its conductance.

STRUCTURAL RESPONSE TIE CONSTRAINTS

In the SR analysis the plates were tied using a master and slave edge definition. As with the HT analysis deactivating the slave did not influence the initial nor the restart analysis. In addition, for this two plate pilot, both the initial and restart analysis ran successfully when deactivating the master. The difference in job completion between the HT and SR analysis is due to the TIE constraint definition based on edges (SR) compared to the constraints based on surfaces (HT) when deactivating a plate-area the edge sets are still valid while surface sets are deactivated. Supressing the TIE constraints associated with a deactivated master plate resulted in an unstable simulation. This is pretty straight forward given boundary conditions are prescribed for the master nodes only to avoid over constraining the slave nodes. When a TIE is supresses the slave plate is cut loose allowing for unconstrained rotation (rigid body) as illustrated in Figure 8.9. So either the TIE constraints should remain active or initially suppressed boundary conditions on the slave nodes should be reactivated.

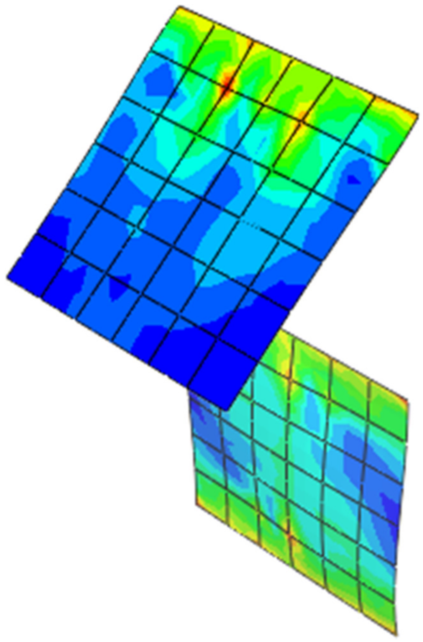


Figure 8.9 – rigid body rotation when deactivating master and supressing TIE constraint (master shown for clarity)

Table 8.7 - Results and possible errors for initial and restart SR analysis on a multiple plate model varying ties and model change interactions.

INITIAL ANALYSIS (SR)				
TIE	MASTER	SLAVE	RESULT	ERROR
active	active	deactivated	Completed	-
active	deactivated	active	Completed	-
supressed	deactivated	active	Aborted	Unstable, not enough displacement BC
RESTART ANALYSIS (SR)				
active	active	deactivated	Completed	-
active	deactivated	active	Completed	(does not work for 4-plate system)
supressed	deactivated	active	Aborted	Unstable, not enough displacement BC

At first sight these SR analyses seemed less challenging but the real challenge occurred while expanding the two plate pilot to a four plate pilot as illustrated in Figure 8.10. For the initial (non restart) simulation both the master and slave plates could be deactivated without causing convergence errors. But when deactivating a master edge in the four plate pilot the 'edge curling' and ultimately convergence error illustrated in Figure 8.11 occurred. The reason this error did not occur during the previous two plate pilot is because of the hinged boundary conditions on the top and bottom of the plates. The removal of a plate causes a sudden stress and stiffness change which proofed too challenging for the solver. A possible solution is to introduce some sort of 'relaxation' step to reinitialize the changed model. Another approach is to effectively remove the plate by gradually lowering its stiffness (factor 0.001), similar to the HT approach discussed previously.

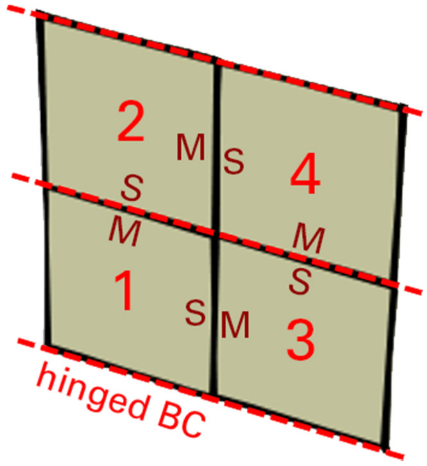


Figure 8.10 - Sketch: Four plate pilot model

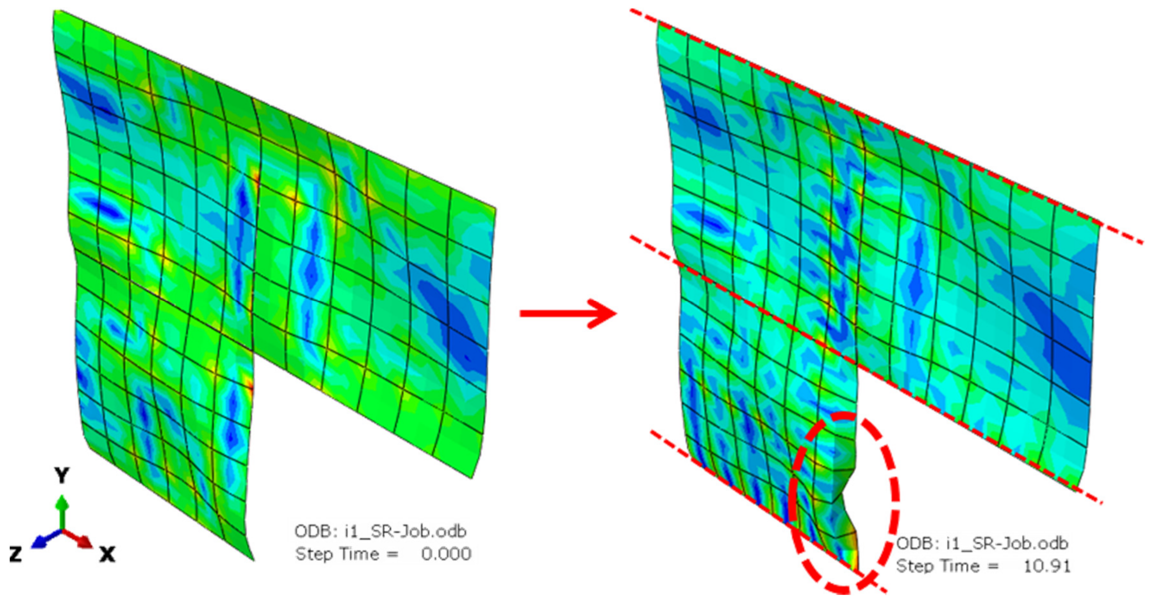


Figure 8.11 – Edge 'curling' discontinuity due to sudden stress and stiffness change.

In summary: The model change interaction causes a sudden stress and stiffness change which proofed too challenging for a restart analysis. Possible solutions are:

- Introduce a 'relaxation' step as transition between complete and partly failed model.
- Effectively remove plate by lowering its stiffness.

9. CONCLUSIONS AND RECOMMENDATIONS

In this chapter the thesis is finalized by drawing conclusions and a separate section on recommendations for future research containing an extensive discussion on possible improvements to the two-way coupling approach and `FDS-2-Abaqus`.

9.1 CONCLUSIONS

This thesis set out to explore the feasibility of two-way coupled CFD fire simulations to FE heat transfer and structural response analysis. Basically it aimed to answer the questions 'Can we do it?' and 'Should we do it?' More specifically it aimed to compare the effectiveness of a one-way coupled to a two-way coupled analysis by first identifying the various analysis steps, both how to perform and implement them in a coupled analysis. Secondly by studying the coupling steps and analyse the typical data exchange between the various analysis steps. And finally provide necessary tools to facilitate this coupling using programs and scripts.

Extensive discussions and explanations on performing and implementing the various analysis and coupling steps were included in their respective chapters (4 - 7). In addition the programs and scripts developed to facilitate a two-way coupling were discussed and summarized in chapter 7. So over the course of these chapters the 'Can we do it?' was answered implicitly by both explaining a possible approach to, and performing a two-way coupling.

The more interesting question, however, is should we perform such types of analysis. Initial studies using the `FDS-2-Abaqus` program developed throughout this thesis illustrated a significant difference in the failure progression of a façade wall between a one-way and two-way coupled analysis. This difference was governed by the change in fire propagation due to geometric updates in the fire, heat transfer, and structural response models. However it is still too early to give an all conclusive answer on its effectiveness mainly due to the lack of validation and the simplified approach to reality. Still it is clear that the influence is of significant magnitude for further analysis. Especially considering the many possible improvements to the various models, scripts and simulations.

Although limited in its current state `FDS-2-Abaqus` and this thesis can be seen as the preliminary framework for the use of two-way coupling in the field of structural fire and safety engineering. More specifically it could contribute to a better understanding of both structural response to fire and the response of the fire propagation to these structural changes. Therefore it could proof a powerful tool for research on fire propagation and structural response. For instance allowing extensive parameter studies on specific scenarios which would be virtually impossible, or economically impracticable, to study with real life in-situ experiments.

The biggest limitations of this research are found in the initial assumptions, the lack of validation, and the specific applications to FDS and Abaqus. Although the overall concept and approach should be applicable to other CFD and FE codes. In addition `FDS-2-Abaqus` and its subprograms are, in its current state, limited to studying structural systems consisting of a limited number of plate-instances. For a detailed discussion on possible improvements and future research is referred to the next section.

In a way, the program `FDS-2-Abaqus` is itself the conclusion. `FDS-2-Abaqus` proofs the concept of two-way coupling, while illustrating the difference in fire and failure propagation of a two-way coupling compared to a one-way coupled analysis. In addition `FDS-2-Abaqus` provides the opportunity to perform various two-way coupled fire-to-thermomechanical studies.

9.2 Recommendations for Future Research

During the initial phase of the research various assumptions were made and simplifications introduced, which, in retrospect proofed suboptimal. For instance, the combination of model change interactions with a restart analysis as extensively discussed in section 8.2 or the simplified approach to fire as a fuel controlled fire compared to a more realistic ventilation controlled compartment fire. Nevertheless, as previously mentioned, this thesis can be seen as the framework for performing two way coupled fire to thermomechanical analysis and by tackling various challenges become an even more powerful research tool. Various improvements and recommendations are discussed in this section subdivided into the separate analysis and coupling steps. In addition the consequences of the improvements on `FDS-2-Abaqus` and its subprograms are discussed.

FDS Model and Fire Simulation

The values for fire load and heat release rate in the FDS simulation were based on literature and implemented as an equally spread fire load with a constant HRR till decay phase. The total floor area was ablaze simulating a post flashover fire. A real life fire is far more random and strongly depends on the occupancy class, interior, and size of the openings. Where a post flashover fire is fuel controlled in case of large openings and ventilation (oxygen) controlled in case of small opening in the boundaries. A more realistic fire model could include a fully modelled interior, using a ventilation controlled fire and a fire scenario from initial to cooling phase. Modelling a ventilation controlled fire would greatly influence the failure progression in a two-way coupled analysis since partial collapse could result in an additional oxygen supply causing backdraft and an overall increase in HRR. Which in turn increases the thermal load on the structure, possibly causing failure, and so on. The redevelopment of the FDS simulation comprising a more realistic fire model and fire scenario would contribute to a more conclusive answer on the feasibility of two-way coupling. A possible implementation of a more advanced model is found in the definition of a complex pyrolysis model as described in the FDS user's Guide section 8.5 [27].

The main advantage for this improvement is that it can be studied separately. Meaning no additional changes are necessary to the other models, programs, and scripts. Although the structural model would be limited to one consisting of multiple plates utilizing a failure criteria based on exceeding the Von Mises stress.

Effectively Remove Plates

The challenge in combining `TIE` constraints with model change interactions and a restart analysis has been discussed extensively in section 8.2. The absolute removal of plates, using model change interactions, proofed suboptimal mainly due to the reliance of slave nodes on master nodes and the sudden changes in the stress field when removing plates. A possible solution is to redevelop the heat transfer model to *effectively* remove plates by gradually increasing its thermal conductance. Similarly the structural response model could be redeveloped to *effectively* remove plates by gradually lowering its stiffness. Using this approach both challenges could be tackled. Extensive pilot experiments should be set up to test this hypothesis.

Redevelopment of the HT and SR models to *effectively* remove failed plates influences both the `basicModel` setups and the additional code appended by the `upGeom` programs. Consequently the `upGeomHT` and `upGeomSR` programs need to be redeveloped to include lines to gradually increase or lower the material properties of failed plates. More specifically the `append_update_geometry` function in both these programs which appends the plate deactivation code should be redesigned. The C++ source code for the `upGeomHT` and `upGeomSR` programs are included in appendix D4 and D5 respectively.

In addition a few lines in `PlateFailureCheck.py` need to be redeveloped. When deactivating a plate-instance in a model the `fieldOutput` container, for this specific instance, returns empty. `PlateFailureCheck.py` currently checks if a container is empty, and if so, skips it since it has already failed and should not be checked. When effectively removing them this approach will not work. It is advised to rewrite these lines. A possible solution is to perform this check based on the material properties of the plate. Additionally the script could be rewritten to use the `_plateFailure.log` file managed by `FDS-2-Abaqus` similar to the `upGeom` programs.

ABAQUS MODELS AND SIMULATIONS

In the initial stage of this research a model room was developed using a thin walled steel façade. This thin walled steel façade was simplified to a wall consisting of steel panels supported by a frame. The frame was modelled as hinged boundary conditions imposed on the top and bottom of the plates. Thin walled steel façade system consist of many components (struts, beams, fasteners, insulation, and panels) which perform differently under fire conditions and influence each other. In addition these components perform on a different scale-level. Accordingly development of multi scale multi component heat transfer and structural response models could contribute to more realistic failure progression and subsequently fire propagation. The main drawback of these multi scale multi component models is that both the FE models and the coupling tools increase in complexity. On the other hand it allows for more specific failure criteria's, for instance failure of fasteners, to be included in the coupled analysis. In the long run these models could be used in advanced two way coupling studies that could support and expand upon current in situ experiments.

VALIDATION

No detailed verification or validation studies were performed during the development of `FDS-2-Abaqus`. Meaning it strongly depends on the validation of the FDS and Abaqus software. The accuracy of a CFD calculation dependents on the resolution of the underlying numerical grid. Initial verification can be completed by performing a grid resolution stud. In addition existing fire tests on thin walled steel structures could be used to validate the model. Although these validation studies should be preceded by the development of more advanced (and verified) fire, heat transfer and structural models.

FDS-2-ABAQUS

Currently `FDS-2-Abaqus` and its subprograms are limited to performing a one or two-way coupled CFD-FEM analysis comprising a structural system consisting of multiple plates and a failure criteria based on the Von Mises stress. The program could be upgraded to include a greater variety of structural systems and failure criteria's. `FDS-2-Abaqus` is sub structured into multiple programs each with a distinct task. These subprograms can be altered independently as long as the new or upgraded program requires and generates the same input and/or output files. A possible improvement to `FDS-2-Abaqus` is to improve the data flow between `FDS-2-Abaqus` and the FDS and Abaqus Simulations. Allowing, for instance, to interrupt the coupling procedure when an error in the FDS or Abaqus Simulation is encountered.

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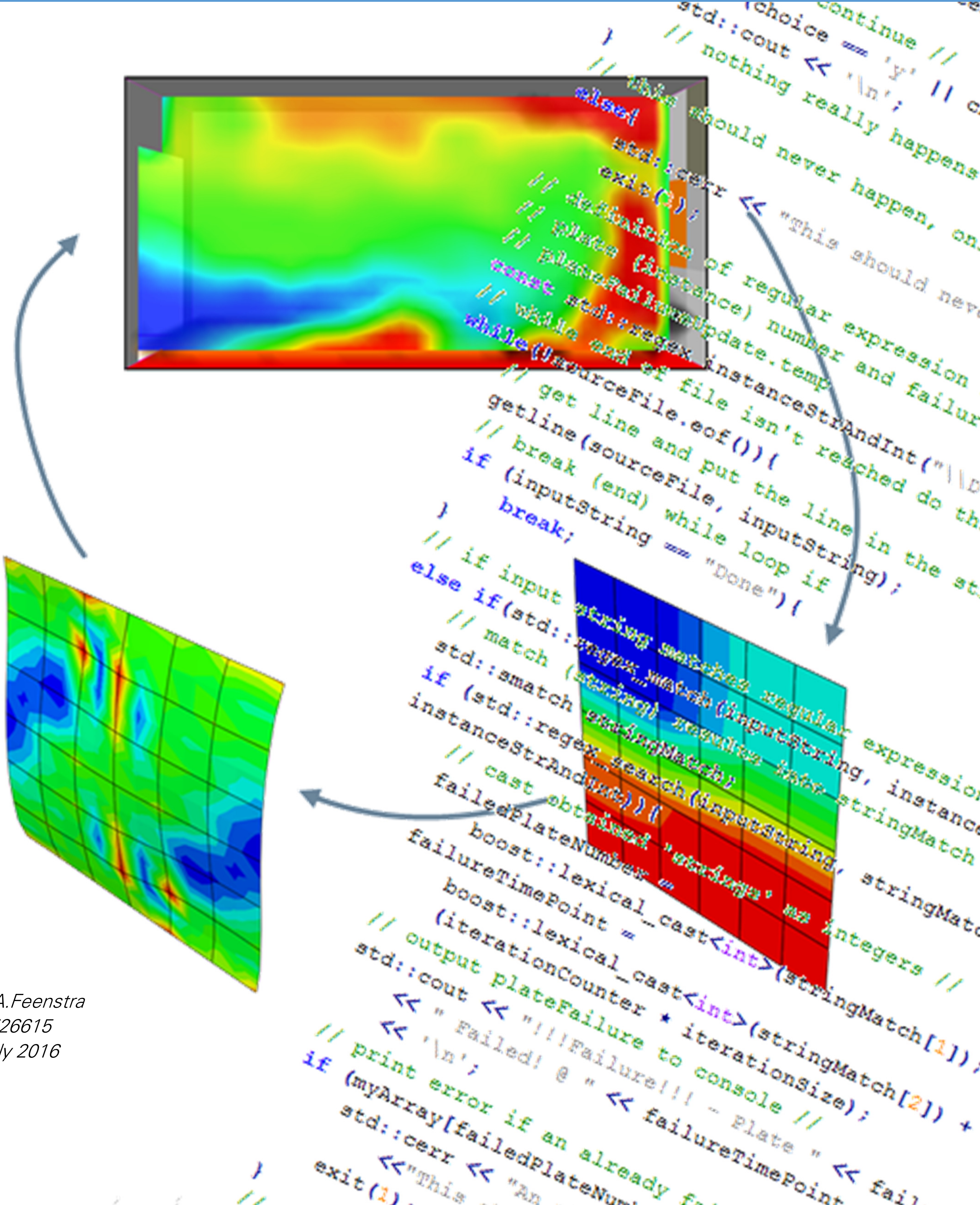
FDS-2-Abaqus

C++ managed automated Python scripted CFD-FEM coupling

Additionally assessing two-way coupling effectiveness

Appendices



J.A.Feenstra
0726615
July 2016

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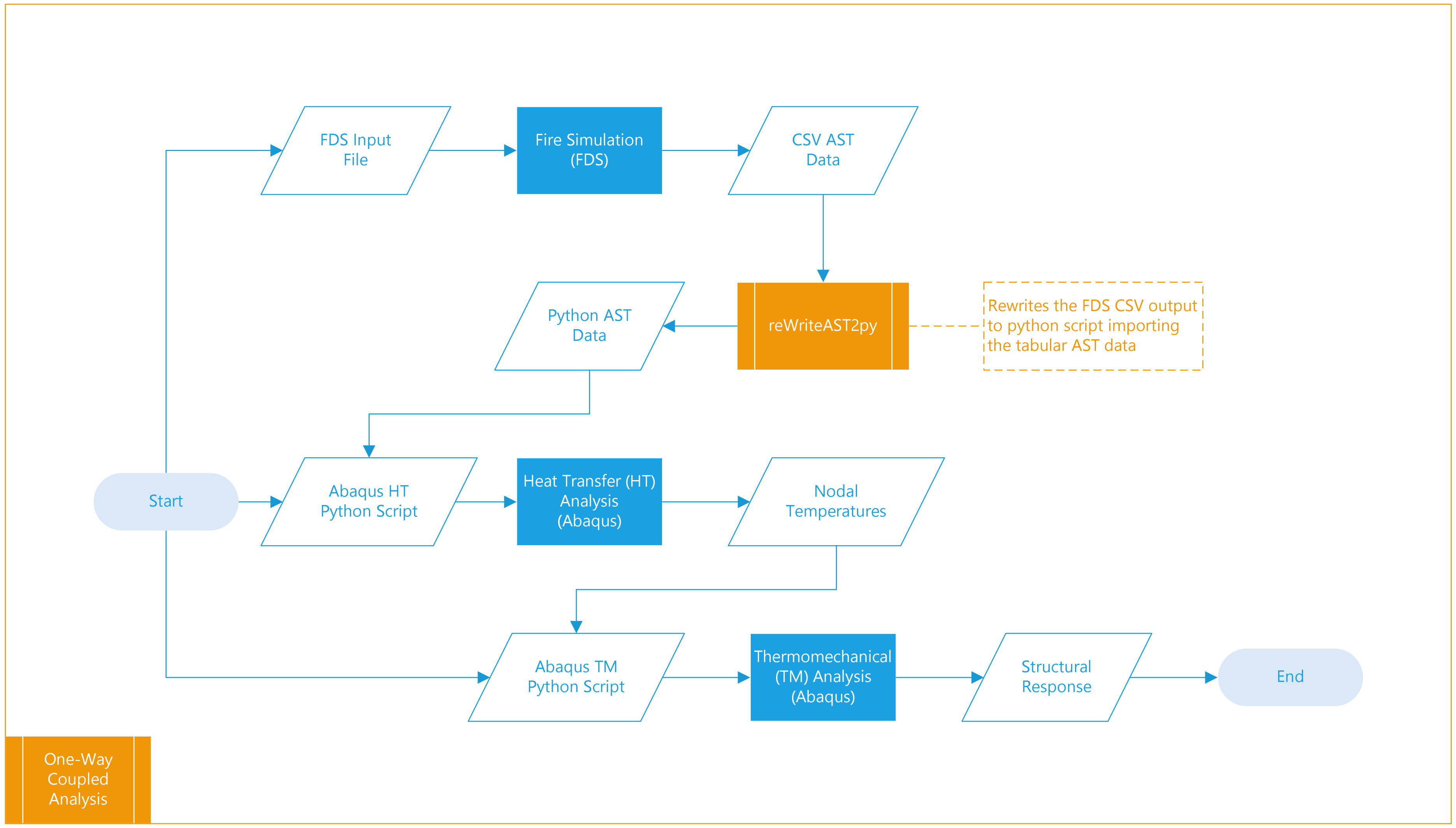
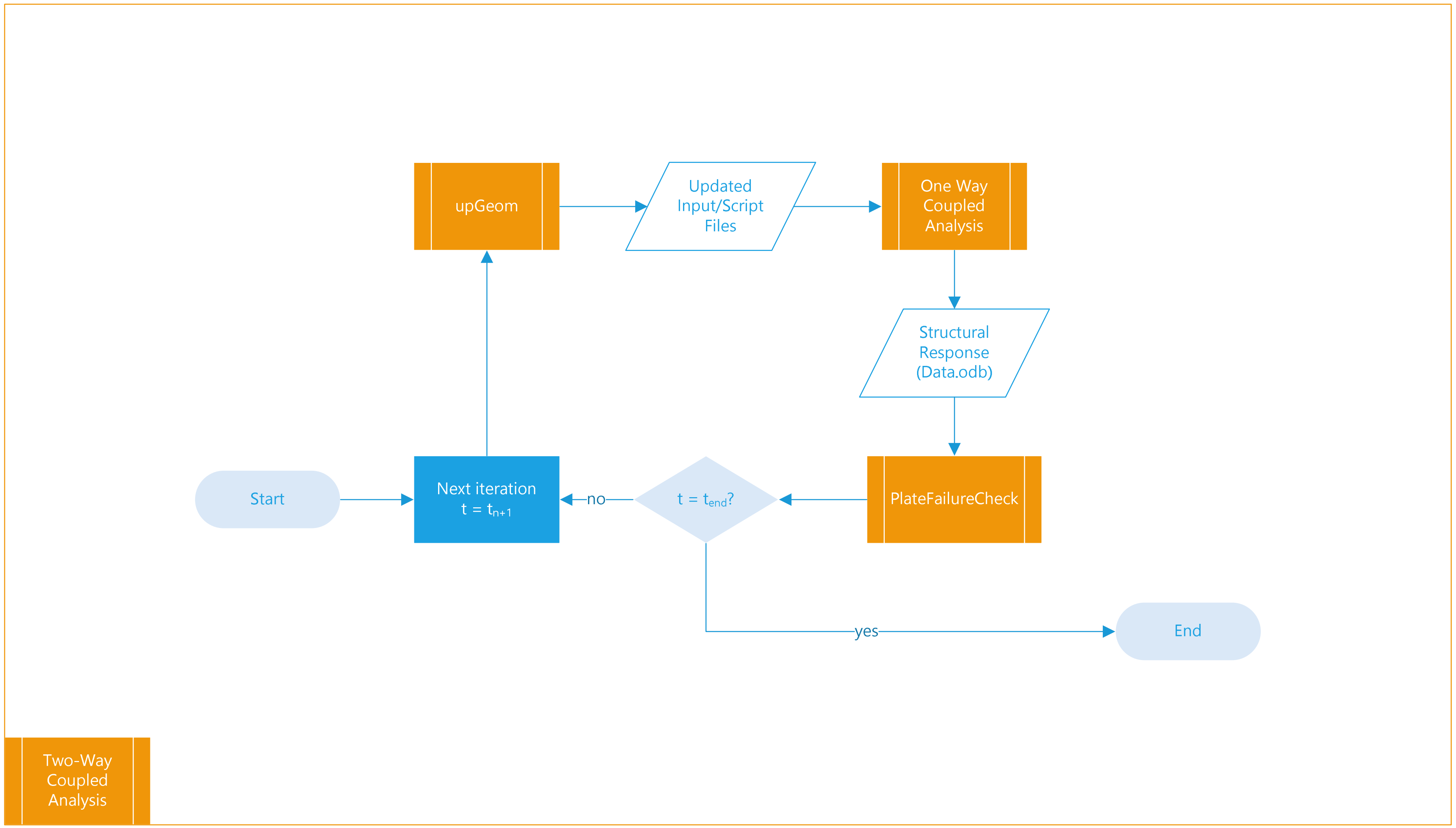
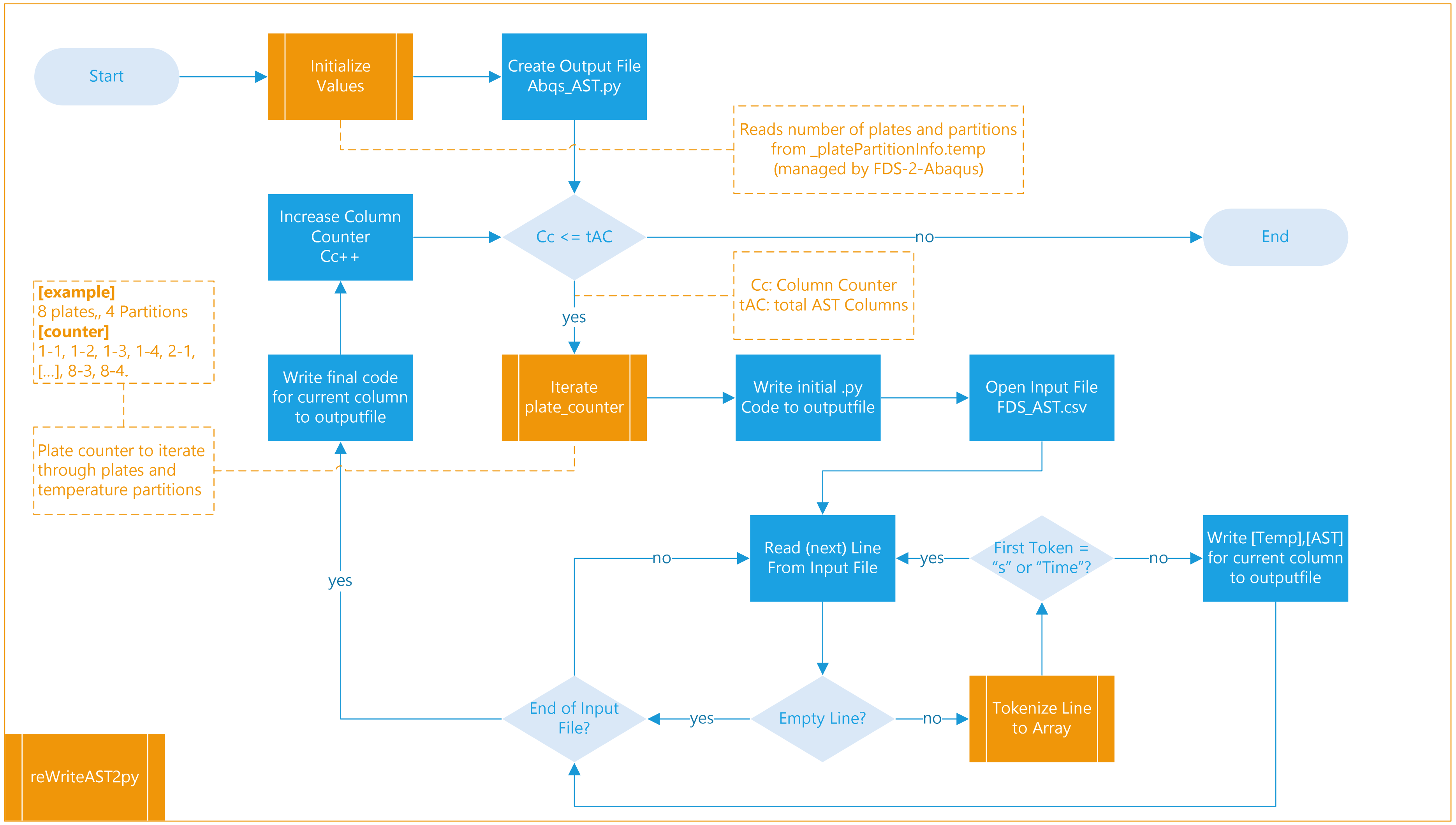
Appendix A1 – Flowchart: One-Way Coupled Thermomechanical Analysis



Appendix A2 – Flowchart: Two-Way Coupled Thermomechanical Analysis

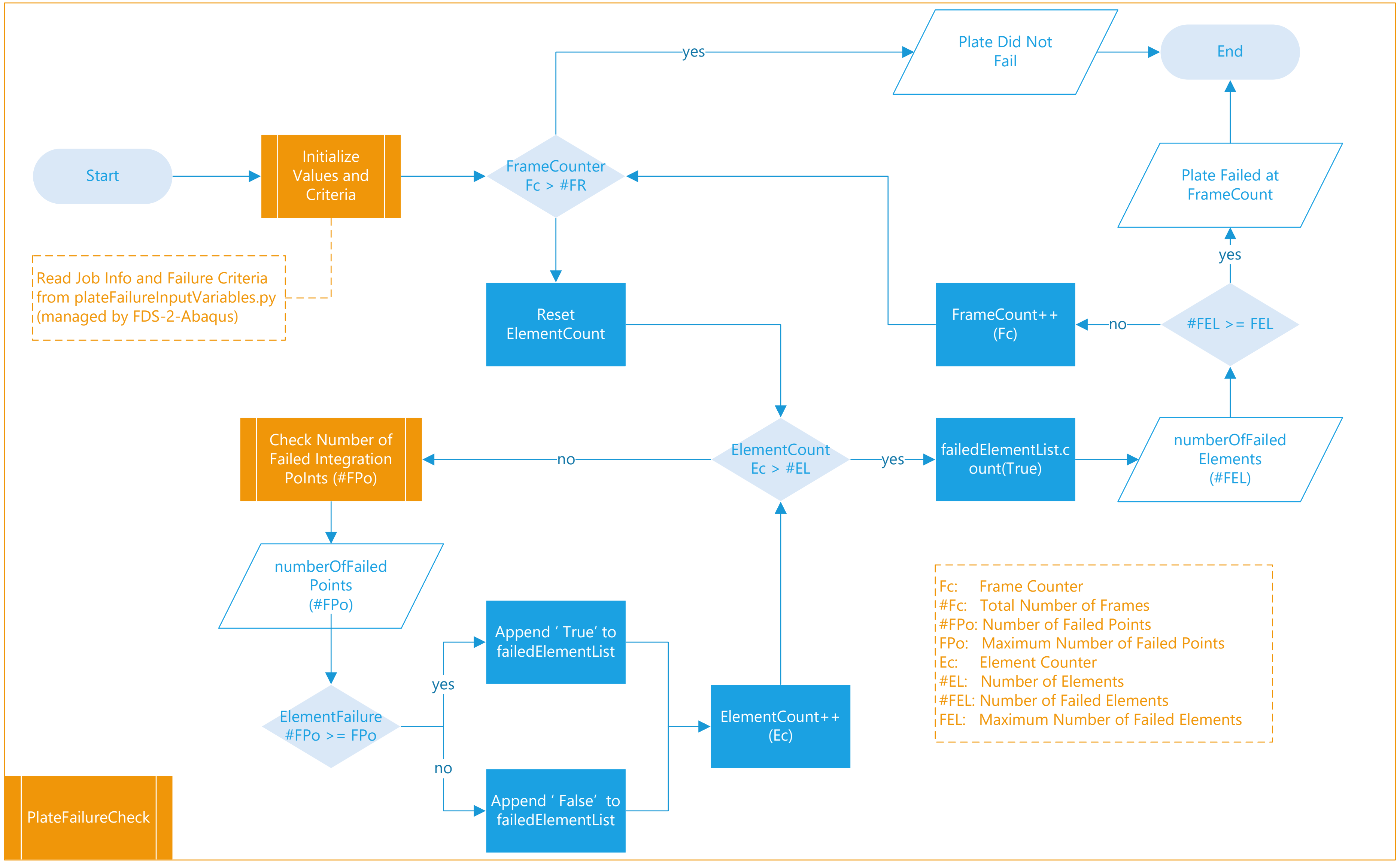


Appendix A3 – Flowchart: reWriteAST2py



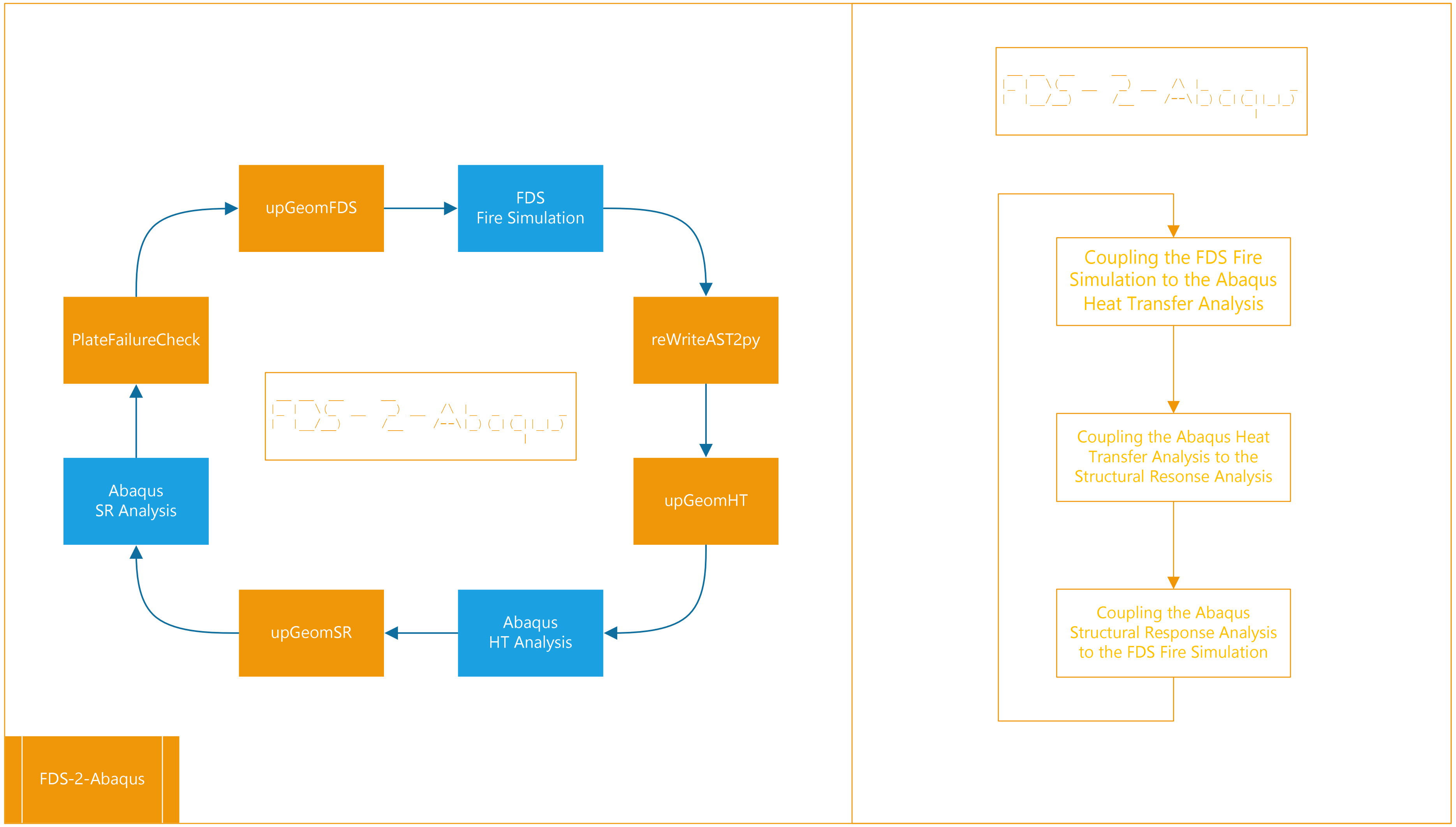
Start
Initialize Values
Create Output File Abqs_AST.py
Reads number of plates and partitions from _platePartitionInfo.temp (managed by FDS-2-Abaqus)
Increase Column Counter Cc++
Cc <= tAC
no
End
Cc: Column Counter
tAC: total AST Columns
yes
[example]
8 plates,, 4 Partitions
[counter]
1-1, 1-2, 1-3, 1-4, 2-1, [...], 8-3, 8-4.
Write final code for current column to outputfile
Iterate plate_counter
Write initial .py Code to outputfile
Open Input File FDS_AST.csv
Plate counter to iterate through plates and temperature partitions
Read (next) Line From Input File
yes
First Token = "s" or "Time"?
no
Write [Temp],[AST] for current column to outputfile
no
yes
End of Input File?
yes
Empty Line?
no
Tokenize Line to Array
reWriteAST2py

APPENDIX A4 – FLOWCHART: PLATEFAILURE.PY

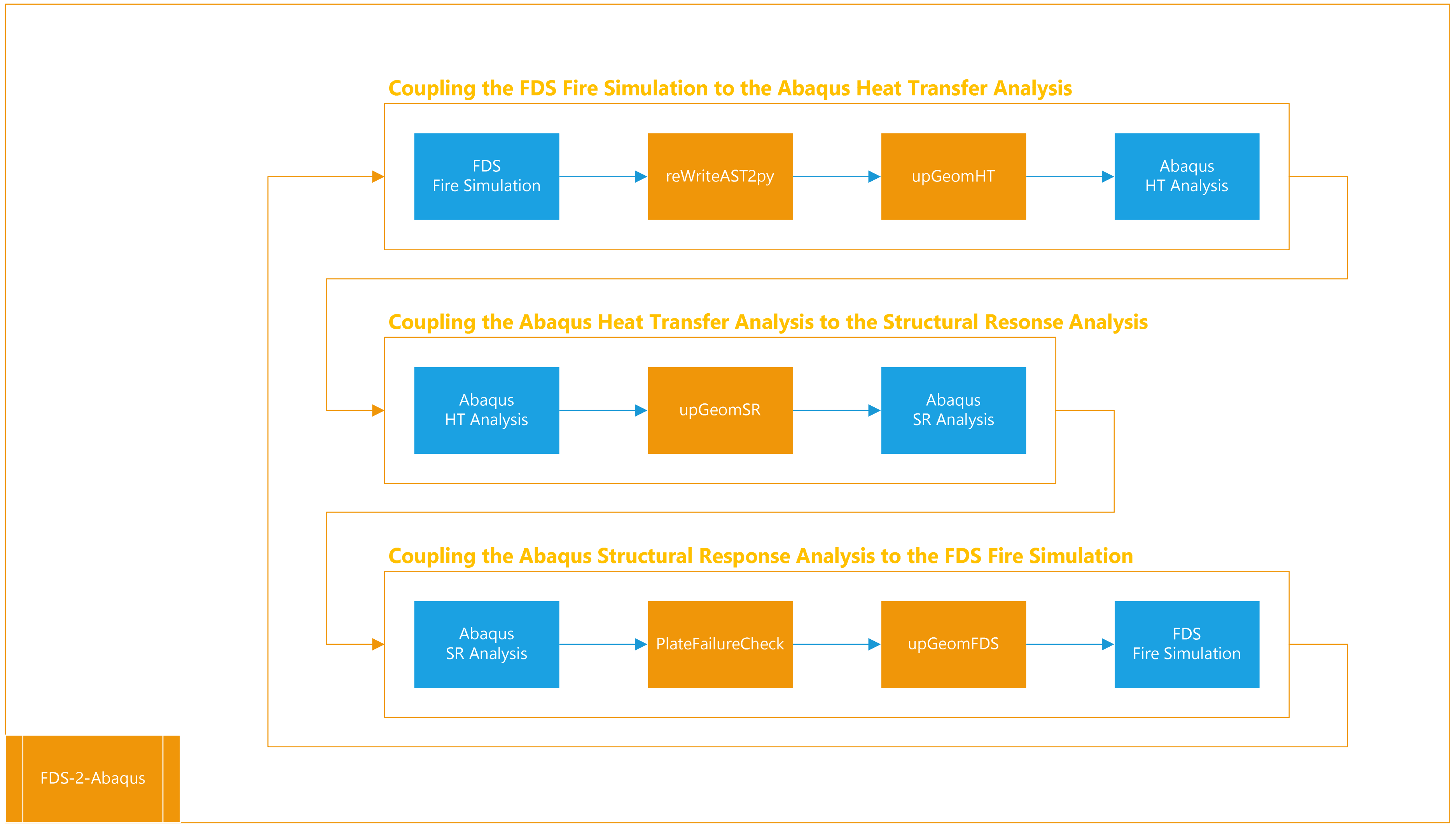

Start
Initialize Values and Criteria
Read Job Info and Failure Criteria from plateFailureInputVariables.py (managed by FDS-2-Abaqus)
FrameCounter Fc > #FR
yes
Plate Did Not Fail
End
Reset ElementCount
FrameCount++ (Fc)
no
#FEL >= FEL
yes
Plate Failed at FrameCount
Check Number of Failed Integration PoInts (#FPo)
no
ElementCount Ec > #EL
yes
failedElementList.count(True)
numberOfFailed Elements (#FEL)
numberOfFailed Points (#FPo)
ElementFailure #FPo >= FPo
yes
no
Append ' True' to failedElementList
Append ' False' to failedElementList
ElementCount++ (Ec)
PlateFailureCheck

Fc:	Frame Counter
#Fc:	Total Number of Frames
#FPo:	Number of Failed Points
FPo:	Maximum Number of Failed Points
Ec:	Element Counter
#EL:	Number of Elements
#FEL:	Number of Failed Elements
FEL:	Maximum Number of Failed Elements

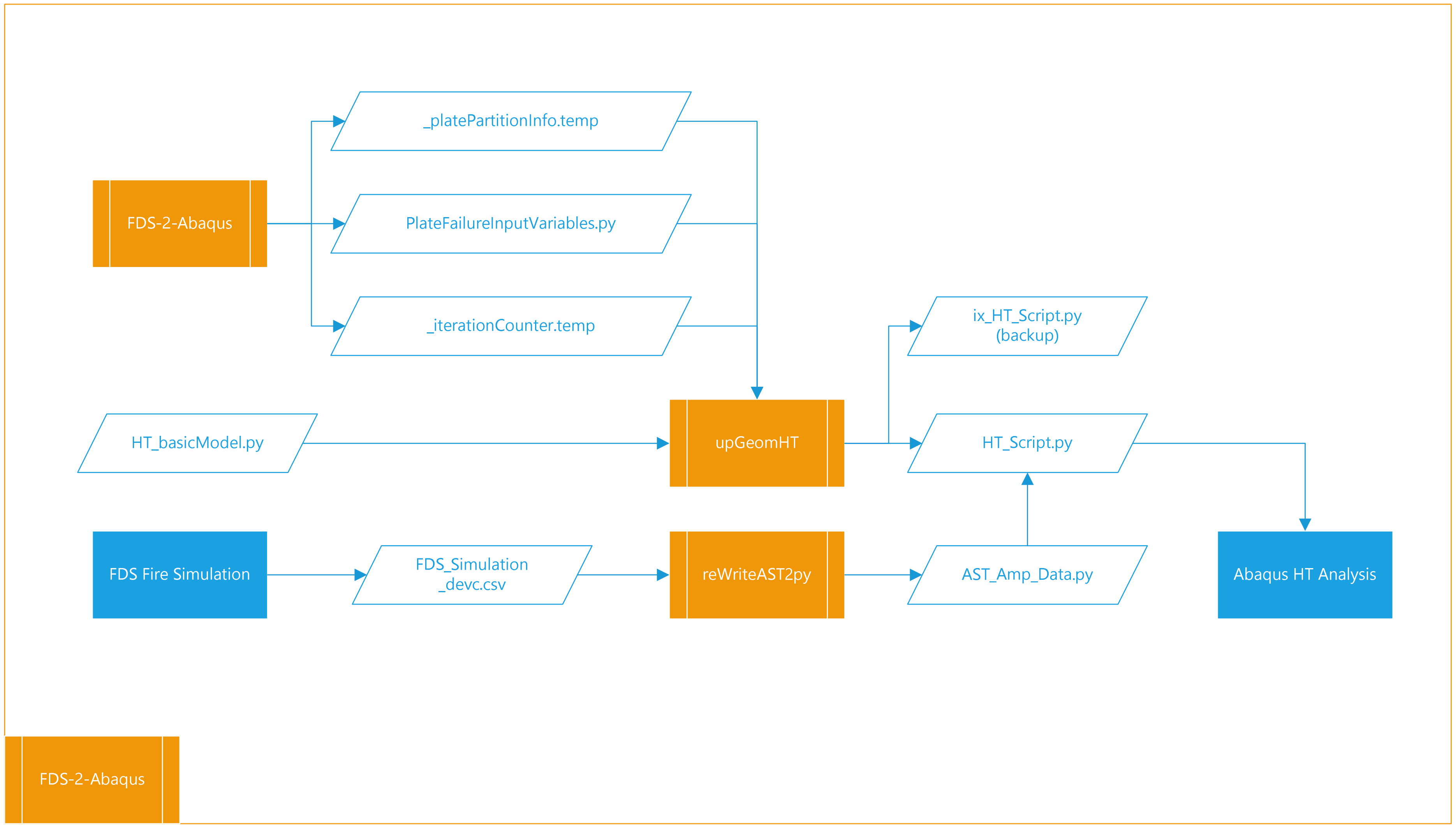
APPENDIX A5.1 – FLOWCHART: FDS-2-ABAQUS – OVERVIEW


upGeomFDS
FDS Fire Simulation
reWriteAST2py
upGeomHT
Abaqus HT Analysis
upGeomSR
Abaqus SR Analysis
PlateFailureCheck
FDS-2-Abaqus
Coupling the FDS Fire Simulation to the Abaqus Heat Transfer Analysis
Coupling the Abaqus Heat Transfer Analysis to the Structural Resonse Analysis
Coupling the Abaqus Structural Response Analysis to the FDS Fire Simulation

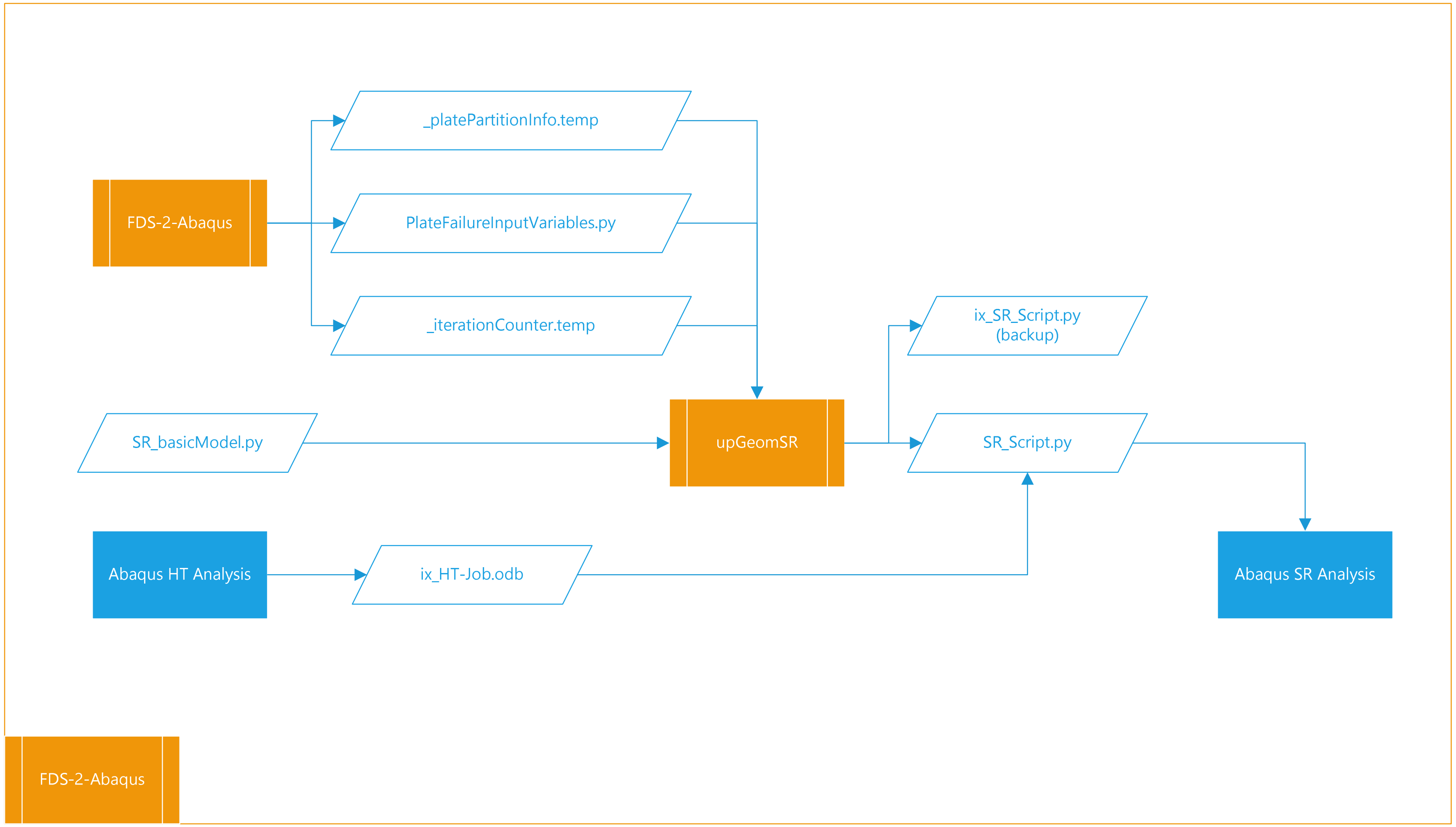
Appendix A5.2 – Flowchart: FDS-2-Abaqus – Divided into Distinctive Coupling Steps


Coupling the FDS Fire Simulation to the Abaqus Heat Transfer Analysis
FDS Fire Simulation
reWriteAST2py
upGeomHT
Abaqus HT Analysis
Coupling the Abaqus Heat Transfer Analysis to the Structural Resonse Analysis
Abaqus HT Analysis
upGeomSR
Abaqus SR Analysis
Coupling the Abaqus Structural Response Analysis to the FDS Fire Simulation
Abaqus SR Analysis
PlateFailureCheck
upGeomFDS
FDS Fire Simulation
FDS-2-Abaqus

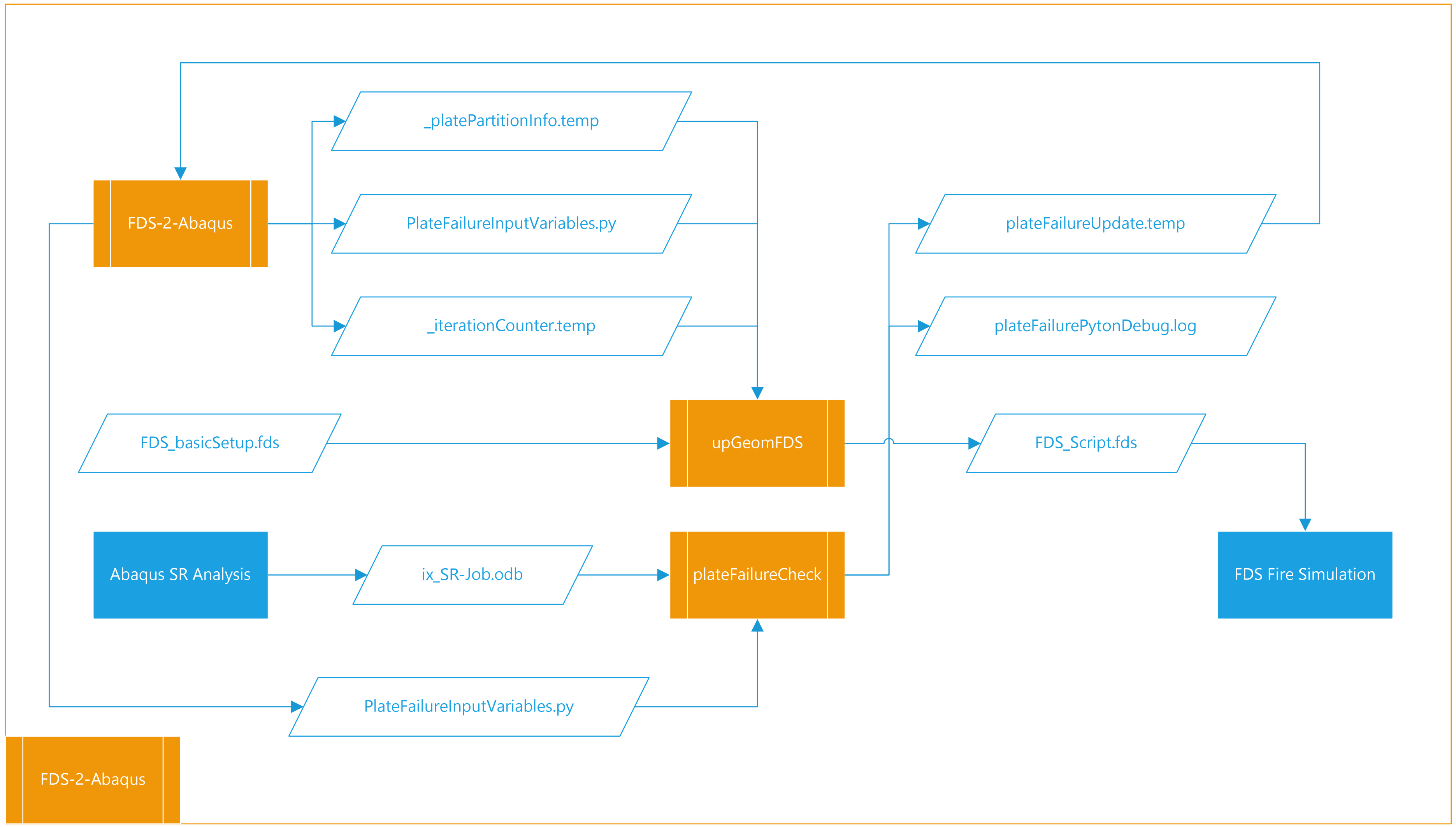
Appendix A5.3 – Flowchart: FDS-2-Abaqus – Coupling of the Fire Simulation to the Heat Transfer Analysis



Appendix A5.4 – Flowchart: FDS-2-Abaqus – Coupling of the Heat Transfer Analysis to the Structural Response Analysis



Appendix A5.5 – Flowchart: FDS-2-Abaqus – Coupling of the Structural Response Analysis to the Heat Transfer Analysis



APPENDIX B1 – FDS_SINGLEPLATE.FDS: FDS INPUT FILE

```
///////////////////////////////////////////////////////////////////////////
// Name:         FDS_singlePlate.fds                                     //
//                                                                       //
// Description: FDS fire model for a single plate one-way coupled        //
//               thermo-mechanical CFD-FEM Analysis.                     //
//                                                                       //
//                                                                       //
// Output:       FDS_Simulation_devc.csv                                 //
//               (Comma separated file containing AST data)              //
//                                                                       //
///////////////////////////////////////////////////////////////////////////
// Version 1.0                                          by J.A.Feenstra //
// August 2016                             jelmerfeenstra1987@gmail.com //
///////////////////////////////////////////////////////////////////////////

//////////////////////////// Begin Input File ////////////////////////////

// Basic Header Info //
&HEAD CHID='FDS_Simulation', TITLE='Basic FDS Model - 12 Plate' /
// Specify Total Simulation Duration //
&TIME T_BEGIN=0, T_END=3650./
// Specify Coordinate system and Discretization //
&MESH IJK=30,12,9, XB=0.0,9.0,0.0,3.6,0.0,2.7 /
// Define Output Request Interval //
&DUMP STATUS_FILES=TRUE, NFRAMES=1460, DT_DEVC=5. /
// Set Default Surface //
&MISC SURF_DEFAULT='CONCRETE_S'
// Define Fuel Type //
&REAC FUEL = 'CELLULOSE'
      FORMULA = 'C4H6O3'
// Specify Enthalpy [kJ/mol] for Species //
&SPEC ID = 'CELLULOSE',
      FORMULA = 'C4H6O3',
      ENTHALPY_OF_FORMATION=-5.13E2 /
// Define Fire Propagation //
&SURF ID='fire',HRRPUA=250.,RAMP_Q='fire',TMP_FRONT=100.,COLOR='RED' /
&RAMP ID='fire',T=   0.,F=0. /
&RAMP ID='fire',T=  10.,F=1. /
&RAMP ID='fire',T=1970.,F=1. /
&RAMP ID='fire',T=3650.,F=0. /
// Define Fire Area //
&VENT XB=1.8,7.2,0.0,3.6,0.0,0.0, SURF_ID='fire' /
// Specify Concrete Material Properties     //
// CONDUCTIVITY [W m-1 K-1], DENSITY [kg m-3] //
// SPECIFIC_HEAT [kJ kg-1 K-1], EMISSIVITY    //
&MATL   ID='CONCRETE_M',
        DENSITY=1800.,
        CONDUCTIVITY=1.15,
        SPECIFIC_HEAT=1.00,
        EMISSIVITY=0.80,    /
// Define Concrete Surface //
&SURF ID='CONCRETE_S', MATL_ID='CONCRETE_M', THICKNESS=0.3, COLOR='GRAY' /
// Define Adiabatic Surface //
&SURF ID='ADIABATIC', ADIABATIC=.TRUE./
// Specify Corridor Wall (And Door) //
&OBST XB=1.8,1.8,0.0,3.6,0,2.7 /
&HOLE XB=1.6,2.0,0.6,3.0,0.0,2.1 /
```

```
// Define Facade Wall //
// This wall consist of 12 separate obstructions to //
// allow for independent obstruction removal         //
// Plate 1 - Column 1, Row 1 //
&OBST XB=7.2,7.2,2.7,3.6,0.0,0.9, SURF_ID='ADIABATIC', COLOR='LIGHT GREY',
    DEVC_ID='RemPlate1' /
// Plate 2 - Column 1, Row 2 //
&OBST XB=7.2,7.2,2.7,3.6,0.9,1.8, SURF_ID='ADIABATIC', COLOR='SILVER',
    DEVC_ID='RemPlate2' /
// Plate 3 - Column 1, Row 3 //
&OBST XB=7.2,7.2,2.7,3.6,1.8,2.7, SURF_ID='ADIABATIC', COLOR='WARM GREY',
    DEVC_ID='RemPlate3' /
// Plate 4 - Column 2, Row 1 //
&OBST XB=7.2,7.2,1.8,2.7,0.0,0.9, SURF_ID='ADIABATIC', COLOR='WARM GREY',
    DEVC_ID='RemPlate4' /
// Plate 5 - Column 2, Row 2 //
&OBST XB=7.2,7.2,1.8,2.7,0.9,1.8, SURF_ID='ADIABATIC', COLOR='LIGHT GREY',
    DEVC_ID='RemPlate5' /
// Plate 6 - Column 2, Row 3 //
&OBST XB=7.2,7.2,1.8,2.7,1.8,2.7, SURF_ID='ADIABATIC', COLOR='SILVER',
    DEVC_ID='RemPlate6' /
// Plate 7 - Column 3, Row 1 //
&OBST XB=7.2,7.2,0.9,1.8,0.0,0.9, SURF_ID='ADIABATIC', COLOR='SILVER',
    DEVC_ID='RemPlate7' /
// Plate 8 - Column 3, Row 2 //
&OBST XB=7.2,7.2,0.9,1.8,0.9,1.8, SURF_ID='ADIABATIC', COLOR='ORANGE',
    DEVC_ID='RemPlate8' /
// Plate 9 - Column 3, Row 3 //
&OBST XB=7.2,7.2,0.9,1.8,1.8,2.7, SURF_ID='ADIABATIC', COLOR='LIGHT GREY',
    DEVC_ID='RemPlate9' /
// Plate 10 - Column 4, Row 1 //
&OBST XB=7.2,7.2,0.0,0.9,0.0,0.9, SURF_ID='ADIABATIC', COLOR='LIGHT GREY',
    DEVC_ID='RemPlate10' /
// Plate 11 - Column 4, Row 2 //
&OBST XB=7.2,7.2,0.0,0.9,0.9,1.8, SURF_ID='ADIABATIC', COLOR='SILVER',
    DEVC_ID='RemPlate11' /
// Plate 12 - Column 4, Row 3 //
&OBST XB=7.2,7.2,0.0,0.9,1.8,2.7, SURF_ID='ADIABATIC', COLOR='WARM GREY',
    DEVC_ID='RemPlate12' /
// Define Vents //
// Removing Obstructions outside Office Space (Front) //
&VENT XB=0.0,1.8,0.0,3.6,0.0,0.0, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,0.0,3.6,2.7,2.7, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,0.0,0.0,0.0,2.7, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,3.6,3.6,0.0,2.7, SURF_ID='OPEN' /
&VENT MB='XMIN', SURF_ID='OPEN' /
// Removing Obstructions outside Office Space (Back) //
&VENT XB=7.2,9.0,0.0,3.6,0.0,0.0, SURF_ID='OPEN' /
&VENT XB=7.2,9.0,0.0,3.6,2.7,2.7, SURF_ID='OPEN' /
&VENT XB=7.2,9.0,0.0,0.0,0.0,2.7, SURF_ID='OPEN' /
&VENT XB=7.2,9.0,3.6,3.6,0.0,2.7, SURF_ID='OPEN' /
&VENT MB='XMAX', SURF_ID='OPEN' /
// Define Slice Files //
&SLCF PBX=3.6,QUANTITY='TEMPERATURE' /
&SLCF PBX=3.6,QUANTITY='HRRPUV' /
&SLCF PBY=1.8,QUANTITY='TEMPERATURE' /
&SLCF PBY=1.8,QUANTITY='HRRPUV' /
```

```
// Create Data Devices                        //
// Devices recording AST temperature data //
// AST Devices for Plate 8 - Column 3, Row 2 //
&DEVC XYZ=7.2,1.575,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_8-1', IOR=-1 /
&DEVC XYZ=7.2,1.575,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_8-2', IOR=-1 /
&DEVC XYZ=7.2,1.125,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_8-3', IOR=-1 /
&DEVC XYZ=7.2,1.125,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_8-4', IOR=-1 /
// Tail //
&Tail /
////////////////////////// End of FDS_BasicSetup //////////////////////////
```

APPENDIX B2 – FDS_BASICSETUP-12.FDS: FDS INPUT FILE

```
///////////////////////////////////////////////////////////////////////////
// Name:         FDS_BasicSetup-12.fds                                  //
//                                                                      //
// Description: Basic Setup for FDS fire simulation model               //
//              comprising a 12 part obstruction facade for use in a    //
//              two-way coupled thermo-mechanical CFD-FEM Analysis.     //
//                                                                      //
// Additional   This script is INCOMPLETE additional input lines are    //
// Info:        appended by geometric update program upGeomFDS based on //
//              the current iteration and failure progression.          //
//              The complete coupling procedure is managed by           //
//              Master Program FDS-2-Abaqus.                            //
//                                                                      //
// Output:      FDS_Simulation_devc.csv                                 //
//              (Comma separated file containing AST data)              //
//                                                                      //
///////////////////////////////////////////////////////////////////////////
// Version 1.0                                        by J.A.Feenstra //
// August 2016                          jelmerfeenstra1987@gmail.com //
///////////////////////////////////////////////////////////////////////////

//////////////////////////// Begin Input File /////////////////////////////

// Basic Header Info //
&HEAD CHID='FDS_Simulation', TITLE='FDS BasicSetup - 12 Plate' /
// Specify Total Simulation Duration //
&TIME T_BEGIN=0, T_END=3650./
// Specify Coordinate system and Discretization //
&MESH IJK=30,12,9, XB=0.0,9.0,0.0,3.6,0.0,2.7 /
// Define Output Request Interval //
&DUMP STATUS_FILES=TRUE, NFRAMES=1460, DT_DEVC=5. /
// Set Default Surface //
&MISC SURF_DEFAULT='CONCRETE_S'
// Define Fuel Type //
&REAC FUEL = 'CELLULOSE'
      FORMULA = 'C4H6O3'
// Specify Enthalpy [kJ/mol] for Species //
&SPEC ID = 'CELLULOSE',
      FORMULA = 'C4H6O3',
      ENTHALPY_OF_FORMATION=-5.13E2 /
// Define Fire Propagation //
&SURF ID='fire',HRRPUA=250.,RAMP_Q='fire',TMP_FRONT=100.,COLOR='RED' /
&RAMP ID='fire',T=   0.,F=0. /
&RAMP ID='fire',T=  10.,F=1. /
&RAMP ID='fire',T=1970.,F=1. /
&RAMP ID='fire',T=3650.,F=0. /
// Define Fire Area //
&VENT XB=1.8,7.2,0.0,3.6,0.0,0.0, SURF_ID='fire' /
// Specify Concrete Material Properties    //
// CONDUCTIVITY [W m-1 K-1], DENSITY [kg m-3] //
// SPECIFIC_HEAT [kJ kg-1 K-1], EMISSIVITY    //
&MATL   ID='CONCRETE_M',
        DENSITY=1800.,
        CONDUCTIVITY=1.15,
        SPECIFIC_HEAT=1.00,
        EMISSIVITY=0.80,    /
// Define Concrete Surface //
&SURF ID='CONCRETE_S', MATL_ID='CONCRETE_M', THICKNESS=0.3, COLOR='GRAY' /
```

```
// Define Adiabatic Surface //
&SURF ID='ADIABATIC', ADIABATIC=.TRUE./
// Specify Corridor Wall (And Door) //
&OBST XB=1.8,1.8,0.0,3.6,0,2.7 /
&HOLE XB=1.6,2.0,0.6,3.0,0.0,2.1 /
// Define Facade Wall //
// This wall consist of 12 separate obstructions to //
// allow for independent obstruction removal        //
// Plate 1 - Column 1, Row 1 //
&OBST XB=7.2,7.2,2.7,3.6,0.0,0.9, SURF_ID='ADIABATIC', COLOR='LIGHT GREY',
    DEVC_ID='RemPlate1' /
// Plate 2 - Column 1, Row 2 //
&OBST XB=7.2,7.2,2.7,3.6,0.9,1.8, SURF_ID='ADIABATIC', COLOR='SILVER',
    DEVC_ID='RemPlate2' /
// Plate 3 - Column 1, Row 3 //
&OBST XB=7.2,7.2,2.7,3.6,1.8,2.7, SURF_ID='ADIABATIC', COLOR='WARM GREY',
    DEVC_ID='RemPlate3' /
// Plate 4 - Column 2, Row 1 //
&OBST XB=7.2,7.2,1.8,2.7,0.0,0.9, SURF_ID='ADIABATIC', COLOR='WARM GREY',
    DEVC_ID='RemPlate4' /
// Plate 5 - Column 2, Row 2 //
&OBST XB=7.2,7.2,1.8,2.7,0.9,1.8, SURF_ID='ADIABATIC', COLOR='LIGHT GREY',
    DEVC_ID='RemPlate5' /
// Plate 6 - Column 2, Row 3 //
&OBST XB=7.2,7.2,1.8,2.7,1.8,2.7, SURF_ID='ADIABATIC', COLOR='SILVER',
    DEVC_ID='RemPlate6' /
// Plate 7 - Column 3, Row 1 //
&OBST XB=7.2,7.2,0.9,1.8,0.0,0.9, SURF_ID='ADIABATIC', COLOR='SILVER',
    DEVC_ID='RemPlate7' /
// Plate 8 - Column 3, Row 2 //
&OBST XB=7.2,7.2,0.9,1.8,0.9,1.8, SURF_ID='ADIABATIC', COLOR='WARM GREY',
    DEVC_ID='RemPlate8' /
// Plate 9 - Column 3, Row 3 //
&OBST XB=7.2,7.2,0.9,1.8,1.8,2.7, SURF_ID='ADIABATIC', COLOR='LIGHT GREY',
    DEVC_ID='RemPlate9' /
// Plate 10 - Column 4, Row 1 //
&OBST XB=7.2,7.2,0.0,0.9,0.0,0.9, SURF_ID='ADIABATIC', COLOR='LIGHT GREY',
    DEVC_ID='RemPlate10' /
// Plate 11 - Column 4, Row 2 //
&OBST XB=7.2,7.2,0.0,0.9,0.9,1.8, SURF_ID='ADIABATIC', COLOR='SILVER',
    DEVC_ID='RemPlate11' /
// Plate 12 - Column 4, Row 3 //
&OBST XB=7.2,7.2,0.0,0.9,1.8,2.7, SURF_ID='ADIABATIC', COLOR='WARM GREY',
    DEVC_ID='RemPlate12' /
// Define Vents //
// Removing Obstructions outside Office Space (Front) //
&VENT XB=0.0,1.8,0.0,3.6,0.0,0.0, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,0.0,3.6,2.7,2.7, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,0.0,0.0,0.0,2.7, SURF_ID='OPEN' /
&VENT XB=0.0,1.8,3.6,3.6,0.0,2.7, SURF_ID='OPEN' /
&VENT MB='XMIN', SURF_ID='OPEN' /
// Removing Obstructions outside Office Space (Back) //
&VENT XB=7.2,9.0,0.0,3.6,0.0,0.0, SURF_ID='OPEN' /
&VENT XB=7.2,9.0,0.0,3.6,2.7,2.7, SURF_ID='OPEN' /
&VENT XB=7.2,9.0,0.0,0.0,0.0,2.7, SURF_ID='OPEN' /
&VENT XB=7.2,9.0,3.6,3.6,0.0,2.7, SURF_ID='OPEN' /
&VENT MB='XMAX', SURF_ID='OPEN' /
```

```
// Define Slice Files //
&SLCF PBX=3.6,QUANTITY='TEMPERATURE' /
&SLCF PBX=3.6,QUANTITY='HRRPUV' /
&SLCF PBY=1.8,QUANTITY='TEMPERATURE' /
&SLCF PBY=1.8,QUANTITY='HRRPUV' /
// Create Data Devices                    //
// Devices recording AST temperature data //
// AST Devices for Plate 1 - Column 1, Row 1 //
&DEVC XYZ=7.2,3.375,0.225, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_1-1', IOR=-1 /
&DEVC XYZ=7.2,3.375,0.675, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_1-2', IOR=-1 /
&DEVC XYZ=7.2,2.925,0.225, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_1-3', IOR=-1 /
&DEVC XYZ=7.2,2.925,0.675, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_1-4', IOR=-1 /
// AST Devices for Plate 2 - Column 1, Row 2 //
&DEVC XYZ=7.2,3.375,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_2-1', IOR=-1 /
&DEVC XYZ=7.2,3.375,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_2-2', IOR=-1 /
&DEVC XYZ=7.2,2.925,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_2-3', IOR=-1 /
&DEVC XYZ=7.2,2.925,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_2-4', IOR=-1 /
// AST Devices for Plate 3 - Column 1, Row 3 //
&DEVC XYZ=7.2,3.375,2.025, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_3-1', IOR=-1 /
&DEVC XYZ=7.2,3.375,2.475, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_3-2', IOR=-1 /
&DEVC XYZ=7.2,2.925,2.025, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_3-3', IOR=-1 /
&DEVC XYZ=7.2,2.925,2.475, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_3-4', IOR=-1 /
// AST Devices for Plate 4 - Column 2, Row 1 //
&DEVC XYZ=7.2,2.475,0.225, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_4-1', IOR=-1 /
&DEVC XYZ=7.2,2.475,0.675, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_4-2', IOR=-1 /
&DEVC XYZ=7.2,2.025,0.225, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_4-3', IOR=-1 /
&DEVC XYZ=7.2,2.025,0.675, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_4-4', IOR=-1 /
// AST Devices for Plate 5 - Column 2, Row 2 //
&DEVC XYZ=7.2,2.475,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_5-1', IOR=-1 /
&DEVC XYZ=7.2,2.475,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_5-2', IOR=-1 /
&DEVC XYZ=7.2,2.025,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_5-3', IOR=-1 /
&DEVC XYZ=7.2,2.025,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_5-4', IOR=-1 /
// AST Devices for Plate 6 - Column 2, Row 3 //
&DEVC XYZ=7.2,2.475,2.025, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_6-1', IOR=-1 /
&DEVC XYZ=7.2,2.475,2.475, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_6-2', IOR=-1 /
&DEVC XYZ=7.2,2.025,2.025, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_6-3', IOR=-1 /
&DEVC XYZ=7.2,2.025,2.475, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_6-4', IOR=-1 /
```

```
// AST Devices for Plate 7 - Column 3, Row 1 //
&DEVC XYZ=7.2,1.575,0.225, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_7-1', IOR=-1 /
&DEVC XYZ=7.2,1.575,0.675, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_7-2', IOR=-1 /
&DEVC XYZ=7.2,1.125,0.225, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_7-3', IOR=-1 /
&DEVC XYZ=7.2,1.125,0.675, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_7-4', IOR=-1 /
// AST Devices for Plate 8 - Column 3, Row 2 //
&DEVC XYZ=7.2,1.575,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_8-1', IOR=-1 /
&DEVC XYZ=7.2,1.575,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_8-2', IOR=-1 /
&DEVC XYZ=7.2,1.125,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_8-3', IOR=-1 /
&DEVC XYZ=7.2,1.125,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_8-4', IOR=-1 /
// AST Devices for Plate 9 - Column 3, Row 3 //
&DEVC XYZ=7.2,1.575,2.025, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_9-1', IOR=-1 /
&DEVC XYZ=7.2,1.575,2.475, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_9-2', IOR=-1 /
&DEVC XYZ=7.2,1.125,2.025, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_9-3', IOR=-1 /
&DEVC XYZ=7.2,1.125,2.475, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_9-4', IOR=-1 /
// AST Devices for Plate 10 - Column 4, Row 1 //
&DEVC XYZ=7.2,0.675,0.225, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_10-1', IOR=-1 /
&DEVC XYZ=7.2,0.675,0.675, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_10-2', IOR=-1 /
&DEVC XYZ=7.2,0.225,0.225, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_10-3', IOR=-1 /
&DEVC XYZ=7.2,0.225,0.675, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_10-4', IOR=-1 /
// AST Devices for Plate 11 - Column 4, Row 2 //
&DEVC XYZ=7.2,0.675,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_11-1', IOR=-1 /
&DEVC XYZ=7.2,0.675,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_11-2', IOR=-1 /
&DEVC XYZ=7.2,0.225,1.125, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_11-3', IOR=-1 /
&DEVC XYZ=7.2,0.225,1.575, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_11-4', IOR=-1 /
// AST Devices for Plate 12 - Column 4, Row 3 //
&DEVC XYZ=7.2,0.675,2.025, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_12-1', IOR=-1 /
&DEVC XYZ=7.2,0.675,2.475, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_12-2', IOR=-1 /
&DEVC XYZ=7.2,0.225,2.025, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_12-3', IOR=-1 /
&DEVC XYZ=7.2,0.225,2.475, QUANTITY='ADIABATIC_SURFACE_TEMPERATURE',
    ID='AST_12-4', IOR=-1 /
///////////////////////// End of FDS_BasicSetup /////////////////////////
```

APPENDIX B3 – FDS_TYPICALAPPEND-12.FDS: FDS INPUT FILE

This appendix contains the FDS code added to the `FDS_BasicSetup.fds` input file by the `upGeomFDS` program to update the input file for the current iteration. The `FDS_BasicSetup.fds` for a fire model comprising a twelve plate structural system is included in appendix B2.

This example is based on a structural system comprising twelve plates where each plate is subdivided in four temperature partitions. It is updated for its 5th 150s iteration (iteration number 4) and has a total simulation duration of 1800s. Plate number 4 failed in a previous iteration

First some basic variables are written to the script.

```
// Iteration Number: 4, IterationSize: 150s.
// IterationTimeSlot: 600-750s, TotalSimulationDuration: 1800s.
// 12 plate(s), 4 partition(s).
```

Then the `FDS_BasicSetup.fds` is copied into the file (appendix B2).

```
////////////////////////////////////////////////////////////////////////////
// Name:        FDS_BasicSetup-12.fds                                    //
//                                                                        //
// …
                                                                       … //
////////////////////////// End of FDS_BasicSetup ////////////////////////
```

Finally the input lines for the current iteration are added.

```
///////////////////// Input Lines added by upGeomFDS /////////////////////

// Set Restart .TRUE./.FALSE. //
&MISC RESTART=.TRUE. /
// Set Kill/Restart Switches for current iteration //
&DEVC ID='nextIteration', QUANTITY='TIME', XYZ=0.1,0.1,0.1,
     LATCH=.FALSE., SETPOINT=750 /
&CTRL ID='restartSwitch', FUNCTION_TYPE='RESTART',
    INPUT_ID='nextIteration', LATCH=.FALSE. /
&CTRL ID='killSwitch', FUNCTION_TYPE='KILL', INPUT_ID='nextIteration',
     LATCH=.FALSE. /
// RemPlate Switches //
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate1', SETPOINT=1950, QUANTITY='TIME',
    INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate2', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate3', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate4', SETPOINT=600, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate5', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate6', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
```

```
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate7', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate8', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate9', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate10', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate11', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate12', SETPOINT=1950, QUANTITY='TIME',
     INITIAL_STATE=.TRUE. /
// Tail
&TAIL /
//////////////////////////// End of Input File ////////////////////////////
```

APPENDIX C1 – HT_SINGLEPLATE.PY: ABAQUS PYTHON SCRIPT

```
############################################################################
## Name:         HT_singlePlate.py                                        ##
##                                                                        ##
## Description: Single Plate Heat Transfer (HT) script for one-way       ##
##               coupled thermo-mechanical CFD-FEM Analysis.              ##
##                                                                        ##
## Input :       AST_Amp_Data.py                                          ##
##               (Tabular Amplitude Data, created by reWriteAST2py)       ##
##                                                                        ##
## Output:       HT_singlePlate.odb                                       ##
##               Requires a \\_outputHT\\ folder to store *.odb output    ##
##                                                                        ##
############################################################################
## Version 1.0                                          by J.A.Feenstra ##
## August 2016                             jelmerfeenstra1987@gmail.com ##
############################################################################

############################## Begin Script ###############################
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *
cliCommand("""session.journalOptions.setValues(replayGeometry=COORDINATE,
    recoverGeometry=COORDINATE)""")
### Specify Working Directory    ###
# exclude '_outputHT' folder
currentPath = 'C:\\currentPath'
### Change Working Directory ###
# don't forget to create a '_outputHT' folder in the working directory
os.chdir(currentPath + '\\_outputHT\\')
### Initial Code Definitions ###
mod = mdb.models['Model-1']
modRa = mod.rootAssembly
### Specify-Attributes ###
mod.setValues(absoluteZero=-273, stefanBoltzmann=5.67e-08)
### Create Part ###
mod.ConstrainedSketch(name='__profile__', sheetSize=2.0)
mod.sketches['__profile__'].rectangle(point1=(0.0, 0.0), point2=(0.9, 0.9))
mod.Part(dimensionality=THREE_D, name='Plate', type=DEFORMABLE_BODY)
modPart = mod.parts['Plate']
modPart.BaseShell(sketch=mod.sketches['__profile__'])
```

```
### Create Sets ###
#Plate-Area, Edge-Top, Edge-Right, Edge-Bot, and Edge-Left
modPartFfa = modPart.faces.findAt
modPartEfa = modPart.edges.findAt
modPart.Set(faces=modPartFfa(((0.45, 0.45, 0.0),)), name='Plate-Area')
modPart.Set(edges=modPartEfa(((0.45, 0.9, 0.0), )), name='Edge-Top')
modPart.Set(edges=modPartEfa(((0.45, 0.0, 0.0), )), name='Edge-Bot')
modPart.Set(edges=modPartEfa(((0.0, 0.45, 0.0), )), name='Edge-Left')
modPart.Set(edges=modPartEfa(((0.9, 0.45, 0.0), )), name='Edge-Right')
modRa.regenerate()
### Create Partitions ###
modPartInPo = modPart.InterestingPoint
modPart.PartitionFaceByShortestPath(faces=modPartFfa(((0.3, 0.3, 0.0), )),
    point1=modPartInPo(modPartEfa((0.675, 0.0, 0.0), ), MIDDLE),
    point2=modPartInPo(modPartEfa((0.225, 0.9, 0.0), ), MIDDLE))
modPart.PartitionFaceByShortestPath(faces=modPartFfa(((0.3, 0.6, 0.0), )),
    point1=modPartInPo(modPartEfa((0.0, 0.225, 0.0), ), MIDDLE),
    point2=modPartInPo(modPartEfa((0.45, 0.675, 0.0), ), MIDDLE))
modPart.PartitionFaceByShortestPath(faces=modPartFfa(((0.6, 0.3, 0.0), )),
    point1=modPart.vertices.findAt((0.45, 0.45, 0.0), ),
    point2=modPartInPo(modPartEfa((0.9, 0.675, 0.0), ), MIDDLE))
### Create Surfaces ###
# Naming Convention
# 1)bottomLeft 2)topLeft 3)bottomRight 4)topRight
modPart.Surface(name='Surf-1', side1Faces=modPartFfa(((0.3, 0.3, 0.0), )))
modPart.Surface(name='Surf-2', side1Faces=modPartFfa(((0.15, 0.6, 0.0),)))
modPart.Surface(name='Surf-3', side1Faces=modPartFfa(((0.75, 0.3, 0.0),)))
modPart.Surface(name='Surf-4', side1Faces=modPartFfa(((0.6, 0.6, 0.0), )))
### Create Material ###
mod.Material(name='Steel')
modMat = mod.materials['Steel']
modMat.Elastic(table=((210000000000.0, 0.29),))
modMat.Density(table=((7850.0, ), ))
modMat.SpecificHeat(table=((452.0, ), ))
modMat.Conductivity(table=((53.3, ), ))
modMat.Expansion(table=((12e-06, ), ))
### Create Section ###
mod.HomogeneousShellSection(material='Steel', name='Section-Plate',
    numIntPts=5, thickness=0.003)
### Assign Section ###
modPart.SectionAssignment(offset=0.0,
    offsetField='', offsetType=MIDDLE_SURFACE, region=
    modPart.sets['Plate-Area'], sectionName=
    'Section-Plate', thicknessAssignment=FROM_SECTION)
### Create Instance ###
modRa.DatumCsysByDefault(CARTESIAN)
modRa.Instance(dependent=ON, name='Plate-1', part=modPart)
### Create Step ###
mod.HeatTransferStep(deltmx=50.0, initialInc=1E-6, maxInc=
    10.0, maxNumInc=1000, minInc=1E-6, name='i0_HT-Step',
    previous='Initial', timePeriod=3650.0)
### Import Adiabatic Temperature Data ###
imp = mod.TabularAmplitude
execfile(r'../AST_Amp_Data.py', __main__.__dict__)
### Request Field Output ###
# Field Output is requested every 5 seconds.
modFOR = mod.fieldOutputRequests['F-Output-1']
modFOR.setValues(variables=('NT',), timeInterval=5.0)
```

```
### Seed Part ###
# NOTE: number of seeds per PARTITION edge
modPart.seedEdgeByNumber(constraint=FINER, edges=modPartEfa(
    ((0.9, 0.7875, 0.0), ), ((0.5625, 0.9, 0.0), ), ((0.1125, 0.9, 0.0), ),
    ((0.0, 0.5625, 0.0), ), ((0.0, 0.1125, 0.0), ), ((0.3375, 0.0, 0.0), ),
    ((0.7875, 0.0, 0.0), ), ((0.9, 0.3375, 0.0), ), ), number=3)
### Mesh Part ###
modPart.generateMesh()
### Set Element Type ###
modPart.setElementType(elemTypes=(ElemType(elemCode=DS8,
    elemLibrary=STANDARD), ElemType(elemCode=DS6, elemLibrary=STANDARD)),
    regions=(modPartFfa(((0.6, 0.6, 0.0),), ((0.15, 0.6, 0.0), ),
    ((0.3, 0.3, 0.0), ), ((0.75, 0.3, 0.0), ), ), ))
modRa.regenerate()
### Import AST Tabular Amplitude data ###
# output from reWriteAST2.py
imp = mod.TabularAmplitude
execfile(r'../AST_Amp_data.py', __main__.__dict__)
### Define Radiation and Convection for all Partitions ###
mod.RadiationToAmbient(name='Rad_1-1', createStepName='i0_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i0_AST_1-1',
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-1'])
mod.FilmCondition(name='Conv_1-1', createStepName='i0_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i0_AST_1-1', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-1'])
mod.RadiationToAmbient(name='Rad_1-2', createStepName='i0_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i0_AST_1-2',
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-2'])
mod.FilmCondition(name='Conv_1-2', createStepName='i0_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i0_AST_1-2', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-2'])
mod.RadiationToAmbient(name='Rad_1-3', createStepName='i0_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i0_AST_1-3',
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-3'])
mod.FilmCondition(name='Conv_1-3', createStepName='i0_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i0_AST_1-3', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-3'])
mod.RadiationToAmbient(name='Rad_1-4', createStepName='i0_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i0_AST_1-4',
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-4'])
mod.FilmCondition(name='Conv_1-4', createStepName='i0_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i0_AST_1-4', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-4'])
### Create and Run Job ###
mdb.Job(name='HT_singlePlate', model='Model-1')
mdb.jobs['HT_singlePlate'].submit(consistencyChecking=OFF)
mdb.jobs['HT_singlePlate'].waitForCompletion()
############################## End-Of-Script ##############################
```

APPENDIX C2 – HT_BASICMODEL-12.PY: ABAQUS PYTHON SCRIPT

```
######################################################################
## Name:        HT_basicModel-12.py                                ##
##                                                                  ##
## Description: Basic Heat Transfer (HT) Model for a 12 plate thin  ##
##              walled steel facade for use in two-way coupled thermo-  ##
##              mechanical CFD-FEM Analysis.                        ##
##                                                                  ##
## Additional   This script is INCOMPLETE additional python code is ##
## Info:        appended by geometric update program upGeomHT based on ##
##              the current iteration and failure progression.      ##
##              The complete coupling procedure is managed by       ##
##              Master Program FDS-2-Abaqus.                        ##
##                                                                  ##
## Input :      AST_Amp_Data.py                                     ##
##              (code calling this script is appended by upGeomHT)  ##
##                                                                  ##
## Output:      HT_Script.odb                                       ##
##              Requires a \\_outputHT\\ folder to store *.odb output ##
##                                                                  ##
######################################################################
## Version 1.0                                      by J.A.Feenstra ##
## August 2016                      jelmerfeenstra1987@gmail.com ##
######################################################################

############################# Begin Script ##############################
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *
cliCommand("""session.journalOptions.setValues(replayGeometry=COORDINATE,
    recoverGeometry=COORDINATE)""")
### Specify Working Directory    ###
# exclude '_outputSR' folder
# use this line for use in FDS-2-Abaqus (relative path)
## currentPath = os.getcwd() # use this
# use this line when running script from Abaqus CEA (direct path)
currentPath = 'C:\\currentPath' # or this
# don't forget to create a '_outputHT' folder in the working directory
### Change Working Directory ###
os.chdir(currentPath + '\\_outputHT\\')
### Initial Code Definitions ###
mod = mdb.models['Model-1']
modRa = mod.rootAssembly
### Specify-Attributes ###
mod.setValues(absoluteZero=-273, stefanBoltzmann=5.67e-08)
```

```
### Create Part ###
mod.ConstrainedSketch(name='__profile__', sheetSize=2.0)
mod.sketches['__profile__'].rectangle(point1=(0.0, 0.0), point2=(0.9, 0.9))
mod.Part(dimensionality=THREE_D, name='Plate', type=DEFORMABLE_BODY)
modPart = mod.parts['Plate']
modPart.BaseShell(sketch=mod.sketches['__profile__'])
### Create Sets ###
#Plate-Area, Edge-Top, Edge-Right, Edge-Bot, and Edge-Left
modPartFfa = modPart.faces.findAt
modPartEfa = modPart.edges.findAt
modPart.Set(faces=modPartFfa(((0.45, 0.45, 0.0),)), name='Plate-Area')
modPart.Set(edges=modPartEfa(((0.45, 0.9, 0.0), )), name='Edge-Top')
modPart.Set(edges=modPartEfa(((0.45, 0.0, 0.0), )), name='Edge-Bot')
modPart.Set(edges=modPartEfa(((0.0, 0.45, 0.0), )), name='Edge-Left')
modPart.Set(edges=modPartEfa(((0.9, 0.45, 0.0), )), name='Edge-Right')
modRa.regenerate()
### Create Partitions ###
modPartInPo = modPart.InterestingPoint
modPart.PartitionFaceByShortestPath(faces=modPartFfa(((0.3, 0.3, 0.0), )),
    point1=modPartInPo(modPartEfa((0.675, 0.0, 0.0), ), MIDDLE),
    point2=modPartInPo(modPartEfa((0.225, 0.9, 0.0), ), MIDDLE))
modPart.PartitionFaceByShortestPath(faces=modPartFfa(((0.3, 0.6, 0.0), )),
    point1=modPartInPo(modPartEfa((0.0, 0.225, 0.0), ), MIDDLE),
    point2=modPartInPo(modPartEfa((0.45, 0.675, 0.0), ), MIDDLE))
modPart.PartitionFaceByShortestPath(faces=modPartFfa(((0.6, 0.3, 0.0), )),
    point1=modPart.vertices.findAt((0.45, 0.45, 0.0), ),
    point2=modPartInPo(modPartEfa((0.9, 0.675, 0.0), ), MIDDLE))
### Create Surfaces ###
# Naming Convention
# 1)bottomLeft 2)topLeft 3)bottomRight 4)topRight
modPart.Surface(name='Surf-1', side1Faces=modPartFfa(((0.3, 0.3, 0.0), )))
modPart.Surface(name='Surf-2', side1Faces=modPartFfa(((0.15, 0.6, 0.0),)))
modPart.Surface(name='Surf-3', side1Faces=modPartFfa(((0.75, 0.3, 0.0),)))
modPart.Surface(name='Surf-4', side1Faces=modPartFfa(((0.6, 0.6, 0.0), )))
### Create Material ###
mod.Material(name='Steel')
modMat = mod.materials['Steel']
modMat.Elastic(table=((210000000000.0, 0.29),))
modMat.Density(table=((7850.0, ), ))
modMat.SpecificHeat(table=((452.0, ), ))
modMat.Conductivity(table=((53.3, ), ))
modMat.Expansion(table=((12e-06, ), ))
### Create Section ###
mod.HomogeneousShellSection(material='Steel', name='Section-Plate',
    numIntPts=5, thickness=0.003)
### Assign Section ###
modPart.SectionAssignment(offset=0.0,
    offsetField='', offsetType=MIDDLE_SURFACE, region=
    modPart.sets['Plate-Area'], sectionName=
    'Section-Plate', thicknessAssignment=FROM_SECTION)
### Create Instance ###
modRa.DatumCsysByDefault(CARTESIAN)
modRa.Instance(dependent=ON, name='Plate-1', part=modPart)
### Pattern Multiple Instances ###
modRa.LinearInstancePattern(instanceList=('Plate-1', ),
    direction1=(1.0, 0.0, 0.0), direction2=(0.0, 1.0, 0.0),
    number1=4, number2=3, spacing1=0.9, spacing2=0.9)
```

```
### Rename Instances ###
# Naming Convention
# 1)bottomLeft 2)midLeft 3) topLeft [...] 11) midRight 12)topRight
modRaFe = modRa.features
modRaFe.changeKey(fromName='Plate-1-lin-1-2', toName='Plate-2')
modRaFe.changeKey(fromName='Plate-1-lin-1-3', toName='Plate-3')
modRaFe.changeKey(fromName='Plate-1-lin-2-1', toName='Plate-4')
modRaFe.changeKey(fromName='Plate-1-lin-2-2', toName='Plate-5')
modRaFe.changeKey(fromName='Plate-1-lin-2-3', toName='Plate-6')
modRaFe.changeKey(fromName='Plate-1-lin-3-1', toName='Plate-7')
modRaFe.changeKey(fromName='Plate-1-lin-3-2', toName='Plate-8')
modRaFe.changeKey(fromName='Plate-1-lin-3-3', toName='Plate-9')
modRaFe.changeKey(fromName='Plate-1-lin-4-1', toName='Plate-10')
modRaFe.changeKey(fromName='Plate-1-lin-4-2', toName='Plate-11')
modRaFe.changeKey(fromName='Plate-1-lin-4-3', toName='Plate-12')
### Create Step ###
# Step is later modified for current iteration (by upGeomHT).
# Defined here for Field Output Request and Model Change Interaction.
mod.HeatTransferStep(deltmx=50.0, initialInc=1E-6, maxInc=
    10.0, maxNumInc=1000, minInc=1E-6, name='i0_HT-Step',
    previous='Initial', timePeriod=3650.0)
### Import Adiabatic Temperature Data ###
imp = mod.TabularAmplitude
### Request Field Output ###
# Field Output is requested every 5 seconds.
modFOR = mod.fieldOutputRequests['F-Output-1']
modFOR.setValues(variables=('NT',), timeInterval=5.0) # use this
# Field Output is requested for every (Abaqus) increment/iteration.
# modFOR.setValues(variables=('NT',), frequency=1.0)  # or this
### Seed Part ###
# NOTE: number of seeds per PARTITION edge
modPart.seedEdgeByNumber(constraint=FINER, edges=modPartEfa(
    ((0.9, 0.7875, 0.0), ), ((0.5625, 0.9, 0.0), ), ((0.1125, 0.9, 0.0), ),
    ((0.0, 0.5625, 0.0), ), ((0.0, 0.1125, 0.0), ), ((0.3375, 0.0, 0.0), ),
    ((0.7875, 0.0, 0.0), ), ((0.9, 0.3375, 0.0), ), ), number=3)
### Mesh Part ###
modPart.generateMesh()
### Set Element Type ###
modPart.setElementType(elemTypes=(ElemType(elemCode=DS8,
    elemLibrary=STANDARD), ElemType(elemCode=DS6, elemLibrary=STANDARD)),
    regions=(modPartFfa(((0.6, 0.6, 0.0),), ((0.15, 0.6, 0.0), ),
    ((0.3, 0.3, 0.0), ), ((0.75, 0.3, 0.0), ), ), ))
modRa.regenerate()
### Request Restart File ###
mod.steps['i0_HT-Step'].Restart(frequency=0, numberIntervals=1, overlay=ON,
    timeMarks=OFF)
### Model change Interaction ###
mod.ModelChange(name='ModelChange', createStepName='i0_HT-Step',
    isRestart=True)
########################## End of HT_basicModel ###########################
```

APPENDIX C3 – HT_TYPICALAPPEND-12.PY: ABAQUS PYTHON SCRIPT

This appendix contains the python code added to the `HT_basicModel.py` script by the `upGeomHT` program to update the HT python script for the current iteration. The `HT_BasicModel.py` python script for a structural model comprising twelve plate-instances is included in appendix C2.

This example is based on a structural system comprising twelve plates where each plate is subdivided in four temperature partitions. It is updated for its 5th 150s iteration (iteration number 4) and has a total simulation duration of 1800s. Plate number 4 failed in a previous iteration

First some basic variables are written to the script.

```
## Iteration Number: 4, IterationSize: 150s.
## IterationTimeSlot: 600-750s, TotalSimulationDuration: 1800s.
## 12 plate(s), 4 partition(s).
```

Then the `HT_BasicModel.py` is copied into the script (appendix C3).

```
############################################################################
## Name:        HT_basicModel-12.py                                      ##
##                                                                       ##
## …
                                                                     …  ##
########################## End of HT_basicModel ##########################
```

Finally the python code for the current iteration is added.

```
######################### Code Added by upGeomHT #########################

### Create/Update Additional Steps ###
mod.HeatTransferStep(name='i3_HT-Step', previous='i0_HT-Step',
    timePeriod=150, maxNumInc=1000, initialInc=0.15,
    minInc=1E-3, maxInc=10.0, deltmx=50.0)
mod.HeatTransferStep(name='i4_HT-Step', previous='i3_HT-Step',
    timePeriod=150, maxNumInc=1000, initialInc=0.15,
    minInc=1E-3, maxInc=10.0, deltmx=50.0)
### Define Restart Job/Step ###
mod.setValues(restartJob='i3_HT-Job', restartStep='i3_HT-Step')
### Request Restart File for New Step ###
mod.steps['i4_HT-Step'].Restart(frequency=0, numberIntervals=1,
    overlay=ON, timeMarks=OFF)
### Update ConRad and AST Data ###
imp = mod.TabularAmplitude
execfile(r'../AST_Amp_data.py', __main__.__dict__)
mod.amplitudes.changeKey(fromName='i0_AST_1-1', toName='i4_AST_1-1')
mod.RadiationToAmbient(name='Rad_1-1', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_1-1',
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-1'])
mod.FilmCondition(name='Conv_1-1', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_1-1', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-1'])
mod.amplitudes.changeKey(fromName='i0_AST_1-2', toName='i4_AST_1-2')
mod.RadiationToAmbient(name='Rad_1-2', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_1-2',
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-2'])
```

```
mod.FilmCondition(name='Conv_1-2', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_1-2', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-2'])
mod.amplitudes.changeKey(fromName='i0_AST_1-3', toName='i4_AST_1-3')
mod.RadiationToAmbient(name='Rad_1-3', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_1-3',
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-3'])
mod.FilmCondition(name='Conv_1-3', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_1-3', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-3'])
mod.amplitudes.changeKey(fromName='i0_AST_1-4', toName='i4_AST_1-4')
mod.RadiationToAmbient(name='Rad_1-4', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_1-4',
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-4'])
mod.FilmCondition(name='Conv_1-4', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_1-4', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-1'].surfaces['Surf-4'])
mod.amplitudes.changeKey(fromName='i0_AST_2-1', toName='i4_AST_2-1')
mod.RadiationToAmbient(name='Rad_2-1', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_2-1',
    surface=mod.rootAssembly.instances['Plate-2'].surfaces['Surf-1'])
mod.FilmCondition(name='Conv_2-1', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_2-1', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-2'].surfaces['Surf-1'])
mod.amplitudes.changeKey(fromName='i0_AST_2-2', toName='i4_AST_2-2')
mod.RadiationToAmbient(name='Rad_2-2', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_2-2',
    surface=mod.rootAssembly.instances['Plate-2'].surfaces['Surf-2'])
mod.FilmCondition(name='Conv_2-2', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_2-2', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-2'].surfaces['Surf-2'])
mod.amplitudes.changeKey(fromName='i0_AST_2-3', toName='i4_AST_2-3')
mod.RadiationToAmbient(name='Rad_2-3', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_2-3',
    surface=mod.rootAssembly.instances['Plate-2'].surfaces['Surf-3'])
mod.FilmCondition(name='Conv_2-3', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_2-3', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-2'].surfaces['Surf-3'])
mod.amplitudes.changeKey(fromName='i0_AST_2-4', toName='i4_AST_2-4')
mod.RadiationToAmbient(name='Rad_2-4', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_2-4',
    surface=mod.rootAssembly.instances['Plate-2'].surfaces['Surf-4'])
mod.FilmCondition(name='Conv_2-4', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_2-4', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-2'].surfaces['Surf-4'])
```

```
##########################################################################
## Code for Plates 3 - 11 is excluded from this appendix               ##
## for obvious reasons (Space, Ink, Paper!)                             ##
## (See also 'for loop' alternative below)                              ##
##########################################################################

mod.amplitudes.changeKey(fromName='i0_AST_12-1', toName='i4_AST_12-1')
mod.RadiationToAmbient(name='Rad_12-1', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_12-1',
    surface=mod.rootAssembly.instances['Plate-12'].surfaces['Surf-1'])
mod.FilmCondition(name='Conv_12-1', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_12-1', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-12'].surfaces['Surf-1'])
mod.amplitudes.changeKey(fromName='i0_AST_12-2', toName='i4_AST_12-2')
mod.RadiationToAmbient(name='Rad_12-2', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_12-2',
    surface=mod.rootAssembly.instances['Plate-12'].surfaces['Surf-2'])
mod.FilmCondition(name='Conv_12-2', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_12-2', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-12'].surfaces['Surf-2'])
mod.amplitudes.changeKey(fromName='i0_AST_12-3', toName='i4_AST_12-3')
mod.RadiationToAmbient(name='Rad_12-3', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_12-3',
    surface=mod.rootAssembly.instances['Plate-12'].surfaces['Surf-3'])
mod.FilmCondition(name='Conv_12-3', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_12-3', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-12'].surfaces['Surf-3'])
mod.amplitudes.changeKey(fromName='i0_AST_12-4', toName='i4_AST_12-4')
mod.RadiationToAmbient(name='Rad_12-4', createStepName='i4_HT-Step',
    emissivity=0.8, ambientTemperature=1.0,
    ambientTemperatureAmp='i4_AST_12-4',
    surface=mod.rootAssembly.instances['Plate-12'].surfaces['Surf-4'])
mod.FilmCondition(name='Conv_12-4', createStepName='i4_HT-Step',
    definition=EMBEDDED_COEFF, filmCoeff=25.0,
    sinkAmplitude='i4_AST_12-4', sinkTemperature=1.0,
    surface=mod.rootAssembly.instances['Plate-12'].surfaces['Surf-4'])
### Update Model Geometry ###
thisPlate = mod.rootAssembly.instances['Plate-4'].sets['Plate-Area']
mod.ModelChange(activeInStep=False, createStepName='i4_HT-Step',
    includeStrain=False, name='deActPlate-4', region=thisPlate)
# If empty: No plates failed this iteration - Still Going Strong!
### Create and Run Job ###
mdb.Job(name='i4_HT-Job', model='Model-1', type=RESTART)
mdb.jobs['i4_HT-Job'].submit(consistencyChecking=OFF)
mdb.jobs['i4_HT-Job'].waitForCompletion()
############################## End-Of-Script ##############################
```

The python code for convective and radiative heat transfer for every partition of every plate could also be described using a for loop. This ‘for loop approach’ is currently not implemented in the upGeomHT program appending the python code for current iteration.

```python
### Alternative Code for Convective and Radiative Heat Transfer ###
numberOfPlates = 12
numberOfPartitions = 4
iterationNumber = 4
for plateCounter in xrange(1,(numberOfPlates + 1)):
    for partitionCounter in xrange(1,(numberOfPartitions + 1)):
        thisPlate = 'Plate-' + str(plateCounter)
        thisSurface = 'Surf-' + str(partitionCounter)
        ppNumber = str(plateCounter) + '-' + str(partitionCounter)
        radName  = 'Rad_'  + ppNumber
        convName = 'Conv_' + ppNumber
        oldAST = 'i0_AST_'+ ppNumber
        newAST = 'i' + str(iterationNumber) + '_AST_' + ppNumber
        thisStep = 'i' + str(iterationNumber) + '_HT-Step'
        mod.amplitudes.changeKey(fromName=oldAST, toName=newAST)
        mod.RadiationToAmbient(name=radName, createStepName=thisStep,
            emissivity=0.8, ambientTemperature=1.0,
            ambientTemperatureAmp=newAST, surface=
            mod.rootAssembly.instances[thisPlate].surfaces[thisSurface])
        mod.FilmCondition(name=convName, createStepName=thisStep,
            definition=EMBEDDED_COEFF, filmCoeff=25.0,
            sinkAmplitude=newAST, sinkTemperature=1.0, surface=
            mod.rootAssembly.instances[thisPlate].surfaces[thisSurface])
### End of Alternative Code ###
```

APPENDIX C4 – SR_SINGLEPLATE.PY: ABAQUS PYTHON SCRIPT

```
############################################################################
## Name:         SR_singlePlate.py                                       ##
##                                                                        ##
## Description:  Single Plate Buckling (buc) script that is used to      ##
##               introduce an imperfection in SR_singlePlate             ##
##               a Structural Response (SR) Analysis                     ##
##                                                                        ##
## Input :       HT_singlePlate (temperatures)                           ##
##               buc_singlePlate.fil (imperfection node file)            ##
##               buc_singlePlate.prt (imperfection part file)            ##
##                                                                        ##
## Output:       SR_singlePlate.odb                                      ##
##               Requires a \\_outputSR\\ folder to store *.odb output   ##
##                                                                        ##
############################################################################
## Version 1.0                                            by J.A.Feenstra ##
## August 2016                              jelmerfeenstra1987@gmail.com ##
############################################################################

############################## Begin Script ################################
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *
cliCommand("""session.journalOptions.setValues(replayGeometry=COORDINATE,
    recoverGeometry=COORDINATE)""")
### Specify Working Directory ###
# exclude '_outputSR' folder
currentPath = 'C:\\currentPath'
### Change Working Directory ###
# don't forget to create a '_outputSR' folder in output directory
os.chdir(currentPath + '\\_outputSR\\')
### Initial Code Definitions ###
mod = mdb.models['Model-1']
modRa = mod.rootAssembly
### Specify-Attributes ###
mod.setValues(absoluteZero=-273, stefanBoltzmann=5.67e-08)
### Create Part ###
mod.ConstrainedSketch(name='__profile__', sheetSize=2.0)
mod.sketches['__profile__'].rectangle(point1=(0.0, 0.0), point2=(0.9, 0.9))
mod.Part(dimensionality=THREE_D, name='Plate', type=DEFORMABLE_BODY)
modPart = mod.parts['Plate']
modPart.BaseShell(sketch=mod.sketches['__profile__'])
```

```
### Create Sets ###
#Plate-Area, Edge-Top, Edge-Right, Edge-Bot, and Edge-Left
modPartFfa = modPart.faces.findAt
modPartEfa = modPart.edges.findAt
modPart.Set(faces=modPartFfa(((0.45, 0.45, 0.0),)), name='Plate-Area')
modPart.Set(edges=modPartEfa(((0.45, 0.9, 0.0), )), name='Edge-Top')
modPart.Set(edges=modPartEfa(((0.45, 0.0, 0.0), )), name='Edge-Bot')
modPart.Set(edges=modPartEfa(((0.0, 0.45, 0.0), )), name='Edge-Left')
modPart.Set(edges=modPartEfa(((0.9, 0.45, 0.0), )), name='Edge-Right')
modRa.regenerate()
### Create Material ###
mod.Material(name='Steel')
modMat = mod.materials['Steel']
modMat.Elastic(table=((210000000000.0, 0.29),))
modMat.Density(table=((7850.0, ), ))
modMat.SpecificHeat(table=((452.0, ), ))
modMat.Conductivity(table=((53.3, ), ))
modMat.Expansion(table=((12e-06, ), ))
### Define Plasticity Material Property ### - S355
modMat.Plastic(table=((320000000.0, 0.0), (357000000.0, 0.002),
    (366100000.0, 0.0157), (541600000.0, 0.1351)))
### Create Section ###
mod.HomogeneousShellSection(material='Steel', name='Section-Plate',
    numIntPts=5, thickness=0.003)
### Assign Section ###
modPart.SectionAssignment(offset=0.0,
    offsetField='', offsetType=MIDDLE_SURFACE, region=
    modPart.sets['Plate-Area'], sectionName=
    'Section-Plate', thicknessAssignment=FROM_SECTION)
### Create Instance ###
modRa.DatumCsysByDefault(CARTESIAN)
modRa.Instance(dependent=ON, name='Plate-1', part=modPart)
### Seed Part ###
modPart.seedEdgeByNumber(constraint=FINER, edges=
    modPartEfa(((0.9, 0.7875, 0.0), ), ((0.5625, 0.9, 0.0), ),
    ((0.1125, 0.9, 0.0), ), ((0.0, 0.5625, 0.0), ), ((0.0, 0.1125, 0.0), ),
    ((0.3375, 0.0, 0.0), ), ((0.7875, 0.0, 0.0), ),
    ((0.9, 0.3375, 0.0), ), ), number=6)
### Mesh Part ###
modPart.generateMesh()
### Set Element Type ###
modPart.setElementType(elemTypes=(ElemType(elemCode=S8R,
    elemLibrary=STANDARD), ElemType(elemCode=STRI65,
    elemLibrary=STANDARD)), regions=(modPartFfa(((0.6, 0.6, 0.0),),
    ((0.15, 0.6, 0.0), ), ((0.3, 0.3, 0.0), ), ((0.75, 0.3, 0.0), ), ), ))
### Create-Step ###
mod.ImplicitDynamicsStep(name='i0_SR-Step', previous='Initial',
    timePeriod=3650.0, maxNumInc=10000, application=QUASI_STATIC,
    initialInc=0.3, minInc=1e-09, maxInc=25.0, nohaf=OFF, amplitude=RAMP,
    alpha=DEFAULT, initialConditions=OFF, nlgeom=ON)
### Import Nodal Temperatures from HT ###
mod.Temperature(absoluteExteriorTolerance=0.0, beginIncrement=None,
    beginStep=1, createStepName='i0_SR-Step', distributionType=FROM_FILE,
    endIncrement=None, endStep=None, exteriorTolerance=0.05,
    fileName='..\_outputHT\HT_singlePlate.odb', interpolate=ON,
    name='i0_Temp-From-HT')
```

```
### Request Field Output ###
# Field Output is requested every 5 seconds.
modFOR = mod.fieldOutputRequests['F-Output-1']
modFOR.setValues(timeInterval=5.0,
    variables=('S','SSAVG', 'E', 'PE', 'PEEQ', 'U', 'NT', 'TEMP'))
## Create BCs ##
mod.DisplacementBC(createStepName='Initial', name='P1-BC-Top',
    region=modRa.instances['Plate-1'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
mod.DisplacementBC(createStepName='Initial', name='P1-BC-Bot',
    region=modRa.instances['Plate-1'].sets['Edge-Bot'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
### Define Imperfection ###
mod.keywordBlock.synchVersions(storeNodesAndElements=False)
mod.keywordBlock.insert(38,
    '\n*Imperfection, file=buc_singlePlate, step=1\n1, 0.003')
### Create and Run Job ###
mdb.Job(name='SR_singlePlate', model='Model-1')
mdb.jobs['SR_singlePlate'].submit(consistencyChecking=OFF)
mdb.jobs['SR_singlePlate'].waitForCompletion()
############################ End-Of-Script ############################
```

APPENDIX C5 – SR_BASICMODEL-12.PY: ABAQUS PYTHON SCRIPT

```
############################################################################
## Name:         SR_basicModel-12.py                                      ##
##                                                                        ##
## Description: Basic Structural Response (SR) Model for a 12 plate thin ##
##               walled steel facade for use in two-way coupled thermo-   ##
##               mechanical CFD-FEM Analysis.                             ##
##                                                                        ##
## Additional    This script is INCOMPLETE additional python code is      ##
## Info:         appended by geometric update program upGeomSR based on   ##
##               the current iteration and failure progression.           ##
##               The complete coupling procedure is managed by            ##
##               Master Program FDS-2-Abaqus.                             ##
##                                                                        ##
## Input :       HT_Script.odb  (temperatures)                            ##
##               i0_buc-Job.fil (imperfection node file)                  ##
##               i0_buc-Job.prt (imperfection part file)                  ##
##                                                                        ##
## Output:       SR_Script.odb                                            ##
##               Requires a \\_outputSR\\ folder to store *.odb output    ##
##                                                                        ##
############################################################################
## Version 1.0                                           by J.A.Feenstra ##
## August 2016                          jelmerfeenstra1987@gmail.com ##
############################################################################

############################## Begin Script ###############################
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *
cliCommand("""session.journalOptions.setValues(replayGeometry=COORDINATE,
    recoverGeometry=COORDINATE)""")
### Specify Working Directory    ###
# exclude '_outputSR' folder
# use this line for use in FDS-2-Abaqus (relative path)
# currentPath = os.getcwd() # use this
# use this line when running script from Abaqus CEA (direct path)
currentPath = 'C:\\currentPath' # or this
# don't forget to create a '_outputSR' folder in the working directory
### Change Working Directory ###
# don't forget to create a '_outputSR' folder in output directory
os.chdir(currentPath + '\\_outputSR\\')
### Initial Code Definitions ###
mod = mdb.models['Model-1']
modRa = mod.rootAssembly
### Specify-Attributes ###
mod.setValues(absoluteZero=-273, stefanBoltzmann=5.67e-08)
```

```
### Create Part ###
mod.ConstrainedSketch(name='__profile__', sheetSize=2.0)
mod.sketches['__profile__'].rectangle(point1=(0.0, 0.0), point2=(0.9, 0.9))
mod.Part(dimensionality=THREE_D, name='Plate', type=DEFORMABLE_BODY)
modPart = mod.parts['Plate']
modPart.BaseShell(sketch=mod.sketches['__profile__'])
### Create Sets ###
#Plate-Area, Edge-Top, Edge-Right, Edge-Bot, and Edge-Left
modPartFfa = modPart.faces.findAt
modPartEfa = modPart.edges.findAt
modPart.Set(faces=modPartFfa(((0.45, 0.45, 0.0),)), name='Plate-Area')
modPart.Set(edges=modPartEfa(((0.45, 0.9, 0.0), )), name='Edge-Top')
modPart.Set(edges=modPartEfa(((0.45, 0.0, 0.0), )), name='Edge-Bot')
modPart.Set(edges=modPartEfa(((0.0, 0.45, 0.0), )), name='Edge-Left')
modPart.Set(edges=modPartEfa(((0.9, 0.45, 0.0), )), name='Edge-Right')
modRa.regenerate()
### Create Material ###
mod.Material(name='Steel')
modMat = mod.materials['Steel']
modMat.Elastic(table=((210000000000.0, 0.29),))
modMat.Density(table=((7850.0, ), ))
modMat.SpecificHeat(table=((452.0, ), ))
modMat.Conductivity(table=((53.3, ), ))
modMat.Expansion(table=((12e-06, ), ))
### Define Plasticity Material Property ### - S355
modMat.Plastic(table=((320000000.0, 0.0), (357000000.0, 0.002),
    (366100000.0, 0.0157), (541600000.0, 0.1351)))
### Create Section ###
mod.HomogeneousShellSection(material='Steel', name='Section-Plate',
    numIntPts=5, thickness=0.003)
### Assign Section ###
modPart.SectionAssignment(offset=0.0,
    offsetField='', offsetType=MIDDLE_SURFACE, region=
    modPart.sets['Plate-Area'], sectionName=
    'Section-Plate', thicknessAssignment=FROM_SECTION)
### Create Instance ###
modRa.DatumCsysByDefault(CARTESIAN)
modRa.Instance(dependent=ON, name='Plate-1', part=modPart)
### Pattern Multiple Instances ###
modRa.LinearInstancePattern(instanceList=('Plate-1', ),
    direction1=(1.0, 0.0, 0.0), direction2=(0.0, 1.0, 0.0),
    number1=4, number2=3, spacing1=0.9, spacing2=0.9)
### Rename Instances ###
#Naming Convention
# 1)bottomLeft 2)midLeft 3) topLeft [...] 11) midRight 12)topRight
modRaFe = modRa.features
modRaFe.changeKey(fromName='Plate-1-lin-1-2', toName='Plate-2')
modRaFe.changeKey(fromName='Plate-1-lin-1-3', toName='Plate-3')
modRaFe.changeKey(fromName='Plate-1-lin-2-1', toName='Plate-4')
modRaFe.changeKey(fromName='Plate-1-lin-2-2', toName='Plate-5')
modRaFe.changeKey(fromName='Plate-1-lin-2-3', toName='Plate-6')
modRaFe.changeKey(fromName='Plate-1-lin-3-1', toName='Plate-7')
modRaFe.changeKey(fromName='Plate-1-lin-3-2', toName='Plate-8')
modRaFe.changeKey(fromName='Plate-1-lin-3-3', toName='Plate-9')
modRaFe.changeKey(fromName='Plate-1-lin-4-1', toName='Plate-10')
modRaFe.changeKey(fromName='Plate-1-lin-4-2', toName='Plate-11')
modRaFe.changeKey(fromName='Plate-1-lin-4-3', toName='Plate-12')
```

```
### Create Step ###
# Step is later modified for current iteration (by upGeomSR).
# Defined here for Field Output Request, and Model Change Interaction.
mod.ImplicitDynamicsStep(name='i0_SR-Step', previous='Initial',
    timePeriod=300.0, maxNumInc=10000, application=QUASI_STATIC,
    initialInc=0.3, minInc=1e-09, maxInc=25.0, nohaf=OFF, amplitude=RAMP,
    alpha=DEFAULT, initialConditions=OFF, nlgeom=ON)
### Request Field Output ###
# Field Output is requested every 5 seconds.
modFOR = mod.fieldOutputRequests['F-Output-1']
modFOR.setValues(timeInterval=5.0, # use this
    variables=('S','SSAVG', 'E', 'PE', 'PEEQ', 'U', 'NT', 'TEMP'))
# Field Output is requested for every (Abaqus) increment/iteration.
#modFOR.setValues(frequency=1.0, # or this
#   variables=('S','SSAVG', 'E', 'PE', 'PEEQ', 'U', 'NT', 'TEMP'))
### Seed Part ###
modPart.seedEdgeByNumber(constraint=FINER, edges=modPartEfa(
    ((0.9, 0.7875, 0.0), ), ((0.5625, 0.9, 0.0), ),((0.1125, 0.9, 0.0), ),
    ((0.0, 0.5625, 0.0), ), ((0.0, 0.1125, 0.0), ),((0.3375, 0.0, 0.0), ),
    ((0.7875, 0.0, 0.0), ), ((0.9, 0.3375, 0.0), ), ), number=6)
### Mesh Part ###
modPart.generateMesh()
### Set Element Type ###
modPart.setElementType(elemTypes=(ElemType(elemCode=S8R,
    elemLibrary=STANDARD), ElemType(elemCode=STRI65,
    elemLibrary=STANDARD)), regions=(modPartFfa(((0.6, 0.6, 0.0),),
    ((0.15, 0.6, 0.0), ), ((0.3, 0.3, 0.0), ), ((0.75, 0.3, 0.0), ), ), ))
### Create BCs ###
# Hinged BCs at top and bottom of every plate
numberOfPlates = 12
for plateCounter in xrange(1,numberOfPlates+1):
    thisPlate = 'Plate-' + str(plateCounter)
    bcTopName = 'P' + str(plateCounter) + '-BC-Top'
    bcBotName = 'P' + str(plateCounter) + '-BC-Bot'
    mod.DisplacementBC(createStepName='Initial', name=bcTopName,
        region=modRa.instances[thisPlate].sets['Edge-Top'],
        u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
    mod.DisplacementBC(createStepName='Initial', name=bcBotName,
        region=modRa.instances[thisPlate].sets['Edge-Bot'],
        u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
### Request Restart File ###
mod.steps['i0_SR-Step'].Restart(frequency=0, numberIntervals=1, overlay=ON,
    timeMarks=OFF)
### Model Change Interaction ###
mod.ModelChange(name='ModelChange', createStepName='i0_SR-Step',
    isRestart=True)
### Define Imperfection ###
# imperfection is removed by upGeomSR for non-initial coupling iterations
mod.keywordBlock.synchVersions(storeNodesAndElements=False)
mod.keywordBlock.insert(115,
    '\n*Imperfection, file=i0_buc-Job, step=1\n1, 0.003')
########################## End of SR_basicModel ###########################
```

APPENDIX C6 – SR_TYPICALAPPEND-12.PY: ABAQUS PYTHON SCRIPT

This appendix contains the python code added to the `SR_basicModel.py` script by the `upGeomSR` program to update the HT python script for the current iteration. The `SR_BasicModel.py` python script for a structural model comprising twelve plate-instances is included in appendix C2.

This example is based on a structural system comprising twelve plates where each plate is subdivided in four temperature partitions. It is updated for its 5th 150s iteration (iteration number 4) and has a total simulation duration of 1800s. Plate number 4 failed in a previous iteration

First some basic variables are written to the script.

```
## Iteration Number: 4, IterationSize: 150s.
## IterationTimeSlot: 600-750s, TotalSimulationDuration: 1800s.
## 12 plate(s), 4 partition(s).
```

Then the `SR_BasicModel.py` is copied into the script (appendix C3).

```
############################################################################
## Name:         SR_basicModel-12.py                                     ##
##                                                                        ##
## …
                                                                       … ##
######################### End of SR_basicModel ##########################
```

Finally the python code for the current iteration is added.

```
######################## Code Added by upGeomSR #########################

### Create/Update Additional Steps ###
mod.ImplicitDynamicsStep(name='i3_SR-Step', previous='i0_SR-Step',
    timePeriod=150, maxNumInc=10000, application=QUASI_STATIC,
    initialInc=0.3, minInc=1e-06, maxInc=10.0, nohaf=OFF, amplitude=RAMP,
    alpha=DEFAULT, initialConditions=OFF, nlgeom=ON)
mod.ImplicitDynamicsStep(name='i4_SR-Step', previous='i3_SR-Step',
    timePeriod=150, maxNumInc=10000, application=QUASI_STATIC,
    initialInc=0.3, minInc=1e-06, maxInc=10.0, nohaf=OFF, amplitude=RAMP,
    alpha=DEFAULT, initialConditions=OFF, nlgeom=ON)
### Define Restart Job/Step ###
mod.setValues(restartJob='i3_SR-Job', restartStep='i3_SR-Step')
### Request Restart File for New Step ###
mod.steps['i4_SR-Step'].Restart(frequency=0, numberIntervals=1,
    overlay=ON, timeMarks=OFF)
### Import Nodal Temperatures from HT ###
mod.Temperature(absoluteExteriorTolerance=0.0, beginIncrement=None,
    beginStep=1, createStepName='i4_SR-Step', distributionType=FROM_FILE,
    endIncrement=None, endStep=None, exteriorTolerance=0.05,
    fileName='..\_outputHT\i4_HT-Job.odb', interpolate=ON,
    name='i4_Temp-From-HT')
```

```
### Update Model Geometry ###
thisPlate = mod.rootAssembly.instances['Plate-4'].sets['Plate-Area']
mod.ModelChange(activeInStep=False, createStepName='i4_SR-Step',
    includeStrain=False, name='deActPlate-4', region=thisPlate)
# If empty: No plates failed this iteration - Still Going Strong!
### Remove Imperfection ###
mdb.models['Model-1'].keywordBlock.setValues(edited = 0)
### Create and Run Job ###
mdb.Job(name='i4_SR-Job', model='Model-1', type=RESTART)
mdb.jobs['i4_SR-Job'].submit(consistencyChecking=OFF)
mdb.jobs['i4_SR-Job'].waitForCompletion()
############################## End-Of-Script ##############################
```

APPENDIX C7 – BUC_SINGLEPLATE.PY: ABAQUS PYTHON SCRIPT

```
##########################################################################
## Name:        buc_singlePlate.py                                      ##
##                                                                      ##
## Description: Single Plate Buckling (buc) script that is used to      ##
##              introduce an imperfection in a Structural Response (SR) ##
##              Analysis                                                ##
##                                                                      ##
## Input :      AST_Amp_Data.py                                         ##
##              (Tabular Amplitude Data, created by reWriteAST2py)      ##
##                                                                      ##
## Output:      buc_singlePlate.fil                                     ##
##              Node file containing imperfection data                  ##
##              Requires a \\_outputSR\\ folder to store *.odb output    ##
##                                                                      ##
##########################################################################
## Version 1.0                                          by J.A.Feenstra ##
## August 2016                           jelmerfeenstra1987@gmail.com ##
##########################################################################

############################## Begin Script ###############################
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *
cliCommand("""session.journalOptions.setValues(replayGeometry=COORDINATE,
    recoverGeometry=COORDINATE)""")
### Specify Working Directory ###
# exclude '_outputSR' folder
currentPath = 'C:\\currentPath'
### Change Working Directory ###
# don't forget to create a '_outputSR' folder in output directory
os.chdir(currentPath + '\\_outputSR\\')
### Initial Code Definitions ###
mod = mdb.models['Model-1']
modRa = mod.rootAssembly
### Specify-Attributes ###
mod.setValues(absoluteZero=-273, stefanBoltzmann=5.67e-08)
### Create Part ###
mod.ConstrainedSketch(name='__profile__', sheetSize=2.0)
mod.sketches['__profile__'].rectangle(point1=(0.0, 0.0), point2=(0.9, 0.9))
mod.Part(dimensionality=THREE_D, name='Plate', type=DEFORMABLE_BODY)
modPart = mod.parts['Plate']
modPart.BaseShell(sketch=mod.sketches['__profile__'])
```

```
### Create Sets ###
#Plate-Area, Edge-Top, Edge-Right, Edge-Bot, and Edge-Left
modPartFfa = modPart.faces.findAt
modPartEfa = modPart.edges.findAt
modPart.Set(faces=modPartFfa(((0.45, 0.45, 0.0),)), name='Plate-Area')
modPart.Set(edges=modPartEfa(((0.45, 0.9, 0.0), )), name='Edge-Top')
modPart.Set(edges=modPartEfa(((0.45, 0.0, 0.0), )), name='Edge-Bot')
modPart.Set(edges=modPartEfa(((0.0, 0.45, 0.0), )), name='Edge-Left')
modPart.Set(edges=modPartEfa(((0.9, 0.45, 0.0), )), name='Edge-Right')
modRa.regenerate()
### Create Material ###
mod.Material(name='Steel')
modMat = mod.materials['Steel']
modMat.Elastic(table=((210000000000.0, 0.29),))
modMat.Density(table=((7850.0, ), ))
modMat.SpecificHeat(table=((452.0, ), ))
modMat.Conductivity(table=((53.3, ), ))
modMat.Expansion(table=((12e-06, ), ))
### Define Plasticity Material Property ### - S355
modMat.Plastic(table=((320000000.0, 0.0), (357000000.0, 0.002),
    (366100000.0, 0.0157), (541600000.0, 0.1351)))
### Create Section ###
mod.HomogeneousShellSection(material='Steel', name='Section-Plate',
    numIntPts=5, thickness=0.003)
### Assign Section ###
modPart.SectionAssignment(offset=0.0,
    offsetField='', offsetType=MIDDLE_SURFACE, region=
    modPart.sets['Plate-Area'], sectionName=
    'Section-Plate', thicknessAssignment=FROM_SECTION)
### Create Instance ###
modRa.DatumCsysByDefault(CARTESIAN)
modRa.Instance(dependent=ON, name='Plate-1', part=modPart)
### Seed Part ###
modPart.seedEdgeByNumber(constraint=FINER, edges=
    modPartEfa(((0.9, 0.7875, 0.0), ), ((0.5625, 0.9, 0.0), ),
    ((0.1125, 0.9, 0.0), ), ((0.0, 0.5625, 0.0), ), ((0.0, 0.1125, 0.0), ),
    ((0.3375, 0.0, 0.0), ), ((0.7875, 0.0, 0.0), ),
    ((0.9, 0.3375, 0.0), ), ), number=6)
### Mesh Part ###
modPart.generateMesh()
### Set Element Type ###
modPart.setElementType(elemTypes=(ElemType(elemCode=S8R,
    elemLibrary=STANDARD), ElemType(elemCode=STRI65,
    elemLibrary=STANDARD)), regions=(modPartFfa(((0.6, 0.6, 0.0),),
    ((0.15, 0.6, 0.0), ), ((0.3, 0.3, 0.0), ), ((0.75, 0.3, 0.0), ), ), ))
### Create-Step ###
mod.BuckleStep(description='Buckling Analysis Step',
    maxIterations=250, name='i0_buc_step', numEigen=4,
    previous='Initial', vectors=8)
### Create-Standardized-Temperature-Field ###
mod.Temperature(name='Buc-Temperature-1', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-1'].sets['Plate-Area'])
### Create BCs ###
mod.DisplacementBC(createStepName='Initial', name='P1-BC-Top',
    region=modRa.instances['Plate-1'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
mod.DisplacementBC(createStepName='Initial', name='P1-BC-Bot',
    region=modRa.instances['Plate-1'].sets['Edge-Bot'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
```

```
### Request-Node-File ###
mod.keywordBlock.synchVersions(storeNodesAndElements=False)
mod.keywordBlock.insert(49, '\n*Node File\nU')
### Create and Run Job ###
mdb.Job(name='buc_singlePlate', model='Model-1')
mdb.jobs['buc_singlePlate'].submit(consistencyChecking=OFF)
mdb.jobs['buc_singlePlate'].waitForCompletion()
############################## End-Of-Script ##############################
```

APPENDIX C8 – BUC_BASICMODEL-12.PY: ABAQUS PYTHON SCRIPT

```
############################################################################
## Name:        buc_basicModel-12.py                                     ##
##                                                                        ##
## Description: Buckling Analysis for introducing imperfection in        ##
##              SR_basicModel-12.py, a 12 plate thin walled steel         ##
##              facade for use in two-way coupled thermo-mechanical       ##
##              CFD-FEM Analysis.                                         ##
##                                                                        ##
## Additional   This script is INCOMPLETE additional python code is      ##
## Info:        appended by geometric update program upGeomSR based on   ##
##              the current iteration and failure progression.           ##
##              The complete coupling procedure is managed by            ##
##              Master Program FDS-2-Abaqus.                             ##
##                                                                        ##
## Output:      i0_buc-Job.fil (imperfection node file)                  ##
##              i0_buc-Job.prt (imperfection part file)                  ##
##              Requires a \\_outputSR\\ folder to store *.odb output    ##
##                                                                        ##
############################################################################
## Version 1.0                                          by J.A.Feenstra ##
## August 2016                          jelmerfeenstra1987@gmail.com ##
############################################################################

############################## Begin Script ###############################
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *
cliCommand("""session.journalOptions.setValues(replayGeometry=COORDINATE,
    recoverGeometry=COORDINATE)""")
### Specify Working Directory ###
# exclude '_outputSR' folder
currentPath = 'C:\\currentPath'
### Change Working Directory ###
# don't forget to create a '_outputSR' folder in output directory
os.chdir(currentPath + '\\_outputSR\\')
## Name Model ##
mod = mdb.models['Model-1']
modRa = mod.rootAssembly
### Specify-Attributes ###
mod.setValues(absoluteZero=-273, stefanBoltzmann=5.67e-08)
### Create Part ###
mod.ConstrainedSketch(name='__profile__', sheetSize=2.0)
mod.sketches['__profile__'].rectangle(point1=(0.0, 0.0), point2=(0.9, 0.9))
mod.Part(dimensionality=THREE_D, name='Plate', type=DEFORMABLE_BODY)
modPart = mod.parts['Plate']
modPart.BaseShell(sketch=mod.sketches['__profile__'])
```

```
### Create Sets ###
#Plate-Area, Edge-Top, Edge-Right, Edge-Bot, and Edge-Left
modPartFfa = modPart.faces.findAt
modPartEfa = modPart.edges.findAt
modPart.Set(faces=modPartFfa(((0.45, 0.45, 0.0),)), name='Plate-Area')
modPart.Set(edges=modPartEfa(((0.45, 0.9, 0.0), )), name='Edge-Top')
modPart.Set(edges=modPartEfa(((0.45, 0.0, 0.0), )), name='Edge-Bot')
modPart.Set(edges=modPartEfa(((0.0, 0.45, 0.0), )), name='Edge-Left')
modPart.Set(edges=modPartEfa(((0.9, 0.45, 0.0), )), name='Edge-Right')
modRa.regenerate()
### Create Material ###
mod.Material(name='Steel')
modMat = mod.materials['Steel']
modMat.Elastic(table=((210000000000.0, 0.29),))
modMat.Density(table=((7850.0, ), ))
modMat.SpecificHeat(table=((452.0, ), ))
modMat.Conductivity(table=((53.3, ), ))
modMat.Expansion(table=((12e-06, ), ))
### Define Plasticity Material Property ### - S355
modMat.Plastic(table=((320000000.0, 0.0), (357000000.0, 0.002),
    (366100000.0, 0.0157), (541600000.0, 0.1351)))
### Create Section ###
mod.HomogeneousShellSection(material='Steel', name='Section-Plate',
    numIntPts=5, thickness=0.003)
### Assign Section ###
modPart.SectionAssignment(offset=0.0,
    offsetField='', offsetType=MIDDLE_SURFACE, region=
    modPart.sets['Plate-Area'], sectionName=
    'Section-Plate', thicknessAssignment=FROM_SECTION)
### Create Instance ###
modRa.DatumCsysByDefault(CARTESIAN)
modRa.Instance(dependent=ON, name='Plate-1', part=modPart)
### Seed Part ###
modPart.seedEdgeByNumber(constraint=FINER, edges=
    modPartEfa(((0.9, 0.7875, 0.0), ), ((0.5625, 0.9, 0.0), ),
    ((0.1125, 0.9, 0.0), ), ((0.0, 0.5625, 0.0), ), ((0.0, 0.1125, 0.0), ),
    ((0.3375, 0.0, 0.0), ), ((0.7875, 0.0, 0.0), ),
    ((0.9, 0.3375, 0.0), ), ), number=6)
### Mesh Part ###
modPart.generateMesh()
### Set Element Type ###
modPart.setElementType(elemTypes=(ElemType(elemCode=S8R,
    elemLibrary=STANDARD), ElemType(elemCode=STRI65,
    elemLibrary=STANDARD)), regions=(modPartFfa(((0.6, 0.6, 0.0),),
    ((0.15, 0.6, 0.0), ), ((0.3, 0.3, 0.0), ), ((0.75, 0.3, 0.0), ), ), ))
### Pattern Multiple Instances ###
modRa.LinearInstancePattern(instanceList=('Plate-1', ),
    direction1=(1.0, 0.0, 0.0), direction2=(0.0, 1.0, 0.0),
    number1=4, number2=3, spacing1=0.9, spacing2=0.9)
### Rename Instances ###
#Naming Convention
# 1)bottomLeft 2)midLeft 3) topLeft [...] 11) midRight 12)topRight
modRaFe = modRa.features
modRaFe.changeKey(fromName='Plate-1-lin-1-2', toName='Plate-2')
modRaFe.changeKey(fromName='Plate-1-lin-1-3', toName='Plate-3')
modRaFe.changeKey(fromName='Plate-1-lin-2-1', toName='Plate-4')
modRaFe.changeKey(fromName='Plate-1-lin-2-2', toName='Plate-5')
modRaFe.changeKey(fromName='Plate-1-lin-2-3', toName='Plate-6')
modRaFe.changeKey(fromName='Plate-1-lin-3-1', toName='Plate-7')
modRaFe.changeKey(fromName='Plate-1-lin-3-2', toName='Plate-8')
modRaFe.changeKey(fromName='Plate-1-lin-3-3', toName='Plate-9')
modRaFe.changeKey(fromName='Plate-1-lin-4-1', toName='Plate-10')
modRaFe.changeKey(fromName='Plate-1-lin-4-2', toName='Plate-11')
modRaFe.changeKey(fromName='Plate-1-lin-4-3', toName='Plate-12')
## Create Node Sets ##
n = modPart.nodes
nodesLeft = n[7:8]+n[14:15]+n[21:22]+n[28:29]+n[35:36]+n[52:53]+n[70:71]\
    +n[83:84]+n[96:97]+n[109:110]+n[122:123]
modPart.Set(nodes=nodesLeft, name='Edge-Left-Node')
nodesRight = n[13:14]+n[20:21]+n[27:28]+n[34:35]+n[41:42]+n[66:67]\
    +n[79:80]+n[92:93]+n[105:106]+n[118:119]+n[131:132]
modPart.Set(nodes=nodesRight, name='Edge-Right-Node')
### Tie Instances ###
# Convention: Lower plateNumber = Master
## Plate 1 Ties ##
mod.Tie(name='Tie_P1-P2',
    master=modRa.instances['Plate-1'].sets['Edge-Top'],
    slave=modRa.instances['Plate-2'].sets['Edge-Bot'],
    positionToleranceMethod=COMPUTED, adjust=ON)
mod.Tie(name='Tie_P1-P4',
    master=modRa.instances['Plate-1'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-4'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 2 Ties ##
mod.Tie(name='Tie_P2-P3',
    master=modRa.instances['Plate-2'].sets['Edge-Top'],
    slave=modRa.instances['Plate-3'].sets['Edge-Bot'],
    positionToleranceMethod=COMPUTED, adjust=ON)
mod.Tie(name='Tie_P2-P5',
    master=modRa.instances['Plate-2'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-5'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 3 Ties ##
mod.Tie(name='Tie_P3-P6',
    master=modRa.instances['Plate-3'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-6'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 4 Ties ##
mod.Tie(name='Tie_P4-P5',
    master=modRa.instances['Plate-4'].sets['Edge-Top'],
    slave=modRa.instances['Plate-5'].sets['Edge-Bot'],
    positionToleranceMethod=COMPUTED, adjust=ON)
mod.Tie(name='Tie_P4-P7',
    master=modRa.instances['Plate-4'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-7'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 5 Ties ##
mod.Tie(name='Tie_P5-P6',
    master=modRa.instances['Plate-5'].sets['Edge-Top'],
    slave=modRa.instances['Plate-6'].sets['Edge-Bot'],
    positionToleranceMethod=COMPUTED, adjust=ON)
mod.Tie(name='Tie_P5-P8',
    master=modRa.instances['Plate-5'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-8'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 6 Ties ##
mod.Tie(name='Tie_P6-P9',
    master=modRa.instances['Plate-6'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-9'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
```

```
## Plate 7 Ties ##
mod.Tie(name='Tie_P7-P8',
    master=modRa.instances['Plate-7'].sets['Edge-Top'],
    slave=modRa.instances['Plate-8'].sets['Edge-Bot'],
    positionToleranceMethod=COMPUTED, adjust=ON)
mod.Tie(name='Tie_P7-P10',
    master=modRa.instances['Plate-7'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-10'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 8 Ties ##
mod.Tie(name='Tie_P8-P9',
    master=modRa.instances['Plate-8'].sets['Edge-Top'],
    slave=modRa.instances['Plate-9'].sets['Edge-Bot'],
    positionToleranceMethod=COMPUTED, adjust=ON)
mod.Tie(name='Tie_P8-P11',
    master=modRa.instances['Plate-8'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-11'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 9 Ties ##
mod.Tie(name='Tie_P9-P12',
    master=modRa.instances['Plate-9'].sets['Edge-Right-Node'],
    slave=modRa.instances['Plate-12'].sets['Edge-Left-Node'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 10 Ties ##
mod.Tie(name='Tie_P10-P11',
    master=modRa.instances['Plate-10'].sets['Edge-Top'],
    slave=modRa.instances['Plate-11'].sets['Edge-Bot'],
    positionToleranceMethod=COMPUTED, adjust=ON)
## Plate 11 Ties ##
mod.Tie(name='Tie_P11-P12',
    master=modRa.instances['Plate-11'].sets['Edge-Top'],
    slave=modRa.instances['Plate-12'].sets['Edge-Bot'],
    positionToleranceMethod=COMPUTED, adjust=ON)
### Create-Step ###
mod.BuckleStep(description='Buckling Analysis Step',
    maxIterations=250, name='i0_buc_step', numEigen=4,
    previous='Initial', vectors=8)
### Create-Standardized-Temperature-Field ###
mod.Temperature(name='Buc-Temperature-1', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-1'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-2', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-2'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-3', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-3'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-4', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-4'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-5', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-5'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-6', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-6'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-7', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-7'].sets['Plate-Area'])
```

```
mod.Temperature(name='Buc-Temperature-8', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-8'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-9', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-9'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-10', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-10'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-11', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-11'].sets['Plate-Area'])
mod.Temperature(name='Buc-Temperature-12', createStepName='i0_buc_step',
    magnitudes=(1.0, ),
    region=modRa.instances['Plate-12'].sets['Plate-Area'])
### Create BCs ###
# Hinged BCs at top of every plateNumber
# Hinged BC at bottom of 1, 4, 7, 10 (bottom row of 4 plates)
## Plate 1 BC ##
mod.DisplacementBC(createStepName='Initial', name='P1-BC-Top',
    region=modRa.instances['Plate-1'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
mod.DisplacementBC(createStepName='Initial', name='P1-BC-Bot',
    region=modRa.instances['Plate-1'].sets['Edge-Bot'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 2 BC ##
mod.DisplacementBC(createStepName='Initial', name='P2-BC-Top',
    region=modRa.instances['Plate-2'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 3 BC ##
mod.DisplacementBC(createStepName='Initial', name='P3-BC-Top',
    region=modRa.instances['Plate-3'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 4 BC ##
mod.DisplacementBC(createStepName='Initial', name='P4-BC-Top',
    region=modRa.instances['Plate-4'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
mod.DisplacementBC(createStepName='Initial', name='P4-BC-Bot',
    region=modRa.instances['Plate-4'].sets['Edge-Bot'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 5 BC ##
mod.DisplacementBC(createStepName='Initial', name='P5-BC-Top',
    region=modRa.instances['Plate-5'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 6 BC ##
mod.DisplacementBC(createStepName='Initial', name='P6-BC-Top',
    region=modRa.instances['Plate-6'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 7 BC ##
mod.DisplacementBC(createStepName='Initial', name='P7-BC-Top',
    region=modRa.instances['Plate-7'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
mod.DisplacementBC(createStepName='Initial', name='P7-BC-Bot',
    region=modRa.instances['Plate-7'].sets['Edge-Bot'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 8 BC ##
mod.DisplacementBC(createStepName='Initial', name='P8-BC-Top',
    region=modRa.instances['Plate-8'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
```

```
## Plate 9 BC ##
mod.DisplacementBC(createStepName='Initial', name='P9-BC-Top',
    region=modRa.instances['Plate-9'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 10 BC ##
mod.DisplacementBC(createStepName='Initial', name='P10-BC-Top',
    region=modRa.instances['Plate-10'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
mod.DisplacementBC(createStepName='Initial', name='P10-BC-Bot',
    region=modRa.instances['Plate-10'].sets['Edge-Bot'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 11 BC ##
mod.DisplacementBC(createStepName='Initial', name='P11-BC-Top',
    region=modRa.instances['Plate-11'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
## Plate 12 BC ##
mod.DisplacementBC(createStepName='Initial', name='P12-BC-Top',
    region=modRa.instances['Plate-12'].sets['Edge-Top'],
    u1=SET, u2=SET, u3=SET, ur1=UNSET, ur2=UNSET, ur3=UNSET)
### Request-Node-File ###
mod.keywordBlock.synchVersions(storeNodesAndElements=False)
mod.keywordBlock.insert(244, '\n*Node File\nU')
### Create Job ###
mdb.Job(name='i0_buc-Job', model='Model-1')
### Run Job ###
mdb.jobs['i0_buc-Job'].submit(consistencyChecking=OFF)
mdb.jobs['i0_buc-Job'].waitForCompletion()
############################## End-Of-Script ##############################
```

APPENDIX C9 – PLATEFAILURECHECK.PY: ABAQUS PYTHON SCRIPT

```
###########################################################################
## Name:        PlateFailureCheck.py                                    ##
##                                                                      ##
## Description: This Abaqus python script checks the ix_SR-Job.odb data  ##
##              from the Structural Response analysis for possible plate ##
##              failure based on a predefined (stress) failure criteria. ##
##              The failure criteria and *.odb path info are read from   ##
##              plateFailureInputVariables.py as controlled by           ##
##              FDS-2-Abaqus. Plate failure data is written to temporary ##
##              update file plateFailureUpdate.temp which is used to     ##
##              update geometries. Additional info is written to log     ##
##              file plateFailurePythonDebug.log.                        ##
##                                                                      ##
## Input:       ix_SR-Job.odb                                           ##
##              plateFailureInputVariables.py                           ##
##                                                                      ##
## Output:      plateFailureUpdate.temp                                 ##
##              plateFailurePythonDebug.log                             ##
##                                                                      ##
## Required     myOdbPath                                               ##
## Parameters   failureStress                                           ##
##              failureNumberOfPoints                                   ##
##              failureNumberOfElements                                 ##
###########################################################################
## Version 1.0                                          by J.A.Feenstra ##
## August 2016                          jelmerfeenstra1987@gmail.com ##
###########################################################################

############################## Begin Script ###############################

### Import and initiate logging ###
import logging
logFile='plateFailurePythonDebug.log'
logging.basicConfig(
    filename=logFile,
    filemode='w',
    level=logging.INFO,
    format='%(asctime)s %(message)s',
    datefmt='%a, %d %b %Y %H:%M:%S',
)
### Import Abaqus libraries ###
from odbAccess import openOdb
from abaqusConstants import *
from abaqus import *
### import input variables (controlled by FDS-2-Abaqus) ###
#- myOdbPath       #
#- failureCriteria #
execfile(r'plateFailureInputVariables.py', __main__.__dict__)
### initial logging ###
logging.info('Script Running')
### Read Odb ###
odb = openOdb(myOdbPath)
### Define Frame Selection ###
selectFrame = odb.steps[stepname].frames
### Count Number of Frames (iteration (output)steps in SR analysis) ###
numberOfFrames = len(selectFrame)
### Count Number of plates (number of active instances) ###
numberOfPlates = len(odb.rootAssembly.instances)
```

```
### Create Lists required for checking FailureCriteria ###
failedElementList = []
elementStressDataList = []
### Create Output File ###
failureUpdate = open('plateFailureUpdate.temp', 'w' )
### Loop to iterate through all instances ###
for plateCounter in range (0, numberOfPlates):
    ### Reading Instance-name from odb file. ###
    instanceName = odb.rootAssembly.instances.keys()[plateCounter]
    ### Select instance by instanceName ###
    selectInstance = odb.rootAssembly.instances[instanceName]
    ### read number of Elements for selected Instance (plate)
    numberOfElements = len(selectInstance.elements)
    ### check if plate already failed/is deactivated ###
    #- if failed, plate deactivated -> no stress data in container) #
    checkPlateDeactivation = selectFrame[0].fieldOutputs['S'].getSubset(
        region = selectInstance,
        position = INTEGRATION_POINT,
        elementType = 'S8R'
    )
    checkForZeroValues = len(checkPlateDeactivation.values)
    ### if stress container is empty continue with next plate ###
    if checkForZeroValues == 0:
        logging.info (
        '%s already failed in a previous iteration' % (
                instanceName,
            )
        )
        continue
    ### loop to iterate through frames
    for frameCount in selectFrame:
        ### empty failedElementList for current frame ###
        failedElementList[:] = []
        ### stressField for current frame ###
        stressField = frameCount.fieldOutputs['S']
        ### Loop to iterate through all elements (for selected instance) ##
        for elementCounter in range (0, numberOfElements):
            ### selecting element ###
            selectElement = selectInstance.elements[elementCounter]
            elementNumber = selectElement.label
            ### selecting Stress Field for selected Element ###
            elementStressField = stressField.getSubset(
                region = selectElement,
                position = INTEGRATION_POINT,
                elementType = 'S8R'
            )
            ### counting number of data points for selected element ###
            #- Integration Points AND Section Points
            numberOfPoints = len(elementStressField.values)
            ### empty elementStressData list for failurecheck ###
            elementStressDataList[:] = []
            for pointCounter in elementStressField.values:
                ### add (append) stress data to elementStressData list ###
                elementStressDataList.append(pointCounter.mises)
            ### checking failure criteria, generating boolean list ###
            elementStressCheckList = [
                i > failureStress for i in elementStressDataList
            ]
            ### counting number of 'True' (=failed points) ###
            #- in boolean list elementStressCheck
            elementNumberOfFailedPoints = elementStressCheckList.\
                count(True)
            ### statement checking if element is considered failed ###
            #- based on failureCriteria
            if elementNumberOfFailedPoints >= failureNumberOfPoints:
                failedElementList.append(True)
            else:
                failedElementList.append(False)
            ### counting number of 'True' (=failed elements) ###
            #- in boolean list failedElementList
            numberOfFailedElements = failedElementList.count(True)
        ### check failure criteria (elements) ###
        if numberOfFailedElements >= failureNumberOfElements:
            ### write plateFailure data to update-file ###
            failureUpdate.write('%s %d\n' % (
                    instanceName,
                    frameCount.frameValue
                )
            )
            ### write plateFailure to logfile (debugging) ###
            logging.info (
                '%s failed at t=%d seconds since %d elements failed' % (
                    instanceName,
                    frameCount.frameValue,
                    numberOfFailedElements
                )
            )
            ### Break 'frameCount for loop' when plate failed ###
            break
    ### write info on non-failed plates to logfile (debugging) ###
    if numberOfFailedElements < failureNumberOfElements:
        logging.info ('%s did not fail, still going strong'
            % (instanceName)
        )
### Finalize and close plateFailureUpdate.temp ###
failureUpdate.write('Done')
failureUpdate.close()
### Finalize log file ###
logging.info ('Completed')
### output completed message to console ###
print 'Completed, see plateFailurePythonDebug.log for details'

############################   End-of-Script   ############################
############################ PlateFailureCheck ############################
```

APPENDIX D1 – FDS-2-ABAQUS: C++ SOURCE CODE

```
//////////////////////////////////////////////////////////////////////////////
// Name:         FDS-2-Abaqus                                               //
//                                                                          //
// Description: This program  manages the two-way coupling of a             //
//              CFD Fire Dynamic Simulator (FDS) fire simulation and        //
//              a sequential coupled FE Abaqus Heat Transfer (HT) and       //
//              Structural Response (SR) analysis. In its current state     //
//              FDS-2-Abaqus is limited to analyzing structures             //
//              consisting of multiple plate-instances using a stress-      //
//              based failure criteria.  The number of plates,              //
//              temperature partitions, simulation duration, iteration      //
//              size, and failure criteria can be varied freely (as         //
//              long as required FDS and Abaqus basic model setups          //
//              are supplied). Basically the programs iterates through      //
//              various one way coupled CFD-FEM analyses. After every       //
//              iteration the program checks plate failure based on         //
//              user-defined stress failure criteria. If failure occurs     //
//              the plates are removed from the models (FDS and Abaqus)     //
//              for the next iteration. The overview of plate failure       //
//              and failure time points is written to _plateFailure.log.    //
//                                                                          //
// Input:       plateFailureUpdate.temp                                     //
//                                                                          //
// Output:      _plateFailure.log                                           //
//              _iterationCounter.temp                                      //
//              _platePartitionCounter.temp                                 //
//              _runIterationTemp.bat                                       //
//              plateFailureInputVariables.py                               //
//                                                                          //
// Required     numberOfPlates           (user console input)               //
// Parameters:  numberOfPartitions       (user console input)               //
//              totalSimulationDuration (user console input)                //
//              iterationSize            (user console input)               //
//              failureStress            (user console input)               //
//              failureNumberOfPoints    (user console input)               //
//              failureNumberOfElements (user console input)                //
//              failedPlateNumber                                           //
//              failureTimePoint                                            //
//////////////////////////////////////////////////////////////////////////////
// Version 1.0                                            by J.A.Feenstra //
// August 2016                                jelmerfeenstra1987@gmail.com //
//////////////////////////////////////////////////////////////////////////////

/////////////////////////////// Begin Code ////////////////////////////////

// Import Libraries //
#include <iostream>
#include <string>
#include <fstream>
#include <cstdlib>
#include <sstream>
#include <stdlib.h>
#include <windows.h>
#include <iomanip>
#include <regex>
#include <limits>

// Import boost Libraries //
#include <boost/lexical_cast.hpp>
```

```
// Define String Parameters //
// output filename to (temporary) store iteration data //
// used in: upGeomFDS, upGeomHT, upGeomSR,
std::string counterFileName = "_iterationCounter.temp";
// output filename to (temporary) store plate/partition info //
// used in: reWriteAST2py, upGeomHT, upGeomSR
std::string platePartitionFileName = "_platePartitionInfo.temp";
// filename for (temporary) batch file containing program //
// sequence for single iteration loop                     //
std::string batchScriptFileName = "_runIterationTemp.bat";
// output filename for log managing plate failure //
// used in: upGeomFDS, upGeomHT, upGeomSR         //
std::string plateFailureFileName = "_plateFailure.log";
// input filename containing possible plate failure        //
// for current iteration (managed by PlateFailureCheck.py) //
std::string updatePlateFailureFileName = "plateFailureUpdate.temp";
// output filename for storing input variables for checking failure //
// used in: PlateFailureCheck.py                                    //
std::string plateFailureInputVariablesFileName =
    "plateFailureInputVariables.py";
// inputString to store line from updatePlateFailureFilename //
std::string inputString;

// filename strings for verification if required files exist //
std::string upGeomFDS = "upGeomFDS.exe";
std::string fdsBasicSetup = "FDS_BasicSetup.fds";
std::string reWriteAST2py = "reWriteAST2py.exe";
std::string upGeomHT = "upGeomHT.exe";
std::string htBasicModel= "HT_basicModel.py";
std::string upGeomSR = "upGeomSR.exe";
std::string srBasicModel = "SR_basicModel.py";
std::string plateFailureCheck = "PlateFailureCheck.py";
std::string bucImperfectionFil = "_outputSR\\i0_buc-Job.fil";
std::string bucImperfectionPrt = "_outputSR\\i0_buc-Job.prt";
std::string exists = "Exists!";
std::string missing = "Missing!";

// Define Integer Parameters //
// numberOfPlates, user input see function request_basic_variables //
int numberOfPlates(1);
// numberOfPartitions, user input see function request_basic_variables //
int numberOfPartitions(1);
// totalSimulationDuration, user input see func. request_basic_variables //
int totalSimulationDuration(50);
// iterationSize, user input see function request_basic_variables //
int iterationSize(10);
// iterationCounter starts at 0 (zeroth iteration) //
int iterationCounter(0); // do not edit //
// arrayCounter to be used in for loops iterating through //
// array managing _plateFailure.log info                  //
int arrayCounter(0);
// Plate/Instance number of failed plate //
// read from plateFailureFileName        //
int failedPlateNumber(0);
// failure time point for plate 'failedPlateNumber' //
// read from plateFailureFileName        //
int failureTimePoint(0);
// Counter managing number of failed plates //
int numberOfFailedPlates(0);
```

```
// failureStress, user input, see function update_failure_criteria //
int failureStress(355);          // [N/mm^2]
// number of SP/IP that should satisfy failure criteria  //
// before element is considered failed.                  //
// user input, see function update_failure criteria      //
int failureNumberOfPoints(4);
// number of elements that should satisfy failure criteria //
// before plate is considered failed.                      //
// user input, see function update_failure criteria        //
int failureNumberOfElements(12);

// Define char variables //
// choice char for selecting/storing yes/no questions //
char choice;

// function requesting input to continue //
// 'pause' function                      //
void press_enter_to_continue()
{
    std::cin.clear();
    std::cout << "Press ENTER to continue...";
    std::cin.ignore(std::numeric_limits<std::streamsize>::max(), '\n');
}

// function to print banner logo to console //
void print_banner_to_console()
{
    // ASCII Title-Art //
    std::cout << '\n';
    std::cout << "    )     "
        << " __ __  __     __                         "
        << "    )   " << '\n';
    std::cout << "   ) \\    "
        << "|_ |  \\(_  __   _) __   /\\ |_  _  _     _ "
        << "   ) \\  " << '\n';
    std::cout << "  / ) (   "
        << "|  |__/__)     /__     /--\\|_)(_|(_||_|_) "
        << "  / ) ( " << '\n';
    std::cout << "  \\(_)/   "
        << "                                   |      "
        << "  \\(_)/ " << '\n';
    std::cout << '\n';
    // Version and Author Info //
    std::cout << "Version 1.0                                   "
        << "by J.A.Feenstra" << '\n';
    std::cout << "August 2016                      "
        << "jelmerfeenstra1987@gmail.com" << '\n';
    std::cout << '\n';
}
```

```
// function to print banner and introductory info to console //
// NOTE: maximum characters on line = 60 //
void welcome_world()
{
    print_banner_to_console();
    std::cout << "[ [ [Description] ] ]" << '\n'
    << "FDS-2-Abaqus manages the two-way coupling of a CFD Fire " << '\n'
    << "Dynamic Simulator (FDS) fire simulation and a sequential "<< '\n'
    << "coupled FE Abaqus Heat Transfer (HT) and Structural " << '\n'
    << "Response (SR) analysis." << '\n' << '\n';
    std::cout << "[ [ [Checking Required Files] ] ]" << '\n'
    << "FDS-2-Abaqus will now check if all required files are " << '\n'
    << "supplied. If any are MISSING verify file(name)s and paths!" <<'\n';
    press_enter_to_continue();
    std::cout << '\n';
}

// function to check if file exists or are missing //
std::string check_file_existence(const std::string& name)
{
    if (FILE *file = fopen(name.c_str(), "r")){
        fclose(file);
        return exists;
    }
    else{
        return missing;
    }
}

void verify_existence_required_files()
{
    std::cout << "[ [ [Required Programs] ] ]" << '\n'
        << "reWriteAST2py.exe          "
        << check_file_existence(reWriteAST2py) << '\n'
        << "upGeomFDS.exe              "
        << check_file_existence(upGeomFDS) << '\n'
        << "upGeomHT.exe               "
        << check_file_existence(upGeomHT) << '\n'
        << "upGeomSR.exe               "
        << check_file_existence(upGeomSR) << '\n';
    std::cout << "[ [ [Required Scripts] ] ]" << '\n'
        << "FDS_BasicSetup.fds         "
        << check_file_existence(fdsBasicSetup) << '\n'
        << "HT_basicModel.py           "
        << check_file_existence(htBasicModel) << '\n'
        << "SR_basicModel.py           "
        << check_file_existence(srBasicModel) << '\n'
        << "PlateFailureCheck.py       "
        << check_file_existence(plateFailureCheck) << '\n';
    std::cout << "[ [ [Required Buckling File] ] ]" << '\n'
        << "i0_buc-Job.fil             "
        << check_file_existence(bucImperfectionFil) << '\n'
        << "i0_buc-Job.prt             "
        << check_file_existence(bucImperfectionPrt) << '\n'
        << "(in \\_outputSR\\ folder)" << '\n';
    std::cout << '\n';
}
```

```
// function to ask user to select yes (Y or y) or no (N or n) //
// and return the selected answer                             //
char select_yes_no()
{
    std::cin >> choice;
    if (choice != 'y' && choice != 'Y' && choice != 'n' && choice != 'N'){
        std::cout << "Please select [y/n]: ";
        select_yes_no();
    }
    // return choice to caller //
    return choice;
}

// function to request input and verify if it is an integer //
int request_and_verify_value(int someInteger)
{
    // request integer input //
    std::cin >> someInteger;
    // verify/check if input is integer //
    while(std::cin.fail()){
        std::cin.clear();
        std::cin.ignore(9999, '\n');
        std::cout << "Error: not an integer, try again!" << '\n';
        std::cin >> someInteger;
    }
    // return the integer to caller //
    return someInteger;
}

// function to create temporary platePartition info file //
void create_plate_partition_temp_file()
{
    // create output stream to temporary platePartition-file //
    std::ofstream platePartitionTemp(platePartitionFileName);
    // write plate and partition info to platePartition-file //
    platePartitionTemp << numberOfPlates << " " << numberOfPartitions
        << '\n' << "numberOfPlates[#] numberOfPartitions (per plate) [#]";
    // close output stream //
    platePartitionTemp.close();
    // NOTE: file is removed in function remove_temp_files() //
}

// function to create temporary iteration info file //
void update_iteration_temp_file()
{
    // create output stream to temporary iteration-file //
    std::ofstream iterationTemp(counterFileName);
    // write iteration-info to iteration-file //
    iterationTemp << iterationCounter << " " << iterationSize << " "
        << totalSimulationDuration << '\n'
        << "iterationNumber[#] iterationSize[s] totalSimulationTime[s]";
    // close output stream //
    iterationTemp.close();
    // NOTE: file is removed in function remove_temp_files() //
}
```

```
// function to print plate failure array to file                    //
// this array manages plate failure data throughout whole coupling //
void print_plate_failure_log_file(int myArray[][3])
{
    // open output stream to plateFailureFileName //
    // NOTE: overwrites already existing file     //
    std::ofstream plateFailureLog(plateFailureFileName);
    // print array to file (row by row) //
    for (arrayCounter = 0; arrayCounter < numberOfPlates; arrayCounter++){
        plateFailureLog
            // write plate number    //
            << myArray[arrayCounter][0] << " "
            // write failure boolean //
            << myArray[arrayCounter][1] << " "
            // write failure time    //
            << myArray[arrayCounter][2] <<'\n';
    }
    // close output stream //
    plateFailureLog.close();
}

// function to create plate failure array of size [numberOfPlates][3] //
// this array manages plate failure data throughout whole coupling    //
void create_plate_failure_log_file(int myArray[][3])
{
    // number each cells of first column from 1 to numberOfPlates //
    for (arrayCounter = 0; arrayCounter < numberOfPlates; arrayCounter++){
        myArray[arrayCounter][0] = {arrayCounter + 1};
    }
    // print/output the plateFailureArray to file (see function above) //
    print_plate_failure_log_file(myArray);
}

// function to update plate failure log file by reading  plate number //
// and failure time from plateFailureUpdate.temp                      //
void update_plate_failure_log_file(int myArray[][3])
{
    // create input stream from failure-update-file //
    std::ifstream sourceFile(updatePlateFailureFileName);
    // print error if update-file can't be read/located //
    if (!sourceFile){
        std::cerr << "Uh oh, plate failure update file "
            << updatePlateFailureFileName
            << " could not be opened or does not exist!" << '\n';
        press_enter_to_continue();
        exit(1);
    }
    // definition of regular expression required to capture //
    // plate (instance) number and failure time point from  //
    // plateFailureUpdate.temp                              //
    const std::regex instanceStrAndInt
        ("\\D*\\s*(\\d+)\\s+(\\d+)\\.*\\d*");
    // while end of file isn't reached do this //
    while(!sourceFile.eof()){
        // get line and put the line in the string inputString //
        getline(sourceFile, inputString);
        // break (end) while loop if getline reads Done //
        if (inputString == "Done"){
            std::cout << "Failure Check Completed!" << '\n' << '\n';
            break;
        }
        // if input string matches regular expression (it should) //
        else if(std::regex_match(inputString, instanceStrAndInt)){
            // match (string) results into stringMatch //
            std::smatch stringMatch;
            if (std::regex_search(inputString, stringMatch,
            instanceStrAndInt)){
                // cast obtained 'strings' as integers //
                failedPlateNumber =
                    boost::lexical_cast<int>(stringMatch[1]);
                failureTimePoint =
                    boost::lexical_cast<int>(stringMatch[2]) +
                    (iterationCounter * iterationSize);
                // output plateFailure to console //
                std::cout << "! ! ! F A I L U R E ! ! !" << '\n'
                    << "Plate " << failedPlateNumber
                    << " Failed @ " << failureTimePoint << " seconds"
                    << '\n';
                // print error if an already failed plate fails again //
                if (myArray[failedPlateNumber - 1][1] == 1){
                    std::cerr << "Error! An already Failed Plate, "
                        <<"Failed Again. This should not happen!" << '\n'
                        <<"Please check scripts/models!";
                    exit(1);
                }
                // update plateFailureArray for this itteration //
                // write failure boolean and failureTimePoint   //
                myArray[failedPlateNumber - 1][1] = 1;
                myArray[failedPlateNumber - 1][2] = failureTimePoint;
                numberOfFailedPlates++;
                // continue with while loop //
                continue;
            }
        }
    }
    // close input stream //
    sourceFile.close();
    // print/output the plateFailureArray to file //
    print_plate_failure_log_file(myArray);
}

// function to request basic values from user and some verification //
void request_basic_variables()
{
    std::cout << "[ [ [ Request Input Variables] ] ]" << '\n'
    << "FDS-2-Abaqus will now request some basic input variables." << '\n'
    << "Make sure the numberOfPlates and numberOfPartitions agree " << '\n'
    << "with the variables defined in the basicModel input files " << '\n'
    << "and scripts." << '\n' << '\n';
    std::cout << "[ [ [Basic Model Info] ] ]"  << '\n';
    // request numberOfPlates //
    std::cout << "Please enter the number of plates [#]: ";
    numberOfPlates = request_and_verify_value(numberOfPlates);
    // request numberOfTemperaturePartitions //
    std::cout << "Please enter the number of temperature " << '\n'
        << "partitions for each plate [#]: ";
    numberOfPartitions = request_and_verify_value(numberOfPartitions);
    // request totalSimulationDuration and iterationSize and verify //
    // if totalsimulationDuration > iterationSize                   //
    do{
        if (iterationSize > totalSimulationDuration){
            std::cout << "Error! iteration size larger than total "
                << "simulation duration, try again!" << '\n';
        }
        // request totalSimulationDuration //
        std::cout << "Please enter the total simulation duration [s]: ";
        totalSimulationDuration =
            request_and_verify_value(totalSimulationDuration);
        // request iterationSize //
        std::cout << "Please enter the iteration size [s]: ";
        iterationSize = request_and_verify_value(iterationSize);
    }
    while (iterationSize > totalSimulationDuration);
    // list selected values //
    std::cout << '\n' << "You selected the values listed below:" << '\n'
        << "Number of Plates = " << numberOfPlates << " plate(s)" << '\n'
        << "Number of Temperature Partitions (per plate) = "
        << numberOfPartitions << " partition(s)" << '\n'
        << "Total Simulation Duration = " << totalSimulationDuration
        << " seconds" << '\n'
        << "Iteration Size = " << iterationSize << " seconds" << '\n'
        << '\n';
    // ask user if selected input is correct //
    std::cout << "are these values correct [y/n]? ";
    select_yes_no();
    // if no -> request new input ('restart function') //
    if (choice == 'n' || choice == 'N'){
        std::cout << '\n';
        request_basic_variables();
    }
    // if yes -> continue //
    else if (choice == 'y' || choice == 'Y'){
        std::cout << '\n';
        // nothing really happens here //
    }
    // this should never happen, only y,Y,n, or N can be returned //
    else{
        std::cerr << "This should never happen only [y/n] is returned";
        press_enter_to_continue();
        exit(1);
    }
}

// function to list 'standard' failure parameters and the possibility //
// to change these parameters                                          //
void update_failure_criteria()
{
    // list standard values //
    std::cout << "[ [ [Failure Criteria] ] ]"  << '\n'
        << "Failure Stress = " << failureStress << " N/mm^2" << '\n'
        << "Number of Failed Points required to consider Element "
            << "as failed: " << failureNumberOfPoints << '\n'
        << "Number of Failed Elements required to consider Plate "
            << "as failed: " << failureNumberOfElements << '\n';
    // ask user if standard input is correct //
    std::cout << '\n' << "are these values correct [y/n]? ";
    select_yes_no();
    // if no ask user for new failure input //
    if (choice == 'n' || choice == 'N'){
        std::cout << '\n';
        std::cout << "[ [ [Failure Criteria] ] ]" << '\n';
        // request failureStress value //
        std::cout << "Please enter the Failure Stress [N/mm^2]: ";
        failureStress = request_and_verify_value(failureStress);
        // request failureNumberOfPoints //
        std::cout << "Please enter the number of Failed Points required "
            << '\n' << "to consider Element as failed [#]: ";
        failureNumberOfPoints =
            request_and_verify_value(failureNumberOfPoints);
        std::cout << "Please enter the number Failed Elements required "
             << '\n' << "to consider Plate as failed [#]: ";
        // request failureNumberOfElements //
        failureNumberOfElements =
            request_and_verify_value(failureNumberOfElements);
        std::cout << '\n' << "You selected the values listed below: "
            << '\n';
        // write values to plateFailureInputVariables.py //
        update_failure_criteria();
    }
    // if yes -> continue //
    else if (choice == 'y' || choice == 'Y'){
        std::cout << std::endl;
            // final check before running simulation //
        std::cout << "[ [ [ Final Check ] ] ]" << '\n'
        << "FDS-2-Abaqus is now ready to begin the coupling procedure!"
        << '\n'
        << "Select YES [y] to start the coupling simulation, select "
        << '\n'
        << "NO [n] to re-enter input variables." << '\n' << '\n'
        << "Start Simulation?: ";
        // selecting NO allows user to re-enter input variables //
        select_yes_no();
        if (choice == 'n' || choice == 'N'){
            std::cout << '\n';
            request_basic_variables();
            update_failure_criteria();
        }
    }
    // this should never happen, only y,Y,n, or N can be returned //
    else{
        std::cerr << "This should never happen only [y/n] is returned";
        press_enter_to_continue();
        exit(1);
    }
}
```

```
// function to write plateFailureInputVariables.py script //
// containing failure info for current iteration.         //
// input for plateFailureCheck.py                         //
void update_plate_failure_input_variables_py()
{
    std::ofstream plateFailureVar(plateFailureInputVariablesFileName);
    plateFailureVar << "## input variables for PlateFailureCheck.py"
        << '\n' << "## Generated by FDS-2-Abaqus" << '\n';
    plateFailureVar << "# Failure Criteria" << '\n'
        << "failureStress = " << failureStress << "E+6" << '\n'
        << "failureNumberOfPoints =" << failureNumberOfPoints << '\n'
        << "failureNumberOfElements =" << failureNumberOfElements << '\n';
    plateFailureVar << "# Input Files and Path" << '\n'
        << "jobname = 'i" << iterationCounter << "_SR-Job'" << '\n'
        << "stepname = 'i" << iterationCounter << "_SR-Step'" << '\n'
        << "path = '_outputSR/'" << '\n'
        << "myOdbPath = path + jobname + '.odb'" << '\n';
}

// batch file executing the various programs and scripts //
// required for a single iteration loop                  //
void create_temp_batch_file()
{
    // create output stream to temp batch file //
    std::ofstream tempBatch(batchScriptFileName);
    // if all plates failed only FDS simulation should continue //
    if (numberOfFailedPlates >= numberOfPlates){
        tempBatch << "call upGeomFDS.exe" << '\n';
        tempBatch << "call fds fds_script.fds" << '\n';
    }
    // write batch (*bat) file for normal iteration loop //
    else{
        tempBatch << "call upGeomFDS.exe" << '\n';
        tempBatch << "call fds fds_script.fds" << '\n';
        tempBatch << "call reWriteAST2Py.exe" << '\n';
        tempBatch << "call upGeomHT.exe" << '\n';
        tempBatch << "call abaqus cae noGUI=HT_Script.py" << '\n';
        tempBatch << "call upGeomSR.exe" << '\n';
        tempBatch << "call abaqus cae noGUI=SR_Script.py" << '\n';
        tempBatch << "call abaqus cae noGUI=PlateFailureCheck.py" << '\n';
    }
    // close output stream //
    tempBatch.close();
}
```

```
// function to call batch command //
// NOTE: works only for windows! //
void run_next_iteration()
{
    //execute bat file
    SHELLEXECUTEINFO shellExWaitCompletion = {0};
    shellExWaitCompletion.cbSize = sizeof(SHELLEXECUTEINFO);
    shellExWaitCompletion.fMask = SEE_MASK_NOCLOSEPROCESS;
    shellExWaitCompletion.hwnd = NULL;
    shellExWaitCompletion.lpVerb = NULL;
    shellExWaitCompletion.lpFile = batchScriptFileName.c_str();
    shellExWaitCompletion.lpParameters = "";
    shellExWaitCompletion.lpDirectory = NULL;
    shellExWaitCompletion.nShow = SW_SHOW;
    shellExWaitCompletion.hInstApp = NULL;
    ShellExecuteEx(&shellExWaitCompletion);
    WaitForSingleObject(shellExWaitCompletion.hProcess,INFINITE);
}

// function to output current iteration info to console //
void print_current_iteration_info()
{
        std::cout << "[ [ [Starting Iteration #" << iterationCounter
            << "] ] ]" << '\n' << "# IterationTimeSlot: "
            << (iterationCounter * iterationSize) << "-"
            << ((iterationCounter + 1) * iterationSize) << "s" << '\n'
            << "TotalSimulationDuration: " << totalSimulationDuration
            << "s." << '\n';
}

// function to only iterate FDS simulation //
// this is called when ALL plates FAILED   //
void iterate_fds_only()
{
    // output all-plates-failed failure message //
    std::cout << "All plates Failed, only finalizing "
        << "FDS Fire Simulation" << '\n';
    // update iteration batch file to only iterate FDS //
    create_temp_batch_file();
    // while loop finalizing simulation (fds only) //
    while (iterationCounter * iterationSize < totalSimulationDuration){
        print_current_iteration_info();
        update_iteration_temp_file();
        run_next_iteration();
        iterationCounter++;
    }
}

// function to clean up some temporary files //
void remove_temp_files()
{
    std::remove(counterFileName.c_str());
    std::remove(platePartitionFileName.c_str());
    std::remove(batchScriptFileName.c_str());
    std::remove(plateFailureInputVariablesFileName.c_str());
    std::remove(updatePlateFailureFileName.c_str());
}
```

```
// function to output starting info to console //
void print_start_coupling_analysis()
{
    std::cout << "[ [ [ S T A R T I N G   C O U P L I N G   "
        << "A N A L Y S I S ] ] ]" << '\n' << '\n';
}

// function to output completion info to console //
void print_completion_info_and_failureArray(int myArray[][3])
{
    std::cout << "[ [ [ C O U P L I N G   A N A L Y S I S   "
        << "C O M P L E T E D ] ] ]" << '\n';
    print_banner_to_console();
     // Simulation Overview/Summary //
    std::cout << "[ [ [Overview of Failed Plates] ] ] " << '\n'
        << "Number of Plates: " << numberOfPlates << '\n'
        << "Number of Failed Plates: " << numberOfFailedPlates << '\n';
    for (arrayCounter = 0; arrayCounter < numberOfPlates; arrayCounter++){
        if (myArray[arrayCounter][1] == 1){
            std::cout << "Plate " << myArray[arrayCounter][0]
                << " Failed @ " << myArray[arrayCounter][2]
                << " seconds" << '\n';
        }
    }
    std::cout << '\n'
        << "NOTE: Always check FDS (*.out) and Abaqus (*.msg)" << '\n'
        << "      files for possible errors!" << '\n';
    std::cout << '\n' << "[ [ [ Thank You For Using FDS-2-Abaqus ] ] ]"
        << '\n';
    press_enter_to_continue();
    press_enter_to_continue();
}

int main()
{
    // welcome and introductory info //
    welcome_world();
    // check if required files exist (in path) //
    verify_existence_required_files();
    // request #plate, #partition, sim. duration, and iteration size //
    request_basic_variables();
    // check and/or request failure criteria //
    update_failure_criteria();
    // create temporary platePartition file //
    create_plate_partition_temp_file();
    // define plateFailureArray                                   //
    // this is defined here since numberOfPlates is required //
    int plateFailureArray[numberOfPlates][3] = {0};
    // create plate failure log file //
    create_plate_failure_log_file(plateFailureArray);
    // create batch file executing the various programs and scripts //
    // for a single iteration loop                                  //
    create_temp_batch_file();
    // Just a banner (time stamps should be included)
    print_start_coupling_analysis();
    // while loop iterating through all steps in //
    // the fully coupled simulation              //
    while(iterationCounter * iterationSize < totalSimulationDuration){
        if (numberOfFailedPlates >= numberOfPlates){
            iterate_fds_only();
            break;
        }
        // output current iteration info to console //
        print_current_iteration_info();
        // update current iteration to temporary file //
        update_iteration_temp_file();
        // update input variables for plateFailureCheck.py //
        // plateFailureCheck.py checks plate failure       //
        update_plate_failure_input_variables_py();
        // run batch file executing the various programs and scripts //
        run_next_iteration();
        // update and print _plateFailure.log //
        update_plate_failure_log_file(plateFailureArray);
        // next iteration
        iterationCounter++;
    }
    // output completion info to console //
    print_completion_info_and_failureArray(plateFailureArray);
    // clean up some temporary files //
    //remove_temp_files();
    return 0;
}

//////////////////////////////  End of Code  //////////////////////////////
////////////////////////////// FDS-2-Abaqus  //////////////////////////////
```

APPENDIX D2 – REWRITEAST2PY: C++ SOURCE CODE

```
////////////////////////////////////////////////////////////////////////////
// Name:        reWriteAST2py                                            //
//                                                                       //
// Description: This program automatically rewrite the comma separated   //
//              adiabatic surface temperature device data                //
//              FDS_Simulation_devc.csv from a FDS fire simulation into  //
//              an Abaqus python script AST_Amp_data.py that imports the //
//              tabular amplitude data required to model convective and  //
//              radiative heat transfer in a coupled Heat Transfer       //
//              analysis.  Required plate and partition info is read     //
//              from _platePartitionInfo.temp a temporary file created   //
//              by 'Master Program' FDS-2-Abaqus.                        //
//                                                                       //
// Input:       FDS_simulation_devc.csv                                  //
//              _platePartitionInfo.temp                                 //
//                                                                       //
// Output:      AST_Amp_data                                             //
//                                                                       //
// Required     numberOfPlates                                           //
// Parameters:  numberOfPartitions                                       //
////////////////////////////////////////////////////////////////////////////
// Version 1.0                                          by J.A.Feenstra //
// August 2016                           jelmerfeenstra1987@gmail.com //
////////////////////////////////////////////////////////////////////////////

/////////////////////////////// Begin Code ////////////////////////////////

// Import Libraries //
#include <iostream>
#include <string>
#include <sstream>
#include <fstream>
#include <cstdlib>

// Import boost-Libraries //
#include <boost/tokenizer.hpp>

// Define String Parameters //
// output filename for python script containing AST amplitude data //
std::string outputFileName = "AST_Amp_data.py";
// input filename for FDS comma separated AST device data //
std::string inputFileName = "FDS_Simulation_devc.csv";
// input filename for temporary file containing plate/partition info //
std::string platePartitionFileName = "_platePartitionInfo.temp";

// Define Integer Parameters //
// read from platePartitionFileName (_platePartitionInfo.temp) //
// managed by FDS-2-Abaqus //
int numberOfPlates(1);
int numberOfPartitions(1);
// calculated from numberOfPlates and numberOfPartitions //
int totalASTColumn(1);
// various counters //
int partitionCounter(0); // do not edit!
int plateCounter(1);     // do not edit!
int ioColumnCounter(1);  // do not edit!
```

```
// function reading numberOfPlates and numberOfPartitions from //
// _platePartitionInfo.temp (governed by FDS-2-Abaqus)         //
void read_number_of_plates_and_partitions()
{
    // create input stream from platePartion-file //
    std::ifstream readPlatePartition(platePartitionFileName);
    // print error if platePartition file can't be read/located //
    if (!readPlatePartition){
        std::cerr << "Uh oh, Plate/Partition info file "
            << platePartitionFileName << " could not be opened or does "
            << "not exist!" << '\n';
            exit(1);
    }
    // read numberOfPlates & numberOfPartitions from platePartition file //
    else{
        readPlatePartition >> numberOfPlates;
        readPlatePartition >> numberOfPartitions;
        // close input stream //
        readPlatePartition.close();
        // Calculating total number of AST columns based on
        // Plate/partition info
        totalASTColumn = numberOfPlates * numberOfPartitions;
    }
}

// Plate counter to iterate through plates and temperature partitions //
// [example] 4 plates, 4 temperature partitions                       //
// [result]  1-1, 1-2, 1-3, 1-4, 2-1, 2-2 ... 4-3, 4-4.               //
void plate_counter()
{
    if (partitionCounter < numberOfPartitions){
        partitionCounter++;
    }
    else{
        plateCounter++;
        if (plateCounter <= numberOfPlates){
            partitionCounter = 1;
        }
        else{
            std::cerr << "Something Went Wrong, Maximum Plate Number "
                << "Already Reached!" << '\n';
            exit(1);
        }
    }
}

// Tokenize and (re)write AST data to python script //
void write_ast_data_to_file()
{
    // Array to temporary store AST line Data //
    std::string fdsArray[totalASTColumn] = { };
    // String to store getline data //
    std::string strInput;
    // Create output stream for to python script
    std::ofstream outPyFile(outputFileName, std::ios::app);
    // writing some initial python code to output script //
    outPyFile << "mod.TabularAmplitude(timeSpan=TOTAL, name='i0_AST_"
        << plateCounter << "-" << partitionCounter << "', data=(";
    // import/read inputfile (AST data from FDS) //
    std::ifstream fds_input(inputFileName);
```

```
        // print error if input file cant be read/located //
        if (!fds_input){
            std::cerr << "Uh oh, input file " << inputFileName << " could not "
                << "be opened or does not exist!" << '\n';
            exit(1);
        }
        else{
            // define seperator for tokenizer //
            boost::char_separator<char> sep(",");
            // define tokenizer_T1 with separator listed above //
            typedef boost::tokenizer\
                < boost::char_separator<char> > tokenizer_T1;
            // initiate while loop
            // this loop continues till end of input file is reached //
            while(!fds_input.eof()){
                // counter for placing tokens in fdsArray //
                int arrayCount=0;
                // getline from input file and put in string strInput //
                getline(fds_input, strInput);
                // statement to check for and skip empty lines //
                if (strInput == ""){
                    continue;
                }
                // tokenize the 'getline in strInput' //
                tokenizer_T1 tok(strInput, sep);
                // for loop placing tokens in fdsArray //
                for(
                    tokenizer_T1::iterator token=tok.begin();
                    token!=tok.end();
                    ++token
                ){
                    fdsArray[arrayCount++] = *token;
                }
                // statement to skip line if first banner line (units) //
                if (fdsArray[0] == "s"){
                    continue;
                }
                // statement to skip line if second banner line (parameters) //
                if (fdsArray[0] == "Time"){
                    continue;
                }
                // output time/AST-temperature data to output script //
                outPyFile << "(" << fdsArray[0] << ","
                    << fdsArray[ioColumnCounter] << ")"<< ",";
            }
        // finalizing python command with closing brackets //
        outPyFile << "))" << '\n';
        outPyFile.close();
        // output append-info to console //
        std::cout << "Successfully appended AST data for Plate "
            << plateCounter << "-" << partitionCounter << " to "
            << outputFileName << '\n';
        }
    }
```

```
// Actual Program //
int main()
{
    read_number_of_plates_and_partitions();
    // (re)Create output python script file //
    std::ofstream create_file(outputFileName);
    // for loop iterating through all plates and partitions //
    for (
        ioColumnCounter = 1;
        ioColumnCounter <= totalASTColumn;
        ioColumnCounter++
    ){
        plate_counter();
        write_ast_data_to_file();
    }
    // output completion info to console //
    std::cout << '\n' << "Done!";
    return 0;
}

//////////////////////////////  End of Code  //////////////////////////////
////////////////////////////// reWriteAST2py //////////////////////////////
```

APPENDIX D3 – UPGEOMFDS: C++ SOURCE CODE

```
////////////////////////////////////////////////////////////////////////////
// Name:         upGeomFDS                                                //
//                                                                        //
// Description: This program creates a FDS input file for the current    //
//              iteration. Basically it copies the basicSetupFile,        //
//              FDS_BasicSetup.fds, to a new input file, FDS_script.fds,  //
//              and appends input lines defining the next iteration and   //
//              plate failure devices. The iteration parameters are read  //
//              from temporary file _iterationCounter.temp and the plate  //
//              failure parameters from _plateFailure.log. Both of which  //
//              are managed by 'Master Program' FDS-2-Abaqus.             //
//                                                                        //
// Input:       FDS_BasicSetup.fds                                        //
//              _iterationCounter.temp                                    //
//              _plateFailure.log                                         //
//                                                                        //
// Output:      FDS_Script.fds                                            //
//                                                                        //
// Required     iterationCounter                                          //
// Parameters:  iterationSize                                             //
//              totalSimulationDuration                                   //
//              failedPlateNumber                                         //
//              failureTimePoint                                          //
//              plateFailureBool                                          //
//                                                                        //
////////////////////////////////////////////////////////////////////////////
// Version 1.0                                          by J.A.Feenstra //
// August 2016                              jelmerfeenstra1987@gmail.com //
////////////////////////////////////////////////////////////////////////////

/////////////////////////////// Begin Code ////////////////////////////////

// Import Libraries //
#include <iostream>
#include <string>
#include <fstream>
#include <cstdlib>

// Define String Parameters //
// input filename for *.fds file containing basic FDS model setup //
std::string basicSetupFileName = "FDS_BasicSetup.fds";
// output filename for updated FDS script //
std::string scriptFileName = "FDS_Script.fds";
// input filename for iterationCounter containing iteration data //
std::string counterFileName = "_iterationCounter.temp";
// input filename for temporary file containing plate/partition info //
std::string platePartitionFileName = "_platePartitionInfo.temp";
// input filename for logfile containing failure-info //
std::string plateFailureFileName = "_plateFailure.log";

// Define Integer Parameters //
// read from counterFileName (_iterationCounter.temp) //
// managed by FDS-2-Abaqus                            //
int iterationCounter(0);
int iterationSize(50);
int totalSimulationDuration(100);
```

```
// read from platePartitionFileName (_platePartitionInfo.temp) //
// managed by FDS-2-Abaqus                                     //
int numberOfPlates(1); // is read from platePartitionFileName
int numberOfPartitions(1);
// read from plateFailureFileName (_plateFailure.log) //
// managed by FDS-2-Abaqus                            //
int failedPlateNumber(0);
int failureTimePoint(0);
// calculated based on iterationInfo //
int currentIterationSetPoint(0);
int nextIterationSetPoint(50);

// Define Boolean Parameters                          //
// read from plateFailureFileName (_plateFailure.log) //
// managed by FDS-2-Abaqus                            //
bool plateFailureBool;

// function importing iteration-info from              //
// _platePartitionInfo.temp (managed by FDS-2-Abaqus)  //
void read_current_iteration()
{
    // create input stream from iteration counter file //
    std::ifstream readCounter(counterFileName);
    // print error if iterationCounter file can't be read/located //
    if (!readCounter){
        std::cerr << "Uh oh, iteration counter file " << counterFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // read/write integers from counterFile to parameters //
    else{
        readCounter >> iterationCounter;
        readCounter >> iterationSize;
        readCounter >> totalSimulationDuration;
        // close input stream //
        readCounter.close();
    }
}

// function importing plate/partition info from       //
// _platePartitionInfo.temp (managed by FDS-2-Abaqus) //
void read_number_of_plates_and_partitions()
{
    // create input stream from plate/partition file //
    std::ifstream readPlatePartition(platePartitionFileName);
    // print error if iterationCounter file can't be read/located //
    if (!readPlatePartition){
        std::cerr << "Uh oh, Plate/Partition info file "
            << platePartitionFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // read/write integers from plate/partition file to parameters //
    else{
        readPlatePartition >> numberOfPlates;
        readPlatePartition >> numberOfPartitions;
        readPlatePartition.close();
    }
}
```

```
// function to copy basic fds input file to new input file //
void copy_basic_setup_to_new_input_file()
{
    // create input stream  from FDS_BasicSetup.fds //
    std::ifstream sourceFile(basicSetupFileName, std::ios::in);
    // create output stream to FDS_script.fds //
    std::ofstream destFile(scriptFileName, std::ios::out);
    // write some initial banner information to output script //
    destFile << "// Iteration Number: " << iterationCounter
        << ", IterationSize: " << iterationSize << "s." << '\n'
        << "// IterationTimeSlot: "<< (iterationCounter * iterationSize)
        << "-" << ((iterationCounter + 1) * iterationSize)
        << "s, TotalSimulationDuration: " << totalSimulationDuration
        << "s." << '\n' << "// " << numberOfPlates << " plate(s), "
        << numberOfPartitions << " partition(s)." << '\n';
    // print error if FDS_BasicSetup.fds  can't be read/located //
    if (!sourceFile){
        std::cerr << "Uh oh, input file " << basicSetupFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // rewrite content from buffer (input stream) to output stream //
    else{
        destFile << sourceFile.rdbuf() << '\n' ;
        // append 'Code Added' line //
        destFile << "///////////////////// Input Lines added by upGeomFDS "
            << "///////////////////////" << '\n';
        // close input and output streams //
        sourceFile.close();
        destFile.close();
    }
}

// function to append Restart/kill input lines to the FDS_Script for //
// the current iteration                                              //
void append_next_iteration()
{
    // create output stream to FDS_script.fds //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    // append &MISC restart line //
    appendToFile << "// Set Restart .TRUE./.FALSE. //" << '\n';
    if (iterationCounter==0){
        appendToFile << "&MISC RESTART=.FALSE. /" << '\n' ;
    }
    else{
        appendToFile << "&MISC RESTART=.TRUE. /" << '\n' ;
    }
    // calculate 'End-Time' for current iteration //
    nextIterationSetPoint = (iterationCounter + 1) * iterationSize;
    // write (time)device, kill and restart input lines for current //
    // iteration                                                    //
    appendToFile << "// Set Kill/Restart Switches for " <<
        "current iteration //" << '\n';
    appendToFile << "&DEVC ID='nextIteration', QUANTITY='TIME', "
        << "XYZ=0.1,0.1,0.1, LATCH=.FALSE., SETPOINT="
        << nextIterationSetPoint << " /" << '\n';
    appendToFile << "&CTRL ID='restartSwitch', FUNCTION_TYPE='RESTART', "
        << "INPUT_ID='nextIteration', LATCH=.FALSE. /" << '\n';
    appendToFile << "&CTRL ID='killSwitch', FUNCTION_TYPE='KILL', "
        << "INPUT_ID='nextIteration', LATCH=.FALSE. /" << '\n';
    // close output stream //
    appendToFile.close();
}

// function to append plate (de)activation input lines to FDS_Script //
// for the current iteration                                          //
void append_plate_failure_device_switches()
{
    // create output stream to FDS_script.fds //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    // create input stream  from plateLogFile //
    std::ifstream plateLogFile(plateFailureFileName, std::ios::in);
    // print error if plateLogFile  can't be read/located //
    if (!plateLogFile){
        std::cerr << "Uh oh, plate failure log file "
            << plateFailureFileName
            << " could not be opened or does not exist!" << '\n';
            exit(1);
    }
    // calculate 'Begin-Time' for current iteration //
    currentIterationSetPoint = iterationCounter * iterationSize;
    // append plate (de)activation input lines to FDS_Script //
    appendToFile << "// RemPlate Switches //" << '\n';
    while(!plateLogFile.eof()){
        // read/write integers from log-file to parameters //
        plateLogFile >> failedPlateNumber;
        plateLogFile >> plateFailureBool;
        plateLogFile >> failureTimePoint;
        // additional end of file check, required to advert double //
        // device data output because of newline/linebreak at the  //
        // end of _platefailure.log                                //
        if(plateLogFile.eof()){
            break;
        }
        // if plate DID NOT fail, set removal time to //
        // end of NEXT iteration                      //
        if(plateFailureBool == 0){
            appendToFile << "&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate"
                << failedPlateNumber << "', SETPOINT="
                << totalSimulationDuration + iterationSize
                << ", QUANTITY='TIME', INITIAL_STATE=.TRUE. /" << '\n';
        }
        // if plate DID fail, set removal time to //
        // begin of CURRENT iteration             //
        else if(plateFailureBool == 1){
            appendToFile << "&DEVC XYZ=0.1,0.1,0.1, ID='RemPlate"
                << failedPlateNumber << "', SETPOINT="
                << failureTimePoint
                << ", QUANTITY='TIME', INITIAL_STATE=.TRUE. /" << '\n';
        }
    }
    // append &TAIL line to finalize FDS_Script.fds //
    appendToFile << "// Tail" << '\n' << "&TAIL /" << '\n';
    // append end of input file line //
    appendToFile << "//////////////////////////// End of Input File "
        << "////////////////////////////";
    // close input and output streams //
    appendToFile.close();
    plateLogFile.close();
}
```

```
// function outputting (simple) completion message to console //
void process_completed()
{
    std::cout << "[ [ [upGeomFDS] ] ]" << '\n'
        << "Successfully updated FDS input file for iteration: "
        << iterationCounter << '\n' << '\n';
}

// Actual Program //
int main()
{
    read_current_iteration();
    read_number_of_plates_and_partitions();
    copy_basic_setup_to_new_input_file();
    append_next_iteration();
    append_plate_failure_device_switches();
    process_completed();
    return 0;
}

/////////////////////////////// End of Code ///////////////////////////////
///////////////////////////////  upGeomFDS  ///////////////////////////////
```

APPENDIX D4 – UPGEOMHT: C++ SOURCE CODE

```
////////////////////////////////////////////////////////////////////////////
// Name:        upGeomHT                                                  //
//                                                                        //
// Description: This program creates an Abaqus Heat Transfer (HT) python //
//              script for the current iteration. Basically it copies    //
//              the basic model setup, HT_basicModel.py, to a new python //
//              script, HT_Script.py, and appends additional python code //
//              to update step, restart, AST, heat transfer and geometry //
//              info for the current iteration. The AST amplitude script //
//              AST_Amp_data.py, which is generated by the reWriteAST2py //
//              program, is used to update the AST data. Required        //
//              iteration parameters are read from temporary file        //
//              _iterationCounter.temp, the plate and partition          //
//              parameters are read from _platePartitionInfo.temp,       //
//              and plate failure parameters from _plateFailure.log.     //
//              All of which are managed by the Master program         //
//              FDS-2-Abaqus.                                            //
//                                                                        //
// Input:       HT_basicModel.py                                          //
//              _iterationCounter.temp                                    //
//              _platePartitionCounter.temp                               //
//              _plateFailure.log                                         //
//              AST_Amp_Data.py                                           //
//                                                                        //
// Output:      HT_Script.py     (script for iteration)                   //
//              ix_HT_Script.py  (backup)                                 //
//                                                                        //
// Required     iterationCounter                                          //
// Parameters:  iterationSize                                             //
//              totalSimulationDuration                                   //
//              numberOfPlates                                            //
//              numberOfPartitions                                        //
//              failedPlateNumber                                         //
//              failureTimePoint                                          //
//              plateFailureBool                                          //
//                                                                        //
////////////////////////////////////////////////////////////////////////////
// Version 1.0                                            by J.A.Feenstra //
// August 2016                          jelmerfeenstra1987@gmail.com //
////////////////////////////////////////////////////////////////////////////

/////////////////////////////// Begin Code ////////////////////////////////

// Import Libraries //
#include <iostream>
#include <string>
#include <fstream>
#include <cstdlib>
#include <sstream>

// Define String Parameters //
// input filename for python script containing basic HT model setup //
std::string basicModelFileName = "HT_basicModel.py";
// output filename for updated HT python script //
std::string scriptFileName = "HT_Script.py";
// input filename for iterationCounter containing iteration data //
std::string counterFileName = "_iterationCounter.temp";
// input filename for temporary file containing plate/partition info //
std::string platePartitionFileName = "_platePartitionInfo.temp";
```

```
// input filename for logfile containing failure-info //
std::string plateFailureFileName = "_plateFailure.log";
// filename for python script containing AST amplitude data //
std::string astAmplitudeDataFile = "AST_Amp_data.py";

// stringstream for storing backup filename
std::stringstream backupFileName_ss;

// Define Integer Parameters //
// read from counterFileName (_iterationCounter.temp) //
// managed by FDS-2-Abaqus                            //
int iterationCounter(0); //
int iterationSize(5);    //
int totalSimulationDuration(10); //
// read from platePartitionFileName (_platePartitionInfo.temp) //
// managed by FDS-2-Abaqus                                     //
int numberOfPlates(1); // is read from platePartitionFileName
int numberOfPartitions(1); // is read from platePartitionFileName
// calculated from numberOfPlates and numberOfPartitions //
int totalNumberOfPartitions(1);
// various counters //
int partitionCounter(0); // do not edit!
int plateCounter(1);     // do not edit!
int ppCounter(1);        // as in Plate-Partition
// read from plateFailureFileName (_plateFailure.log) //
// managed by FDS-2-Abaqus                            //
int failedPlateNumber(0);
int failureTimePoint(0);
// Define Boolean Parameters                          //
// read from plateFailureFileName (_plateFailure.log) //
// managed by FDS-2-Abaqus                            //
bool plateFailureBool;

// function importing iteration-info from               //
// _platePartitionInfo.temp (managed by FDS-2-Abaqus)   //
void read_current_iteration()
{
    // create input stream from iteration counter file //
    std::ifstream readCounter(counterFileName);
    // print error if iterationCounter file can't be read/located //
    if (!readCounter){
        std::cerr << "Uh oh, iteration counter file " << counterFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // read/write integers from counterFile to parameters //
    else{
        readCounter >> iterationCounter;
        readCounter >> iterationSize;
        readCounter >> totalSimulationDuration;
        readCounter.close();
    }
}
```

```
// function importing plate/partition info from       //
// _platePartitionInfo.temp (managed by FDS-2-Abaqus) //
void read_number_of_plates_and_partitions()
{
    // create input stream from plate/partition file //
    std::ifstream readPlatePartition(platePartitionFileName);
    // print error if iterationCounter file can't be read/located //
    if (!readPlatePartition){
        std::cerr << "Uh oh, Plate/Partition info file "
            << platePartitionFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // read/write integers from plate/partition file to parameters //
    else{
        readPlatePartition >> numberOfPlates;
        readPlatePartition >> numberOfPartitions;
        readPlatePartition.close();
    }
}

// Plate counter to iterate through plates and temperature partitions //
// [example] 4 plates, 4 temperature partitions                       //
// [result]  1-1, 1-2, 1-3, 1-4, 2-1, 2-2 ... 4-3, 4-4.               //
void plate_counter()
{
    if (partitionCounter < numberOfPartitions){
        partitionCounter++;
    }
    else{
        plateCounter++;
        if (plateCounter <= numberOfPlates){
            partitionCounter = 1;
        }
    }
}

// function to copy basic HT model python script to a new script //
// for the current iteration                                     //
void copy_basic_model_to_new_py()
{
    // create input stream  from HT_basicModel.py //
    std::ifstream sourceFile(basicModelFileName, std::ios::in);
    // create output stream to HT_script.py //
    std::ofstream destFile(scriptFileName, std::ios::out);
    // write some initial banner information to output script //
    destFile << "# Iteration Number: " << iterationCounter
        << ", IterationSize: " << iterationSize << "s." << '\n'
        << "# IterationTimeSlot: "<< (iterationCounter * iterationSize)
        << "-" << ((iterationCounter + 1) * iterationSize)
        << "s, TotalSimulationDuration: " << totalSimulationDuration
        << "s." << '\n' << "# " << numberOfPlates<< " plate(s), "
        << numberOfPartitions << " partition(s)."<< '\n';
    // print error if HT_basicModel.py can't be read/located //
    if (!sourceFile){
        std::cerr << "Uh oh, input file " << basicModelFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // rewrite content from buffer (input stream) to output stream //
    else{
        destFile << sourceFile.rdbuf() << '\n' << '\n';
        // append 'Code Added' line //
        destFile << "######################### Code Added by upGeomHT "
            << "###########################" << '\n';
        // close input and output streams //
        sourceFile.close();
        destFile.close();
    }
}

// function to append new or update old step   //
// based on iterationCounter and iterationSize //
void append_new_step() //
{
    // create output stream to HT_script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    appendToFile << "### Create/Update Additional Steps ###" << '\n';
    // if initial (zeroth) iteration update parameters in i0_HT-Step //
    if (iterationCounter == 0){
        appendToFile << "mod.steps['i0_HT-Step'].setValues(timePeriod="
        << iterationSize << ")" << '\n';
    }
    // if first (after initial) iteration add i1_HT-Step //
    else if (iterationCounter == 1){
        appendToFile << "mod.HeatTransferStep(name='i1_HT-Step', "
            << "previous='i0_HT-Step', timePeriod=" << iterationSize
            << ", maxNumInc=1000, initialInc=" << 0.001 * iterationSize
            << ", minInc=1E-3, " << "maxInc=10.0, deltmx=50.0)" << '\n';
    }
    // if non initial or first iteration add step for //
    // previous and current iteration                 //
    else if (iterationCounter > 1){
        // previous iteration //
        appendToFile << "mod.HeatTransferStep(name='i"
            << (iterationCounter - 1)
            << "_HT-Step', previous='i0_HT-Step', timePeriod="
            << iterationSize << ", maxNumInc=1000, "
            << "initialInc=" << 0.001 * iterationSize
            << ", minInc=1E-3, maxInc=10.0, deltmx=50.0)" << '\n';
        // current iteration //
        appendToFile << "mod.HeatTransferStep(name='i"
            << (iterationCounter) << "_HT-Step', previous='i"
            << (iterationCounter - 1) << "_HT-Step', timePeriod="
            << iterationSize << ", maxNumInc=1000, "
            << "initialInc=" << 0.001 * iterationSize
            << ", minInc=1E-3, maxInc=10.0, deltmx=50.0)" << '\n';
    }
    // close output stream //
    appendToFile.close();
}
```

```
// function to append code to read the restart file from previous //
// iteration and request a new restart file for this iteration    //
void append_restart_job_step()
{
    // create output stream to HT_script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    appendToFile << "### Define Restart Job/Step ###" << '\n';
    // if non-zeroth iteration then append python code to read restart //
    // file from previous iteration and request a new restart file     //
    // for this iteration //
    if (iterationCounter > 0){
        appendToFile << "mod.setValues(restartJob='i"
            << (iterationCounter - 1) << "_HT-Job', restartStep='i"
            << (iterationCounter - 1) << "_HT-Step')" << '\n';
        appendToFile << "### Request Restart File for New Step ###"<< '\n';
        appendToFile << "mod.steps['i" << iterationCounter
            << "_HT-Step'].Restart(frequency=0, numberIntervals=1, "
            << "overlay=ON, timeMarks=OFF)" << '\n';
    }
    // if zeroth iteration then no additional code is written //
    // (only a comment)                                       //
    else if (iterationCounter == 0){
        appendToFile << "#no additional restart information is written "
            << "since it is the initial (zero'th) iteration" << '\n';
    }
    // print error if iteration counter is negative //
    // (should never occur)                         //
    else if (iterationCounter < 0){
        std::cerr << "Uh oh, iteration counter is negative check "
            << counterFileName << '\n';
        exit(1);
    }
    // close output stream //
    appendToFile.close();
}

// function to append python code to update AST tabular amplitude data //
// and defining convective and radiative heat transfer                 //
void append_update_ConRad_AST_Data()
{
    // create output stream to HT_script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    appendToFile << "### Update ConRad and AST Data ###" << '\n';
    appendToFile << "imp = mod.TabularAmplitude" << '\n';
    // code to update AST data (AST_Amp_Data.py)          //
    // NOTE: this python-command refers to a relative path //
    appendToFile << "execfile(r'../" << astAmplitudeDataFile
        << "', __main__.__dict__)" << '\n';
    // calculate total number of partitions to use in for loop //
    totalNumberOfPartitions = numberOfPlates * numberOfPartitions;
    // for loop iterating through all plates and partitions //
    for (ppCounter = 1; ppCounter <= totalNumberOfPartitions; ppCounter++){
        // iterate plate_counter function //
        plate_counter();
        // change tabular amplitude name to current iteration          //
        // if this is not included the number of iterations is limited //
        appendToFile << "mod.amplitudes.changeKey(fromName='i0_AST_"
            << plateCounter << "-" << partitionCounter << "', toName='i"
            << iterationCounter << "_AST_" << plateCounter << "-"
            << partitionCounter << "')" << '\n';
        // python to code assign Radiation to PlateSurface //
         appendToFile << "mod.RadiationToAmbient(name='Rad_"<< plateCounter
            << "-" << partitionCounter << "', createStepName='i"
            << iterationCounter << "_HT-Step', " << '\n'
            << "    emissivity=0.8, ambientTemperature=1.0," << '\n'
            << "    ambientTemperatureAmp='i" << (iterationCounter)
            << "_AST_" << plateCounter << "-" << partitionCounter
            << "'," << '\n'
            << "    surface=mod.rootAssembly."<< "instances['Plate-"
            << plateCounter << "'].surfaces['Surf-"<< partitionCounter
            << "'])" << '\n';
        // python code to assign Convection to PlateSurface //
        appendToFile << "mod.FilmCondition(name='Conv_" << plateCounter
            << "-" << partitionCounter << "', createStepName='i"
            << iterationCounter << "_HT-Step', " << '\n'
            << "    definition=EMBEDDED_COEFF, filmCoeff=25.0, " << '\n'
            << "    sinkAmplitude='i" << (iterationCounter) << "_AST_"
            << plateCounter << "-" << partitionCounter
            << "', sinkTemperature=1.0, " << '\n'
            << "    surface=mod.rootAssembly."<< "instances['Plate-"
            << plateCounter << "'].surfaces['Surf-"<< partitionCounter
            << "'])" << '\n';
    }
    // close output stream //
    appendToFile.close();
}

// function to append instance (plate) (de)activation python code //
// for the current iteration                                      //
void append_update_geometry()
{
    // create output stream to HT_Script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    // create input stream  from plateLogFile //
    std::ifstream plateLogFile(plateFailureFileName, std::ios::in);
    // print error if plateLogFile  can't be read/located //
    if (!plateLogFile){
        std::cerr << "Uh oh, plate failure log file "
            << plateFailureFileName
            << " could not be opened or does not exist!" << '\n';
            exit(1);
    }
    appendToFile << "### Update Model Geometry ###" << '\n';
    if (numberOfPlates == 1){
        appendToFile << "# only a single plate in the model, "
            << "therefore no update is required" << '\n';
    }
    else if (numberOfPlates > 1){
        // while loop updating through input file //
        while(!plateLogFile.eof()){
            plateLogFile >> failedPlateNumber;
            plateLogFile >> plateFailureBool;
            plateLogFile >> failureTimePoint;
            // additional end of file check, required to advert  //
            // duplicate plate deactivation code because of      //
            // newline/linebreak at the end of _platefailure.log //
            if(plateLogFile.eof()){
                break;
            }
            // if plate DID NOT fail, continue //
            if(plateFailureBool==0){
                // nothing really happens here xD //
                continue;
            }
            // if plate DID fail, append python code to //
            // deactivate instance (= remove plate)     //
            else{
                appendToFile << "thisPlate = mod.rootAssembly.instances"
                    << "['Plate-" << failedPlateNumber
                    << "'].sets['Plate-Area']" << '\n';
                appendToFile << "mod.ModelChange(activeInStep=False, "
                    << "createStepName='i" << iterationCounter
                    << "_HT-Step', includeStrain=False, name='deActPlate-"
                    << failedPlateNumber << "', region=thisPlate)" << '\n';
            }
        }
        // just some info //
        appendToFile << "# If empty: No plates failed this iteration "
            << "- Still Going Strong!" << '\n';
    }
    // close input and output streams //
    appendToFile.close();
    plateLogFile.close();
}

// function appending python code to create and run (restart) job //
// 'normal' job for initial (zeroth) iteration, restart for other //
void append_create_and_run_job()
{
    // create output stream to HT_Script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    appendToFile << "### Create and Run Job ###" << '\n';
    // if initial (zeroth) iteration append standard Job python code //
    if (iterationCounter == 0){
        appendToFile << "mdb.Job(name='i0_HT-Job', model='Model-1')"
        << '\n';
    }
    // if NON-initial iteration append restart Job python code //
    else if (iterationCounter > 0){
        appendToFile << "mdb.Job(name='i" << iterationCounter
            << "_HT-Job', model='Model-1', type=RESTART)" << '\n';
    }
    // append submit and run job python code to script //
    appendToFile << "mdb.jobs['i" << iterationCounter
        << "_HT-Job'].submit(consistencyChecking=OFF)" << '\n';
    appendToFile << "mdb.jobs['i" << iterationCounter
        << "_HT-Job'].waitForCompletion()" << '\n';
    // append end of script line //
    appendToFile << "############################### "
        << "End-Of-Script ###############################";
    // close output stream //
    appendToFile.close();
}

// function to backup HT_Script for current iteration //
// rewriting script into file named ix_HT_Script.py   //
void create_backup_for_current_iteration()
{
    // create input stream  from HT_Script.py //
    std::ifstream sourceFile(scriptFileName, std::ios::in);
    // write backup filename to stringstream
    backupFileName_ss.clear();
    backupFileName_ss << "i" << iterationCounter << "_HT_Script.py";
    // create output stream to HT_Script.py //
    std::ofstream destFile(backupFileName_ss.str(), std::ios::out);
    // print error if HT_Script.py can't be read/located //
    if (!sourceFile){
        std::cerr << "Uh oh, input file " << scriptFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // rewrite content from buffer (input stream) to output stream //
    else{
        destFile << sourceFile.rdbuf() << '\n';
        // close input and output streams //
        sourceFile.close();
        destFile.close();
    }
}

// function outputting (simple) completion message to console //
void process_completed()
{
    std::cout << "[ [ [upGeomHT] ] ]" << '\n'
        << "Successfully updated HT python script for iteration: "
        << iterationCounter << '\n' << '\n';
}

int main()
{
    read_current_iteration();
    read_number_of_plates_and_partitions();
    copy_basic_model_to_new_py();
    append_new_step();
    append_restart_job_step();
    append_update_ConRad_AST_Data();
    append_update_geometry();
    append_create_and_run_job();
    create_backup_for_current_iteration();
    process_completed();
    return 0;
}

//////////////////////////////// End of Code ////////////////////////////////
////////////////////////////////  upGeomHT   ////////////////////////////////
```

APPENDIX D5 – UPGEOMSR: C++ SOURCE CODE

```
///////////////////////////////////////////////////////////////////////////
// Name:         upGeomSR                                                //
//                                                                       //
// Description: This program creates an Abaqus Structural Response (SR)  //
//               python script for the current iteration. Basically it   //
//               copies the basic model setup, SR_basicModel.py, to a    //
//               new python script, SR_Script.py, and appends additional //
//               python code to update step, restart, temperature, and   //
//               geometry info for the current iteration. Required       //
//               iteration parameters are read from temporary file       //
//               _iterationCounter.temp, the plate and partition         //
//               parameters are read from _platePartitionInfo.temp,      //
//               and plate failure parameters from _plateFailure.log.    //
//               All of which are managed by the Master program        //
//               FDS-2-Abaqus.                                           //
//                                                                       //
// Input:        SR_basicModel.py                                        //
//               _iterationCounter.temp                                  //
//               _platePartitionCounter.temp                             //
//               _plateFailure.log                                       //
//                                                                       //
// Output:       SR_Script.py     (script for iteration)                 //
//               ix_SR_Script.py  (backup)                               //
//                                                                       //
// Required      iterationCounter                                        //
// Parameters:   iterationSize                                           //
//               totalSimulationDuration                                 //
//               numberOfPlates                                          //
//               numberOfPartitions                                      //
//               failedPlateNumber                                       //
//               failureTimePoint                                        //
//               plateFailureBool                                        //
//                                                                       //
///////////////////////////////////////////////////////////////////////////
// Version 1.0                                           by J.A.Feenstra //
// August 2016                          jelmerfeenstra1987@gmail.com //
///////////////////////////////////////////////////////////////////////////

/////////////////////////////// Begin Code ////////////////////////////////

// Import Libraries //
#include <iostream>
#include <string>
#include <fstream>
#include <cstdlib>
#include <sstream>

// Define String Parameters //
// input filename for python script containing basic SR model setup //
std::string basicModelFileName = "SR_basicModel.py";
// output filename for updated SR python script //
std::string scriptFileName = "SR_Script.py";
// input filename for iterationCounter containing iteration data //
std::string counterFileName = "_iterationCounter.temp";
// input filename for temporary file containing plate/partition info //
std::string platePartitionFileName = "_platePartitionInfo.temp";
// input filename for logfile containing failure-info //
std::string plateFailureFileName = "_plateFailure.log";
```

```
// stringstream for storing backup filename
std::stringstream backupFileName_ss;

// Define Integer Parameters //
// read from counterFileName (_iterationCounter.temp) //
// managed by FDS-2-Abaqus                            //
int iterationCounter(0);
int iterationSize(5);
int totalSimulationDuration(10);
// read from platePartitionFileName (_platePartitionInfo.temp) //
// managed by FDS-2-Abaqus                                     //
int numberOfPlates(1); // is read from platePartitionFileName
int numberOfPartitions(1);
// read from plateFailureFileName (_plateFailure.log) //
// managed by FDS-2-Abaqus                            //
int failedPlateNumber(0); //
int failureTimePoint(0);
// Define Boolean Parameters                          //
// read from plateFailureFileName (_plateFailure.log) //
// managed by FDS-2-Abaqus                            //
bool plateFailureBool;

// function importing iteration-info from              //
// _platePartitionInfo.temp (managed by FDS-2-Abaqus)  //
void read_current_iteration()
{
    // create input stream from iteration counter file //
    std::ifstream readCounter(counterFileName);
    // print error if iterationCounter file can't be read/located //
    if (!readCounter){
        std::cerr << "Uh oh, iteration counter file "
            << counterFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // read/write integers from counterFile to parameters //
    else{
        readCounter >> iterationCounter;
        readCounter >> iterationSize;
        readCounter >> totalSimulationDuration;
        readCounter.close();
    }
}

// function importing plate/partition info from       //
// _platePartitionInfo.temp (managed by FDS-2-Abaqus) //
void read_number_of_plates_and_partitions()
{
    // create input stream from plate/partition file //
    std::ifstream readPlatePartition(platePartitionFileName);
    // print error if iterationCounter file can't be read/located //
    if (!readPlatePartition){
        std::cerr << "Uh oh, Plate/Partition info file "
            << platePartitionFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // read/write integers from plate/partition file to parameters //
    else{
        readPlatePartition >> numberOfPlates;
        readPlatePartition >> numberOfPartitions;
        readPlatePartition.close();
    }
}

// function to copy basic SR model python script to a new script //
// for the current iteration                                    //
void copy_basic_model_to_new_py()
{
    // create input stream  from SR_basicModel.py //
    std::ifstream sourceFile(basicModelFileName, std::ios::in);
    // create output stream to SR_script.py //
    std::ofstream destFile(scriptFileName, std::ios::out);
    // write some initial banner information to output script //
    destFile << "# Iteration Number: " << iterationCounter
        << ", IterationSize: " << iterationSize << "s." << '\n'
        << "# IterationTimeSlot: "<< (iterationCounter * iterationSize)
        << "-" << ((iterationCounter + 1) * iterationSize)
        << "s, TotalSimulationDuration: " << totalSimulationDuration
        << "s." << '\n' << "# " << numberOfPlates << " plate(s), "
        << numberOfPartitions << " partition(s)." << '\n';
    // print error if HT_basicModel.py can't be read/located //
    if (!sourceFile){ // for when file cant be read
        std::cerr << "Uh oh, input file " << basicModelFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // rewrite content from buffer (input stream) to output stream //
    else{
        destFile << sourceFile.rdbuf() << '\n';
        // append 'Code Added' line //
        destFile << "######################### Code Added by upGeomSR "
            << "##########################" << '\n';
        // close input and output streams //
        sourceFile.close();
        destFile.close();
    }
}

// function to append new or update old step   //
// based on iterationCounter and iterationSize //
void append_new_step()
{
    // create output stream to SR_script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    appendToFile << "### Create/Update Additional Steps ###" << '\n';
    // if initial (zeroth) iteration update parameters in i0_SR-Step //
    if (iterationCounter == 0){
        appendToFile << "mod.steps['i0_SR-Step'].setValues(timePeriod="
            << iterationSize << ")" << '\n';
    }
    // if first (after initial) iteration add i1_SR-Step //
    else if (iterationCounter == 1){
        appendToFile << "mod.ImplicitDynamicsStep(name='i1_SR-Step', "
            << "previous='i0_SR-Step', timePeriod=" << iterationSize
            << ", maxNumInc=10000, application=QUASI_STATIC, "
            << "initialInc=0.3, minInc=1e-06, maxInc=10.0, nohaf=OFF, "
            << "amplitude=RAMP, alpha=DEFAULT, initialConditions=OFF, "
            << "nlgeom=ON)"<< '\n';
    }
    // if non initial or first iteration add step for //
    // previous and current iteration                 //
    else if (iterationCounter > 1){
        // previous iteration //

        appendToFile << "mod.ImplicitDynamicsStep(name='i"
            << (iterationCounter - 1) << "_SR-Step', previous="
            << "'i0_SR-Step', timePeriod=" << iterationSize
            << ", maxNumInc=10000, application=QUASI_STATIC, "
            << "initialInc=0.3, minInc=1e-06, maxInc=10.0, nohaf=OFF, "
            << "amplitude=RAMP, alpha=DEFAULT, initialConditions=OFF, "
            << "nlgeom=ON)" << '\n';
        // current iteration //
        appendToFile << "mod.ImplicitDynamicsStep(name='i"
            << (iterationCounter) << "_SR-Step', previous='i"
            << (iterationCounter - 1) << "_SR-Step', timePeriod="
            << iterationSize << ", maxNumInc=10000, "
            << "application=QUASI_STATIC, " << "initialInc=0.3"
            << ", minInc=1e-06, maxInc=10.0, "
            << "nohaf=OFF, amplitude=RAMP, alpha=DEFAULT, "
            << "initialConditions=OFF, nlgeom=ON)"<< '\n';
    }
    // close output stream //
    appendToFile.close();
}

// function to add python code to script to import temperature //
// data from previous HT analysis                               //
void import_temperature_data()
{
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    appendToFile << "### Import Nodal Temperatures from HT ###" << '\n';
    // stringstream to store path for ix_HT_Job.odb //
    std::stringstream currentTempFilePath;
    currentTempFilePath << "..\\_outputHT\\i" << (iterationCounter)
        << "_HT-Job.odb";
    // append python code to import ix_HT-Job.odb into SR analysis //
    appendToFile << "mod.Temperature(absoluteExteriorTolerance=0.0, "
        << "beginIncrement=None, beginStep=1, createStepName='i"
        << (iterationCounter) << "_SR-Step', distributionType=FROM_FILE, "
        << "endIncrement=None, endStep=None, exteriorTolerance=0.05, "
        << "fileName='" << currentTempFilePath.str()
        << "', interpolate=ON, name='i" << (iterationCounter)
        << "_Temp-From-HT')" << '\n';
    // clear stringstream //
    currentTempFilePath.clear();
    // close output stream //
    appendToFile.close();
}
```

```
// function to append code to read the restart file from previous //
// iteration and request a new restart file for this iteration    //
void append_restart_job_step()
{
    // create output stream to SR_script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    appendToFile << "### Define Restart Job/Step ###" << '\n';
    // if non-zeroth iteration then append python code to read restart //
    // file from previous iteration and request a new restart file     //
    // for this iteration //
    if (iterationCounter > 0){
        appendToFile << "mod.setValues(restartJob='i"
            << (iterationCounter - 1) << "_SR-Job', restartStep='i"
            << (iterationCounter - 1) << "_SR-Step')" << '\n';
        appendToFile << "### Request Restart File for New Step ###"<< '\n';
        appendToFile << "mod.steps['i" << iterationCounter
            << "_SR-Step'].Restart(frequency=0, numberIntervals=1, "
            << "overlay=ON, timeMarks=OFF)" << '\n';
    }
    // if zeroth iteration then no additional code is written //
    // (only a comment)                                       //
    else if (iterationCounter == 0){
        appendToFile << "#no additional restart information is written "
            << "since it is the initial (zero'th) iteration" << '\n';
    }
    // print error if iteration counter is negative //
    // (should never occur)                         //
    else if (iterationCounter < 0){
        std::cerr << "Uh oh, iteration counter is negative check "
            << counterFileName << '\n';
        exit(1);
    }
    // close output stream //
    appendToFile.close();
}

// function to append instance (plate) (de)activation python code //
// for the current iteration                                       //
void append_update_geometry()
{
    // create output stream to SR_Script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    // create input stream  from plateLogFile //
    std::ifstream plateLogFile(plateFailureFileName, std::ios::in);
    // print error if plateLogFile  can't be read/located //
    if (!plateLogFile){
        std::cerr << "Uh oh, plate failure log file "
            << plateFailureFileName
            << " could not be opened or does not exist!" << '\n';
            exit(1);
    }
    appendToFile << "### Update Model Geometry ###" << '\n';
    if (numberOfPlates == 1){
        appendToFile << "# only a single plate in the model, "
            << "therefore no update is required" << '\n';
    }
    else if (numberOfPlates > 1){
        // while loop updating through input file //
        while(!plateLogFile.eof()){
            plateLogFile >> failedPlateNumber;
            plateLogFile >> plateFailureBool;
            plateLogFile >> failureTimePoint;
            // additional end of file check, required to advert  //
            // duplicate plate deactivation code because of      //
            // newline/linebreak at the end of _platefailure.log //
            if(plateLogFile.eof()){
                break;
            }
            if(plateFailureBool==0){ // plate did not fail
                // nothing really happens here xD //
                continue;
            }
            // if plate DID fail, append python code to //
            // deactivate instance (= remove plate)     //
            else{
                appendToFile << "thisPlate = mod.rootAssembly.instances"
                    << "['Plate-" << failedPlateNumber <<
                    "'].sets['Plate-Area']" << '\n';
                appendToFile << "mod.ModelChange(activeInStep=False, "
                    << "createStepName='i" << iterationCounter
                    << "_SR-Step', includeStrain=False, name='deActPlate-"
                    << failedPlateNumber << "', region=thisPlate)" << '\n';
            }
        }
        // just some info //
        appendToFile << "# If empty: No plates failed this iteration - "
            << "Still Going Strong!" << '\n';
    }
    // close input and output streams //
    appendToFile.close();
    plateLogFile.close();
}

// function to remove the imperfection from a restart simulation //
// remove imperfection from ALL but the INITIAL iteration        //
void remove_imperfection()
{
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    if (iterationCounter != 0){
        appendToFile << "### Remove Imperfection ###" << '\n';
        appendToFile << "mdb.models['Model-1'].keywordBlock."
            << "setValues(edited = 0)" << '\n';
    }
    appendToFile.close();
}
```

```
// function appending python code to create and run (restart) job //
// 'normal' job for initial (zeroth) iteration, restart for other //
void append_create_and_run_job()
{
    // create output stream to SR_Script.py //
    std::ofstream appendToFile(scriptFileName, std::ios::app);
    appendToFile << "### Create and Run Job ###" << '\n';
     // if initial (zeroth) iteration append standard Job python code //
    if (iterationCounter == 0){
        appendToFile << "mdb.Job(name='i0_SR-Job', model='Model-1')"
            << '\n';
    }
    // if NON-initial iteration append restart Job python code //
    else if (iterationCounter > 0){
        appendToFile << "mdb.Job(name='i" << iterationCounter
            << "_SR-Job', model='Model-1', type=RESTART)" << '\n';
    }
    // append submit and run job python code to script //
    appendToFile << "mdb.jobs['i" << iterationCounter
        << "_SR-Job'].submit(consistencyChecking=OFF)" << '\n';
    appendToFile << "mdb.jobs['i" << iterationCounter
        << "_SR-Job'].waitForCompletion()" << '\n';
    // append end of script line //
    appendToFile << "############################### "
        << "End-Of-Script ###############################";
    // close output stream //
    appendToFile.close();
}

// function to backup SR_script for current iteration //
// rewriting script into file named ix_SR_script.py   //
void create_backup_for_current_iteration()
{
    // create input stream  from SR_Script.py //
    std::ifstream sourceFile(scriptFileName, std::ios::in);
    // write backup filename to stringstream
    backupFileName_ss.clear();
    backupFileName_ss << "i" << iterationCounter << "_SR_Script.py";
    // create output stream to SR_Script.py //
    std::ofstream destFile(backupFileName_ss.str(), std::ios::out);
    // print error if HT_Script.py can't be read/located //
    if (!sourceFile){
        std::cerr << "Uh oh, input file " << scriptFileName
            << " could not be opened or does not exist!" << '\n';
        exit(1);
    }
    // rewrite content from buffer (input stream) to output stream //
    else{
        destFile << sourceFile.rdbuf() << '\n';
        // close input and output streams //
        sourceFile.close();
        destFile.close();
    }
}
```

```
// function outputting (simple) completion message to console //
void process_completed()
{
    std::cout << "[ [ [upGeomSR] ] ]" << '\n'
        << "Successfully updated SR python script for iteration: "
        << iterationCounter << '\n' << '\n';
}

int main()
{
    read_current_iteration();
    read_number_of_plates_and_partitions();
    copy_basic_model_to_new_py();
    append_new_step();
    append_restart_job_step();
    import_temperature_data();
    append_update_geometry();
    remove_imperfection();
    append_create_and_run_job();
    create_backup_for_current_iteration();
    process_completed();
    return 0;
}

//////////////////////////////// End of Code ////////////////////////////////
////////////////////////////////  upGeomSR   ////////////////////////////////
```

Appendix E1 - FDS-2-Abaqus Installation Guide

This document illustrates the installation off `FDS-2-Abaqus`. A worked example is included in Appendix E2. The required files for an initial run can be obtained from: http://tinyurl.com/fds2abaqus.

Step 1 Install Fire Dynamic Simulator

Fire Dynamic Similator is free/open source software developed by NIST and can be obtained from: https://pages.nist.gov/fds-smv/

Note: FDS-2-Abaqus was developed using FDS version 6.1.12

Step 2 Install Abaqus

Abaqus is commercial software. An Abaqus license is required to use Abaqus and `FDS-2-Abaqus`. For additional information is refered to:
http://www.3ds.com/products-services/simulia/products/abaqus/

Note: FDS-2-Abaqus was developed using FDS version 6.1.12

Step 3 Initial Setup

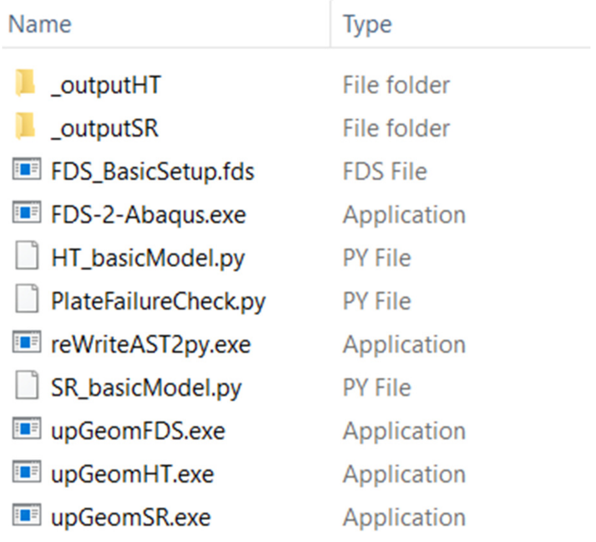
Make sure all required files, folders, programs and scripts are located within the same path as `FDS-2-Abaqus.exe`.

`FDS-2-Abaqus` requires:

```
FDS_BasicSetup.fds
upGeomFDS.exe
reWriteAst2py.exe
HT_basicModel.py
upGeomHT.exe
SR_basicModel.fds
upGeomSR.exe
PlateFailureCheck.py
_outputHT [folder]
_outputSR [folder]
I0_buc-Job.fil *
I0_buc-Job.prt *
```

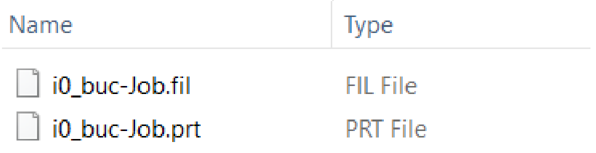
*buckling imperfection files should be placed inside the `_outputSR` folder

…`\FDS-2-Abaqus-Example\`



Name	Type
_outputHT	File folder
_outputSR	File folder
FDS_BasicSetup.fds	FDS File
FDS-2-Abaqus.exe	Application
HT_basicModel.py	PY File
PlateFailureCheck.py	PY File
reWriteAST2py.exe	Application
SR_basicModel.py	PY File
upGeomFDS.exe	Application
upGeomHT.exe	Application
upGeomSR.exe	Application

…`\FDS-2-Abaqus-Example\_outputSR\`



Name	Type
i0_buc-Job.fil	FIL File
i0_buc-Job.prt	PRT File

Step 4 Run FDS-2-Abaqus

Run `FDS-2-Abaqus`, the program will output some basic information and check the existence of prementioned files. The interface will request some input variables and a failure criteria before starting the coupling procedure. A detailed example is included in Appendix E2.

Note: an overview of possible errors and solutions is included in the `FDS-2-Abaqus` debug guide included in appendix E3.

APPENDIX E2 - FDS-2-ABAQUS USER'S GUIDE

This document illustrates the use of `FDS-2-Abaqus` through a worked example. The files used in this example can be downloaded from: http://tinyurl.com/fds2abaqus.

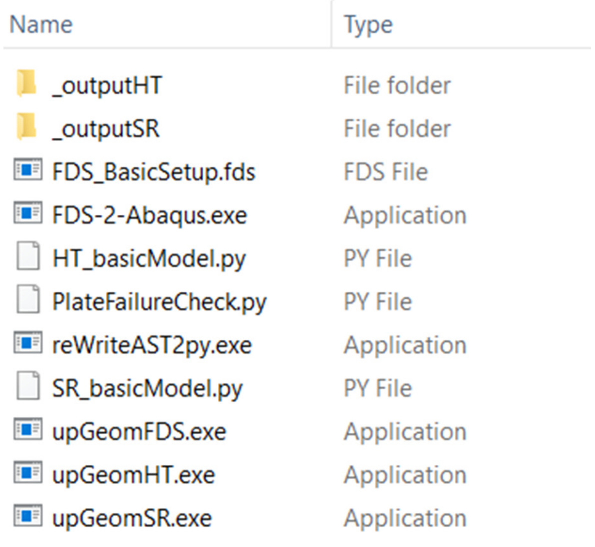
STEP 1 INITIAL SETUP

Make sure all required files, folders, programs and scripts are located within the same path as `FDS-2-Abaqus.exe`.

`FDS-2-Abaqus` **requires:**
```
FDS_BasicSetup.fds
upGeomFDS.exe
reWriteAst2py.exe
HT_basicModel.py
upGeomHT.exe
SR_basicModel.fds
upGeomSR.exe
PlateFailureCheck.py
_outputHT [folder]
_outputSR [folder]
I0_buc-Job.fil *
I0_buc-Job.prt *
```

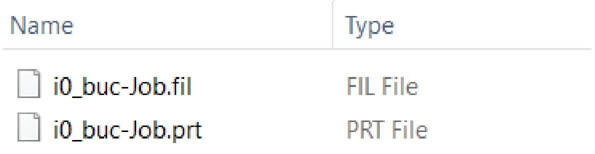
*buckling imperfection files should be placed inside the `_outputSR` folder

…\FDS-2-Abaqus-Example\



Name	Type
_outputHT	File folder
_outputSR	File folder
FDS_BasicSetup.fds	FDS File
FDS-2-Abaqus.exe	Application
HT_basicModel.py	PY File
PlateFailureCheck.py	PY File
reWriteAST2py.exe	Application
SR_basicModel.py	PY File
upGeomFDS.exe	Application
upGeomHT.exe	Application
upGeomSR.exe	Application

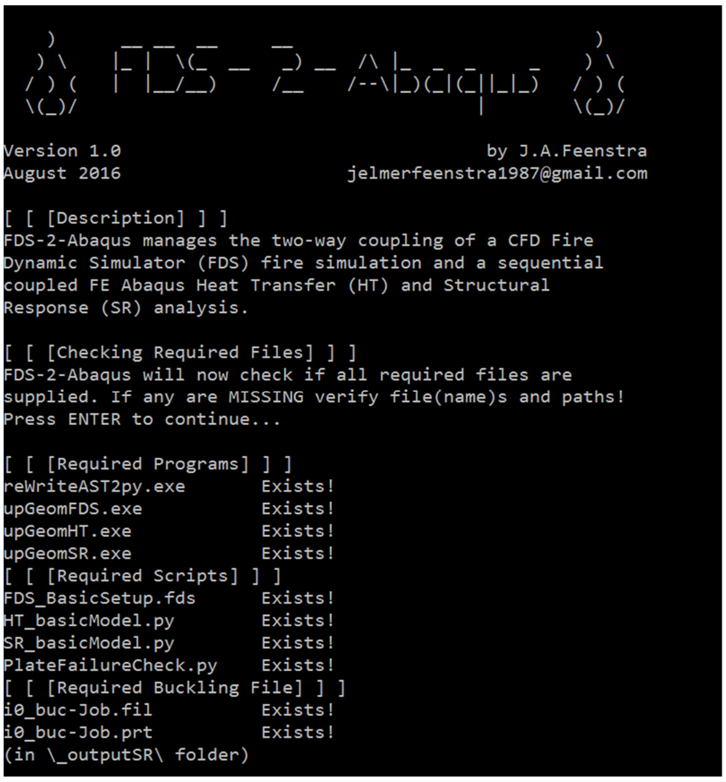
…\FDS-2-Abaqus-Example_outputSR\



Name	Type
i0_buc-Job.fil	FIL File
i0_buc-Job.prt	PRT File

STEP 2 RUN FDS-2-ABAQUS

Run `FDS-2-Abaqus`, the program will output some basic information and check the existence of prementioned files. If any are missing verify filenames and paths.



```
    )                                                          )
   ) \     __ __  __      __                                  ) \
  / ) (   |_ |  \(_  __   _) __   /\ |_   _   _       _      / ) (
  \(_)/   |  |__/__)     /__     /--\|_)(_|(_||_|_)          \(_)/
                                                |

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August 2016                                jelmerfeenstra1987@gmail.com

[ [ [Description] ] ]
FDS-2-Abaqus manages the two-way coupling of a CFD Fire
Dynamic Simulator (FDS) fire simulation and a sequential
coupled FE Abaqus Heat Transfer (HT) and Structural
Response (SR) analysis.

[ [ [Checking Required Files] ] ]
FDS-2-Abaqus will now check if all required files are
supplied. If any are MISSING verify file(name)s and paths!
Press ENTER to continue...

[ [ [Required Programs] ] ]
reWriteAST2py.exe        Exists!
upGeomFDS.exe            Exists!
upGeomHT.exe             Exists!
upGeomSR.exe             Exists!
[ [ [Required Scripts] ] ]
FDS_BasicSetup.fds       Exists!
HT_basicModel.py         Exists!
SR_basicModel.py         Exists!
PlateFailureCheck.py     Exists!
[ [ [Required Buckling File] ] ]
i0_buc-Job.fil           Exists!
i0_buc-Job.prt           Exists!
(in \_outputSR\ folder)
```
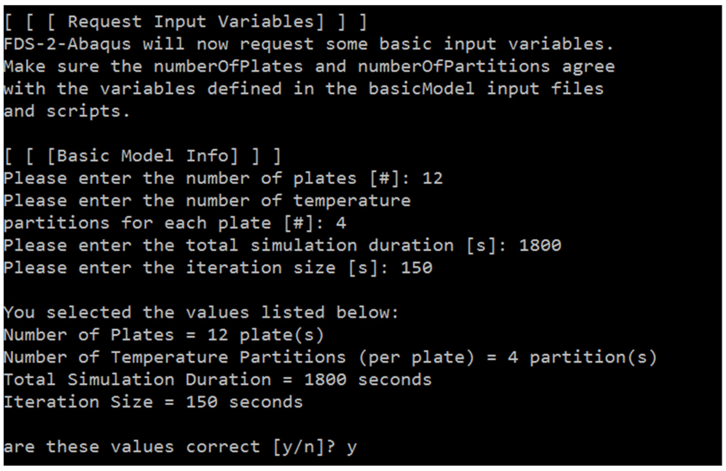

STEP 3 SPECIFY INPUT VARIABLES

FDS-2-Abaqus will request some basic variables. Input the number of plates and number of temperature partitions per plate in the FE models.

In addition the total simulation duration and the iteration size for the two-way coupling should be specified.

(When performing a one way coupling the total simulation duration should be equal to the iteration size.)

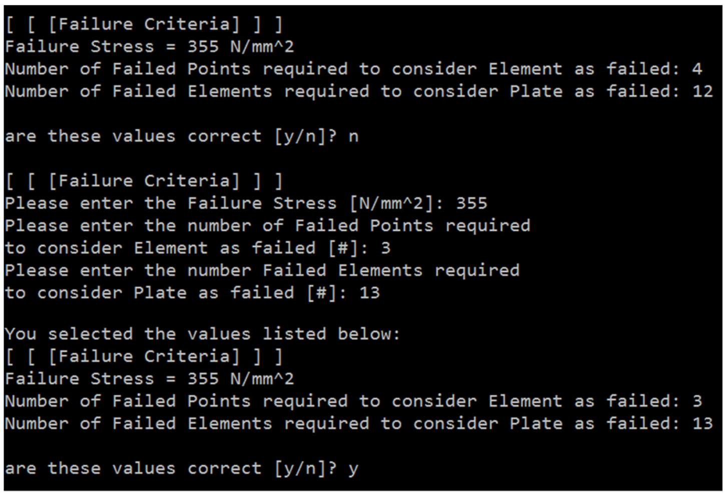


```
[ [ [ Request Input Variables] ] ]
FDS-2-Abaqus will now request some basic input variables.
Make sure the numberOfPlates and numberOfPartitions agree
with the variables defined in the basicModel input files
and scripts.

[ [ [Basic Model Info] ] ]
Please enter the number of plates [#]: 12
Please enter the number of temperature
partitions for each plate [#]: 4
Please enter the total simulation duration [s]: 1800
Please enter the iteration size [s]: 150

You selected the values listed below:
Number of Plates = 12 plate(s)
Number of Temperature Partitions (per plate) = 4 partition(s)
Total Simulation Duration = 1800 seconds
Iteration Size = 150 seconds

are these values correct [y/n]? y
```

STEP 4 SPECIFY FAILURE CRITERIA

Specify the failure stress, number of failed points per element (integration and section point), and number of failed elements per plate.

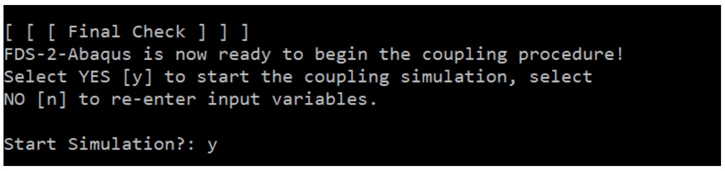
The failure criteria is checked for each element when the number of failed points exceeds the given number the element is considered failed. Subsequently a plate is considered failed when the number of failed elements is reached.



```
[ [ [Failure Criteria] ] ]
Failure Stress = 355 N/mm^2
Number of Failed Points required to consider Element as failed: 4
Number of Failed Elements required to consider Plate as failed: 12

are these values correct [y/n]? n

[ [ [Failure Criteria] ] ]
Please enter the Failure Stress [N/mm^2]: 355
Please enter the number of Failed Points required
to consider Element as failed [#]: 3
Please enter the number Failed Elements required
to consider Plate as failed [#]: 13

You selected the values listed below:
[ [ [Failure Criteria] ] ]
Failure Stress = 355 N/mm^2
Number of Failed Points required to consider Element as failed: 3
Number of Failed Elements required to consider Plate as failed: 13

are these values correct [y/n]? y
```

STEP 5 FINAL CHECK

FDS-2-Abaqus is ready to perform the two-way coupled analysis. Verify input and select [y] to start the simulation. Select [n] to re-enter variables



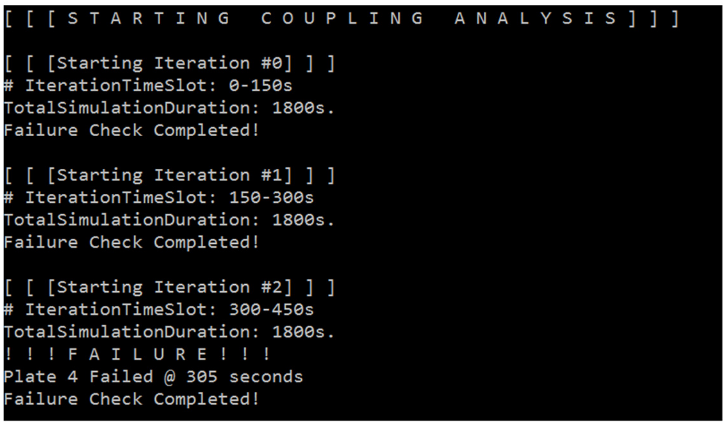
```
[ [ [ Final Check ] ] ]
FDS-2-Abaqus is now ready to begin the coupling procedure!
Select YES [y] to start the coupling simulation, select
NO [n] to re-enter input variables.

Start Simulation?: y
```

Note: an overview of possible errors and solutions is included in the FDS-2-Abaqus *debug guide included in appendix E3.*

STEP 6 PERFORMING COUPLING ANALYSIS

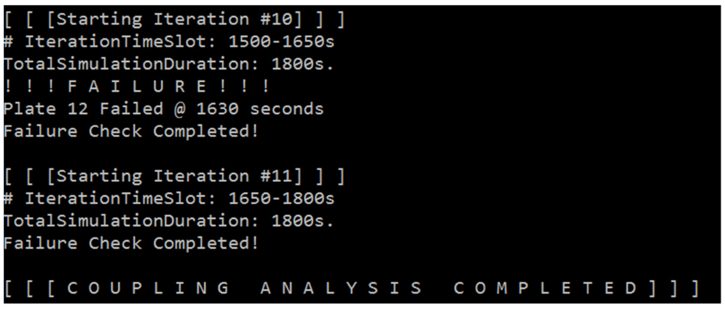
FDS-2-Abaqus will now run the fully coupled analysis. No futher user input is required.

The current iteration progress and plate failure is output to the console.



```
[ [ [ S T A R T I N G   C O U P L I N G   A N A L Y S I S ] ] ]

[ [ [Starting Iteration #0] ] ]
# IterationTimeSlot: 0-150s
TotalSimulationDuration: 1800s.
Failure Check Completed!

[ [ [Starting Iteration #1] ] ]
# IterationTimeSlot: 150-300s
TotalSimulationDuration: 1800s.
Failure Check Completed!

[ [ [Starting Iteration #2] ] ]
# IterationTimeSlot: 300-450s
TotalSimulationDuration: 1800s.
! ! ! F A I L U R E ! ! !
Plate 4 Failed @ 305 seconds
Failure Check Completed!
```

[…iterations 3 – 9…]

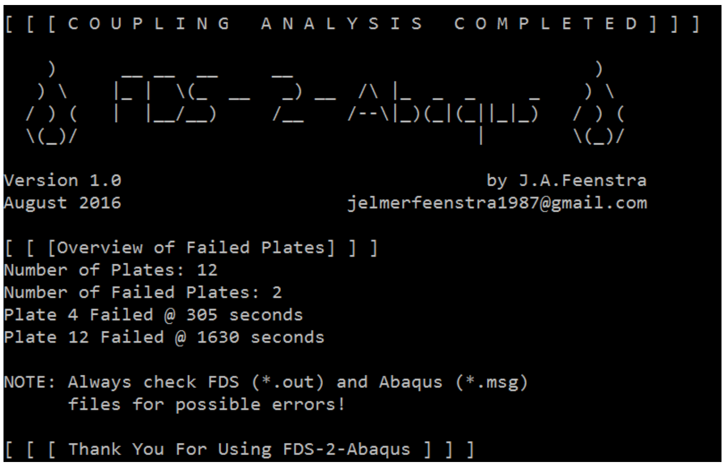


```
[ [ [Starting Iteration #10] ] ]
# IterationTimeSlot: 1500-1650s
TotalSimulationDuration: 1800s.
! ! ! F A I L U R E ! ! !
Plate 12 Failed @ 1630 seconds
Failure Check Completed!

[ [ [Starting Iteration #11] ] ]
# IterationTimeSlot: 1650-1800s
TotalSimulationDuration: 1800s.
Failure Check Completed!

[ [ [ C O U P L I N G   A N A L Y S I S   C O M P L E T E D ] ] ]
```

STEP 7 RESULTS SUMARRY

As soon as the coupling is completed the results are summarized. The plate failure progression is additionaly stored in _plateFailure.log

It is important to always check the FDS output and abaqus message and reply files for possible errors.



```
[ [ [ C O U P L I N G   A N A L Y S I S   C O M P L E T E D ] ] ]

    )      __ __ __    __                         )
   ) \    |_ |  \(_ __  _) __  /\ |_  _  _    _   ) \
  / ) (   |  |__/__)   /__    /--\|_)(_|(_||_|_) / ) (
  \(_)/                                    |      \(_)/

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August 2016                         jelmerfeenstra1987@gmail.com

[ [ [Overview of Failed Plates] ] ]
Number of Plates: 12
Number of Failed Plates: 2
Plate 4 Failed @ 305 seconds
Plate 12 Failed @ 1630 seconds

NOTE: Always check FDS (*.out) and Abaqus (*.msg)
      files for possible errors!

[ [ [ Thank You For Using FDS-2-Abaqus ] ] ]
```

APPENDIX E3 - FDS-2-ABAQUS DEBUG GUIDE

This docement gives a brief overview of possible challenges during a `FDS-2-Abaqus` managed two-way coupled CFD-FEM analysis.

"FDS-2-Abaqus seems to run correctly but does not show the completion info"

- Due to its interdependency on the various scripts and programs a simple discontinuity (for instance wrongly described paths) can result in crashing the complete program tree.
- Possible solution:
    - Check the FDS output (*.out) and abaqus message (*.msg) and reply (*.rpy) files for possible errors.

"FDS Fire modelling crashes – Numerical instability"

- Debug FDS model by running isloted FDS simulation.
- A possible reason for a Numerical Instability is the occurance of unrealistic velocities due to sudden changes in HRR.
- Possible solution:
    - Change HRR value

"FDS-2-Abaqus stuck in structural response simulation"

- Sometimes `FDS-2-Abaqus` gets stuck due to a convergence error. Possibly due to multiple stable solution as a result of the various buckling modes.
- Possible solutions include:
    - Change imperfection size.
    - Change (`FDS-2-Abaqus`) iteration size.
    - Change 'Request fieldOutput interval'

"FDS-2-Abaqus stuck in PlateFailureCheck.py"

- The number of stress values in the output database increases quickly based on the number of plates, the field output request interval, and the simulation duration. Patience is key.