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THE EFFECT OF TRIPLE GLAZING OF NEARLY ZERO ENERGY BUILDINGS ON THEIR FIRE SAFETY



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ABSTRACT

Low-energy dwellings (such as the passive house concept or nearly Zero Energy houses) will lead to application of triple glazing. Glass fallout is an important factor that influences the fire development during an enclosure fire. A smouldering fire seems more likely when the glazing system remains intact, while a flaming fire will be more likely in a situation with major glass fallout. The experimental research uses a fire furnace and supporting simulations to generate a fire scenario as such in a highly insulated dwelling with a double and triple glazing assembly. The analysis of the results revealed a wide spread between temperatures and glass fallout.

1 INTRODUCTION

In the Netherlands nearly half of all deathly casualties during an enclosure fire occur in residential buildings, making fire safety in dwellings an important topic. The risk of casualties depends on various characteristics such as the building occupants, the present fire load, and the building envelope. The last two characteristics determine the indoor conditions during a fire, which can be translated to tenability limits for the occupants. The building envelope is adapting on the demand for sustainability from conventional constructions to envelopes with high insulation and air tight facades. Multiple studies by Cornil et al. [1] and Molkens [2] have indicated that an enclosure fire in a low-energy dwelling or a passive house behaves differently compared to a conventional dwelling due to the new building methods. These studies suggest a kind of smouldering fire for low-energy dwellings, which in turn might cause specific toxicity hazards for the occupants or the right conditions for a backdraft.

Both the study by Cornil et al. [1], and the study by Molkens [2] are based on the assumption that glazing in a conventional dwelling will fallout at an early stage in a fire, while triple glass in a low-energy dwelling will remain intact. However, this assumption is not supported by any scientific

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basis. Until today no comprehensive studies exist, within the current knowledge of the author, which addresses the performance of triple glazing during fire. Therefore, this study is initiated to give more insight on this subject and to check if the assumption involving glass fallout is justified. The primary subject of this study consists of an experimental research to assess the performance of triple and double glazing with the use of a fire furnace. The method will discuss the boundary conditions and measurement setup. The results will compare the performance between triple and double glass in relation to glass fallout. The second part will involve simulations to support the experimental research. Finally the experimental results are discussed and compared to results from simulated enclosure fires in dwellings.

2 METHODOLOGY

In order to comprehend the presented study it is appropriate to provide some theory about glass breakage and the used physics. The thermal breaking mechanism of glass can be categorized in the following categories [3, p. 3]:

- *Intensive heat flux*: if an intense heat flux is suddenly applied on one side of a glass pane, a steep thermal gradient will be created across the thickness of the layer. This phenomena is called ‘’thermal shock’’ and causes thermal stresses which could break the pane;
- *Thermal gradient*: a thermal gradient over the thickness of the pane will cause the planar plane to deform. The boundary conditions (edge conditions, glass type etc.) will cause stresses which are the largest in the corners of the plane. These stresses could become particular high in very small panes, controversially for the larger panes which are more flexible;
- *Non-uniform heating*: thermal stresses and tension will occur when the glass pane is not uniformly heated. This situation occurs when parts of the glass are shaded from radiation, which is the case for the shielded edge of the window by the shading of the frame. As a result the maximum stress will always occur at the rim of the pane. The non-uniform heating between the central glass pane and the shaded area will be addressed in this study as the temperature difference (ΔT).

The non-uniform heating is in practice the most normative parameter during a fire. Additionally pressure variations could also potentially affect the failure of glass planes. However, the influence of pressure will be beyond the scope of the present study.

3 EXPERIMENTS

Results of two fire experiments in which a double and triple glazing assembly were exposed to a fire furnace are presented and discussed. The dimensions of the fire furnace are according to the ISO 834 standard, with respectively 3.0 m in height, 4.05 m in width, and 0.75 m in depth. The goal will be to obtain an indication about the time before the occurrence of glass fallout.

The experimental rig and maintained method during the experiment is discussed in Appendix I. The experimental rig, as discussed in this paragraph, will provide a summary of the boundary conditions and used method. The measurement setup consist of four small windows at the upper section of the frame and four large windows at the lower level, with dimension of respectively 924 by 924 mm (0.854 m^2) and 1897 x 924 mm (1.753m^2). The sample frame with double glazing consists of 6 windows with standard double glass and 2 windows of HE++ (high-efficiency) glass. The sample frame with triple glazing consists entirely of the same type of triple glass (8 windows). The composition of the frame is identical for both glazing assemblies. The seam along the concrete test frame is sealed with Rockwool insulation. 1 gives an overview of the dimensions and numbering of the glazing assembly.

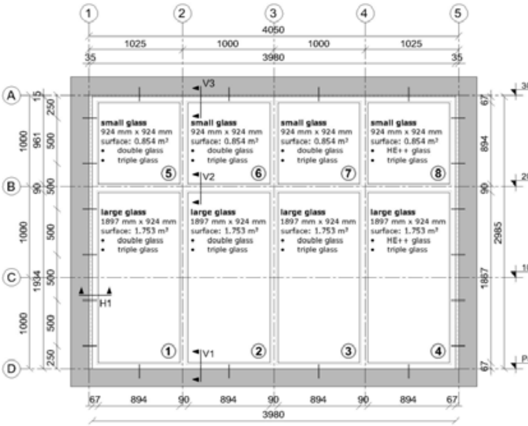


Fig. 1. Experimental assembly

Fig. 2. Experimental setup triple glazing

The standard double glazing consists of a composition with two panes of 4 mm Soda Lime Silica glass and a cavity in-between of 12 mm filled with 90% Argon gas. The composition of the triple glass is approximately similar, and consists of two cavities of 12 mm filled with 90% Argon gas and three panes of 4 mm Soda Lime Silica glass. Both HE++ and triple glazing are equipped with a coating on the inner side of the inner pane, additionally triple glass has a coating on the inside of the outer pane. Standard double glazing is not equipped with a coating. The dimensions of the windows are more or less the same as maintained in the full-scale fire experiments of double glazing by Shields, Silcock, and Flood [4], and Shields et al. [5]. *Table 1* describes the specific composition and insulation properties of the maint-ained glazing systems. The Soda Lime Silica (SLS) float glass consists approximately of 75% SIO_2, 15% NA_2O, and 10% CaO%.

Table 1. Glazing systems

Name	Type	Composition [mm]	U-value [W/(m²·K)]
Double glass	Thermobel standard	4 - 12 Ar 90% - 4	2.7
HE++	Thermobel Top N+	4 – 12 Ar 90% - 4	1.3
Triple glass	Thermobel TG Tri Top N+	4 – 12 Ar 90% - 4 – 12 Ar 90% - 4	0.7

The temperature inside the fire furnace can be raised according to various fire curves. These fire curves are in daily practise used for classifying the fire resistance of construction-elements, and are unrelated to the temperature development in case of an enclosure fire. The standard fire curve according to NEN-EN 1363-1 [6] is based on flashover-conditions, to replicate a fully developed fire scenario. This scenario would be expected after glass fallout in an enclosure. In case of a ventilation controlled fire the temperatures will be much lower. Additionally it is more evident to assess the performance of multi-pane glazing during the initial phase of the fire. The slow heating curve according to NEN-EN 1363-2 [7], seems to be more suitable to resemble the initial phase of an enclosure fire. The influence of thermal shock will be less prominent due to the more gradual temperature rise, which one would also expect during an enclosure fire. The slow heating curve will increase in severity after 21 minutes. This will enable also an assessment of the performance during higher temperatures, which might also be the case for some situations. For these reasons, the slow heating curve gives a suitable temperature development, and provides at the same time a reproducible method. *Fig. 3* gives the graph of the slow heating curve in relation to the standard fire curve. *Fig. 4* shows the experiment at approximately 1400 seconds.

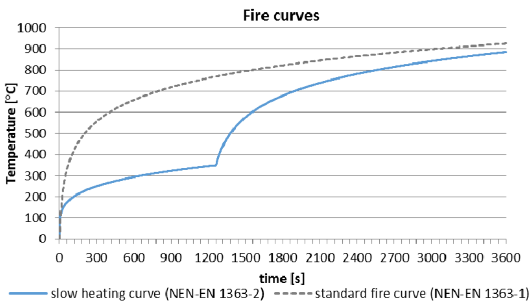


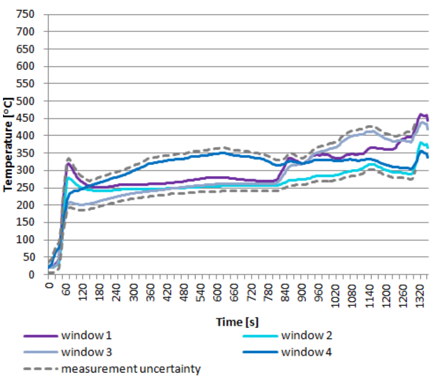
Fig. 3. Slow heating curve in relation to standard fire curve

Fig. 4. Experiment in progress

The surface temperatures were recorded with the use of thermocouples. The studies by Keski-Rahkonen [3], Emmons [8], and Pagni and Joshi [9] have addressed the temperature difference as parameter to assess glass breakage. In addition the experimental studies by Shields et al. [10] assessed the glass temperature, and the temperature differences in relation to glass breakage. This approach is taken as basis for the positioning of the thermocouples on the glazing assembly. The thermocouples were located on the inner and outer pane for all windows at the upper shaded area, and the central glass surface their difference is the calculated temperature difference. Additionally an infrared camera and a video camera were used to record the fallout of glass.

4 EXPERIMENTAL RESULTS

Fig. 5 gives the local gas temperature distribution for the sample with double glass near the large windows inside the fire furnace. After approximately 800 seconds and later, some slight fluctuations can be seen in the temperature as a result of small glass fallout. *Fig. 6* gives the gas temperature for the triple glazing assembly inside the fire furnace at the lower section. After approximately 1400 seconds and later major glass fallout disrupts the increase in temperature in the fire furnace, which in turn causes fluctuations and lower temperatures.



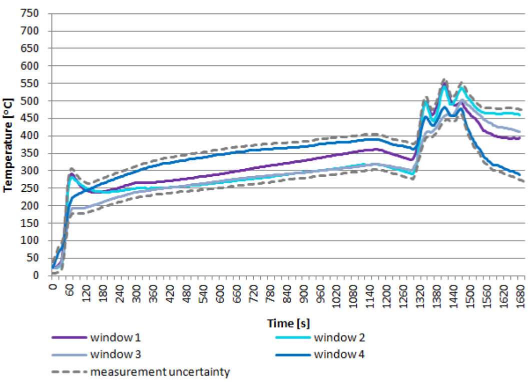


Fig. 5. Lower local gas temperatures in the fire furnace for the sample with double glazing

Fig. 6. Lower local gas temperatures in the fire furnace for the sample with triple glazing

Table 2 gives an overview of the results from the experiment with double glazing for each individual window.

Table 2. Results for the assembly with double glazing (measurement uncertainty of + 3 ^{o}C)

Window number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type	Double	Double	Double	HE++	Double	Double	Double	HE++
Time to first crack [s]	110	81	70	72	55	66	58	70
Time to fallout [s]	-	1320	1322	-	-	-	1005	-
Glass temperature at fallout [^{o}C]	-	188.6	158.6	-	-	-	193.6	-
Max outer pane [^{o}C]	158.9	188.6	158.6	125.2	273.8	187.6	199.0	264.8
ΔT at fallout	-	78.3	52.0	-	-	-	74.1	-
Max ΔT [^{o}C]	25.0	78.3	52.0	11.8	113.5	35.6	98.3	140.6
Min ΔT [^{o}C]	-11.8	0.0	-107.1	-43.8	-35.2	-31.7	0.0	-12.4

Table 3 gives an overview of the results from the experiment with triple glazing for each individual window.

Table 3. Results for the assembly with triple glazing

Window number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Type	Triple	Triple	Triple	Triple	Triple	Triple	Triple	Triple
Time to first crack [s]	n.a.	n.a.	55	n.a.	76	56	51	n.a.
Time to fallout [s]	1410	1708	-	1474	-	1535	1341	-
Glass temperature at fallout [^{o}C]	168.0	202.0	-	168.1	-	82.7	143.2	-
Max outer pane [^{o}C]	168.0	203.2	184.1	168.1	223.1	82.7	145.3	221.1
ΔT at fallout	n.a.	25.9	-	45.7	-	-101.1	34.8	-
Max ΔT [^{o}C]	16.1	78.3	14.4	45.7	29.3	0.3	36.6	44.7
Min ΔT [^{o}C]	-15.8	-6.1	-17.7	-13.8	-29.2	-101.1	-18.3	-44.8

Table 4 gives the average percentages of glass fallout at some specific times for both the double as the triple glazing assembly.

Table 4. Percentage of fallout in relation to time

	Average fallout of double glass		**Average fallout of triple glass**	
Time [mm:ss]	Large windows [%]	Small windows [%]	Large windows [%]	Small windows [%]
0:00	0.0	0.0	0.0	0.0
10:00	0.3	0.0	0.0	0.0
15:00	1.0	0.0	0.0	0.0
20:00	1.0	0.0	1.7	0.0
21:00	4.3	12.7	1.7	0.0
22:26	48.7	13.0	1.7	8.3
25:00	-	-	40.8	8.3
28:50	-	-	41.7	29.7

5 SIMULATION

Several studies have already addressed the performance of simulation programs to predict glass breakage. The simulation program BREAK1 provided by Pagni and Joshi [11] is suitable for a calculation of the time before the initial crack based on the temperature difference. Experimental research by Skelly et al. [12] and Pagni and Joshi [13, 14] validated the established program. The study by Pope et al. [15] and Dembele et al [16], presents a probabilistic approach of the glass breakage through a simulation model. The use of a field model (FDS) to predict glass breakage is presented in the study by Kang [17] and Qing-Song [18]. Dembele et al. [19] proposed a new simulation model based on the finite element method and assessed the influence of different edge conditions. *Fig. 7* gives an overview of the most suitable methods with their specific purpose.

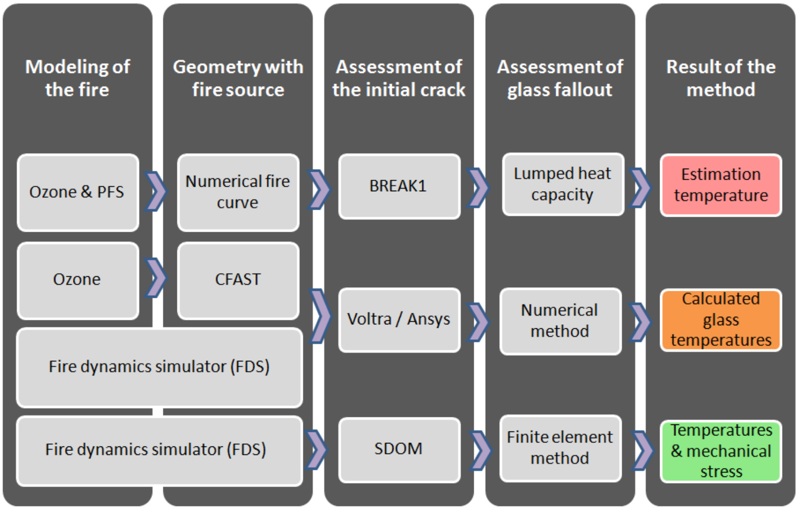


Fig. 7. Model approach

The numerical simulation is initiated to retrieve the conditions during the experiment, in order to assess the representativeness of the experiment versus an enclosure fire. The simulation model is conducted with VOLTRA, version 6.0w. The model consists of a small and large window with the same dimensions as in the experiment.

The simulations are conducted with the use of OZone version 2.2.6. The study by Spijkerboer [20] already established some key parameters which will have a large influence on the fire scenario.

The calibration of the fire experiment with the numerical simulation model indicates that only a rough estimation of the temperatures can be obtained through this method. Due to the many variables such as the influence of the glass, boundary conditions of the composition, material properties, and conditions in the fire furnace it is impossible to obtain a more accurate result in the current simulation model. It seems that the results indicate a lower radiation level in the fire furnace than one would expect during an enclosure fire, however the combined heat is consistently higher than the radiation from the refractory bricks alone. Based on the current simulation model it is impossible to quantify the difference in radiation compared to an enclosure fire. Nevertheless, the found criterion as a function of internal gasvolume seems adequate for a rough estimation of glass fallout, since the combined temperatures on the inside of the glass are relatively small.

6 DISCUSSION AND RESULTS

The experimental results show a detectable difference between the performance of the double and triple glazing glass. The triple glazing assembly remained longer intact than the double glazing assembly, and could withstand the first part of the slow heating curve without major glass fallout. Double glass experienced small percentages of glass fallout after approximately 10 minutes, compared to 19 minutes for small percentages of glass fallout for triple glass. In both cases the

percentage of glass fallout became larger as the fire intensity increased (after 21 minutes). There seems to be a relatively good agreement with the criteria for the initial crack and the experimental data at the initial crack. The dispersion was relatively high between glass fallout and individual glass surface temperatures and temperature differences. At some cases the temperature difference was relatively high while glass fallout did not occur. Contrarily, glass fallout occurred in some cases at relative low temperature differences. Therefore no correlation can be found in the experimental results between the temperature difference and individual glass fallout. The various criteria for glass fallout based on the temperature difference seem too simplistic and conservative to provide a realistic time-based approach. The deviation indicates an apparent randomness in individual glass fallout, which can be explained by a large influence of imperfections in the glass and deviations during assembly. Additionally the smaller windows endured higher temperatures, while the large windows endured lower temperatures due to the difference in the upper and lower gas temperature inside the fire furnace. Therefore, a comparison of the performance makes most sense when it is expressed as a function of internal energy in the gas volume, which takes into account the difference in temperature. This comparison indicates that the smaller windows can endure a higher internal energy in gas volume before glass fallout occurs, when compared to large windows. The large windows of double glazing experienced no major glass fallout before approximately 147 kJ/m^3, while the large triple glass windows experienced no major glass fallout before 153 kJ/m^3. The small windows with double glazing did not experience major glass fallout before approximately 159 kJ/m^3, while the small windows for the triple glazing did not experience major glass fallout before 170 kJ/m^3. The assessment based on the averaged gas temperature in the fire furnace indicates that the double glazing assembly did not experience major glass fallout before a gas temperature of 375 ^oC. The composition with triple glazing did not experience major glass fallout before a gas temperature of 475 ^oC. Overall it can be stated that the difference in performance between the glazing systems, although detectable, might be less than originally expected. This is due to the fact that the double glass remained also relatively long intact before major glass fallout occurred.
The comparison with different fire scenarios in relation to the found critical levels in the experiment indicate that a local and medium fire do not generate enough energy to cause glass fallout for both triple and double glazing. However, it seems plausible that the rapid and intense fire do generate enough energy and/or heat to cause fallout at an early stage during an enclosure fire. The detectable difference in performance of triple glazing compared to double glazing seems to make only a difference for a limited amount of situations. Furthermore the size of the window seems to be more normative than the difference between triple and double glass in relation to the fallout criteria. Finally the glass fallout seems to be more dependent on the fire scenario; as a consequence this will be most decisive whether a smouldering fire or a fully developed fire will occur.
With the use of double glass, the risk on a smouldering fire scenario will be increased compared to a situation with single glass, which is known to fallout very rapidly. The risk on a smouldering fire scenario will become only slightly higher with the use of triple glazing.

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