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Design of Glass for High, Short Duration Wind Loads

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This paper describes a case study for the design of structural glazed IGUs for the New Concert Hall in Reykjavik, Iceland, which is subjected to high local wind loads of approximately 10kN/m^2, with a load duration of approximately 0.1s. The paper focuses on how to interpret the current available codes and research to obtain a glass thickness with adequate resistance for the high short duration loads. The paper also focuses on the wind loads to be applied when calculating the fixing system, the structural silicone, the embedded aluminium profiles and the toggles which fix the glass to the aluminium mullions. For short duration wind loads, then currently available codes and guidelines only provide the equivalent glass stress for a 3s load duration, equivalent to a k_{mod} = 1. The paper explains how wind load from wind tunnel tests should be used when sizing glass, and concludes how the IGUs for the Reykjavik New Concert Hall were sized.

Keywords: Glass, Short duration loads, Wind loads, Bomb blast

1. Introduction

The New Concert Hall in Reykjavik Iceland, is situated in the old harbour and is thus exposed to heavy loads from winds coming from the Atlantic. The reference wind speed used in Iceland is 35.5m/s, and the wind load used in sizing the structures and the facades is based on the Euro code 1991 [1]. The architectural form of the building with its many edges and corners exposed to the open sea is problematic. The exposed corners result in high pressure coefficients, where wind suction appears on the back face of the building‘s corners. Figure 1 and figure 2 show the building from the south elevation and the north elevation.

Figure 1: Rendering of south elevation, Reykjavik New Concert Hall, HLA.

Figure 2. Rendering of north elevation, Reykjavik New Concert Hall, HLA

2. Wind Action on building

The characteristic local wind action is determined by combining the directional dependent characteristic peak velocity pressure with measured wind loads on a model of the structure on a scale of 1:200 in a boundary layer wind tunnel. The local wind loads are used in the design of small structural elements and fixings of the structure, e.g. in the design of the glass structures for the Concert and Conference Centre in Reykjavik. The characteristic external local wind load $w_e(\theta)$ for wind direction θ is given by:

$$w_e(\theta) = c_{pe}(\theta)\, q_p(\theta) \tag{1}$$

Where $c_{pe}(\theta)$ is the pressure coefficient determined in the wind tunnel tests carried out, and $q_p(\theta)$ is the characteristic peak velocity pressure for wind direction θ. This normalisation of pressures measured in the wind tunnel is also used in the Euro code 1991 [1]. The pressure coefficients obtained by the wind tunnel tests carried out may therefore be compared directly with the specifications given in Euro code 1991 [1]. The basic wind velocity used to determine the characteristic peak velocity pressures is assumed to be 35.5 m/s as specified in the Icelandic National Application Document (NAD). The characteristic peak velocity pressures for the water exposure and city exposure of the site become 2.65kN/m^2 and 2.27kN/m^2, respectively, at a reference height of 43m.

3. Wind tunnel test

The geometric scale chosen for the tests is 1:200, see figure 3. This choice of geometric scale is based on the following considerations: accurate geometric representation, easy model construction, limiting wind tunnel blockage, and the providing of sufficient space in the wind tunnel for the surrounding buildings. Surrounding buildings, which may be expected to have significant influence on the wind action, are included on the model. The majority of tests have been carried out with the planned surrounding buildings included in the wind tunnel. For selected wind directions, additional tests have been carried out without the planned buildings. The model has been equipped with a large number of pressure taps. Each pressure tap has an area of less than 1m^2 indicating that the measurements in one pressure tap will provide safe estimates of the wind action in areas of 1m^2. Typically, the pressure taps on the model are located in clusters of 3 to 5 taps relatively close together, see figure 4. The pressures in each pressure tap cluster have been measured simultaneously indicating that spatial averaging could be used to estimate the wind action in different areas of up to approximately 10m^2.

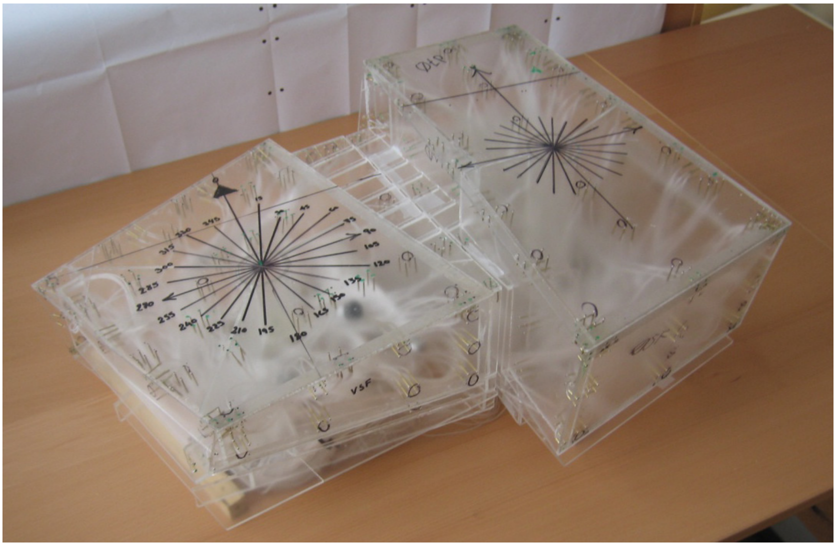

Figure 3. Photo of the 1:200 scale model of the Concert Hall.

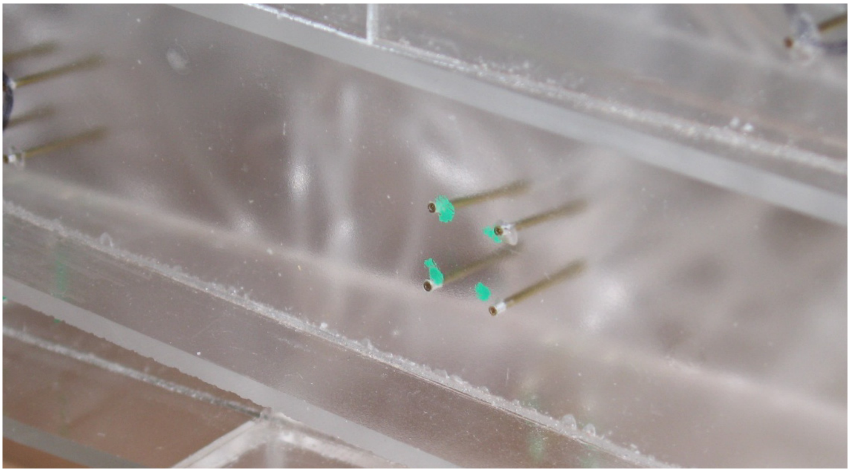

Figure 4. Photo of one of the pressure tap clusters located on the model.

4. Pressure coefficients measured

The most extreme wind suction peaks measured correspond to a pressure coefficient of approximately -4. In combination with the design peak velocity pressure of approximately 2.5 kN/m² this gives a design local wind action of approximately 10 kN/m² to be used in the design of the glass structures. Area 23 is the most critical area on the building in relation to maximum wind load; it is shown in figure 5.

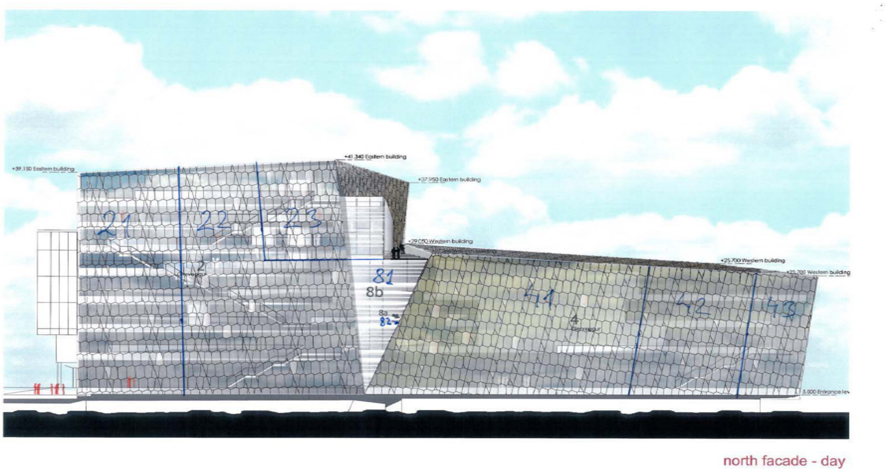

Figure 5, Area 23 in the north elevation of the Concert Hall.

The critical characteristic wind load on area 23 is -6.64kN/m2 for a $1m^2$ area load with a duration of 0.1s. This gives a design value of the wind load which is approx -10kN/m2. The largest suction peaks have very short durations of the order of 0.1s. For these durations the resistance of the local structure may be larger than assumed in the design calculation, and this may give an additional safety of the local structures. Figure 6 shows an example of characteristic pressure coefficients as function of load durations for loaded areas of $1m^2$, $2\text{-}3m^2$ and $10m^2$, respectively. The effect of load duration is significant for all loaded areas considered. Especially for short durations, the averaging effect is pronounced. It may be observed that the pressure coefficient is approximately 30-40% smaller for the $10m^2$ loads with duration of approximately 1s compared to its value for $1m^2$ loads with duration of approximately 0.1s.

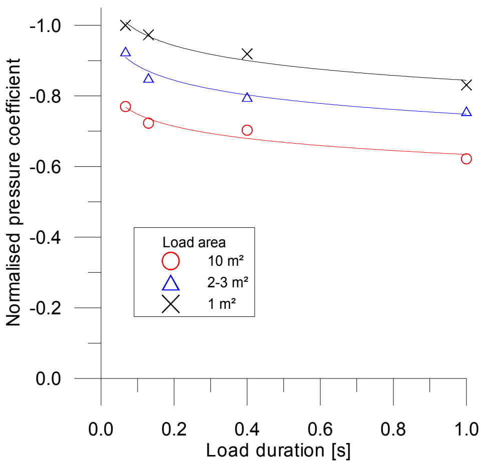

Figure 6. Example of normalised pressure coefficients as function of load duration and load area. The data shown is measured on the eastern facade of the Concert Hall.

More accurate design calculations could be carried out if the wind load data could be combined with structural resistances of glass as function of load durations. However, the resistance data available for the glass structures are not sufficiently accurate to support a detailed design of this nature. In the sections below are shown ways of estimating the structural resistance of glass for short load durations.

5. Glass codes regarding short duration loads

The glass codes which are considered in the paper in relation to short duration wind loads are the prEn13474 [2] and the TRAV [3]. From prEN13474 [2], equation 5 the k_{mod} factor can be calculated for different load durations. The factor for the load duration of annealed glass is:

$$k_{\text{mod}} = 0{,}663 t^{-\frac{1}{16}} \tag{2}$$

Where t is the load duration in hours. In the prEN13474 the factor k_{mod} has a maximum value of $k_{\text{mod}} = 1$ and a minimum value of $k_{\text{mod}} = 0{,}25$. For $k_{mod} = 1$ then the time duration is 3 seconds which means that the strength of glass for shorter duration is not given in the prEN13474 [2]. However if t = 0.1s is used in equation (1), then $k_{mod} = 1.28$. If $k_{mod} = 1.28$ then the corresponding stress values can be calculated, the corresponding allowable stresses according to the prEn13474 [2] are shown in Table 1:

Table 1:

Glass type	unfactored stress (prEN13474 [2])
Annealed float glass	57.6MPa
Heat strengthen float glass	82.6MPa
Toughened float glass	132.6MPa

In the TRAV [3], section 6.4.4 is given stress values for short duration dynamic loading. The stresses have been derived by testing glass according to the pendulum test described in the EN12600 [4]. The stresses are shown in table 2.

Table 2:

Glass type	Stress (TRAV [2])
Annealed float glass	80MPa
Heat strengthen float glass	120MPa
Toughened float glass	170MPa

If the stress values in table1 and table 2 are compared to each other, then the impact strength of the glass from the pendulum test is higher than the calculated stress derived from the prEN13474 [2] with $k_{mod} = 1.28$. From this it can be concluded that values in table 2 which is derived from Equation (2) do not fully reflect the strength of glass at short load durations.

6. Experience from bomb blast

Experience from bomb blast tests has also given knowledge of glass strength under high short duration loads. The following information is derived from tests undertaken by the UK Home Office in the 1990s as a consequence of the IRA bombings in the UK. Figure 7 shows the curves from bomb blast test of a window similar to the ones used at the Reykjavik Concert Hall.

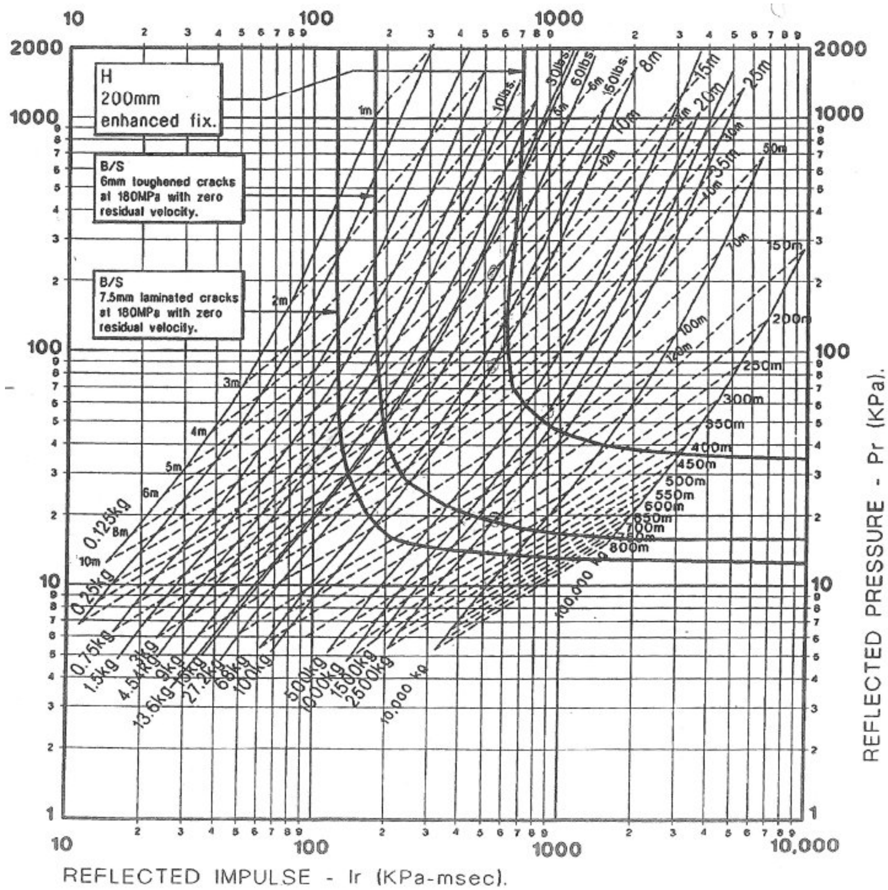

Figure 7. Pressure and Impulse grid from bomb blast test, with data for an IGU similar to the one used at the Concert Hall.

The glass breakage stress is also described in *"Blast effect on building",* table 9.1 [5].The stress value where the glass starts to crack is shown in Table 3:

Table 3:

Glass type	Breakage stress (Bomb blast test)
Annealed float glass	80MPa
Heat strengthen float glass	100-120 MPa
Toughened float glass	180-250 MPa

The bomb blast test delivers a high load on the glass within 20ms. The test commonly performed is based on a 100kg TNT bomb, placed at various distances. Figure 8 shows a pressure time graph for a 100 kg TNT bomb placed at 25m from the facade. The test is shown in "*Computation of Blast Resistant Window and Facade Constructions*" page 5 [6].

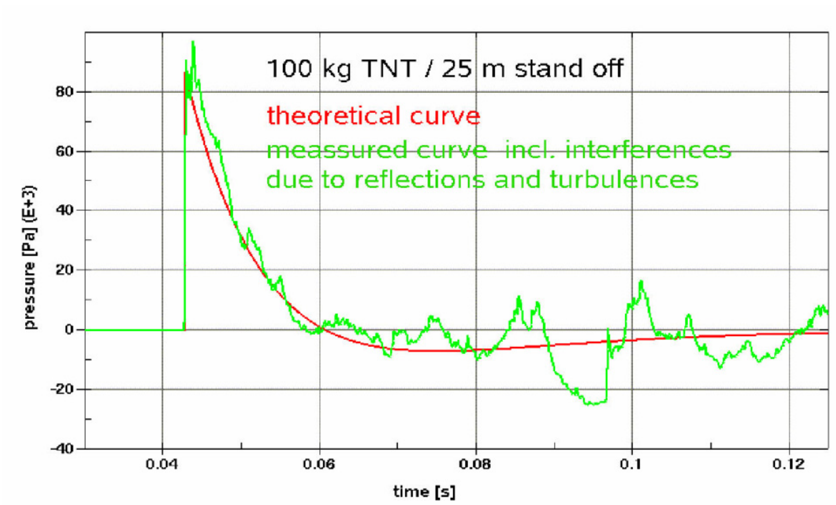

Figure 8. Measured and computed pressure-time-curve (measurement source: Bollrath Pro FORCE) [6].

The figure gives an indication of the magnitude of the loads and the load durations. If the stresses in table 2 and table 3 are compared, it is seen that there are similarities between the stress values. This indicates a reasonable consistency for the breaking strength of glass under short duration loads determined by different test methods.

7. Sizing glass on the Reykjavik Concert Hall

For the sizing of the glass for the Concert Hall, the high wind loads are very critical. Because they are the govern factor for sizing the glass thickness in a relative big area of the facades. However because of the missing guidelines it was difficult to know how to deal with this issue. The issue was initially approached by disregarding the high loads based on 1m^2 values and to use the 10m^2 values instead, but with 1s load duration. This reduced the loads by approximately 40%, as described in section 4. However this could not be justified for the glass at the edge, in a two metres zone. All these glass panels have a unique shape because of the architectural intent, most of them with a size smaller than 1m^2. The same applied for the fixing of the glass. The glass is structural glazing, fixed with a toggle system. Therefore the structural silicone in the IGU and the Uchannel profile and the toggle were sized by using the $10kN/m^2$ wind load based on the $1m^2$ value. For the sizing of the glass itself it was accepted that the glass could break under high wind loads. However, the hazard was estimated to be very low, because a glass breakage and the risk of falling glass would not cause danger to anyone. In other places of the building, where there is a danger of falling glass in case of glass breakage, the glass is laminated on the outside of the IGU to prevent it from falling down. However, with the information from this article it would be possible to use the stresses in Table 2 and Table 3, and estimate the glass for risk of potential breakage under high short duration wind loads. The stresses calculated for the edge glass panes on the concert Hall are by far smaller than the breakage value described in section 5 and section 6.

8. Conclusion

Based on the issues which came up in sizing the IGUs for the New Concert Hall in Reykjavik, then it has been investigated what the breaking stress for glass is for high short duration loads. It has been shown which assumption was made to accommodate the high short duration wind loads as a result of the wind tunnel test. From this paper it can be concluded that the values mentioned in table 2 and table 3 for annealed glass, heat strengthen glass and toughened glass can be used for high short duration wind loads, and that there are considerable redundancy in glass panes placed in critical facade areas of the Concert Hall. The question remains which safety factor should be added to the breakage stress mentioned in table 2 and table 3, for use in a design purpose. The stress values would be applicable for load durations between 1ms to approximately 0.1s. However, some research still remains in determining which load duration can be considered a conservative assumption in relation to the corresponding glass stress. Tests are being performed at the moment to determine this relation, but unfortunately the tests were not finished when this paper was submitted.

9. Acknowledgement

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10. References

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