Testing of self-supporting laminated glass balustrades

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Abstract

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The work carried out within Task 2 Experimental work of the ÅForsk funded project “Structural safety of glass components” is presented in this report. The main goal of this project was to improve the understanding about the structural safety of self-supporting glass components. In particular, the results of the project intended to extend the current knowledge about the effect of impact and related testing methods regarding the safety of glass structures.

Static and impact tests were conducted on a self-supporting glass balustrade with point-fixings. The laminated glass consisted of two 10 mm thick layers of laminated glass and a 0.76 mm thick interlayer made of EVA (ethylene vinyl acetate). A static line load was cyclically applied to the top of the specimen to gain an understanding of the static behaviour of the glass structure and to minimize the settlement in the structure prior to applying impact loading. The specimen was subsequently subjected to dynamic loading by impact tests based on EN 12600 (pendulum impact) with different drop heights until attaining failure. The dynamic structural response of the glass balustrade was analysed by three-dimensional Digital Image Correlation (3D-DIC). This measurement technique made it possible to directly relate the measurement of any point to the specimen and to study the deformed 3D shape in detail during the impact test. The FE-analysis (FEA) conducted using SJ Mepla was found to correlate rather well with the dynamic test results particularly up to the initial peak displacement.

Key words: safety, impact testing, glass balustrade, laminated glass, digital image correlation, finite-element analysis

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Preface

The work presented in this report is related to the ÅForsk financed project (ÅForsk ref. nr. 18-510) entitled “Structural safety of glass components”. This project took place between July 2018-December 2019 and was coordinated by Lund University (LTH) with contributions from RISE Research Institutes of Sweden and Fasadglas Bäcklin AB.

The results presented herein are related to Task 2 Experimental work of this project, and comprise static and impact testing on a glass balustrade coupled with optical measurement techniques and numerical analyses.

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Borås in November 2019

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1 Introduction

1.1 Project background

The work presented in this report is related to the ÅForsk financed project entitled “Structural safety of glass components”. This project took place between July 2018-December 2019 and was coordinated by Lund University with contributions from RISE Research Institutes of Sweden and Fasadglas Bäcklin AB.

Although glass has been used in buildings for a very long time, a significant development in structural glass design has been made in the past decades, see e.g. [1]. The evolution from a secondary infill material to a load-bearing primary structural material facilitated the use of large amounts of glass in e.g. atriums, skylights, partition walls, balustrades, facades and enclosures providing natural light and transparency popularized in modern architecture. Despite these developments, there is a lack of generally accepted and comprehensive standardized approaches for the structural design of glass components in Europe, which hinders the structural use of glass compared to traditional construction material.

The main goal of this project is to improve the understanding about the structural safety of self-supporting glass components. The project aims to contribute to the development of future guidelines for architectural glazing applications. In particular, the results of the project intend to extend the current knowledge about the effect of impact and related testing methods regarding the safety of glass structures.

1.2 Impact loading on glass barriers

Standard design approaches for glass barriers typically involve basic load requirements, such as wind load and static barrier load. Impact loads are only considered in a limited number of cases, which is due to the lack of clear requirements in standards. The behavior of glass panes under impact loading should however play an important role in the design of glass structures and it is especially critical when it comes to the safety of users [2]. In current practice, the performance of glazing under impact testing is simply classified according to drop height class and mode of breakage, see e.g. EN 12600 [3] and ISO 29584 [4]. These tests help classify glazing components yet do not lead to a deeper understanding of their dynamic structural response.

The brittleness of glass and its linear-elastic stress-strain-relation without plastic deformability can lead to an instantaneous and disastrous failure under both hard and soft body impact. It is important to note that the dynamic fracture toughness of glass is usually lower than most other building materials, therefore, if one wants to use glass as a replacement for commonly used structural materials, one must make a precise (exact) analysis to ensure that its design ensures the safety of users [5].
1.3 Method

Static and impact tests were conducted on a self-supporting glass balustrade with point-fixings. A static line load was cyclically applied to the top of the specimen up to 0.5 N/mm to gain an understanding of the static behaviour of the glass structure and to minimize the settlement in the structure prior to applying impact loading. Thereafter, the glass specimen underwent impact load testing based on EN 12600 [3]. The dynamic structural response of the glass balustrade was analysed by three-dimensional Digital Image Correlation (3D-DIC). FE-analysis was also conducted using SJ Mepla [6] for comparison purposes with the static and 3D-DIC results.

1.4 Limitations

The main limitations of the work presented in this report are summarized in the following:

- Testing was conducted on one laminated glass balustrade specimen. It is to say that the uncertainty of the test results and the effect of various parameters (i.e. geometry, thickness of glass, interfacing layers, adapter design and placement) were not quantified. The tests conducted were primarily utilized to develop and verify the optical measurement technique applied in this work.
- Another limitation is related to the impact test setup. The pendulum target location was selected to be rather high (200 mm from top edge of glass), thus these tests present a more extreme loading scenario compared to the standard mid-height.
2 Experimental programme

2.1 Specimen configuration

One self-supporting, point-fixed balustrade specimen without handrails was tested in this work. The glass consisted of two 10 mm thick layers of laminated glass and a 0.76 mm thick interlayer made of EVA (ethylene vinyl acetate). The geometry of the specimen, shown in Figure 1, was designed to accommodate two rows of adapters at the base and to fulfill a minimum balustrade height of 1.1 m mandated by BFS 2011:6 Boverkets byggregler (Boverket’s building regulations) [7]. Standard glass adapters (see Figure 2) were installed to fasten the base of the balustrade to the given supporting structure. The indicated measurement points, top (500,1393), impact (500, 1193) and bottom (500, 0), will be referred to throughout the report. Moreover, the horizontal displacement of the glass system will be evaluated herein which corresponds to the out-of-plane displacement in the z-direction.

![Figure 1 Specimen geometry and measurement points, dimension given in mm.](image)
2.2 Static testing

The static test setup applied in this work is shown in Figure 3. A steel supporting structure was securely fixed to a concrete floor. The laminated glass specimen was fastened to a steel beam affixed to the supporting structure by means of glass adapters. The specimen was loaded by a line load applied to the top of glass by means of a square hollow steel beam and load cell (rated capacity of 5 kN). The deformations were measured using LVDTs at the bottom (500, 0) and top (500, 1393) coordinates of the specimen during loading (refer to Figure 1).
2.3 Impact testing

Impact testing was conducted using two pneumatic tyres (weight of 50 kg) as an impactor according to EN 12600 [3]. The tests were carried out with various drop heights causing elastic deformations and finally leading to glass breakage. The pendulum target location was selected as 200 mm from top edge of glass, which is denoted as the impact point (500, 1193). The drop height could be adjusted according to desired height. High speed cameras captured the deflection and displacement fields pertaining to the glass during testing, which is further described in Section 2.4.

![Figure 4 Overview of the impact test setup.](image)

2.4 Measurement technique

The dynamic structural response of the glass balustrade was analysed by three-dimensional Digital Image Correlation (3D-DIC), using a stereoscopic camera setup with two high-speed cameras as illustrated in Figure 5.
The basic idea behind DIC is to measure the deformation of a specimen under testing by analyzing a naturally occurring or applied surface speckle pattern, in a series of digital images acquired during loading. This is done by tracking the position of discrete pixel subsets of the speckle pattern within the images. The unique grey value speckle pattern of each subset is used to perform correlation calculations, such that each subset can be tracked with sub-pixel accuracy from one image to the next for all stages. The deformations of the specimens are then calculated by correlating the positions and displacements of subsets in the undeformed reference image and the deformed images to produce a deformation vector field.

A photo of the measurement system setup can be seen in Figure 6. One Photron FASTCAM SA4 (CamL) and one Photron FASTCAM SAZ (CamR) were used. Both cameras were provided with Nikon lenses with a fixed focal length of 50 mm. They were mounted on rigid tripods, at a distance of 4.0 m from the surface of the specimen and a relative distance of 2.2 m, corresponding to a relative camera angle (α) of approximately 30°. The system configuration was calibrated for a measuring volume of approximately 1.6x1.6x1.6 m³.
Figure 6 Photo of the measurement system setup.

In the two initial tests, speckle patterns were only applied at specific positions by self-adhesive labels. In the following tests, a global speckle pattern was used to be able to monitor the deformation of the entire balustrade. A global speckle pattern was achieved by first applying white retro-reflective paint as a background, followed by black stains using a rough brush. To obtain high contrast levels, the specimen was illuminated by a high-power white LED light panel.

Figure 7 Photo of local speckle pattern (left) and global speckle pattern (right) on the glass balustrade.
An image resolution of 1024x1024 pixels and an acquisition rate of 3 000 frames per second (fps) were used, corresponding to a time resolution of approximately 0.33 ms. The imaging of the cameras was synchronized in time by connecting the SA4 (master camera) to the SAZ (slave camera) by a synchronization cable. The start of the high-speed imaging was triggered manually at the weight impact with a centre mode recording, meaning that approximately an equal number of images were recorded before and after the impact.

The images from the high-speed cameras were analysed by the DIC technique using the software GOM Correlate Professional [9]. The dimensions of each subset were 15x15 pixels and the subset step was 10 pixels, which corresponds to a subset size and data point spacing of approximately 23 mm and 16 mm, respectively. The displacement resolution was determined to approximately 0.01 mm for both x- and y-displacement (in-plane) components and approximately 0.02 mm for z-displacement (out of plane), determined as the standard deviation between a sequence of static images of the specimen before loading.
3 Experimental tests and results

3.1 Static testing

The glass balustrade was subjected to cyclic static loading up to a maximum load of 0.5 N/mm, which is equivalent to 0.5 kN when applied as a line load across the width of the specimen. The load was incrementally applied from 0 to 0.1-0.5 N/mm in five consecutive load cycles, see Figure 8. The maximum load and maximum displacements at both top (500, 1393) and bottom (500, 0) points are reported in Table 1.

<table>
<thead>
<tr>
<th>Load cycle</th>
<th>Maximum load [N/mm]</th>
<th>Max. displacement [mm]</th>
<th>Slope change loading/unloading [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Top (500, 1393)</td>
<td>Bottom (500, 0)</td>
</tr>
<tr>
<td>1</td>
<td>0.1</td>
<td>4.63</td>
<td>-0.24</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>9.78</td>
<td>-0.54</td>
</tr>
<tr>
<td>3</td>
<td>0.3</td>
<td>15.41</td>
<td>-0.90</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>21.36</td>
<td>-1.30</td>
</tr>
<tr>
<td>5</td>
<td>0.5</td>
<td>27.74</td>
<td>-1.74</td>
</tr>
</tbody>
</table>

A change in stiffness or so-called “settlement” in the system can be identified by analysing the change in slope between loading and unloading curves. The change in slope between the loading and unloading curves was calculated between 30-60% of the maximum load for each cycle. It was observed that at the top point (500, 1393), that the slope change was most significant during Cycle 2, as for the bottom point (500,0), it took place during Cycle 1. It is presumed that the glass adapter shims significantly contributed to the change in stiffness of the system, as the expansion of these could be observed during loading.
3.2 Impact testing

The glass balustrade was subjected to dynamic loading by impact tests with different drop heights. In total, five impact tests were performed sequentially on the specimen according to Table 2. The maximum displacement (in z-dir.) values reported in the table were extracted from the DIC measurements for the top (500, 1393), impact (500, 1193) and bottom (500, 0) points (refer to Figure 1).

Table 2 Summary of impact test results.

<table>
<thead>
<tr>
<th>Test</th>
<th>Drop height [mm]</th>
<th>Speckle pattern</th>
<th>Max. displacement, z-dir. [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Top (500, 1393)</td>
</tr>
<tr>
<td>1</td>
<td>65</td>
<td>Local</td>
<td>34.0</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>Local</td>
<td>47.5</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>Global</td>
<td>47.7</td>
</tr>
<tr>
<td>4</td>
<td>190</td>
<td>Global</td>
<td>62.2</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>Global</td>
<td>-</td>
</tr>
</tbody>
</table>
In the first two tests at 65 and 110 mm drop height, local speckle patterns were used to measure the displacement at pre-defined points. In the three subsequent tests at 110, 190 and 300 mm drop height, a global speckle pattern was used, which enables the visualization of the displacement field over the entire glass surface during testing. A comparison of the horizontal (z-dir.) displacement at the impact point for the different drop heights are shown in Figure 9. The results of the individual tests can be seen in Figure 10 to Figure 14.

As can be observed, the general behaviour is very similar between the tests. As expected, the amplitude of the displacements increases with increased drop height. After the initial peak displacement, there is a so-called plateau in the displacement-time curve, associated with a second smaller impact between the weight and the balustrade. This could also be observed in the images from the DIC measurements pertaining to Tests 1 and 2, where only the local speckle pattern was used. After impact, the balustrade oscillates back and forth in a bending mode around its original position, and the amplitude of the displacements successively decreases to zero with time. However, due to the limited recording time of the high speed-cameras, the entire oscillation phase could not be captured in these tests. At 300 mm drop height (Test 5), the glass balustrade continued to deform in global bending after impact and finally fractured just above the upper fixing points.

Figure 9 Horzontal displacement (z-dir.) at impact point (500, 1193) versus time for different drop heights.
Figure 10 Horizontal displacement (z-dir.) at top (500, 1393), impact (500, 1193) and bottom (500, 0) points versus time for Test 1 with 65 mm drop height.

Figure 11 Horizontal displacement (z-dir.) at top (500, 1393), impact (500, 1193) and bottom (500, 0) points versus time for Test 2 with 110 mm drop height.
Figure 12: Horizontal displacement (z-dir.) at top (500, 1393), impact (500, 1193) and bottom (500, 0) points versus time for Test 3 with 110 mm drop height.

Figure 13: Horizontal displacement (z-dir.) at top (500, 1393), impact (500, 1193) and bottom (500, 0) points versus time for Test 4 with 190 mm drop height.
Figure 14 Horizontal displacement (z-dir.) at top (500, 1393), impact (500, 1193) and bottom (500, 0) points versus time for Test 5 with 300 mm drop height.

The use of a global speckle pattern enables the visualization of the displacement field as a contour plot over the entire glass surface during testing (Tests 3 to 5). This can be represented as a contour plot mapped to the 2D image or as full 3D displacement field as illustrated for Test 4 in Figure 15. This makes it possible to directly relate the measurement of any point to the specimen and to study the deformed 3D shape in detail during the impact test. A sequence of the deformed shape during the failure process of the glass balustrade in Test 5 is shown Figure 16.
Figure 15 Displacement (z-dir.) field contour plot mapped to the 2D image (left) and 3D displacement field representation for Test 4 at maximum displacement.
Figure 16 3D displacement (z-dir.) field for Test 5 at the top point displacement of 100 mm (upper left), 400 mm (upper right) and 800 mm (lower).
4  FE-analysis

FE-analysis was performed in SJ Mepla [6], which is an FE program specifically developed for both static and dynamic calculations of structural glass. A model was developed based on the static and impact testing of the glass balustrade specimen. The numerical results are compared to the experimental results herein.

4.1 Static testing

Static testing was modelled on the glass balustrade in SJ Mepla [6]. A given line load expressed in N/mm was applied at the top of the glass between (0, 1393) and (1000, 1393).

4.1.1 Model input

The mechanical properties defined for the three layers in the laminated glass are listed in Table 3. The values were taken from the SJ Mepla material database [6].

Table 3  Mechanical properties assumed for the glass structure.

<table>
<thead>
<tr>
<th>Layer</th>
<th>E-modulus [N/mm²]</th>
<th>Poisson’s ratio [-]</th>
<th>Thickness [mm]</th>
<th>Density [kg/m³]</th>
<th>Coefficient of thermal conductivity [1/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Glass, fully toughened</td>
<td>70 000</td>
<td>0.23</td>
<td>10.00</td>
<td>2550</td>
<td>1.0x10⁻⁵</td>
</tr>
<tr>
<td>2. EVASAFE &lt; 30°C, duration &lt; 1h</td>
<td>7.25</td>
<td>0.45</td>
<td>0.76</td>
<td>950</td>
<td>3.0x10⁻³</td>
</tr>
<tr>
<td>3. Glass, fully toughened</td>
<td>70 000</td>
<td>0.23</td>
<td>10.00</td>
<td>2550</td>
<td>1.0x10⁻⁵</td>
</tr>
</tbody>
</table>

Glass fixing adapters were represented using a disk fixing configuration in the model, see Figure 17. The geometry of the disk fixing was defined as having a bush radius, \( r_b \), of 5.25 mm and disk radius, \( r_d \), of 25 mm. The E-modulus of silicon rubber making up both the shim, \( E_s \), and bush, \( E_b \), of the adapter was set to 1.0 N/mm² in the static model [10]. The thickness of the shim and bush were not quantified in this work. Accordingly, the effect of the change in shim thickness, \( t_s \), between 1.5 to 2.0 mm on the displacement is shown in the results section. The thickness of the bush, \( t_b \), was found to have a minimal impact on the results.

Figure 17  Schematic of the disk fixing configuration [6].
The spring rigidities describe the rigidity of the sub-construction at the place of the fixings base point. The spring rigidities and rotational degrees of freedom at the base point of the point fixings were set to $1 \times 10^6$ N/mm or N/rad for $C_x$, $C_y$, $C_z$, $C_\phi$ and $C_\theta$. The rigidity was selected to simulate a stiff sub-construction without rotation. The validity of these values were not analysed in this work.

### 4.1.2 Result comparison

The displacement corresponding to the maximum static load for the bottom (500, 0) and top (500, 1393) points were extracted for comparison with the FEA results. The effect of changing the shim thickness, $t_s$, from 1.5 to 2.0 mm was evaluated. From Figure 18, it can be calculated that the numerical displacements at the bottom point have an absolute average error ranging between 4.3-8.5% from the experimental values (normalized to the scale of the top values). The FEA results for the top point, shown in Figure 19, have an absolute average error ranging between 0.6-9.9% from the experimental values. For the modelling of the impact testing in Section 4.2, a shim thickness of 1.7 mm was applied, as it yielded results having a reasonable agreement with the experimental results (average error of 0.6% and 6.0% with top and bottom values, respectively).

![Figure 18](image-url) Applied static load versus measured displacement at the bottom point (500, 0) - comparison between FEA and experimental results.
4.2 Impact testing

Impact testing was modelled on the glass balustrade in SJ Mepla [6]. A pendulum impact load according to EN 12600 [3], i.e. twin tyre impactor, was applied to the glass at the prescribed impact point (500, 1193).

4.2.1 Model input

Defining the laminated glass as a monolithic structure, with a thickness of 20.76 mm, led to an improved correlation with the test results. An effective E-modulus of 100 000 N/mm² was used for the monolithic structure, which amounts to an approximate increase of the “glass, fully toughened” E-modulus by 40%. The other mechanical properties were defined according to the glass layers as stated in Table 3.

Based on the results in Section 4.1.2, a shim thickness of 1.7 mm was defined. The E-modulus of both the shim and bush pertaining to the adapters was increased to compensate for a stiffening effect of the silicon rubber occurring during impact loading. It is to say that an E-modulus of 2.2 N/mm² was found to be suitable.

A pendulum impact load according to EN 12600 [3], i.e. twin tyre impactor, was applied to the glass at the prescribed impact point (500, 1193).
4.2.2 Result comparison

FEA results are compared to the impact test results in Figure 20 with respect to the horizontal displacement at the impact point (500, 1193) versus time from impact.

![Figure 20](image)

Figure 20 Horizontal displacement at the impact point (500, 1193) versus time from impact for different drop heights – comparison between FEA and experimental results.

From Figure 20, the general behaviour is similar to the tests, such that the amplitude of the horizontal displacement increases with an increase in drop height. It can be further observed that the initial peak displacement occurs approximately at the same time from impact and within the same magnitude for both the test and FEA results, see Table 4.

<table>
<thead>
<tr>
<th>Test</th>
<th>Drop height [mm]</th>
<th>Max. displacement [mm]</th>
<th>Time from impact [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Impact (500, 1193)</td>
<td>FEA Impact (500, 1193)</td>
<td>Test</td>
</tr>
<tr>
<td>1</td>
<td>65</td>
<td>27.8</td>
<td>28.4</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>39.2</td>
<td>37.0</td>
</tr>
<tr>
<td>4</td>
<td>190</td>
<td>51.1</td>
<td>48.6</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>-</td>
<td>61.1</td>
</tr>
</tbody>
</table>

The drop in displacement after the peak is however noted to be greater for the FEA results in all cases; the difference in displacement drop appears to increase as the drop height increases. The FEA results also capture this so-called “plateau” effect that was previously discussed in Section 3.2, yet the slope differs. Following the impact, the
balustrade oscillates similarly to that observed in the tests. In the model, the oscillations, in terms of amplitude and period, do however remain constant over time which is due to the fact that the defined mechanical properties for the glass and associated components remain constant throughout loading. The period of the oscillations correlate relatively well with the test results up until 0.18 s. To be able to capture a realistic oscillation with a dampening effect, non-linear material behaviour would need to be implemented in the model. Lastly, the failure of the glass balustrade was not captured in the model at a drop height of 300 mm.
5 Concluding remarks

This report summarizes the work carried out within Task 2 Experimental work of the “Structural safety of glass components” project. These results enable a deeper understanding of both the static and dynamic response of a self-supporting glass component.

A static line load was cyclically applied to the top of the specimen up to 0.5 N/mm to gain an understanding of the static behaviour of the glass structure and to minimize the settlement in the structure prior to applying impact loading.

The glass balustrade was thereafter subjected to dynamic loading by impact tests based on EN 12600 (pendulum impact – twin tyre impactor) with different drop heights until attaining failure. The dynamic structural response of the glass balustrade was analysed by three-dimensional Digital Image Correlation (3D-DIC). This measurement technique made it possible to directly relate the measurement of any point to the specimen and to study the deformed 3D shape in detail during the impact test.

FE-analysis was also conducted using SJ Mepla for comparison purposes with the static and impact results. The model related to the static tests aided in selecting the most suitable input data, such as mechanical properties for the glass and adapter configuration. For the impact tests, the general behaviour was captured in the model, such that the amplitude of the horizontal displacement increased with an increase in drop height. The magnitude of the initial peak displacement was slightly lower for the FEA results yet these peak values occurred at a time from impact similar to that of the tests. The inclusion of non-linear material properties in the model would improve the post-peak behaviour, so-to-say be able to capture a realistic oscillation with a dampening effect.
References


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