Exploratory Finite Element Analysis of Monolithic Toughened Glass Panes Subjected to Hard-Body Impact

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Abstract. The paper reports the results of an extensive experimental campaign, in which simply supported toughened glass samples with dimensions of $500 \times 360 \text{ mm}^2$ and three thicknesses (6, 8 and 10 mm) were subjected to hard-body impact. A steel ball (4.11 kg) was released from different drop heights, starting from 10 cm above the sample and increasing by 1 cm in each step until glass breakage occurred. In this way, for all samples a critical drop height (causing fracture of glass) was determined. Experiments were carried out for 35 samples for each thickness; thus 105 samples were tested in total. A 3D numerical model of the experimental setup was developed using the commercial finite element analysis (FEA) software ABAQUS and Implicit Dynamic solver. The numerical study was aimed at numerical reproduction of the experiments and determination of the maximum principal stress in the glass that occurs during the impact. To reduce the number of FEs and increase the computational efficiency of the simulations, only a quarter of the nominal geometry with appropriate boundary conditions were modelled. The simulations were performed for a given weight of the steel impactor, glass thickness and the corresponding critical/breaking drop height found in the experimental campaign. In this way, an impact strength of the toughened glass was retrospectively evaluated. The simulations were used to investigate the impact history in terms of stress in glass, acceleration and velocity. Moreover, the resulting history of impact force was determined.

1. Introduction
During the last decades, glass has become an increasingly common building material in modern architecture. It has been used not only for building enclosures, but also for load-bearing elements, such as columns, beams, walls and all-glass entrances to buildings. The mechanical resistance of these members is an important feature with direct impact on safety due to its intrinsic vulnerability, brittleness and relatively low strength compared to other structural materials [1], [2].

A safe design approach, which is typically applied to load-bearing elements made of glass, requires technical solutions without the risk of catastrophic collapse [3]. To achieve that, in addition to permanent and typical (static) imposed loads, it is necessary to consider also the effects caused by accidental events, such as impact [4]. In these considerations, a special care must be paid to the glass strength, since the glass resistance under severe dynamic loads may be 1.5-3 times higher than its value under the static
loads [5]. The knowledge of the impact strength of glass is essential, in particular, for the design process since the use of incorrect strength value may lead to uneconomic designs.

The paper contributes to the area of glass strength under extremely short dynamic events. The paper’s main objective is to retrospectively evaluate the tensile strength of glass under impact using numerical methods and results of experiments.

2. Overview of experimental campaign

Experimental results, used in the current study, were taken from an internal, technical report of Institute of Ceramics and Building Materials in Krakow, Poland [6]. The experimental work focused on investigating the impact strength of tempered glass panes based on a drop ball test. It was vital to determine the maximum drop height for each thickness of panes, at which the glass sample fractures. The results of the study were partially reported in [7]. In the current study, it was decided to analyze the results collected by Ziembka et al. [6] and build upon them a numerical investigation described further in Section 3. In the following section, the results of the experiments are presented.

2.1. Test specimens and test set-up

Regular soda-lime silicate float glass was used in this study. This type of glass is the most frequently used glass type in the building industry and regularly used for structural glazing. The study is devoted to fully tempered (FT) glass, which shows much greater strength than annealed glass [3]. According to PN-EN 16612:2020, the characteristic tensile bending strength of FT glass amounts to 120 MPa due to the application of a thermal tempering process that results in a beneficial surface compressive pre-stress zones [8], [9]. During tempering process, compressive stress appears on outer surface, whereas in inner zone, tensile stress forms that counterpoise the compressive stress [3]. Thus, as a result, higher mechanical strength of glass is achieved in comparison to annealed floated glass. Strength of FT is 2 or even 3 times greater than strength of annealed glass [1].

Impact resistance is a resistance of the pane to impact, which is a relevant issue in designing of glass structures, especially in structural applications. The purpose of choosing FT glass was its high impact resistance compared to annealed glass and heat strengthened glass [3].

Experimental studies were devoted to FT glass monolithic panes with dimensions of 500 × 360 mm². The samples had three different thicknesses (6, 8 and 10 mm). Before the tests, thickness of all specimens were measured according to PN-EN 12150-1. All edges of the samples were polished. It was key to choose polished samples’ edges, because the strength of glass samples increases with level of its finishing, due to appearance of Griffith flaws [10]. It is also necessary to prepare edges before tempering process, to avoid cracks, or even destruction of the pane, during tempering [11].

Experiments were performed on deliberately prepared testing machine presented in figure 1a. The samples were carefully placed on revolving steel cylinders 50 mm in diameter and length of 365 mm. The cylinders were covered with a thin layer of rubber, elastic material. The machine had an electromechanical arm with a magnet, in which a steel ball (impactor) with the weight of 4.11 kg was mounted before testing. The initial position was measured, equalled to 10 cm above the sample (figure 1b). For all specimens, the impactor was released from increasing height (step 10 cm). Tests were conducted until the point when samples fractured and destructive height was measured on the machine. All tests were performed at room temperature at 50% relative humidity.

Tests were carried out for 35 samples for each thickness, thus 105 samples were tested in total. A large number of the experiment group of samples was chosen purposely. Bending strength of glass panes due to surface microcracks shows considerable variability, therefore a group of samples should have significant size, due to uncertainty and common large scatter of results [PN-EN 1288-1:2000].
Figure 1 Testing machine for impact studies [7]: a) experimental test set-up, b) specific parts of testing machine from side view. The numbers represent specific parts of the testing machine: 1- steel support, 2- revolving steel cylinders with thin rubber layer, 3- glass pane, 4- steel ball- impactor, 5- electromechanical arm with magnet, 6- device to measure the height.

2.2. Experimental results

Results from experimental impact tests are shown in table 1. Results are presented for every thickness that was considered. It was decided to present mean values of destructive height with corresponding values of standard deviation and coefficient of variation. Diagrams for specific thicknesses presenting the variation of values are shown in figures 2-4.

| Nominal thickness, mm | Number of tests | Mean value of destructive height, m | Standard deviation, m | Coefficient of Variation, % |
|-----------------------|----------------|------------------------------------|-----------------------|----------------------------|
| 6                     | 35             | 0.76                               | 0.24                  | 31                         |
| 8                     | 35             | 0.91                               | 0.29                  | 32                         |
| 10                    | 35             | 1.37                               | 0.39                  | 29                         |

Figure 2. Experimental results for 6 mm samples.
Figure 3. Experimental results for 8 mm samples.

Figure 4. Experimental results for 10 mm samples.

Figure 5 shows relationship between the values of critical drop height vs. thickness of glass samples. It can be seen that the drop height increases with the thickness of the samples. It is evident that higher impact energy is required to break a thicker sample. The same observation was reported in [12].

Figure 5. Results of experimental study: mean values for all samples with standard deviations.
3. Numerical study
The numerical study’s main aim is to reproduce the experiments numerically, investigate the overall performance of the sample and determine the history of impact force, velocity and the maximum principal stress in glass that occurs during the impact. The procedure is performed for a given geometry of the samples, weight of the impactor, glass thicknesses and initial velocities that correspond to the critical drop heights (mean values and bounds) found in the experimental campaign. In this way, the behaviour of the sample can be investigated, and impact strength of glass can potentially be retrospectively evaluated.

A 3D numerical model of the experimental set-up is developed using the commercial Finite Element (FE) analysis software ABAQUS [13]. All simulations are run in the Implicit Dynamic solver. To reduce the number of FE s and increase the computational efficiency of the simulations, only a quarter of the nominal geometry with appropriate boundary conditions is modelled (figure 6).

The numerical model consists of three components: a glass sample, an impactor and a roller support. The glass pane is modelled with a set of 3D 8-node, solid elements with full integration (C3D8 type from ABAQUS element library [13]). In the study, three pane thicknesses are considered: 6, 8 and 10 mm, corresponding to the experimental campaign's samples. The ball and roller support are modelled using discrete rigid surfaces (R3D4 type from ABAQUS element library [13]). The rigid surfaces correspond to the steel impactor's outer surface and roller support (both 50 mm in diameter), respectively. All nodes of the rigid surfaces are linked to reference points where fully fixed boundary restraints are assumed. This is valid except for the reference point of the ball, in which translation along Z (vertical) axis is released to allow the impactor to be set in motion. Taking into account the weight of the steel ball (4.11 kg), an isotropic mass of 0.51375 kg (1/8 of the total weight) is applied to the reference point of the impactor. At initial position, the impactor is placed 0.5 mm above the sample.

Between the sample and the impactor, surface-to-surface contact interaction allowing for lifting and relative sliding with a friction coefficient of 0.7 was assumed [14]. A rubber pad 8×40 mm² is modelled between the sample and the roller support to avoid direct contact of glass and the rigid surface which could lead to undesired stress concentrations in glass.

Careful consideration was paid to the mechanical characterisation of materials. Glass is represented using linear elastic material properties with the density \( \rho = 2500 \text{ kg/m}^3 \), Young’s modulus \( E = 70 \text{ GPa} \) and Poisson’s ratio \( \nu = 0.23 \) [PN-EN 16612:2020-3]. Despite the fact that for monolithic glass its damping effects are known to be limited [5], a value of viscous damping ratio is set to \( \xi = 1\% \) [15].
Rubber is modelled with the following linear elastic material model properties: Young’s modulus of 1000 MPa (100 x typical value for rubber materials due to impact loading) and ν = 0.48. To account for the high damping characteristics of rubber, the value of viscous damping ratio is set to ξ=5%.

Following a convergence study aimed at verifying of the mesh quality and investigating how the model converges on the true solution depending on the FE size, an irregular mesh pattern is applied to the glass pane. At the impact location (zone 50×50 mm²) a fine mesh 1x1 mm² is applied, it produces local stresses, which do not differ more than 1% compared to the true solution. The same mesh pattern was applied to the surface of the impactor. In the other zones, a coarse mesh with the same FE size as the thickness of the sample is applied. In the thickness of the pane, three FE s are defined. In terms of mesh pattern, for the rubber pad and the discreet rigid surface (roller), the mesh size is equal to the mesh pattern of adjacent components.

To simulate the impact of the ball on the pane at the central point, the ball was set into free fall motion with an initial velocity $v_0$ (in meters per second) calculated for a given drop height $h$ (in meters) with the gravitational acceleration $g = 9.81 \text{ m/s}^2$, according to the formula (1).

$$v_0 = \sqrt{2gh}$$

(1)

4. Results and discussions
To explain the phenomena that occur while the impact simulations, a sample with a nominal thickness of 6 mm is used. The specimen is subjected to impact with an initial velocity corresponding to the critical drop height of 0.76 m (mean value obtained from experiments).

Figure 7 shows the history of impact force, velocity, displacement and the maximum principal stress in glass. From the figure 7, a complex dynamic behaviour can be recognised. In terms of impact force (figure 7a), several peaks of contact force can be identified. The first peak occurs right after contact and reaches the value of approximately 1200 N. Subsequently, throughout the simulations, several other peaks can be noticed. Moreover, oscillation of the force curve can be observed. This fact appears due to the dynamic coupling effect between the impactor and the sample and is typically observed in the hard body impacts [16]. More insight into the simulations provides the history of velocity (figure 7b) for the impactor and the control point at the sample located at the impact location. In the figure, three characteristic spots can be identified. The first spot occurs right after the impact, where the sample increases its velocity (from 0 m/s) to match the velocity of the impactor. In the next stage, the impactor and the sample slow down, and at time approximately equals to 3ms, the sample drastically increases its velocity up to approximately 3.9 m/s. The observation is related to the common behaviour observed during impact studies, in which after first contact with the impactor, the sample accelerates, loses the physical contact with the impactor (figure 7c), and experiences elastic deformation and returns to the initial position colliding the impactor again [17]. The same circumstance repeats later in time (at approximately 7 ms), however, its magnitude is much lower. The characteristic phases in the form of contour plots of deformation are also shown in figure 8. The history of maximum principal stress in glass that governs its breakage (and therefor is essential in design), is shown in figure 7d. Due to the complexity of the dynamic event and several impacts throughout simulation (figure 7a and 7b), several picks of stress can be identified (figure 7d). First stress peak (193.7 MPa) occurs at time 0.36 ms and it relates to the elastic deformation after first contact, however, higher values of stress occur later in the simulation. It is known fact reported in literature, where thee maximum stresses occur after first contact at the later stage of the dynamic event [18], [19]. For the considered case, the maximum stress was found to be 262.8 MPa at time equals to 4.8 ms, which is 35.7% higher than the principal stress in glass, right after the first contact.
Figure 7. Numerical results for selected sample (glass thickness 6 mm, initial velocity $v_0=3.862$ m/s): (a) impact force, (b) velocity, (c) displacement, (d) maximum principal stress in glass (lower surface at impact location).

Figure 8. Numerical results for selected sample (glass thickness 6 mm, initial velocity $v_0=3.862$ m/s): deformation of sample at selected times of simulation. Values in legend in m.
During the physical experiments, besides the critical drop height, no additional data was recorded. Thus, it is futile to compare the numerical and experimental results and judge at what point of the FE analysis failure appears. Therefore, for the purpose of the study, which was aimed at determining the impact strength of toughened glass, a conservative approach is applied. Namely, it is assumed that glass failure occurs after the first contact at the time < 1ms.

Table 2 presents numerical results for all considered configurations in terms of maximum principal stress in glass. For each thickness (6, 8 and 10 mm) three values of stress which correspond to the mean value of critical drop height (together with the lower and upper bounds) are provided. In the table, corresponding values of kinetic energy are given for comparable value of maximal principal stress. The impact energy is calculated according to the formula (2), in which \( m = 4.11 \text{kg} \) is the weight of the impactor and \( v_0 \) is the initial velocity calculated in respect of the formula (1).

\[
E_k = \frac{1}{2}mv_0^2
\]  

Table 2. Results of numerical study: Max principal stress in glass (at first peak at t<1 ms) at impact location for corresponding impact energy.

| 6 mm thickness | 8 mm thickness | 10 mm thickness |
|---------------|---------------|---------------|
| Max principal stress, MPa | Kinetic energy, J | Max principal stress, MPa | Kinetic energy, J | Max principal stress, MPa | Kinetic energy, J |
| Lower bound | 160.0 | 21.0 | 148.3 | 25.0 | 165.0 | 39.5 |
| Mean | 193.7 | 30.6 | 179.7 | 36.7 | 195.2 | 55.2 |
| Upper bound | 222.6 | 40.3 | 206.4 | 48.4 | 221.0 | 71.0 |

Figure 9 presents results of the retrospective numerical analyses aimed at determination of breaking stress based on given breaking velocity of the impactor obtained from the experiments. The average value of maximum principal stress in glass (for all thicknesses) is 189.5 MPa. The value is in good agreement with the recommended tensile strength of glass under impact loads 180-200 MPa according to [20]. Taking into account the characteristic tensile bending strength of FT glass loaded in quasi-static manner (120 MPa according to PN-EN 16612:2020), it was found that the Dynamic Increment Factor (DIF) corresponds to the value of 1.58.

![Figure 9. Results of numerical study: breaking stress vs. glass thickness.](image-url)
5. Conclusions and further work
In this paper, a nonlinear 3D finite element model was developed to simulate the dynamic response of a monolithic toughened glass pane subjected to hard-body impact. The finite element model was used to determine retrospectively the impact strength of glass based on the results of experiments. It should be noted that the conclusions are valid for the assumptions and geometrical features of the samples. From the performed studies, the following conclusions are drawn:

- In the experimental campaign, for the simply-supported monolithic glass panes (with the dimensions of 360×500 mm² subjected to impact of a steel ball with the mass of 4.11 kg), the mean values of destructive drop height were found to be 0.76, 0.91 and 1.37 m for the specimen thicknesses of 6, 8 and 10 mm, respectively.
- The numerical model developed within the study allows for retrospective determination of maximum bending tensile stress in glass for a given critical drop height. It was found that the average value of maximum principal stress in glass (for all thicknesses) is 189.5 MPa, which results in the Dynamic Increment Factor (DIF) of 1.58 for impact loads in comparison to the characteristic, quasi-static glass strength.

The current study shows potential of numerical methods to investigate the dynamic performance of glass samples subjected to hard-body impacts. However, it is worth noting that in the experimental campaign, besides the critical drop height causing glass fracture, no additional data was collected to be potentially used for validation of the model. Therefore, additional experimental studies are planned in the near future. These will involve testing of glass panes equipped with high-resolution sensors, such as strain gauges, accelerometers or LVDTs. New data will be further used for improving and validating of the numerical model.

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