Coupled Systems Mechanics, *Vol. 10, No. 6 (2021) 475-490*
https://doi.org/10.12989/csm.2021.10.6.475

Some aspects of the analyses of glass structures exposed to impact load

Gabrijela Grozdanić*, Mirela Galić[a] and Pavao Marović[b]

Department of Civil Engineering, Faculty of Civil Engineering, Architecture and Geodesy, University of Split, Matice hrvatske 15, HR-21000 Split, Croatia

(Received June 28, 2021, Revised October 19, 2021, Accepted October 29, 2021)

Abstract. With glass becoming a structural material there is a whole new approach for loading and ensuring the safety of construction. Due to its brittle nature, it is necessary to predict all possible problems so that structural integrity would not be endangered. In this paper, different approaches to modelling the glass elements are presented with references to the advantages, disadvantages, and application of each of them. The intention is clear, there is a need to improve and simplify the design guidelines. Given the increasing use of glass in construction it is not practical to produce experimental tests each time when the verification is needed. Today, architecture is bringing us different types of structures and every project presents a new challenge for engineers. A practical and simple approach is crucial for progress and efficiency. In this paper, different approaches to modelling glass are presented with an emphasis on soft body impact.

Keywords: glass structures; impact load; pendulum test

1. Introduction

As one of the most attractive materials of the modern age, glass has become an irreplaceable element of structures. To be able to respond to the structural challenges, it became the subject of many researches, especially those where the behaviour of glass elements exposed to different types of loads is analysed. For a proper analysis of glass response, it is important to be acquainted with the production process. Throughout history, glass was firstly present as obsidian (natural glass formed in a volcano) which was used as a tool (Carter and Norton 2013).

Later, production began by melting an ingredients and development of the blowing technique. Glass blowing technique was used until the end of the 19th century as a main production technique for all types of glass including flat window glass. With the development of industry, the production of flat glass improves and different techniques (such as rollers) were used to form glass sheets from the molten glass. A turning point in production of flat glass is invention of Float process, by Sir Alastair Pilkington in 1959 (Carter and Norton 2013). The majority of today's flat glass is produced by Float process. In the Float process a tin bath (molten tin) is used as a base for cooling molten

*Corresponding author, Ph.D. Student, E-mail: gabrijela.grozdanic@gradst.hr
[a]Professor, E-mail: mirela.galic@gradst.hr
[b]Professor, E-mail: pavao.marovic@gradst.hr

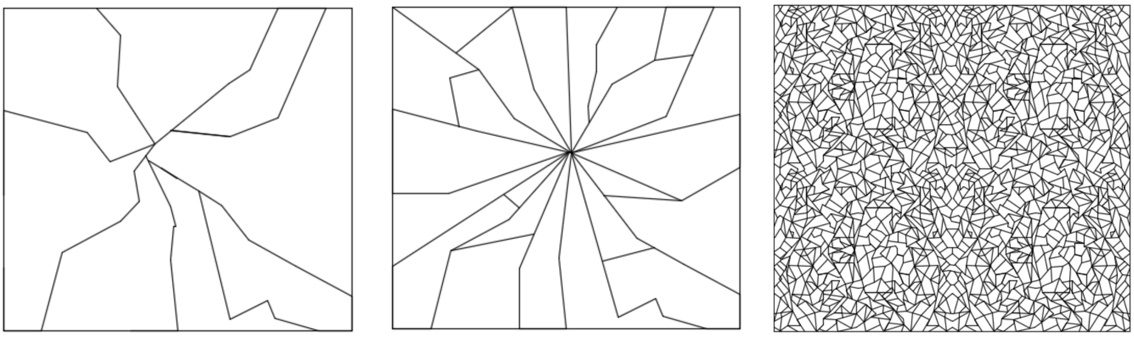
http://www.techno-press.org/?journal=csm&subpage=8 ISSN: 2234-2184 (Print), 2234-2192 (Online)

Table 1 Basic mechanical properties of glass according to prEN 13474:2009

Properties	Middle value	Interval
Glass density	ρ=2,500 kg/m³	2,250-2,750 kg/m³
Young's modulus	E=70,000 MPa	63,000 MPa-77,000 MPa
Poisson number	μ=0.22	0.20-0.25

Table 2 Characteristic bending strength of each type of glass according to prEN 13474:2009

Annealed glass/float glass	Heat strengthened glass (HSG)	Thermally toughened glass (TTG)
45 N/mm²	70 N/mm²	120 N/mm²



(a) Annealed glass / float glass (b) Heat strengthened glass (c) Thermally toughened glass

Fig. 1 Breakage pattern for each type of glass

glass, consequently producing flat surface that does not require any additional treatment.

The most used type of glass is Soda-lime glass (in text referred as "glass") consisted of SiO_2-Na_2O-CaO (with additional ingredients). It can be used without any additional treatment if there is no demand for increased strength and safety. Considering part of the Float process in which heated glass is slowly cooled to release residual stresses, basic non-threated glass is called annealed glass. Basic mechanical properties of glass are shown in Table 1 and characteristic bending strength according to prEN 13474:2009 is presented in Table 2.

It is very important to point out that glass is eco-friendly, recyclable material. It can be melted over numerous times and reused to produce new glass products. Recycling ability of glass saves great amount of space in landfills. Compared with other building materials it does not lose its properties when reprocessed. Glass cullet melts on lower temperature, significantly reducing amount of energy used to melt only raw materials.

By combining different additional elements it is possible to affect some glass properties, such as heat resistance, colour, etc. Apart from adding elements into chemical structure, there are few treatments that improve glass mechanical properties. When focusing on safety and strength of glass elements it is important to mention tempering. Tempered glass is a glass of increased strength with the ability of safe breakage, meaning the glass will not break into sharp and heavy pieces that can cause injuries. Tempering can be produced by chemical treatment (exchange of ions) or by heating and fast cooling of the glass sheet. The final effect of both processes is developing compression on surface and tension inside, resulting in increased tension strength of glass element. The most obvious difference between annealed and tempered glass is in their breakage pattern. Sharp and heavy pieces from annealed glass and small cubical harmless pieces from broken tempered glass are shown in Fig. 1. Heat strengthened glass is tempered glass exposed to slower cooling, consequently producing lower stress on surface and inside glass.

Most types of glass can be involved in the process called laminating. Laminated glass is made of at least two glass sheets connected with interlayer. The aim is to provide post breakage safety while ensuring integrity of glass during the breakage. Interlayer ensures integrity after breakage and in case of unbroken sheet it provides post-breakage capacity (Molnár *et al*. 2012, Hána *et al*. 2018, Timmel *et al*. 2007).

2. Regulations and standards for glass structures

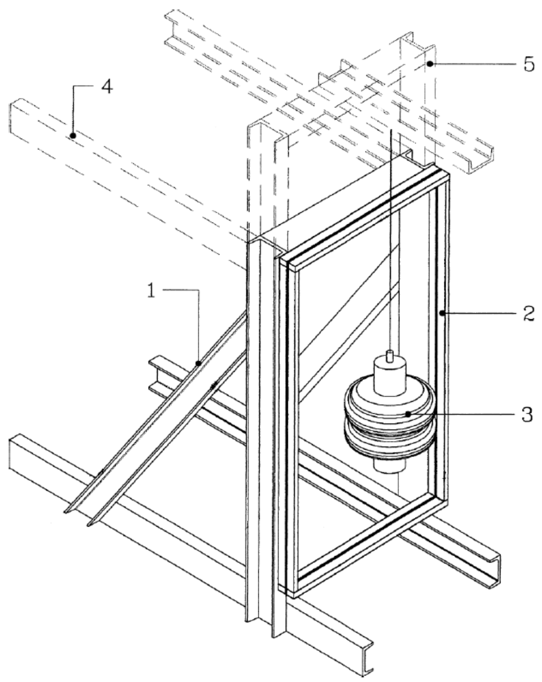
Development of glass resulted in need to define regulations and design guidelines. It could be said that regulations in Europe are late behind architectural and constructional works with glass. In the last 30 years, many facilities were built with a glass facade and other glass elements relying on national codes that cover only a small part of domain. European draft standard prEN 13474:2009 was released in 2009, and in 2014 the Guidance for European Structural Design of Glass Components (in text referred as Guidance) was released as a second draft edition for future Eurocode. The Guidance (2014) contains information about material properties, products made of glass, and the basis for the design. Most analytical expressions and methods are proposed for the static load and there is scarce information for dynamic behaviour. Regarding dynamic loads, there are rules relating to the design of glass elements such as type of glass, robustness, etc. Impact load, as one of the most common dynamic loads, tends to cause great damage in brittle materials. Current regulations do not provide enough information to determine resistance of glass element to different types of impact loading.

According to Guidance (2014), impact loading classification is divided into hard body and soft body impact. The division is characteristic for glass because of its unfavourable effects in contact with other materials, harder than the glass. There are few regulations describing test methods to determine glass resistance to impact load. Soft body impact according to HR EN 12600:2006 (EN 12600:2002) is a test method used for simulation of impact of the human body on glass barrier. Test setup consists of glass panel with prescribed dimensions placed in a four-sided supporting frame, exposed to impact of the pendulum from different drop heights. Based on impact resistance of glass panel for different drop heights (applied energy) classification is proposed. Classification is defined according to glass damage at each of three drop heights, until fracture occurs.

This code does not provide a precise load level and glass resistance. Results are determined only by experimental classification and visual determination. Test setup is shown in Fig. 2.

HRN EN 356:2006 (EN 356:1999) is regulation that defines test of hard body impact by steel sphere. Test is developed for classification of security glazing products. Within different drop height 1,500 mm-9,000 mm (depending on required category of resistance) and defined number of strikes, ball must not penetrate the glass. Besides steel sphere impact, this code also describes an axe strike test.

In Guidance (2014) requirements for improving and developing regulations related to glass floors and horizontal glazing accessible for maintenance are described. Post failure resistance is an important demand in floor structures made of glass, and therefore it is forbidden to use only tempered glass in most national regulations. Also, glass barriers and glass parapets are described and the suggestion is to provide classification according to bearing type. Safety level should be



Legend:

1 - Main frame
2 - Clamping frame
3 - Impactor
4 - Optional support member
5 - Optimal suspension device

Fig. 2 Test setup for soft body impact according to HR EN 12600:2006 (EN 12600:2002)

determined depending on the existence of an additional load-supporting element (handrail), and other aspects regarding the type of support, type of glass, etc. From the aspect of dynamic impact load the Guidance (2014) suggests the norm EN 12600:2002 (HR EN 12600:2006) as an experimental test, remarking that larger panels, different substructure stiffness, and support characteristics are not taken into consideration. Experiment can also be done with original parameters from the observed constructions. Besides experimental verification, Guidance (2014) is describing two dynamic calculations. Method 1 is transient numerical method for defining stress evolution in the glass panel, while Method 2 uses equivalent loads defined through a double mass oscillator. Both methods are considering impact energy of E=100 Nm which is developed from a body mass of 80 kg at impact speed of v=2.04 m/s with 60% resonance mass.

3. Glass as a structural material

Glass as a structural material (primary or secondary) ought to sustain different types of actions. Due to its brittle nature, elements are usually designed to be robust. Lack of post-failure behaviour is replaced by additional substructure elements or improvements within glass elements (as laminated glass). Design methods for different structures mostly relate to static loading and there is not much information about glass resistance to dynamic loading.

3.1 Glass under static loading-basic theories

Glass behaviour under static load is linear-elastic until failure, when it breaks without any plastic deformation. Defining the strength of glass under static load is a great challenge considering many factors that affect glass behaviour. By exploring the difference between actual (measured) strength and the theoretical strength (from physical data) for glass, Griffith (1920) found that it is possible to create rods and fibers made of glass that have strength closer to the theoretical strength. The thinner fiber, there is smaller possibility that it will have imperfections such as flaws. The basis of Griffith theory is that the glass surface is not perfectly smooth but it contains small flaws, not visible to the naked eye but of great importance for material strength. A simple test with metal wire scratched spirally on the surface, loaded under the elastic limit and resulting in permanent deformation is proof of the great influence of surface imperfections. Flaws inside material contribute to the development of stress concentrations. As a test, Griffith observed one artificial flaw on the glass panel loaded in Mode 1 and concluded that the fracture stress (σ_f) of thin glass plate is inversely proportional to the square root of the crack length (2*a*)

$$C \approx \sigma_f \cdot \sqrt{a} \tag{1}$$

In further observation, to avoid problem of infinite stress at the peak of the sharp flaw from linear elastic theory, Griffith used a reversible thermodynamic system (Conservation of Energy) to model a static crack. Using theorem of minimum energy and adding increase in potential energy, caused by work from destroying cohesive forces in crack formation, Griffith describes energy balanced concept

$$\frac{dU}{da} = 0 \tag{2}$$

where *U* presents the total energy of system as a sum of mechanical energy U_M and U_S as a free energy used for creating new crack. The *a* is the length of crack.

Further, critical stress related to critical crack length is defined. The Eq. (3) defines the relation between crack length and critical stress describing at what level of stress the propagation will occur for defined crack length a_c (where *E* is Young's modulus and *γ* is unit surface energy density)

$$\sigma_f = \sqrt{\frac{2 \cdot E \cdot \gamma}{\pi \cdot a_c}} \tag{3}$$

Griffith's expression accurately defines behaviour only for the brittle materials. Following Griffith's work, Irwin (1957) defined an improved fracture criterion. The criterion is based on a stress intensity factor K_1 and a comparison with the value of critical stress intensity factor K_{1c} (fracture toughness) which is property of material

$$K_1 \geq K_{1c} \tag{4}$$

The stress intensity factor for Mode 1 type of loading by Irwin (1957) is expressed in Eq. (5), where *Y* presents geometry factor and σ_n is nominal tensile stress perpendicular to the crack (in plane)

$$K_1 = Y \cdot \sigma_n \cdot \sqrt{\pi \cdot a} \tag{5}$$

Influence of crack occurrences on stress in elements can be described with comparison of Orowan (1948) Eq. (6) for stress causing bond breakage and Griffith's Eq. (3). In Eq. (6) r_0 is equilibrium spacing of the atoms and *γ* is surface energy density of the material

$$\sigma_m = \sqrt{E \cdot \gamma / r_0} \tag{6}$$

A good overview regarding surface energy determination is given in Reich *et al*. (2018). For example if there is a glass with modulus of elasticity E=70 GPa, surface energy density γ=3 Jm^{-2} and equilibrium distance of the atoms r_0=0.2 nm

$$\sigma_m = \sqrt{E \cdot \gamma / r_0} = \sqrt{70 \cdot 10^9 \text{ N/m}^2 \cdot 3 \text{ Jm}^{-2} / (2.0 \cdot 10^{-10} \text{ m})}$$
$$\sigma_m = 3.24 \cdot 10^{10} \text{ N/m}^2 = 32.4 \text{ GPa}$$

Here, σ_m describes stress required to break bonds between atoms to provoke crack opening. If there is a 0.1 mm long (2a=0.1 mm) flaw on the surface of the same glass panel then critical stress for crack growth is:

$$\sigma_f = \sqrt{\frac{2 \cdot E \cdot \gamma}{\pi \cdot a_c}} = \sqrt{\frac{2 \cdot 70 \cdot 10^9 \text{ N/m}^2 \cdot 3 \text{ Jm}^{-2}}{\pi \cdot 0{,}00005 \text{ m}}}$$
$$\sigma_f = 5.171 \cdot 10^7 \text{N/m}^2 = 51.709 \text{ MPa} = 0.0517 \text{ GPa}$$

If the above mentioned fracture mechanics relations and rules would be the only criterion for fracture, glass structures would not be so unpredictable. But, failure may still occur even if stress is lower than critical. It is proven from Griffith that glass elements have a strength decrease while aging (even in just a few hours after production). In conditions of humidity and small static load, subcritical crack growth occurs. The crack growth depends on properties of glass and the flaw, and loading history. According to Overend *et al.* (2007) it also depends on relationship between crack velocity v and stress factor K_1 from Irwin's relation

$$v = \frac{da}{dt} = v_0 \cdot (K_I / K_{Ic})^n \tag{7}$$

In the Eq. (7), v_0 is a crack velocity parameter and n is a parameter determined experimentally. According to Overend *et al.* (2007): "The crack velocity parameters v_0 and n depend on the humidity, the temperature and the pH value of the environment, the chemical composition of the glass, the age of the flaws and even on the speed of loading. Typical values for design purposes are n=16 and v_0=6 mm/s."

3.2 Glass under dynamic loading

Known theories (Griffith 1920, Orowan 1948, Irwin 1957) are only the basic starting points in the analyses of glass structures exposed to dynamic load. To accurately predict behaviour under dynamic load, certain coefficients and design guidelines should be proposed. Response to dynamic load is affected by many parameters related to type and duration of load, impactor characteristics, boundary conditions, glass type, etc. Great number of studies (Zhang *et al.* 2012, Osnes *et al.* 2020, Peroni *et al.* 2011, Daryadel *et al.* 2016) have shown dependency of strain rate both for dynamic and static strength.

Osnes *et al.* (2020) proved that the fracture strength of glass element increases with increase of loading rate. Conclusion came from two test types: quasi-static punch tests and low velocity impact tests, all with the intention of verifying Strength Prediction Model (SPM) developed by Yankelevsky (2014). With purpose of defining more accurate failure prediction for dynamic loading Osnes *et al.* (2020) used strain-rate dependent dynamic fracture toughness K_{ID}

$$K_{ID} = K_{IC} \cdot \left(\frac{\bar{\dot{\varepsilon}}}{\dot{\varepsilon_0}}\right)^{1/(1+N_S)} \geq K_{IC} \tag{8}$$

where $\dot{\varepsilon}_0$ is a reference strain rate that presents limit below which a static value K_{IC} applies. To determine dynamic fracture toughness, a time averaged strain rate $\bar{\dot{\varepsilon}}$ should be calculated. Combining input information (stress and strain) from finite element model that is developed in ABAQUS with SPM, Osnes *et al.* (2020) found that model results coincided with stress and strain data measured in the experimental tests. Peroni *et al.* (2011), Zhang *et al.* (2012) presented increase in tensile strength of glass with higher strain rate using Brazilian test (Splitting tensile test). The other test results (Zhang *et al.* 2012, Osnes *et al.* 2020, Peroni *et al.* 2011, Daryadel *et al.* 2016, Zhang 2015) approve that glass tensile strength increases with increase of strain rate and that Young modulus is not dependent on strain rate. Discrepancy of results happens in calculations of compressive strength, for which some authors claim that is independent of strain rate while, others proved dependency.

Modelling glass with continuum damage or plasticity model (Do *et al*. 2018, Imamovic *et al.* 2019) is another approach. Those models can capture the entire process of fracturing without the implementation of random artificial flaws. Do *et al*. (2018) developed a continuum viscodamage-embedded discontinuity model for dynamic failure of brittle and ductile materials which includes strain rate dependency. The model is primarily developed for concrete and it combines rate dependent continuum damage model for describing behaviour before reaching a peak, and an embedded displacement discontinuity model for modelling behaviour after reaching the peak where the macro crack is developed. This approach enables more detailed modelling of the whole dynamic fracture process, but it can be very demanding for such brittle material as glass.

4. Simulations of pendulum test

Since glass resistance to dynamic load is mostly proved by pendulum impact test it is no surprise that a lot of researchers tend to develop it numerically. Defining behaviour and energy release in pendulum test is a step to better understanding glass behaviour under soft impact. Lately, many researchers work on a numerical solution to avoid expensive experimental tests and geometrical limitations. Schneider and Schula (2013) describe how to model soft body impact by two proposed numerical methods from DIN 18008-4. Regarding the pendulum impact test, a finite element transient numerical method is described. It is a method for determination of time-dependent structural behaviour of glass. The basis of the method is in incremental solving of the dynamic equilibrium

$$M \cdot \ddot{u} + D \cdot \dot{u} + K \cdot u = R - F \tag{9}$$

where *R* and *F* represent inner and outer nodal forces. Increment should be in range from 1/20-1/60 of the total time span. It is required to first develop a model with proper elements presenting pendulum and glass plate. Then, the model needs to be calibrated. Schneider and Schula (2013) describe calibration according to DIN 18008-4 where diagrams are presented in order to calibrate the model. Diagrams relate on pendulum acceleration in three cases of impact: impact to a rigid body, impact on 8 mm continuously supported plate and two-sided supported plate. After verifying model different geometries can be calculated. Second presented method is a simplified engineering model with equivalent static loads. It is two-degrees-of-freedom (2-DOF) model simulating a coupled system of glass plate and pendulum. The stiffness equivalent to the glass plate is defined through Kirchhoff's plate theory and analytical expressions. Idealized stiffness of pendulum is defined by Schneider's previous work and plate stiffness is determined in correlation to impact

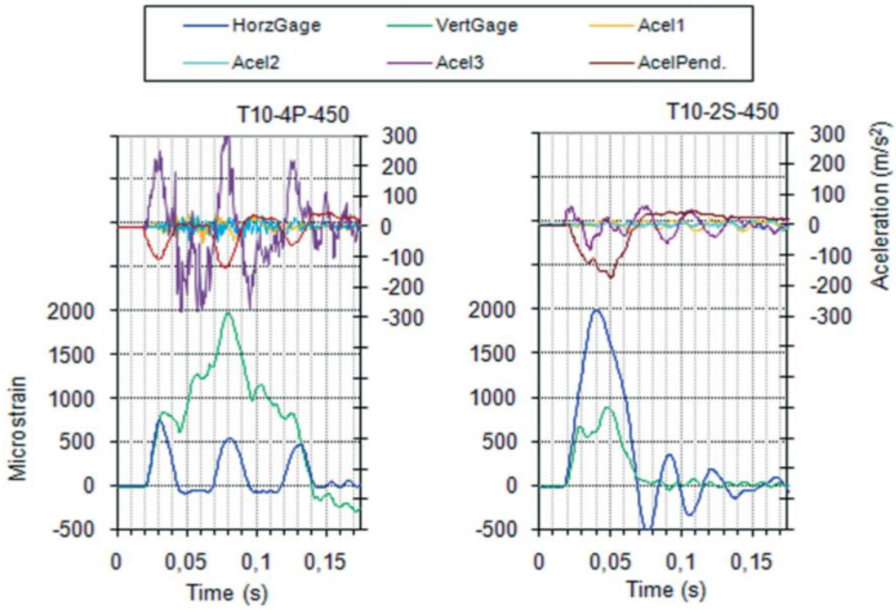


Fig. 3 Experimental results from pendulum impact test on four point supported (4P) and two sides (2S) supported glass panel, for same drop height (450 mm) (Pacios *et al.* 2011)

point and type of support.

Pacios *et al.* (2011) preformed experimental pendulum test on 17 specimens, performing 240 impacts in total, with varying different types of support and different drop heights. The results are shown in Fig. 3. Specimens are combination of laminated glass panels and monolithic tempered glass, but the focus is on tempered glass. In test, four accelerometers are used to measure: stability of frame (2 accelerometers), glass response (1 accelerometer) and acceleration of pendulum (1 accelerometer). Besides acceleration, strains are measured in the centre of plate and displacement of pendulum is recorded during different stages. Experiments show that the results are more influenced by the type of panel support than by the drop height of the pendulum. With the increase in the drop height, the shape of the strain-time diagram stays similar, and values are increasing according to height. Duration time of the impact is similar. But, for the same drop height and the same type of glass, only with a different type of support, the strain-time curve shows a different response. On a four-point supported panel, duration of the impact is almost three times longer than on a two-sided supported panel for the same drop height. During that time the pendulum and glass panel manage to vibrate for three times before separation, consequently adding more load to the panel. Pacios *et al.* (2011) came to conclusion that type of support is of great influence in dynamic response of glass panel. To compare a great number of test results, Alonso *et al.* (2019) presented method for comparing time histories of different specimens. A similarity index is calculated so that difference between results in similar test setup can be easily compared.

Referring on DIN 18008, EN 12600:2002 and Pacios *et al.* (2011), Parra *et al.* (2019) analyse real amount of load that is transferred from pendulum to panel. They observed a difference between initial energy of pendulum (for drop height) and load applied to the glass plate. Effective impulse is defined as integral of applied load obtained from multiplying mass of pendulum and measured acceleration. Global impulse is defined from pendulum drop and rebound height. The comparison

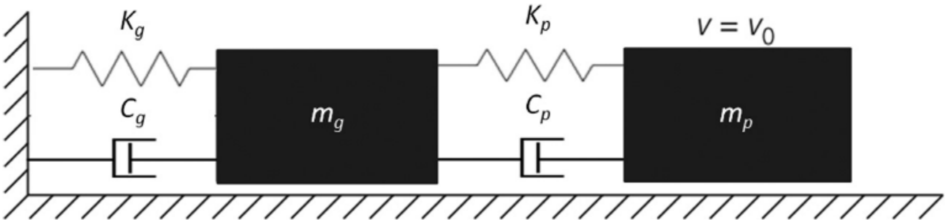


Fig. 4 Two degree of freedom model for simulation pendulum - glass contact during impact (Parra *et al.* 2019)

of the effective impulse and the global impulse shows that effective impulse is always lower. That difference is further analysed by developing a model from results of Reference campaign (experimental tests from Pacios *et al.* 2011). It is assumed that energy dissipation occurs during the contact of pendulum and glass panel. A simplified 2-DOF model is used to analyse contact between components (Fig. 4). To accurately define the proposed model, natural frequencies and damping ratio of components are determined. Parra *et al.* (2019) concluded that global energy is divided into energy that is affecting the glass panel (effective) and residual energy that applies to the remaining parts of the test configuration. Difference is described with a distribution coefficient "*r*" and proof is evaluated with comparing experimental results from Reference campaign (Pacios *et al.* 2011). Approximately 20% of pendulum energy is transformed in deformation and excitation of the remaining elements from test configuration, transferring ~80% of total energy on the glass panel. This conclusion is also confirmed by the fact that results in the model are always larger than in the experiment.

Brendler *et al.* (2004) made a numerical model in LS DYNA of pendulum impact test on toughened and insulated glass. First the pendulum was validated by comparing accelerations from the model with the experiments for rigid wall impact. It is also noticed that there is significantly lower impact energy compared with potential energy for defined height. Considering the accelerations of pendulum, the model results coincide with experimental measurements. Pelfrene *et al.* (2016) developed numerical simulation of pendulum test. First a detail model of impactor (according to EN 12600:2002) is developed and validated by experiment. Experiment and numerical model are shown in Fig. 5. To validate impactor a glass panel is replaced with pressure plate to measure impact forces, tire footprint and distribution of pressure. Model is made in commercial software ABAQUS. Pendulum is modelled in real shape consisting of two tires with internal pressure (3.5 bars). The initial angular velocity is given to pendulum according to the simulated drop height. Regarding developed force, a good coincidence came out from the experimental and numerical tests of pendulum impact on force plate. Pelfrene *et al.* (2016) used and commercial program SJ MEPLA 3.5.9. (Finite element software developed for calculations of glass structures) to develop another numerical model for pendulum test with laminated glass panel. Pelfrene *et al.* (2016) replaced laminated glass with monolithic panel of the same thickness due to stiff behaviour of interlayer in dynamic load. Comparing results from experimental test, ABAQUS model and MEPLA model it can be seen that numerical models overestimate acceleration and strain. Detailed model from ABAQUS provides better match to experimental results. Viviani *et al.* (2021) developed a simplified model of pendulum impact test similar to the early mentioned 2-DOF model, but with a different approach to the plate modelling. The proposed dynamic system neglects the mass of the glass panel (inertial forces) and represents the panel with appurtenant stiffness and observes pendulum with

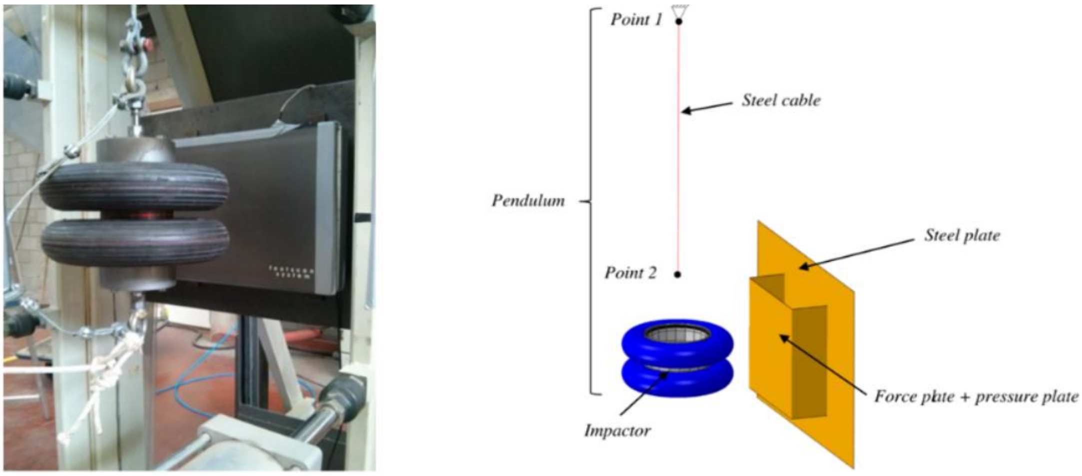


Fig. 5 Test setup with pendulum and pressure plate, simulation of pendulum test (Pelfrene *et al.* (2016))

mass and stiffness. Comparing results of that model with a model in SJ MEPLA software minimal error occurs. This model is described as applicable in cases where the participating mass of the panel is smaller than the mass of the impactor. Further, authors (Viviani *et al.* 2021) presented a model that can be used in complex structures on the basis of proposed 2-DOF model. It consists of two types of beams reproducing pendulum pressure on the elliptic area (tire print). Froling *et al.* (2014) also made a simplified finite element model developed on basis of the Rayleigh-Ritz method for determining maximum stress on the glass panels in the pendulum test. The aim of the work is to produce a simple model for stress determination without the need to use advanced commercial software. Model is created in finite element program CALFEM, as a part of MATLAB software. Froling *et al.* (2014) compared the model with the one developed in ABAQUS, and the results coincide. Recommendation from author is not to use simplified model at larger glass panels with small thickness because of effects of geometrical nonlinearity. All mentioned commercial software (ABAQUS, LS DYNA, ANSYS and MEPLA) use finite element method to determine construction behaviour.

Since damping is one of the most important factors in glass dynamic response, a more detailed approach than Rayleigh's is in some cases more appropriate (depending on the type of loading). Taking into account different types (causes) of dissipation such as failure mechanisms like plasticity and damage (Ibrahimbegovic *et al.* 2021) without dependence on the size of the panel or number of frequencies would lead to a more accurate simulation of glass element behaviour.

In presented studies, great focus is on detailed modelling of the pendulum so that dissipation and applied force could be better understood. Pendulum is conceived as a representation of human body impact and there are many compromises accepted. In human body impact on the glass surface, it is possible for rebound not to happen (at horizontal structures), and in case of that scenario, it is important to investigate post breakage capacity of laminated glass. Since laminated glass is mostly in use as a bearing element it is also important to understand the behaviour of interlayers in dynamic loading. Interlayer behaviour and material characteristics are influenced by load duration and environmental conditions including humidity and temperature. At higher temperatures, the material characteristics of most commercial interlayers are decreasing, losing shear stiffness and the ability to accurately transfer load between panels.

Besides standard test frame, other type of supports can be found in literature. For example, Biolzi *et al.* (2018), Quaglini *et al.* (2020) performed static and dynamic tests on laminated glass cantilever beam (in the function of a balustrade). Biolzi *et al.* (2018) developed numerical model after performing experimental tests according to the Italian code and Quaglini *et al.* (2020) performed only numerical tests. Authors concluded that the type of support is of great influence on stress development during impact and static loading in cantilevered systems. Quaglini *et al.* (2020) made a comparison of joint configuration and fastener type with different interlayers in laminated glass. Comparison is made in the aspect of stress development in glass balustrade and observations are different for static and dynamic loading. The influence of interlayer is observed only in case of static loading. Ionoplast interlayer is described as a best option in combination with countersunk bolts. Biolzi *et al.* (2018) compared static and dynamic response of PVB and ionoplast interlayer. For same load, a peak stress measured in PVB laminated glass is two times bigger than in glass with ionoplast interlayer.

5. Other types of dynamic tests

In the case of horizontal glass structures, post-breakage capacity is very important for safety. A horizontal frame with a pendulum is a good solution to verify this category of glass behaviour. When focusing on post breakage capacity it is important to notice that interlayer has a major role in the behaviour of structure since laminated glass is the only product that can provide it (Timmel *et al.* 2007, Pelfrene 2016). Interlayer brings time-dependent and temperature-dependent behaviour. Drop weight tests have the possibility to simulate a fully plastic crash and to give insight into the post breakage capacity of the structure.

Van Dam *et al.* (2014) performed small scale drop weight tests on annealed glass with addition of safety window film. Intention is to study resistance and post-fracture performances of glass reinforced with safety window film. Test pieces are cut in circular shape with radius of 235 mm and placed horizontally in test frame. Two types of impactor (indenter) were used. Harder indenter is a spherical shape made of steel with 10 mm radius and a soft indenter is made of rubber with radius of approximately 28 mm. Mass of impactor is 7.64 kg for soft indenter and 7.38 kg for hard indenter. As in previous articles, acceleration of impactor was measured and high speed camera was used to observe crack development in the glass. Displacement and force sensors are included ensuring more options to determine test results and compare them. Since specimens are reinforced with safety window film on one side, tests were performed with impact on both sides. Only in case of soft indenter impact, safety window film managed to prevent penetration of impactor (impact on film side). Results obtained from different measuring instruments were compared, showing a good match. Van Dam *et al.* (2014) concluded that in the case of hard indenter there is a small influence of the position of safety film resulting in slightly larger decrease of measured velocity. In the test with soft indenter there is noticeable influence of the position and thickness of the film, affecting velocity and acceleration decrease. With increasing of the film thickness, velocity loss is higher and deceleration is larger.

Another frequent research of structural glass is in the domain of blast loading and wooden debris impact (Zhang *et al.* 2013, Zhang *et al.* 2015, Pelfrene *et al.* 2016, Zhang *et al.* 2019) where a significant contribution of interlayer in preventing injury is also proven.

6. Numerical modeling of glass strength and fragmentation under the low velocity impact

Simulating fracture and fragmentation of brittle material is a great challenge for researchers. Today there are different computational methods developed to accurately simulate the glass behaviour. Depending on the stress condition inside the glass panel, a different types of breakage pattern are achieved, each of them appropriate for different use. Modelling those types of fragmentation can be provided with numerical programs that are based on continuum or discontinuum methods. Pelfrene (2016), in his dissertation, described different methods for simulating glass fracture. He used Smoothed Particle Hydrodynamics (SPH), a mesh free method that is using particles to simulate continuum, in this case a glass fragmentation. Author concluded that SPH is good option for simulation of extreme load cases, such as high speed impact. The softened stiffness of glass panel is observed at low velocity impact. Another method presented is Cohesive Zone Method (CZM), a continuum method that enables crack propagation though element boundaries with no need for initial crack. Crack formation occurs when cohesive forces (traction) are decreased to zero at critical separation distance. To be able to form crack in CZM a cohesive elements need to be added. Since Pelfrene (2016) is simulating glass fracture, the cohesive elements are added to all interelement boundaries in existing mesh. In CZM expected degree of fragmentation did not occur, instead element only softened. Author (Pelfrene 2016) finally choose Element Deletion Technique with crack delay model that is based on principle of decreasing stiffness to zero for element that reached fracture criterion or stress limit. In this method, the whole element is not deleted because it would have resulted in mass instability. Osnes *et al.* (2019) created numerical model to simulate fragmentation of glass panel exposed to blast loading. Explicit finite element is developed using IMPETUS Afea Solver. Software uses high order elements and node splitting technique. Authors describe it as suitable for large deformations and extreme loading conditions. Node splitting technique activates when integration point reaches fracture criterion. Stress dependence is chosen as a condition for crack initiation.

Wang *et al.* (2017) made a comparison study of four methods encompassing continuum methods (Finite Element Method (FEM) and Extended Finite Element Method (XFEM)), and discontinuum based methods (Discrete Element Method (DEM) and Combined Finite-Discrete Element Method (FEM/DEM)). Models simulate dynamic fracture of glass beam exposed to low-velocity hard body impact. Continuum-based models (FEM, XFEM) are used in commercial program ABAQUS, and DEM and FEM/DEM are performed in PFC and Y2D respectively. In FEM analysis smeared model is used for simulating discontinuous cracking failure with crack initiation according to Rankine theory (maximum principal stress exceeds tensile strength). It considers only Mode 1 for crack initiation but adopts Mode 1 and Mode 2 for crack propagation. Displacement u_{no} in Mode 1 is defined as quotient of energy G_f required to cause unit area of crack opening and peak cracking stress σ_{tu} (Wang *et al.* 2017)

$$u_{no} = \frac{2 \cdot G_f}{\sigma_{tu}} \tag{10}$$

XFEM is using phantom nodes and linear elastic fracture mechanics (LEFM) with additional functions. Phantom nodes use overlapping elements to bridge discontinuity and to avoid introduction of additional unknowns. DEM discretizes the observed domain in a large number of elements connected with the boundaries. Those numerous particles act individually when force is applied producing realistic simulations for progressive fracturing of brittle materials. FEM/DEM is using

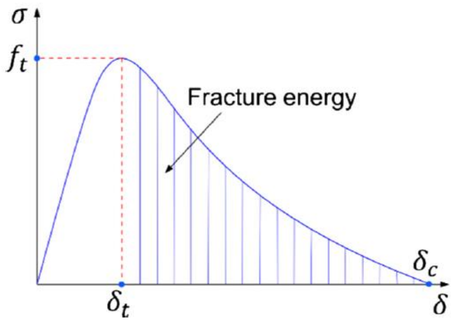


Fig. 6 A Typical stress-displacement curve (Wang *et al.* 2017)

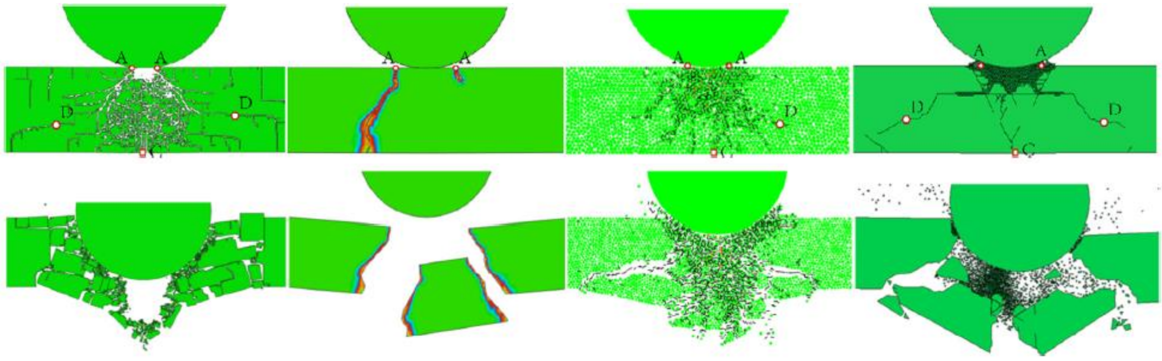


Fig. 7 Evolution of crack pattern for different calculation methods (from left to right FEM, XFEM, DEM and FEM/DEM respectively) (Wang *et al.* 2017)

the same crack initiation criteria and critical energy release as FEM. Stress-displacement curve is used to model Mode 1 behaviour (Fig. 6). The surface under the curve presents a critical energy release rate described as 2γ (surface energy). In the strain-softening interval ($\delta_t - \delta_c$) the softening function is used to describe a decrease in bond stress. Bond stress vanishes at the point where the crack is initiated. The softening function is defined by the constants determined from experimental results of the observed material. Shear behaviour is also calculated using a softening function and penalty function method (Wang *et al.* 2017).

By comparing four described methods Wang *et al.* (2017) found that FEM/DEM is the most accurate method for predicting the real behaviour of glass under different types of low-velocity impact. XFEM results differ most in manner of fragmentation, as it can be seen in Fig. 7. The points marked on picture present initiation point for different cracks.

7. Conclusions

Regulations suggest an experimental classification of glass panel exposed to impact load. But those experiments are high-cost and time-consuming while classification is not always precise. It is clear why there is an intention to develop a numerical simulation of the test that will provide a more affordable classification and adaptable configuration. There are different approaches to determine glass behaviour under impact loads, still mostly verified through experiments. Similar studies and models are developed for the automotive industry where tests are performed for head impact during a car accident. In existing Guidance (2014) there are two proposed methods to calculate glass under dynamic load. Both methods are the subject of research of different authors with the intention of simplifying and defining clear verification procedures. Inside different approaches a connection is noticeable in aspect of energy dissipation, strain rate dependency and numerical issues. We can corroborate significant progress in numerical modelling of glass behaviour in the last ten years.

Acknowledgement

This research is partially supported through project KK.01.1.1.02.0027, a project co-financed by the Croatian Government and the European Union through the European Regional Development Fund-the Competitiveness and Cohesion Operational Programme.

References

Alonso, J., Parra, J.A., Pacios, A. and Huerta, M.C. (2019), "Similarity index: A procedure for comparing impact time histories validated with soft impact test", *Eng. Struct.*, **198**, 109513. https://doi.org/10.1016/j.engstruct.2019.109513.

Brendler, J.S., Haufe, A. and Ummenhofer, T. (2004), "A detailed numerical investigation of insulated glass subjected to the standard pendulum test", *Proceedings of the International Symposium on the Application of Architectural Glass*, München, Germany, November.

Carter, C.B. and Norton, M.G. (2013), *Ceramic Materials*, Springer-Verlag, New York, New York, USA.

Daryadel, S.S., Mantena, P.R., Kim, K., Stoddard, D. and Rajendran, A.M. (2016), "Dynamic response of glass under low-velocity impact and high strain-rate SHPB compression loading", *J. Non-Crystal. Solid.*, **432**(Part B), 432-439. https://doi.org/10.1016/j.jnoncrysol.2015.10.043.

Do, X.N. and Ibrahimbegovic, A. (2018), "2D continuum viscodamage-embedded discontinuity model with second order mid-point scheme", *Couple. Syst. Mech.*, **7**(6), 669-690. https://doi.org/10.12989/csm.2018.7.6.669.

Fröling, M., Persson, K. and Austrell, P.E. (2014), "A reduced model for the design of glass structures subjected to dynamic impulse load", *Eng. Struct.*, **80**, 53-60. https://doi.org/10.1016/j.engstruct.2014.08.043.

Griffith, A.A. (1920), "The phenomena of rupture and flow in solids", *Philos. Tran., Ser. A*, **221**, 163-198.

Guidance for European Structural Design of Glass Components (2014), European Commission, Joint Research Centre, Report EUR 26439 EN, Luxembourg.

Hán, T., Eliášová, M. and Sokol, Z. (2018), "Four point bending tests of double laminated glass panels", *Proceedings of the 24th International Conference Engineering Mechanics 2018*, Svratka, Czech Republic.

HR EN 12600:2006 (EN 12600:2002) (2006), Glass in Building-Pendulum Test-Impact Test Method and Classification for Flat Glass, Croatian Standards Institute, Zagreb, Croatia.

HR EN 356:2006 (EN 356:1999) (2006), Glass in Building-Security Glazing-Testing and Classification of Resistance against Manual Attack, Croatian Standards Institute, Zagreb, Croatia.

Ibrahimbegovic, A. and Mejia Nava, R.A. (2021), "Heterogeneities and material-scales providing physically-based damping to replace Rayleigh damping for any structure size", *Couple. Syst. Mech.*, **10**(3), 201-216. https://doi.org/10.12989/csm.2021.10.3.201.

Imamovic, I., Ibrahimbegovic, A. and Hajdo, E. (2019), "Geometrically exact initially curved Kirchhoff's planar elasto-plastic beam", *Couple. Syst. Mech.*, **8**(6), 537-553. https://doi.org/10.12989/csm.2019.8.6.537.

Irwin, G.R. (1957), "Analysis of stresses and strains near the end of a crack traversing a plate", *J. Appl. Mech.*,

24, 361-364. https://doi.org/10.1115/1.4011547.
Molnár, G., Vigh, L.G., Stocker, G. and Dunai, L. (2012), "Finite element analysis of laminated structural glass plates with polyvinyl butyral (PVB) interlayer", *Periodica Polytechnica Civil Eng.*, **56**(1), 35-42. https://doi.org/10.3311/pp.ci.2012-1.04.
Orowan, E. (1949), "Fracture and strength of solids", *Rep. Prog. Phys.*, **12**(1), 185-232.
Osnes, K., Holmen, J.K., Hopperstad, O.S. and Børvik, T. (2019), "Fracture and fragmentation of blast-loaded laminated glass: An experimental and numerical study", *Int. J. Impact Eng.*, **132**, 103334. https://doi.org/10.1016/j.ijimpeng.2019.103334.
Osnes, K., Hopperstad, O.S. and Børvik, T. (2020), "Rate dependent fracture of monolithic and laminated glass: Experiments and simulations", *Eng. Struct.*, **212**, 110516. https://doi.org/10.1016/j.engstruct.2020.110516.
Overend, M., De Gaetano, S. and Haldimann, M. (2007), "Diagnostic interpretation of glass failure", *Struct. Eng. Int.*, **17**(2), 151-158. https://doi.org/10.2749/101686607780680790.
Pacios, A., Postigo, S. and Huerta, C. (2011), "Relationship between characteristic parameters of impact test for safety glasses", *Stahlbau Spezial*, **80**(S1), 61-66. https://doi.org/10.1002/stab.201120008.
Parra, J.A., Alonso, J., Pacios, A. and Huerta, M.C. (2019), "Effective energy applied to a glass plate during an impact test", *Int. J. Impact Eng.*, **130**(3-4), 11-18. https://doi.org/10.1016/j.ijimpeng.2019.03.008.
Pelfrene, J. (2016), "Numerical analysis of the post-fracture response of laminated glass under impact and blast loading", Ph.D. Dissertation, Ghent University, Ghent, Belgium.
Pelfrene, J., Kuntsche, J., Van Dam, S., Van Paepegem, W. and Schneider, J. (2016), "Critical assessment of the post-breakage performance of blast loaded laminated glazing: Experiments and simulations", *Int. J. Impact Eng.*, **88**, 61-71. https://doi.org/10.1016/j.ijimpeng.2015.09.008.
Pelfrene, J., Van Dam, S., Kuntsche, J. and Van Paepegem, W. (2016), "Numerical simulation of the EN 12600 pendulum test for structural glass", *Proceedings of the Conference on Architectural and Structural Applications of Glass-Challenging Glass 5*, Ghent, Belgium, June.
Peroni, M., Solomos, G., Pizzinato, V. and Larcher, M. (2011), "Experimental investigation of high strain-rate behaviour of glass", *Appl. Mech. Mater.*, **82**, 63-68. https://doi.org/10.4028/www.scientific.net/AMM.82.63.
prEN 13474-3 (2009), Glass in Building-Determination of the Strength of Glass Panes-Part 3: General Method of Calculation and Determination of Strength of Glass by Testing, European Committee for Standardization, Brussels, Belgium.
Quaglini, V., Cattaneo, S. and Biolzi, L. (2020), "Numerical assessment of laminated cantilevered glass plates with point fixings", *Glass Struct. Eng.*, **5**, 187-204. https://doi.org/10.1007/s40940-020-00119-5.
Reich, S. and Sagar Vanapalli, M.R. (2018), "Hard body impact on glass panes and the fracture energy equilibrium", *Procedia Struct. Integ.*, **13**, 28-33. https://doi.org/10.1016/j.prostr.2018.12.005.
Schneider, J. and Schula, S. (2013), "Simulating soft body impact on glass structures", *Struct. Build.*, **169(**6), 416-431. http://doi.org/10.1680/jstbu.13.00112.
Timmel, M., Kolling, S., Osterrieder, P. and Du Bois, P.A. (2007), "A finite element model for impact simulation with laminated glass", *Int. J. Impact Eng.*, **34**(8), 1465-1478. https://doi.org/10.1016/j.ijimpeng.2006.07.008.
Van Dam, S., Pelfrene, J., De Pauw, S. and Van Paepegem, W. (2014), "Experimental study on the dynamic behaviour of glass fitted with safety window film with a small-scale drop weight set-up", *Int. J. Impact Eng.*, **73**, 101-111. https://doi.org/10.1016/j.ijimpeng.2014.06.002.
Viviani, L., Consolaro, A., Maffeis, M. and Royer-Carfagni, G. (2021), "Engineered modelling of the soft-body impact test on glazed surfaces", *Eng. Struct.*, **226**(S1), 111315. https://doi.org/10.1016/j.engstruct.2020.111315.
Wang, X., Yang, J., Liu, Q., Zhang, Y. and Zhao, C. (2017), "A comparative study of numerical modelling techniques for the fracture of brittle materials with specific reference to glass", *Eng. Struct.*, **152**, 493-505. https://doi.org/10.1016/j.engstruct.2017.08.050.
Yankelevsky, D.Z. (2014), "Strength prediction of annealed glass plates-A new model", *Eng. Struct.*, **79**, 244-255. https://doi.org/10.1016/j.engstruct.2014.08.017.

Zhang, X. and Hao, H. (2015), “Experimental and numerical study of boundary and anchorage effect on laminated glass windows under blast loading”, *Eng. Struct.*, **90**, 96-116. https://doi.org/10.1016/j.engstruct.2015.02.022.

Zhang, X., Hao, H. and Ma, G. (2013), “Laboratory test and numerical simulation of laminated glass window vulnerability to debris impact”, *Int. J. Impact Eng.*, **55**, 49-62. https://doi.org/10.1016/j.ijimpeng.2013.01.002.

Zhang, X., Hao, H. and Wang, Z. (2015), “Experimental study of laminated glass window responses under impulsive and blast loading”, *Int. J. Impact Eng.*, **78**, 1-19. https://doi.org/10.1016/j.ijimpeng.2014.11.020.

Zhang, X., Zou, Y., Hao, H., Li, X., Ma, G. and Liu, K. (2012), “Laboratory test on dynamic material properties of annealed float glass”, *Int. J. Protect. Struct.*, **3**(4), 407-430. https://doi.org/10.1260/2041-4196.3.4.407.