Effective energy applied to a glass plate during an impact test

J.A. Parra*, J. Alonso, A. Pacios, M.C. Huerta

Mechanical Engineering Dept., Universidad Politécnica de Madrid, Calle de José Gutiérrez Abascal, 2, 28006, Madrid, Spain

ARTICLE INFO

Keywords:

Glass
Impact
Impulse
Pendulum
2DoF
Human impact
Dynamic load
Effective energy

ABSTRACT

The study of the behaviour of glass plates under dynamic loads presents difficulties due to the uncertainty of the definition of load level, particularly in the case of human impact. The main differences from other impact tests are the dimensions of the specimens and the support structures for the various configurations, especially when tests are performed on a specific part of the building, for example, the facade. Even in tests performed under controlled conditions, in accordance with the standards, it can be observed that the level of excitation of the glass plate is clearly lower than expected if the initial height of the impactor is used. This has been observed in a test campaign involving 240 impacts, undertaken in accordance with EN 12,600. The analysis of the data shows that a percentage of energy (20%) does not deform the glass and is distributed among the remaining parts of the configuration. An experimental model has been developed in regard to the energy dissipation in order to obtain a more realistic level of excitation of the plate, using the effective impulse obtained from an accelerometer located on the pendulum head.

1. Introduction

In regard to safety glass in buildings, there are regulatory standards for sizing glass plates for various load scenarios [6,8]. After a detailed review of these regulations, a clear definition has been formulated for static loads, but there are only a few vague ideas in the case of dynamic loads. The complexity of producing a definition for these cases is due to the fragile nature of the glass. In fact, many studies have been performed on testing and modelling the strength capacity of glass for static behaviour [15] and for complex dynamic loads, such as low velocity soft impacts up to 3.3 m/s [20], dynamic deflection of a glass panel subject to point contact impact [17], laminated glass windows subjected to windborne wooden block impact [34] and stone impact resistance of a monolithic glass ply [31]. Complex dynamic loads also include both explosions [14] and human impact [25]. In various countries, the normative associated with these dynamic loads only presents a general classification of glass plates based on test results with respect to human impact [7], explosion pressure [9] and air blast loadings [3]. In addition, in the case of human impact, these standards do not cover the great variety of existing plate sizes and support configurations, which are present in the industry itself.

In the case of human impact, the area of load application generates high stress in small zones of the plate with values that are higher than those used for static sizing. As it is a fragile material, it is also well known that the velocity of the load significantly affects the rupture

stress of the glass [19]. In regard to experimental verifications, it is important to bear in mind the way to analyse the rupture of the glass and the actual level of applied load.

While human impacts are characterized by their impacting element and initial height, explosions are defined by their peak pressure and the form of the pressure wave over time [18], and also in some cases, the impulse applied by pressure impulse (PeI) diagrams [35,36].

A human impact can be classified as a type of soft impact due to its typical duration of between 40 and 100 ms. Since the end of the 20th century, different regulations, which define tests, have been established. The main difference between these tests is the shape of the impacting element. For example, in the USA [2,10] a bag containing lead shot is used, while in Europe a metal cylinder with two tyres is applied [7]. Both regulations establish drop heights of the pendulum in order to define the level of impact applied to the glass plates. This is insufficient for gaining more insight into the mechanical response of glass breakage by impact and determining the optimum values for all possible parameters [11].

Since 2013, the German Standard DIN 18008 [12] includes an appendix regarding the aspect of the dynamic phenomenon during contact with an impacting element. This standard sets forth several time histories of the acceleration of the pendulum head and deformations at the centre of the glass plate. The cases studied by this standard are for two energy levels associated with two initial drop heights and three glass configurations. Monolithic tempered 10 mm glass, which is used as a

* Corresponding author.

E-mail address: jose.parra.hidalgo@alumnos.upm.es (J.A. Parra).

reference in the Standard EN 12600 [7], is not included in the DIN 18008.

Currently, industry tests [33] are routinely performed on building facades. The support structure of the pendulum and the registration of the initial height present greater difficulties in controlling tests with higher uncertainties concerning the actual applied impact. Human impact phenomenon have been studied with the data obtained from an extensive testing campaign developed in accordance with the Standard EN 12600 [22]. This test campaign has already been published and is referred as the "Reference Campaign" in this article. Since the initial stages, a difference between the initial energy of the pendulum and the actual load applied to the plate has been detected. The response of any model is always higher than test measurements. In this test campaign, 21 glass plates, divided into 7 different configurations, were tested during 240 impacts. All samples were tested from several initial drop heights with energy levels of up to 590 J. The size of the glasses and their boundary conditions were: 876×1938 mm with four supported sides (4S) and four supported points (4P) and 876×1200 mm for two supported sides (2S). The types of glass tested include monolithic tempered glass with a thickness of 5 mm (T05) and 10 mm (T10) and annealed laminated glass with a thickness of 3 + 3 mm (L33), 4 + 4 mm (L44) and 5 + 5 mm (L55). In the case of annealed laminated glass, the polyvinyl butyral (PVB) layer between the glass plates had a thickness of 0.38 mm. Fig. 1 shows a general view of the test facilities with the glass plate specimen supported by a steel frame. The pendulum is supported by an independent and adjustable steel frame. For each impact, the time histories of the seven sensors were recorded by the data acquisition system.

Almost all registered impacts present difference between the initial energy of the pendulum and the response of the plate. This response is always smaller than that expected. For a better understanding of the

phenomenon, this paper presents the study of three glass configurations from the reference campaign: T10 4S, T05 4S and L55 4S. The drop heights of the impact analysed in this work are: 200 mm and 450 mm

To support the results of the Reference Campaign, a simplified model of two degrees of freedom (2DoF) was developed [1,26]. Other authors also use this type of model to study this phenomena [13,28]. 2DoF models reduce the computing time compared to full transient simulations, which are based on Finite Element Methods [27]. Finite Element Methods are more focused on the simulation of fracture behaviour of the glass plate [5,32]. Usually, a DoF is assigned to the mass of the pendulum head and another to the dynamic behaviour of glass. These kinds of simplified models are also used as time saving analytical techniques of other dynamic loads such as blast [4]. In this case, a single degree of freedom model can be estimated by applying the principles of the conservation of momentum and the conversion of kinetic energy into strain energy immediately following impact [17].

Using a simplified 2DoF model, the time histories of DIN 18008 can be reproduced for: a) an 876×1938 mm monolithic tempered glass plate with a thickness of 8 mm, supported on its four edges and b) a rigid wall. The time histories corresponding to 200 mm (100 Nm) and 450 mm (220Nm) of drop height are analysed. Figs. 2a) and b) show the time histories of the pendulum acceleration defined in DIN 18008. For each time history, the upper bounds (Ub) and lower bounds (Lb) defined by the standard are shown by dotted lines. The curves, shown by dashed lines, are those obtained from the simplified 2DoF model. Thus, the simplified model is validated for the calculation. These two drop heights are selected since they reproduce the real effect of a human impact against a glass plate [29].

The same model is used to obtain time histories (Fig. 3) of the acceleration with the T10 4S glass plate, which is considered a benchmark in the EN 12600 Standard.

The time histories of the 2DoF model for the T10 4S glass plate are compared with the results recorded in the Reference Campaign for the two initial heights. In Fig. 3, it is observed that the accelerations measured for the pendulum are lower (between 5% and 20%) than those obtained from the 2DoF model for both initial energies: 100 and 220 J.

The load applied to the glass during the test can be obtained by multiplying the pendulum mass by its acceleration. The effective impulse can be calculated by the integral of the load applied to the glass over the impact duration. The global impulse can be obtained from the initial and rebound heights of the pendulum, if an ideal pendulum is accepted. The effective impulse applied on the glass plate is always lower than the global values. All impacts of the Reference Campaign present the same behaviour. Therefore, the effective energy applied to the glass plate during the human impact test cannot be estimated by the initial height of the pendulum and another measurement should be used.

The difference found between an effective impulse applied to glass plate and a global impulse is studied by developing a model from the experimental data. The loss of energy by damping, not incorporated in the previous models, is taken into account. Additionally, a possible distribution of the initial energy between the pendulum and remaining system (pendulum and glass supports) during the entire phenomenon is included in this model.

The objective of this paper is to present the experimental model, which explains the difference between the global impulse of the pendulum and the effective impulse applied to the glass plate. This model is applied to data obtained from a test campaign developed according to the Standard EN 12600.

As a result, the use of the accelerometer measurement of the pendulum head, instead of the drop height of the pendulum, is proposed. In this manner, the level of impact on the glass may be characterised more precisely.

Fig. 1. "Reference Campaign" test set up.

Fig. 2. DIN 18008 reference diagrams.

Fig. 3. Comparison between tests and 2DoF time histories.

2. Experimental model: initial effective velocity of the pendulum

In the Reference Campaign, the time evolution of the pendulum behaviour is recorded for each impact, thereby noting its position and acceleration. An ACT2000C from RDP Electronic Linear Variable Differential Transformer (LVDT) with 100 mm travel located close to the pivot point of the pendulum and a piezoelectric accelerometer type 4371 from Brüel & Kjær, located on the mass, is used for this purpose. Fig. 4 shows the measurements of the sensors for nominal glass (T10 4S) at a height of 450 mm. From these time histories, the following data related to energy and impulse is obtained: the initial height, the rebound height and the impulse registered during the contact stage. The latter is obtained by the integral of the applied force (the product of the mass of the head multiplied by acceleration).

This phenomenon can be analysed from two different points of view: the global behaviour of the pendulum or the load (excitation) applied to the glass.

In order to study the global behaviour, each impact is characterized by the following parameters: the initial height (h_0), the rebound height (h_f) of the pendulum obtained from LVDT measurement and the mass of the pendulum head (m_p). With these parameters, the overall movement of the pendulum is described below with its initial (E_0), final energy (E_f) and dissipated energy (ΔE), Eqs. (1) (3). Additionally, the global impulse (I) can be obtained from the maximum velocities of the pendulum corresponding to the initial height (v_0) and rebound height (v_f) (Eq. (4)).

$$E_0 = m_p g h_0 = \frac{m_p v_0^2}{2} \quad (1)$$

$$E_f = m_p g h_f = \frac{m_p v_f^2}{2} \quad (2)$$

$$\Delta E = E_f - E_0 \quad (3)$$

$$I = \Delta p = -\sqrt{2g} m_p (h_f^{1/2} + h_0^{1/2}) = m_p (v_f - v_0) \quad (4)$$

For the study of the plate behaviour, the effective impulse (I_{ef}) is obtained as an integral of the acceleration ($\ddot{x}_p$) multiplied by the mass of the pendulum head, which corresponds to the excitation applied by the glass plate due to the inertial force of the pendulum head during the contact stage Eq. (5). At this point, initial (v_{eff}) and final (v_{eff}) effective velocities are defined to reflect the excitation produced on the glass with the corresponding energy and impulse (Eqs. (5) (6)).

$$I_{ef} = \Delta p_{ef} = \int_0^f m_p \ddot{x}_p dt = m_p \Delta v_{ef} = m_p (v_{eff} - v_{eff}) \quad (5)$$

$$\Delta E_{ef} = 1/2 m_p (v_{eff}^2 - v_{eff}^2) \quad (6)$$

To develop the proposed model and estimate the actual load level for the glass, only one hypothesis has been considered, which is that the energy lost during the global phenomenon (ΔE) occurs during the contact stage. According to this hypothesis, the energy lost from a global point of view can be equated with the loss of effective initial energy (ΔE_{ef}) during contact (Eq. (7)).

$$\Delta E_{ef} = \Delta E = m_p g (h_f - h_0) \quad (7)$$

By using the previous equations, the actual velocities (v_{eff} and v_{eff}) can be obtained from the test parameters h_0 , h_f and I_{ef} as shown in Eq. (8) (11).

$$m_p g (h_f - h_0) = 1/2 m_p (v_{eff}^2 - v_{eff}^2) \quad (8)$$

$$v_{eff} = \frac{I_{ef}}{m_p} + v_{eff} \quad (9)$$

$$m_p g (h_f - h_0) = 1/2 m_p \left(\left(\frac{I_{ef}}{m_p} \right)^2 + 2 \frac{I_{ef}}{m_p} v_{eff} + v_{eff}^2 - v_{eff}^2 \right) \quad (10)$$

$$2g (h_f - h_0) = \left(\left(\frac{I_{ef}}{m_p} \right)^2 + 2 \frac{I_{ef}}{m_p} v_{eff} \right) \quad (11)$$

The final expressions used to obtain the values for the effective velocities are as follows Eqs. (12) (13).

$$v_{eff} = \frac{m_p g (h_f - h_0)}{I_{ef}} + \frac{I_{ef}}{2m_p} \quad (12)$$

$$v_{eff} = \frac{m_p g (h_f - h_0)}{I_{ef}} - \frac{I_{ef}}{2m_p} \quad (13)$$

In Fig. 5, the global impulse (Eq. (4)) and effective impulse (Eq. (5)) are plotted for the all impacts tested in the Reference Campaign. As can be observed, the global impulse (I) is always clearly higher than the effective one (I_{ef}). Thus, not all the energy of the pendulum is being applied to the glass plate.

The initial global energy (E_0) is distributed between the effective

Fig. 4. Main parameters of the pendulum impact.

Fig. 5. Comparisson between global and effective impulse.

energy (E_{ef}) applied to the glass and the residual energy (E_{res}) applied to the remaining parts. To quantify this difference, a distribution coefficient (r) is defined as the ratio between E_{ef} and E_0 (Eqs.14 15) and can be obtained from previous results.

$$E_0 = E_{ef} + E_{res} = rE_0 + E_{res} \quad (14)$$

$$r = \frac{(v_{eff}^2)}{2g h_0} \quad (15)$$

The previous equations are applied to the accelerometer time histories presented in Figs. 2a, b and 3: the experimental data for the T10 4S plate and the hypothesis $h_0 = h_f$ for the DIN18008 data [28].

Table 1 illustrates that the magnitude of the global and effective impulse has the same value in the case of the impacts defined by the

Table 1
Proposed model applied to the DIN18008.

	h_0 [m]	h_f [m]	I [Kg m/s]	I_{ef} [Kg m/s]	v_{eff} [m/s]	r [%]
Rigid E 100 Std	0.2	0.2	198.09	197.84	1.98	100
Rigid E 220 Std	0.45	0.45	297.14	297.03	2.97	100
T08-4L E 100 Std	0.2	0.2	198.09	197.57	1.98	100
T08-4L E 220 Std	0.45	0.45	297.14	296.98	2.97	100
T10-4L E 100 ref.	0.21	0.17	191.12	159.22	1.71	72
T10-4L E 220 ref.	0.46	0.37	285.92	244.74	2.63	76

standard. Therefore, in the time histories of the standard all the initial energy of the pendulum is transmitted to the glass ($r = 100\%$). In the case of the data obtained from the Reference Campaign, the global impulse is higher than the effective impulse and a distribution coefficient of 72% results. This indicates that insofar as measured impacts, a portion of the energy of the pendulum is not applied to the glass plate.

3. Dissipated energy: damping contribution

The main hypothesis used to develop this study is that the energy lost during the impact is produced during the contact stage due to the deformation of the pendulum and glass plate. In order to verify this hypothesis, a comparison of the loss of energy during the impact and the damping of the coupled system (pendulum with glass in contact) has been performed.

The values for the first magnitude are obtained directly from the test with the initial and final height of the pendulum measured with the LVDT. For the second magnitude, damping coefficients, measured during modal tests, are used in combination with the 2DoF model.

3.1. Two 2DoF model including damping

As shown in Fig. 6, a 2DoF common model is used, including damping. The first DoF corresponds to the mass (m_p), stiffness (k_p) and damping (C_p) of the pendulum head. The other DoF represents the equivalent mass (m_g) stiffness (k_g) and damping (C_g) of the first mode of glass at the centre of the plate. These values are obtained using the modal component of the first mode, normalized to unit mass (ϕ_c), and the natural frequency (ω_g) by the following expressions: $k_g = \omega_g^2 / \phi_c^2$ and $m_g = k_g / \omega_g^2$.

In order to calculate the response of the glass, an initial velocity of the pendulum DoF and a modal superposition technique is used to solve for the transient response. Therefore, the modal damping for the two mode shapes should be defined by using the damping of the model.

Modal and static tests on the plate and pendulum head are used to obtain the values of the 2DoF model (Table 2).

The equilibrium equation of the system with viscous damping can be expressed by the mass (M), damping (C) and stiffness (K) matrix (Eq. (16))

$$M\ddot{x} + C\dot{x} + Kx = 0 \quad (16)$$

Assuming proportional damping, real mode shapes appear (ϕ_{ij}) ($i = g, p$ and $j = 1, 2$) and the eigenvalue (λ_j) includes the natural frequency (ω_j) and modal damping ratio (ζ_{-j}) Eqs. (17) (18) (Singiresu S. [30]).

$$\phi = \begin{bmatrix} \phi_{g1} & \phi_{g2} \\ \phi_{p1} & \phi_{p2} \end{bmatrix} \quad (17)$$

$$\lambda_j = \zeta_j \omega_j - i \omega_j \sqrt{1 - \zeta_j^2} \quad (18)$$

To estimate the damping ratio of each mode (ζ_{-j}) the total loss of energy in a cycle can be calculated (ΔE_j) and divided by the total elastic energy (E_{0j}) (Eq. (19)). This energy can be considered as the sum of strain energies of each DoF (Eq. (20)). The loss of energy for each element is proportional to the elastic energy (E_{0pj}, E_{0gj}) and the specific damping ratio (ζ_p, ζ_g) (Eq. (21))

Table 2

Test results: independent modal test and quasistatic test.

	Glass Plates			Pendulum head	
	T10-4S	T05-4S	L55-4S	Dynamic	Quasi-static
Frequency (Hz)	35.60	20.38	36.24	13.27	–
Damping ratio (%)	0.86	0.77	1.78	4.03	3.50–4.50
Apparent Stiffness (KN/m)	898.3	83.3	881.0	350.0	350.0
Apparent Mass (Kg)	17.95	5.08	16.99	50.35	50.00

$$\frac{\Delta E_j}{E_{0j}} = 4\pi\zeta_j \quad (19)$$

$$E_{0j} = 1/2 k_p (\phi_{pj} - \phi_{gj})^2 + 1/2 k_g (\phi_{gj})^2 = E_{0pj} + E_{0gj} \quad (20)$$

$$\Delta E_j = 4\pi\zeta_p E_{0pj} + 4\pi\zeta_g E_{0gj} \quad (21)$$

The modal damping ratio of each mode ($j = 1, 2$) of the coupled structure (pendulum and glass) is obtained by (Eq. (22)).

$$\frac{\Delta E_j}{E_{0j}} = 4\pi\zeta_j = 4\pi \frac{\zeta_p E_{0pj} + \zeta_g E_{0gj}}{E_{0pj} + E_{0gj}} \quad (22)$$

Modal superposition is applied to solve the dynamic response. Each mode behaves as one DoF with its own damping coefficient. Thus, a better approximation is obtained for the structural damping ratio.

3.2. Characterisation tests: obtaining experimental damping

To apply the 2DoF model presented above, the characteristics of the pendulum head and glass should be defined. For this purpose, modal and quasi static tests for the pendulum head and a modal test for the plate were conducted.

• Characteristics of pendulum head

A modal test was performed on the pendulum head, simply supported over a reaction mass, to obtain its dynamic characteristics. The response was acquired by two accelerometers located at points one and two. An instrumented hammer was used to apply a load on point one. Fig. 7 shows the test set up and that of the measured frequency response functions (FRFs) with an adjusted one. Due to the nature of the tyres, complex mode shapes have been used to adjust the FRFs. The first mode corresponds to the vertical movement of the mass and the second to the pitch movement.

The adjusted natural frequency and damping coefficient obtained for the first mode are shown in Table 2. During this test, the load applied to the pendulum head was very low (max 200 N) compared with the load levels found during the impact that may reach 10 kN. Therefore, a quasi static test was carried out at a more realistic load level in order to study the effect of possible non linearities of stiffness and damping.

The quasi static characterization of the pendulum tyre is performed using a static testing machine. To study the dependence of damping with different factors, several sinusoidal loads were tested at different load levels and frequencies. The time histories of load and displacement were measured during each test. In Fig. 8, the configuration of the test is shown, as well as a typical force versus displacement curve for several load amplitudes and frequencies.

Fig. 6. Two DoF model.

Fig. 7. Modal test set up and FRF obtained.

The damping is estimated by the area inside the force displacement curve that corresponds to the dissipated energy. Tests with a similar force level and frequencies between 0.001 to 0.01 Hz produced similar damping and stiffness values for the tyre. When the load was varied between 2000 and 4000 N, a similar stiffness was obtained and damping varied within the range of 3.5 4.5%, in accordance with the results obtained in the modal test.

- Glass plate:

During the Reference Campaign, a modal test was performed prior to the impact test. Table 2 shows the stiffness, mass, natural frequency and damping ratio obtained for the selected plates: T10 4S, T05 4S and L55 4S. The characteristics of the pendulum are also included.

From the results presented in Table 2, it may be observed that the dynamic characteristics (stiffness and natural frequency) of the glasses T10 4S and L55 4S are similar [23]. The main difference is the higher damping for laminated glass. On the other hand, when comparing the glass T10 4S with the T05 4S, significant changes in the stiffness are obtained, but the damping of these two glass plates is similar. For the pendulum, the stiffness and damping ratio have been verified by static and dynamic tests, thereby obtaining similar results for stiffness and damping. Therefore, with these specimens, the model that studies the influence of damping for the same stiffness and the stiffness for the same damping can be verified.

With this experimental data, an estimate may be performed for the damping of the two modes of the couple behaviour by using the 2DoF model. Table 3 sets forth the natural frequency mode shapes and modal damping.

Table 3
Modal parameters for 2Dof models.

Mode shape	J	f_n [Hz]	ϕ_p	ϕ_g	ζ_p [%]	Damping ζ_g [%]	ζ_j [%]
Glass plate							
T10 4S	1	10.9	1.39E-01	4.19E-02	4.03	0.84	2.98
	2	43.8	2.49E-02	2.34E-01	4.03	0.84	1.86
L55 4S	1	10.9	1.39E-01	4.55E-02	4.03	2.01	3.30
	2	43.4	2.56E-02	2.47E-01	4.03	2.01	2.70
T05 4S	1	8.31	1.39E-01	8.47E-02	4.03	0.88	1.98
	2	54.3	2.74E-02	4.28E-01	4.03	0.88	2.76

3.3. Comparison of the damping with the loss of energy during impact

The main hypothesis, formulated for the experimental model, is that the loss of energy of the pendulum head is due to dissipation during contact with the plate corresponding to one half of the vibration cycle. For verification purposes, a loss of energy damping (ζ_{ef}) for each impact may be estimated by using the loss of energy of the pendulum (Eq. (23)) measured by its initial and final height.

$$\zeta_{ef} = \frac{2\Delta E}{4\pi E_0} \quad (23)$$

The hypothesis is admissible for the model if the effective initial velocity, obtained from the equation (Eq. (24)) with loss of energy damping (ζ_{ef}), is comparable with the value obtained from modal damping (ζ_1).

$$\zeta_{ef} = \frac{(v_{efI}^2 - v_{efF}^2)}{2\pi v_{efI}^2} \quad (24)$$

Table 4 shows the effective initial velocity obtained from both damping coefficients: the loss of energy damping (ζ_{ef}) and the modal

Fig. 8. Static set up and results.

Table 4

Initial effective velocity obtained from loss of energy damping and modal damping.

Height [mm]		v_{eff} (m/s)		Relative change v_{eff} [%]
		ζ_{ef}	ζ_1	
T10	200	1.71	1.67	2
	450	2.63	2.57	2
T05	200	1.68	1.63	3
	450	2.60	2.51	4
L55	200	1.61	1.55	4
	450*	2.38	2.20	7

Fig. 9. Broken laminate glass plate after impact.

damping of the first mode (ζ_1). The relative change between both values of v_{eff} is lower than 4% for five impacts. Therefore, it can be said that the hypothesis formulated for loss of energy is valid for the estimation of the effective initial velocity.

Note that the impact test of the laminated glass plate L55 and from a drop height of 450 mm, marked with an asterisk, corresponds to an impact applied to a plate with one fractured ply (see Fig. 9). As widely recognized, after the rupture of one ply, the plate has a remaining structural capacity [16] and the dynamic behaviour of such plate changes substantially [21, 24]. Thus, this value is inadequate for verifying the hypothesis, and it would be necessary to update the dynamic characteristics of the plate. The remaining impacts, presented in this paper, do not present any kind of fracture.

4. Impact test results

Using the model presented in Section 2, the following values for the description of the six impacts obtained for three different plates and two initial drop heights are shown in Table 5.

Table 5

Effective velocities and energy distribution obtained from the proposed model.

	h_0 [m]	h_f [m]	I_{ef} [Kg m/s]	v_{eff} [m/s]	v_{eff} [m/s]	r [%]
T10-4S	0.21	0.17	159.22	1.71	1.47	72
	0.46	0.37	244.74	2.63	2.27	76
T05-4S	0.20	0.17	157.66	1.68	1.47	71
	0.46	0.37	242.61	2.60	2.25	75
L55-4S	0.20	0.15	146.13	1.61	1.31	67
	0.46*	0.34	207.83	2.38	1.78	62

Fig. 10. Proposed 2DoF model vs Tests.

The effective impulse obtained from the accelerometer is similar for equal impacts with the same height for the three plates. However, it is lower than the global impulse, as may be observed in Fig. 5. The energy distribution coefficient (r) is between 67% and 76% for all glass plates, except for L55 4S with a drop height of 0.46 m. This is due to the higher damping of the remaining plate.

Fig. 10 illustrates a comparison of the time histories, obtained from the proposed model simulation and test for T10 4S. Throughout the entire time history, the proposed model performs better than the previous 2DoF model shown in Fig. 3. Table 6 presents the impulse applied during the impact for the previous 2DoF model, the proposed one and the test for the reference plate.

Table 7 shows the initial global velocities of the pendulum due to the initial height and the effective initial velocities with the relative change between them. In all cases, the effective initial velocity is lower, so the actual level of load applied to the glass may always be lower than expected by measuring the initial height. The error made in measuring the initial drop height, as a reference for the velocity applied to the glass, is between 15% and 22% of the global initial velocity. Therefore, the use of the proposed experimental model is significant when the actual applied load to the glass plate is significant for the test.

In addition, the same conclusion may be obtained by taking into account the final velocities, thereby supporting the hypothesis made for damping. Dissipation occurs mainly during the stage when the pendulum makes contact with the glass.

5. Conclusions

This article concerns an experimental study of human impact on safety glass. This study explains the difference between the accelerations, recorded in the Reference Campaign, under controlled conditions and the nominal values calculated from the initial height of the pendulum. The dissipated energy is associated with the contact stage. It has been found that the energy of the pendulum is distributed between the glass plate and the remaining parts of the system. The effective velocity is obtained from the impulse and the damping estimates from the impact test or modal test. A 2DoF model has been used as support for the

Table 6

Effective impulse, maximum Acceleration and duration for the reference plate.

	h_0 [m]	I_{ef} [Kg m/s]	Max. acceleration [m/s ²]	Duration [s]
Test	0.21	159.22	122.84	0.048
	0.46	244.74	200.68	0.045
Previous 2DoF	0.21	193.60	143.78	0.045
	0.46	288.07	212.31	0.044
Proposed 2DoF	0.21	143.82	104.59	0.045
	0.46	237.23	171.43	0.044

Table 7

Difference between global velocities and effective velocities.

	h_0 [m]	v_0 [m/s]	v_{eff} [m/s]	Rel. change [%]	v_f [m/s]	v_{eff} [m/s]	Rel. change [%]
T10-4S	0.21	2.01	1.71	17	1.81	1.47	19
	0.46	3.01	2.63	15	2.71	2.27	16
T05-4S	0.20	2.00	1.68	19	1.83	1.47	20
	0.46	3.01	2.60	16	2.71	2.25	17
L55-4S	0.20	1.97	1.61	22	1.73	1.31	24
	0.46*	3.02	2.38	27	2.57	1.78	31

study.

The following are the main conclusions of this work:

1. The impulse from the pendulum acceleration corresponding to the nominal value of the drop heights for the impacts, defined by the standards, is obtained. For all the impacts recorded in the Reference Campaign, they are lower. This difference does not correspond with the energy dissipation, as this magnitude is controlled by the measured initial and the final height of the pendulum.
2. The initial effective velocity has been obtained under the assumption that the energy dissipates during the contact stage. Consequently, it becomes obvious that there is a distribution of the pendulum energy (r) between the glass and the deformation of the remaining elements of the system.
3. The hypothesis that the energy dissipation occurs mainly during the contact stage is validated. The measured energy loss during the test is compared with a mixed theatrical experimental estimation of the damping. The differences between the estimated initial velocities are less than 4%.
4. Therefore, a good model for characterising the impact may be defined by the impulse and the damping of the coupled behaviour.
5. The study shows that the energy used for the excitation of the glass plate is between 67% and 76% of the initial global energy of the pendulum measured by the initial drop height. This entails a relative change of up to 22% of the initial velocities.

Finally, it is advisable to use an accelerometer located on the pendulum head to replace the drop height of the pendulum to achieve a more accurate level of the impact on the glass.

References

- [1] Alonso J, Parra-Hidalgo JA, Huerta Gómez de Merodio MC. Simplified model for the behavior of human impact against glass plates. In *4th International Conference on Mechanical Models in Structural Engineering*. 2017.
- [2] ASC, 2015. ANSI Z97.1 Safety glazing materials used in buildings - Safety performance specifications and methods of test.
- [3] ASTM, 2004. Standard test method for glazing and glazing systems subject to air-blast loadings.
- [4] Bedon C, Amadio C, Sinico A. Numerical and analytical investigation on the dynamic buckling behavior of glass columns under blast. *Eng Struct* 2014;79:322–40.
- [5] Du Bois P, Kolling S, Fassnacht W. Modelling of safety glass for crash simulation. *Comput Mater Sci* 2003;28(3–4):675–83.
- [6] CEN, 2016. EN 1026 Windows and doors. air permeability. Test method.
- [7] CEN, 2002. EN 12600: gGlass in building – pendulum test – impact test method and classification for flat glass.
- [8] CEN, 2000. EN 1288 Glass in building. Determination of the bending strength of glass.
- [9] CEN, 2001. EN 1354 Testing and classification of resistance against explosion pressure.
- [10] CFR, 2012. 16 CFR 1201 - Safety standard for architectural glazing materials.
- [11] Van Dam S, et al. 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* 2014;73:101–11.
- [12] DIN, 2013. DIN 18008-4 Design and construction rules - Part 4: aAdditional requirements for barrier glazing.
- [13] Fröling M, Persson K, Austrell P-E. A reduced model for the design of glass structures subjected to dynamic impulse load. *Eng Struct* 2014;80:53–60.
- [14] Hidallana-Gamage HD, Thambiratnam DP, Perera NJ. Influence of structural sealant joints on the blast performance of laminated glass panels. *J Perform Constr Facil* 2015;29(6).
- [15] Huerta Gómez de Merodio MC, et al. Influencia de un recubrimiento de vinilo en la tensión de fractura del vidrio en ensayos de anillos concéntricos con gran superficie. In *XXXI Encuentro del Grupo Español de Fractura*. 2014.
- [16] Kott A, Vogel T. Safety of laminated glass structures after initial failure. *Struct Eng Int* 2004;14(2):134–8.
- [17] Lam NTK, et al. Impact resistance of annealed glass panels. *J Perform Constr Facil* 2011;25(5):422–32.
- [18] Larcher M, et al. Experimental and numerical investigations of laminated glass subjected to blast loading. *Int J Impact Eng* 2012;39(1):42–50.
- [19] Mohagheghian I, Wang Y, Zhou J, et al. Deformation and damage mechanisms of laminated glass windows subjected to high velocity soft impact. *Int J Solids Struct* 2017;46–62.
- [20] Mohagheghian I, Wang Y, Jiang L, et al. Quasi-static bending and low velocity impact performance of monolithic and laminated glass windows employing chemically strengthened glass. *Eur J Mech* 2017;63:165–86.
- [21] Pacios-Alvarez A, et al. Post-fracture behaviour of laminated plates after human impact test. *COST Action TU0905 Mid-Term Conference on Structural Glass*. Escuela Técnica Superior de Ingenieros Industriales. Spain: Universidad Politécnica de Madrid; 2013. p. 165–72.
- [22] Pacios A, Postigo S, Huerta C. Relationship between characteristic parameters of impact test for safety glasses. *Stahlbau* 2011;80(SPEC. ISSUE):61–6.
- [23] Parra-Hidalgo JA, et al. Laminated glass resistance against human impact. 6th International Operational Modal Analysis Conference. IOMAC 2015; 2015.
- [24] Pelfrene J, et al. Critical assessment of the post-breakage performance of blast loaded laminated glazing: experiments and simulations. *Int J Impact Eng* 2016;88:61–71.
- [25] Postigo S, Pacios A, Huerta C. Basic design criteria for an impact test frame for safety glazing. *Boletín de la Sociedad Española de Cerámica y Vidrio* 2011;50(5):273–8.
- [26] Postigo Pozo S. Estudio teórico experimental de impactos humanos contra vidrios de acristalamientos de edificación. UPM Escuela Técnica Superior de Ingenieros Industriales; 2010.
- [27] Rück R, Weschler M. Numerical simulation of the pendulum test with a glass plate. *Otto-Graf-J* 2000;11:109–22.
- [28] Schneider J, Schula S. Simulating soft body impact on glass structures. *Proc Instit Civil Eng* 2016;169(6):416–31.
- [29] Schneider J, Schula S, Burmeister A. Two mechanical design concepts for simulating the soft body impact at glazings part 1: numerical, transient finite element simulation and simplified concept with equivalent static loads | Zwei Verfahren zum rechnerischen Nachweis der dynamischen Beanspruchung. *Stahlbau* 2011(SPEC. ISSU).
- [30] Rao Singiresu S. Mechanical vibrations. 5th ed PEARSON; 1986.
- [31] Sun X, Khaleel MA, Davies RW. Modeling of stone-impact resistance of monolithic glass ply using continuum damage mechanics. *Int J Damage Mech* 2005;14(2):165–78.
- [32] Timmel M, et al. A finite element model for impact simulation with laminated glass. *Int J Impact Eng* 2007;34(8):1465–78.
- [33] Vidal, A., An innovative insulating glass unit. *Freeminds Bellapart Construction*.
- [34] Zhang X, Hao H, Ma G. Dynamic material model of annealed soda-lime glass. *Int J Impact Eng* 2014;77:108–19.
- [35] Zhang X, Hao H, Ma G. Parametric study of laminated glass window response to blast loads. *Eng Struct* 2013;56:1707–17.
- [36] Zhang X, Hao H, Wang Z. Experimental study of laminated glass window responses under impulsive and blast loading. *Int J Impact Eng* 2015;78:1–19.