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EXPERIMENTAL TESTING OF BURGLAR RESISTANCE OF FENESTRATION

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Research article

Abstract: Currently, windows and glass facades are increasingly being used as a building envelope. These are elements that are functional and aesthetic, but there is a need to focus on their safety. Windows as a part of protection system are one of the most vulnerable assets, so they need to be addressed. The paper is focused on the experimental investigation of two types of windows that are commonly used in buildings. The subjects of the interests are wooden frame windows and PVC frame windows. In the experiment, burglar resistance was investigate, carried out by dynamic tests with different weights of steel balls dropped from various heights. Results of the experimental measurement pointed to the limit energy glass panels were broken. Windows with safety film were also tested. The measured results were further evaluated.

Keywords: Glass windows, impact test, impact resistance, security glazing, burglar resistance.

Introduction

Security of assets is one of the most important aspects to be considered in the protection of property and people. The essential matter of protecting assets is to know their vulnerability. One of the most vulnerable part of the buildings are windows and glass facades creating part of the building envelope. If we want to increase the resistance of the elements of protection, we need to identify their resistance to the negative phenomena as burglar attack is. Several standards describe various approaches how to examine their resistance. In consequences mentioned standards classify them into several resistance classes according to the different criteria. In this paper, we focused on an experimental investigation of the resistance of two types of windows under dynamic load. The dynamic performance of these systems was performed following the drop ball standard.

Windows and glass facades

Glass is a material with different applications. It is used in windows, doors, and building facades. There are many options for selecting its functions (security, functionality). Glass is a brittle material, is weak in stress due to the nature of its atomic structure and the resulting susceptibility to deficiencies and the inability to resist crack propagation. Glass behaves purely elastically until it suddenly reaches maximum tensile strength, unlike structural steels, aluminium alloys, and even reinforced concrete, which can adapt to plastic deformation after the yield point. High stressed glass and larger stretched surfaces result in a higher probability of failure. Thus, the glass has very little or if some deformation and suddenly fail. In the glass, there is a slow growth of micro-cracks in a permanent or cyclic load situation. Once the cracks reach a critical size, the glass may instantly fail. The following figure shows the behaviour of glass, steel and aluminium alloys under tensile stress (Code, 2018).

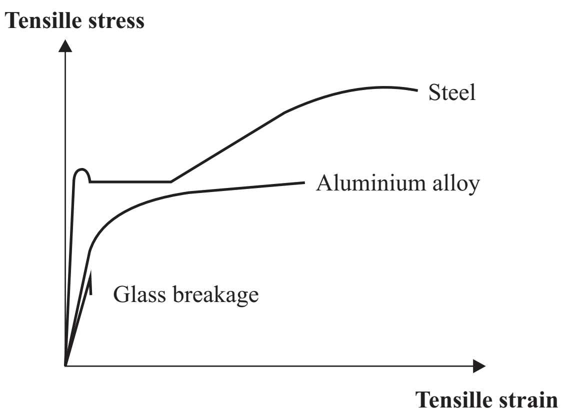

Fig. 1 Strength of individual materials under tensile stress-strain (Code, 2018)

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The limit state of glass can be defined as the state beyond which the structure no longer meets the relevant design criteria. The limit state design is based on the requirement of resistance, which should be greater than the load effect. This statement can be expressed by (Code, 2018):

$$\text{Resistance} \geq \text{Load effect}$$

The strength of the glass varies greatly depending on the particular heat treatment cycle used in its manufacture, resulting in different types of glass. There are many glasses, which can include (Code, 2018):

- Annealed glass (ordinary Float glass) - produced by melting glass and breaking into large fragments with sharp edges.
- Heat-strengthened glass - glass that has been heated above its softening point and cooled rapidly to increase its strength. It breaks like annealed glass.
- Insulating glass- it is an assembly consisting of two or more glass panes separated by a bar spacing to form a cavity between the glass panes.
- Safety glass - these are glass or facades that are "break safe", such as laminated or toughened glass.

Laminated glass is a safety glass used in construction, architecture, often as building structures (partitions, railings). The structure of the glass is consisting of two or more pieces of glass bonded by one or more PVB (poly vinyl-butyral) films. If the glass is damaged, the film holds the fragments together (Laminated, 2019).

Tempered safety glass is specially heat-treated so that when broken, the glass is broken into small pieces. Tempered glass is formed by rapidly cooling the outer surface of the glass. The result is four times more resistant to impact than annealed glass (Guidelines, 2013).

As already mentioned, each glass (window) has different properties that reflect its resistance. The dynamic response of windows depends on the strength and stiffness of the glass. If a dynamic load is applied to the window, several failures may occur when (Code, 2018):

- The tensile strength of the glass is achieved.
- The maximum bending deformation (or the maximum slope of the deformation curve of the structure) has been exceeded.
- The entire window construction is torn from masonry or other wall material.

Safety glass must be made of quality materials. The measure their quality, some standards need to be met to talk about safety glasses. These glasses are strengthened to resist breakage, or if the force applied is too great, the glass is broken carefully. Safety glass can be reinforced in two ways: laminating or tempering (Which, 2019). We know a set of several standards to determine the resistance of windows. In the area of security of objects, property, and persons, glass (general windows and glass facades) is very important.

Fenestration and their function in the field of security

Asset protection can be defined as the complex of security, technical, and regime measures aimed at impeding any adverse event against a protected assets and persons. The aim is to prevent attacks on persons and property, but also to prevent violations of the established regime, peace, and order in the protected area. Asset protection is realized by integrating forces and means on multiple layers of protection (Hofreiter, 2015). Windows and glass facades play an important function in the envelope protection of assets. This layer of protection is one of the most important because separates the external space from the internal environment.

Physical security is a summary of security measures implemented on assets and buildings. This protection aims to prevent entry into the building, to deter and slow down the intruder. It consists of building elements (walls, ceilings...), which are complemented by structural parts. Among the structural parts we can include (Mach, 2010):

- doors and their components,
- windows and their components,
- bars, blinds, roll-top.

Windows and glass facades are often used in buildings. Often they become places, used by perpetrators to enter into the assets. Therefore, their function is not only to lighten the individual spaces of the buildings, but also to secure the building envelope sufficiently. A burglar can use several ways to break the glass. One possibility is to break glass with an object (stone) or a tool (hammer). Another way is to break a glass by using its strength (shoulder punch, leg). The standard that deals with burglary resistance of windows classifies several sets of tools to overcome the window. In practice, crowbar, hammer, ax are the most commonly used tools for breaking windows. Based on their resistance, their passive safety can be determined (Zvaková and Kavický, 2016). In many cases, their resistance is

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defined by a set of standards. Relevant standards are described in the following.

Standards concerned with the resistance of glass and windows

One of the most essential standards analysing the resistance of the structural glass is EN 12 600 Glass in Building - Pendulum test - Impact test method and classification for flat glass. It used to test the strength of safety glass for application in buildings. The standard defines safety glass as glass which must have passed an impact test and either must not break or must break safely. The glass is subjected to a test where rubber tires weighing 50 kg are released into the glass pane at different heights. Three-digit ratings are given to the glass, e.g. 3B2 or 3C1 depending on the limited height of the pendulum the type of rupture of damaged glass (EN 12 600).

The standard classifies tests into three major resistance classes (Tab. 1). The first number represents the height class from which the pendulum dropped when the glass was not broken or broken into small fragments. The second letter represents the type of breakage mode. The third letter shall be given for a height class in which the glass does not break or does not allow penetration (Which, 2019).

Tab. 1 Resistance classes according to EN 12 600 (Šubrt and Petrtyl, 2019)

Classification	Drop height [mm]
3	190
2	450
1	1200

The effect of the impactor is similar to the person hitting the glass with the shoulder. This classification is complemented by the types of infringement which are (Šubrt and Petrtyl, 2019):

- Type A - numerous cracks appear, forming separate fragments with sharp edges, some of which are large,
- Type B - numerous cracks appear, but fragments are joined and not separated; (failure mode typical of coated and laminated glass),
- Type C - disintegration occurs, resulting in a large number of small particles that are relatively harmless (toughened glass).

The following figure (Fig. 2) shows the test equipment, where we can also see where the drop height is measured.

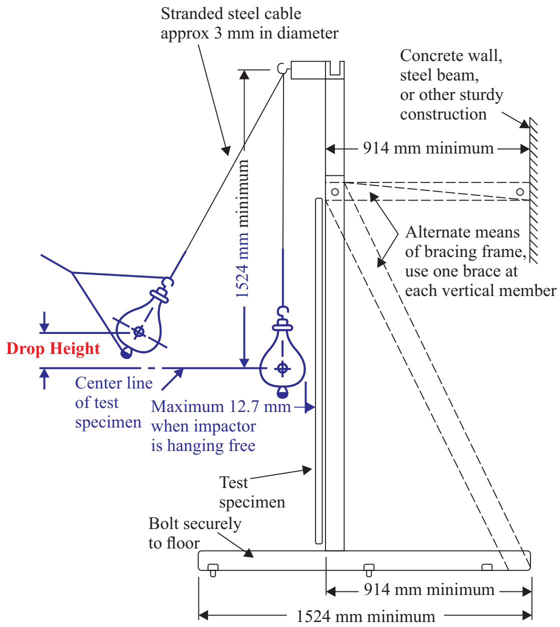

Fig. 2 Standard measurement scheme (EN 12 600, 2017)

Another important standard dealing with the resistance of glass, respectively of windows is EN 356 Glass in building - Security glazing - Testing and classification of resistance against manual attack. This standard classifies individual glasses into 8 levels. In the testing process, the glass is subjected to several tests to determine its strength. The standard divides windows into two classes depending on type of test, (Šubrt and Petrtyl, 2019):

- P1A to P5A,
- P6B to P8B.

In the first 5 levels, the test is based on the drop of the ball. The test is carried out using a steel ball with the mass of 4.11 kg for classes P1A to P5A and an axe for classes P6B to P8B. The ball is dropped on the test sample several times from different defined heights according to the resistance class. The ball shall not penetrate the glass for the test item to pass the examination. Specifications for these test levels are summarised below.

Tab. 2 Resistance classes according to EN 356 (Šubrt and Petrtyl, 2019)

Resistance category	Examination
P1A	Drop height 1 500 mm + 3 strikes of axe in triangle
P2A	Drop height3 000 mm + 3 strikes of axe in triangle
P3A	Drop height6 000 mm + 3 strikes of axe in triangle
P4A	Drop height 9 000 mm + 3 strikes of axe in triangle
P5A	Drop height9 000 mm + 3x3 strikes of axe in triangle
P6B	From 30 to 50 strikes of axe
P7B	From 51 to 70 strikes of axe
P8B	Over 70 strikes of axe

The last three levels of the EN 356 test are based on an axe test. These are permanent attacks with a tool (the axe) against the glass. The test includes a hydraulically driven hammerhead with a size of 40 mm and a weight of 2 kg, used to attacks the glass. The intention is to cut a 400 x 400 mm hole in the glass and the product is classified according to the number of strikes needed to reach this point (Which, 2019). Individual window categories are recommended for specific building types. According to the "Safe and Security Glass" the impact energy shown in Table 3 is developed for each class of resistance (EN 356 Specs).

Tab. 3 Impact energy for resistance categories according to EN 356 (Which, 2019)

Resistance category	Height of dropped [mm]	Impact energy [J]	Glass thickness [mm]
P1A	1 500	62	6.8
P2A	3 000	123	8.8
P3A	6 000	247	9.1
P4A	9 000	370	9.5
P5A	9 000	370	10.3

In addition to the aforementioned standards, the resistance of glass apertures can also be classified in terms of their resistance to wind loads and the resistance against bullet attack. Separated group of dynamical testing are testing of windows for blast resistance. Test procedure of the window systems reaction to a shockwave load is described in (Zvakova, 2016). In the present paper, however, we deal with the resistance of glass using a drop ball only.

Experimental testing of windows under dynamic load

Above mentioned standards have been described according to determinacy of the window panes resistance, the impactor of a certain weight or dropped ball test. In both cases, we are talking about the safety or security glass, having its quality and thickness. In our experiment, we focused mainly on commercially used window systems. These were, in particular, wooden-frame windows typical from the 1960s produced in Czechoslovakia and still in use. The second sample consisted of plastic frame windows, currently used. The experiment was focused on determination of the dynamic resistance of glass windows.

We performed a series of dynamic experiments, carried out in a laboratory at the Faculty of Civil Engineering of the University of Žilina. Windows were fixed in the testing frame. Commercially used window systems were investigated during the experiment. Particular attention was paid to the sensitivity of their impact on the type and properties of the support frame. The glass sample to be tested consists of annealed glass for both windows. Annealed glass is the basic product in the form of a glass sheet through the float process. This glass breaks into large jagged shards and is relatively susceptible to impact. The window that has been tested is classified in the RC 1 resistance class and the resistances of glass requirements are not specified. The window is defined against wind load in class C4. This means that a wind of 1600 Pa does not cause the frame to deform more than 1/300 of its length. Glass panes are placed in the window frame and sealed with permanently flexible two-component sealant with excellent mechanical properties. The nominal glass thickness was 3 mm for wooden samples and 4 mm for samples with PVC frames. In terms of glass size, dimensions are defined from the overall size of the window samples and frames used. The glass surface for the wooden frame windows was 1.22 x 1.05 m and 0.81 x 0.97 m for the PVC frame windows. The mounting of the wooden frame window in the test structure is shown in the following figure (Fig. 3).

Dynamic load testing was performed with various impactors. These were two steel balls with a nominal weight of 2.644 kg and 4.571 kg, which were dropped from different drop heights (i.e. the horizontal distance between the centre of the window and the ball). Among other things, the acceleration was measured in each test using a sensor located at the bottom of the glass (from the right and bottom edges at a distance of 0.2 m).

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Another significant device was a high-speed camera (FASTEC TS31000SC4256 Imaging), which was used to examine the speed of the incident ball based on slow motion. The high-speed camera has a resolution of 1280 x 1024 and 725 frame per second. It has a multimedia display and 4 hour battery life. The measurement scheme and the location of the devices are shown below (Fig. 4).


Fig. 3 Wooden window in the test frame


Fig. 4 Arrangement of the sample and the measuring instruments

During the experiment, 3 windows with a wooden frame and 1 with a PVC frame were used. Various sizes of steel ball (2.644 kg and 4.571 kg) were used in the test, which gradually started from defined distances. Each measurement was recorded with a high-speed camera and an accelerometer sensor. Individual drop heights were increased until the glass panel was damage. Subsequently, the total impact energy values were evaluated. These values were calculated according to equation (1) using slow-motion recordings from a high-speed camera:

$$E = \frac{1}{2} m v^2 \quad (1)$$

The following table shows the individual results for the sample types, the ball mass and the drop height from which they were triggered.

Tab. 4 Dynamic impact measurement results (Figuli, 2019)

Window frame	Ball mass [kg]	Impact horizontal distance [m]	Impact velocity [m/s]	Energy [J]
Wood	2.644	1.30	2.42	7.72
Wood	2.644	0.90	1.60	3.36
Wood	2.644	1.40	2.59	8.90
PVC	4.571	1.50	2.94	19.75

The table shows the individual impact distances at which the glass pane of the window has been damaged. Looking at the wooden-frame windows, it can be said that 2 samples were broken at nearly equal distances. Another sample was damaged quite soon, what could be due to several factors (frame stiffness, environmental effects on the window, etc.) Compared to a window that had a PVC frame, it can be seen that it can withstand more energy.

Discussion

The results of the measurements showed the energy that the individual samples can withstand. To confirm the impact resistance, it is advisable to perform several measurements on such PVC Windows. Compared to EN 356, the tested samples are considerably more resistance. This is mainly due to the thickness of the glasses that are used tested in the standard and our test.

For future measurements, the durability of wooden and PVC windows under dynamic loading using safety film will be investigated. The effect of the film on increasing the resistance of windows will be evaluated. Besides it is possible to investigate fragments of glass breakage in individual damage.

Conclusion

The paper was focused on a series of experiments on the impact of a steel ball on a glass pane, to estimate the burglar resistance. During the tests wooden frame and PVC frame windows were used. The results pointed to the limit impact energy. The results show that the wooden windows used in the 1960s could not resist as much energy as a plastic window. The study is part of an ongoing project that will include analytical and numerical analyses of the examined systems.

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