Chapter 18
Experimental Analysis of Impact and Blast Resistance for Various Built Security Components

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Abstract This work is a review of selected own research in the field of resistance of selected built protective components for impacts by projectiles and air blast wave caused by the explosion of explosive material or air-fuel mixture. Background of those research were previously published (Kruszka and Rekucki, Appl Mech Mater 82:422–427, 2011; Kruszka and Rekucki, Resistance analysis of protective doors, windows and built wall to the effect of impact, blast loading and burglary. In: Proceedings of 7th international symposium on impact engineering, 4–7 July 2010. Military University of Technology, Warsaw, pp 421–445, 2010). Experimental bullet-proof investigation results of two types of steel protective doors under the comparative perforation tests using various projectiles shot from short and long typical fire-arms are presented here. The protective windows are tested under a soft impact of 30 kg mass and under an aerial shock wave due to the explosion of an explosive charge and a fuel-air mixture. The structural material of the door glazing, is Polish standard building steel, while the window leaves – Polish architectural protective glass of P4A class and duplex hardened glass.

Keywords Experimental testing · Blast · Impact · Protective doors and windows

18.1 Introduction

Currently, particularly after the terrorist attacks of September 11, 2001 in the USA, the interest of research centers around the world is growing in the problems of combating terrorism, crime and vandalism. One of undertaken directions is the development of experimental work broadly related to the protection of important buildings (banks, currency exchange bureaux), particularly of their supporting structures against terrorist-type actions [1–4], as well as of residential buildings.

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Elements of the building protection system include technical devices used in buildings to protect human life and health and to protect property, including confidential information. Among them we can mention the following:

1. Mechanical and construction measures providing a mechanical barrier which can be broken only with the use of force, leaving traces (also significant in the context of criminal investigation techniques). An important criterion is effective provided resistance. Mechanical barriers are primarily walls in combination with construction elements (doors, windows, ventilation, etc.) and mechanical devices (fixed and lowered steel bars, anti-burglary shutters, steel wire grids, locks, chains).
2. Electrical (electronic) alarm devices (anti-burglary and anti-robbery), which provide automatic signaling of attempts to break into or force entry to guarded premises. An important criterion of effectiveness here is the time between the signal and entry into the place of origin of the signal.
3. Fire alarm devices, serving to give a direct alert to persons in case of a fire hazard and/or to detect fire and give a suitable advance warning of it. They are also designed to protect people and property.
4. Devices for monitoring the outdoor areas around closed buildings. These are technical devices placed without protected space, usually within the boundaries of the site. They include mechanical and construction elements (fences, walls, barriers, gates, gatehouses, guardrooms, lighting), electronic detection devices (central security units, detectors, sensors, video/TV, entry control systems, transmission of information to higher units) and/or measures connected with related to staff and organization (personnel, observation, supervision, special groups, guard dogs, alarm action programs).

The optimal solution for securing buildings consists of mechanical and construction measures together with properly installed electronic alarm and control devices.

One of the most difficult tasks, the aspects of building security is to determine the degree of risk to particular premises and the amount that should to be spent on the work necessary to make them secure. This is the basis for analyzing the safety of "weak points" in a complex (a building) combined with calculation of costs and benefits. On the basis of the analysis the safety of buildings and premises, the most important task is to secure the door and window gaps [5]. Safety windows and doors are used as mechanical safety measures for these gaps.

This paper contains the research methodology and the results of an experimental analysis of the resistance of steel protective doors to impacts by various projectiles fired from typical short and long firearms, and of an aluminum protective window for cash desks to soft impact by a mass of 30 kg and the air shock wave produced by an explosion. The window pane was also subjected to a static force applied in the centre of the window. The structural material of the door leaves is construction steel, class A-0, type St0S, whereas the windows are made of anti-burglary building glass, class P4A. In order to properly design the protective construction elements, including evaluation of their impact resistance and to ensuring that the protective buildings are safe to use, the construction engineer must have knowledge in both, exterior and terminal ballistics. When calculating and checking structural protective elements of various types of building, including in particular shooting ranges (police and

military), it is necessary to be familiar with certain formulae [6, 7]. It should be emphasized that the problem of penetration of the projectiles into a half-space or into a target has been widely analyzed for a long time, e.g. [8–11]. Numerical solutions to this problem can also be obtained by means of many commercial computer programs, e.g. AUTODYN 2D and 3D [12]. However, in order to obtain proper numerical and analytic solutions, particularly in the case of problems with projectile penetration, it is necessary to know the model and material parameters of the material used, and these can be obtained primarily through experimental analysis.

18.2 Tests of the Resistance of Steel Bullet-Proof Protection Doors

Testing of resistance to penetration by various projectiles fired from small-caliber firearms were carried out on the leaves of reinforced protective doors manufactured in Poland using St0S structural steel. These doors can be used in premises where goods of considerable value are stored, as well as in certain types of defensive structures. Currently, they are used as the basic element of mechanical protection in rooms of protected general and special buildings [13–17].

The doors were denoted with the codes "A" (steel plate doors for bank premises) and "B" (anti-burglary plate doors made of steel sheet, ribbed with shaped sections, for houses and other closed premises, e.g. currency exchange bureaux, cash desk counters, etc.). Penetration tests are among the basic strength tests aimed at determining the resistance of a material to perforation by pistol and rifle bullets. Problems relating to the resistance of structural building materials are not widely known, therefore materials related to experimental tests are not easily available [18]. It should be pointed out that perforation tests are of fundamental importance in criminal investigation techniques, in the investigation of criminal tracks [19].

18.2.1 Testing Methodology

The perforation tests were carried out on the experimental firing range belonging to the Central Forensic Laboratory of the Central Police Headquarters. During the tests the doors were fastened to a bullet trap, their frames being supported from behind on vertical wooden poles. On the front surface (the attack surface) of each door leaf, eight test sectors of the steel door were marked, numbered from I to VIII (see Fig. 18.1).

Three shots were fired into each sector, such so that the distance between impacts was not less than 15 cm. The shots were fired from a distance of 5 m in the case of short weapons and 10 m in the case of long weapons. On each occasion a measurement was taken of the bullet velocity v_k before striking the door. The experiments were performed according to the schedule in Table 18.1.

Fig. 18.1 Protective steel doors, type A (left) and B (right), following laboratory perforation tests

18.2.2 Results of Perforation Tests

To evaluate the perforation of the steel door, the following cases were considered:

1. a projectile passed through the back of the door;
2. a cracking of the back surface of the door caused by the projectile or part of it, even if the projectile was visibly detained at the back of the door;
3. a pass-through hole made in the door, even if the hole then has been closed by the projectile.

If none of these criteria applied, there was deemed to be no perforation. Sample results of perforation tests on type A protective doors are given in Tables 18.2 and 18.3.

Table 18.1 Schedule of perforation tests of protective doors

Sector no.	Weapon	Barrel length [mm]	Cartridge	Projectile
I	Kalashnikov AK 74 5.45 mm rifle	415	Medium cal. 5.45 × 39	FMJ 3.4 g
II	SWD cal. 7.62 mm sniper rifle	620	Rifle cal. 7.62 mm Mosin	FMJ 9.5 g
VII	Kalashnikov AK 47 7.62 mm rifle	415	Medium cal. 7.62 mm model 43	FMJ 7.9 g
IV	CZ 75 9 mm pistol	120	Pistol cal. 9 mm Luger	FMJ 8 g
V	0.357 Magnum Desert Eagle gun	161	Revolver cal. 0.357 Magnum	SJ 10.2 g
VI	0.44 Magnum Desert Eagle gun	161	Revolver cal. 0.44 Magnum	SJ 15.5 g
III	The TT-33 7.62 mm pistol	116	Pistol cal. 7.62 mm model 30	FMJ 5.5 g
VIII	UZI 9 mm machine pistol	260	Pistol cal. 9 mm Luger	FMJ 8 g

Table 18.2 Door type A test results – sheet metal thickness 3.0 mm

Sector no.	Shot no.	v_k [m/s]	$v_{k\ average}$ [m/s]	Impact energy E [J]	Puncture
Long weapon, fired from a distance of 10 m					
I	1	941.0	937.4	1494	**Yes**
	2	933.5			**Yes**
	3	937.7			**Yes**
II	1	846.6	846.3	3402	**Yes**
	2	854.1			**Yes**
	3	838.1			**Yes**
VII	1	718.4	715.1	2020	**Yes**
	2	711.3			**Yes**
	3	715.7			**Yes**
Short weapon, fired from a distance of 5 m					
IV	1	347.5	343.2	471	No
	2	339.1			No
	3	343.1			No
V	1	392.6	396.5	802	No
	2	389.2			No
	3	407.6			No
VI	1	446.7	446.3	1544	**Yes**
	2	445.8			**Yes**
	3	446.4			**Yes**
III	1	453.8	451.7	561	No
	2	447.4			No
	3	453.8			No
VIII	1	384.1	376.8	568	No
	2	372.5			No
	3	374.0			No

Table 18.3 Test results of type B doors – sheet metal thickness 2.5 mm

Sector no.	Shot no.	v_k [m/s]	$v_{k\ average}$ [m/s]	Impact energy E [J]	Puncture
Long weapon, fired from a distance of 10 m					
I	1	950.0	946.3	1522	**Yes**
	2	939.6			**Yes**
	3	949.3			**Yes**
II	1	843.8	864.8	3552	**Yes**
	2	881.6			**Yes**
	3	868.9			**Yes**
VII	1	706.1	710.8	1996	**Yes**
	2	717.6			**Yes**
	3	708.8			**Yes**
Short weapon, fired from a distance of 5 m					
IV	1	351.5	346.9	481	No
	2	346.0			No
	3	343.3			No
V	1	392.7	395.8	799	No
	2	396.5			**Yes**
	3	398.2			No
VI	1	456.2	449.4	1565	No
	2	445.5			**Yes**
	3	446.5			**Yes**
III	1	445.9	450.1	557	No
	2	444.1			**Yes**
	3	460.3			**Yes**
VIII	1	381.8	378.2	572	No
	2	378.6			No
	3	374.2			No

The perforation tests showed that the bullets from long weapons usually penetrate the steel structure of both types of door leaf. The type A reinforced steel doors have a slightly higher resistance to the projectiles fired from short weapons. The doors of that type were not penetrated by a bullet fired from the TT-33 pistol, UZI machine pistol, CZ model 75 pistol or 0.357 Magnum Desert Eagle gun.

The type B doors, on the other hand, were not penetrated by the bullets fired from the TT-33 pistol (every in three shots), UZI machine pistol, CZ model 75 pistol, 0.357 Magnum Desert Eagle gun (twice in three shots) or 0.44 Magnum Desert Eagle gun (every in three shots). When a long weapon was fired, a full perforation was recorded for both types of door.

The analysis of the data contained in Tables 18.2 and 18.3 shows that the perforation of the structure of the protective door leaves made of steel sheet (St0S

structural steel) with a thickness of 2.5–3 mm requires impact energy E not less than approximately 1400 J depending on the caliber and shape of the bullet. In the case of SJ type bullets the energy required for perforation is about 10% higher than in the case of FMJ type. Noteworthy is the penetrability of a 2.5 mm thick plate by an FMJ 5.5 g bullet fired from the 7.62 mm TT-33 pistol from a distance of 5 m, when the kinetic energy of the impact is only about 560 J. However, the same bullet does not penetrate a 3 mm thick steel plate.

The average velocity of projectiles at the moment of impact with partition, vk average, when fired from a long weapon varied over the range 710–946 m/s. When a short weapon was used, the average impact velocity v_k was in the range 343–451 m/s.

18.3   Characteristics of Perforation Properties of Steel Door Leaves

The mechanism of destruction of the partition (door leaf) depends on the static and dynamic strength properties of the structural material, impact velocity of the bullet, shape of the bullet, method of fastening of the partition, and the dimensions of the bullet (caliber, length) and of the partition (thickness, length, width). Figure 18.2 shows certain types of perforations of thin and thick plates made of various structural materials [20]. In the tests of steel protective doors, the observed shot marks had a mechanism of destruction corresponding to the mechanism illustrated in Fig. 18.2f). A sample image of the shot marks obtained is shown in Fig. 18.3.

For determination of the depth of penetration of bullets in partitions made of various structural materials (steel, concrete, ceramic, reinforced concrete, earth, glass, etc.) a general terminal ballistic formula can be applied in the following form [21, 22]:

$$h_p = \left(\lambda_1 \, \lambda_2 \, k_p \, m \, v_k \, \cos \alpha \right) / d^2 \tag{18.1}$$

where:

λ_1 is the ogive coefficient,
λ_2 is the coefficient of influence of the caliber on the depth of penetration,
d is the bullet caliber [m],
m is the bullet mass [kg],
v_k is the bullet velocity at the moment of impact [m/s],
l_0 is the length of the ogive part of the bullet [m],
h_p is the depth of penetration [m],
k_p is a coefficient characterizing the strength properties of the material [m^2s/kg],
$\propto$ is the angle between the tangent to the path and the normal to the partition at the point of impact [°].

Fig. 18.2 Mechanism of
puncture of various types of
structural materials [18] **a** –
brittle damage, **b** – puncture
leaving radial cracks, **c** –
spalling, **d** – plastic
penetration, **e** – knocking
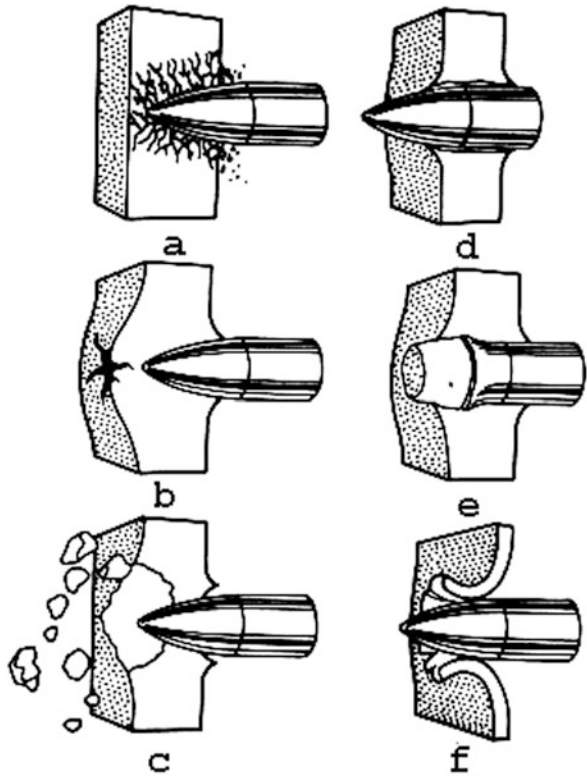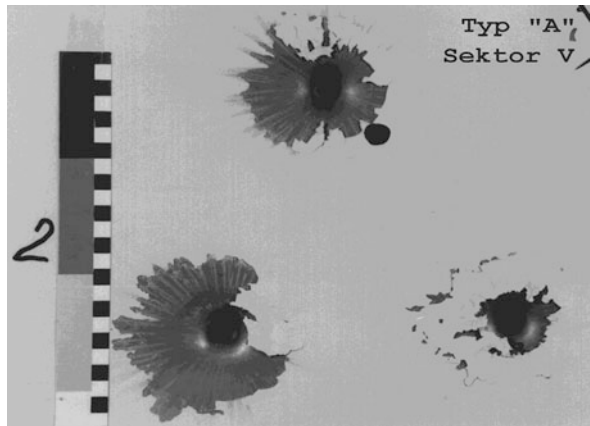out a cork, **f** – leaving a
ductile crack

Fig. 18.3 Shot marks
produced in sector V of an A
type door

Coefficients that take into account the shape of bullet and ogive dimensions can be found according to the following formulae:

$$\lambda_1 = 0.5 + 0.4^3\sqrt{(l_0/d)} \tag{18.2}$$

$$\lambda_2 = 2.8^3\sqrt{d} - 1.3\sqrt{d} \tag{18.3}$$

Based on a series of experiments for evaluation of the required thicknesses of door plates made of certain types of structural materials based on assumed criteria of impact resistance, the formula given by de Marre can be used [21]:

$$m\, v_k^2/d^3 = \beta h_p^{1.4}/d^{1.5} \tag{18.4}$$

The constant β must be determined experimentally for a given type of structural material. Experiments have shown that the calculations based on formula (18.3) are more reliable for plates less than 25 mm thick.

In the tests of resistance to shots fired from the TT-33 caliber 7.62 mm pistol into the type B protective doors (Table 18.3, sector no. III) it can be in calculating the coefficient characterizing the strength properties of the material that the velocity of the bullet at exit was close to zero, since in one case out of three the bullet remained in the material in the final stage of penetration.

On that assumption, after the appropriate transformation of the formulae (18.1), we can calculate the value of the coefficient k_p characterizing the penetration properties of the structural plate of doors made from St0S steel. The following values were adopted for calculations based on Tables 18.2 and 18.3 and the conditions of tests performed on the doors: $d = 0.0762$ m, $m = 0.0055$ kg, $\lambda_1 = 0.708$, $\lambda_2 = 0.665$, $h_p = 0.0025$ m, $\alpha = 0°$, $v_k = 450.1$ m/s.

$$k_p = h_p\, d^2/(\lambda_1\, \lambda_2\, m\, v_k\, cos\alpha) = 1.26 \cdot 10^{-7}\,\left[\text{ms}^2/\text{kg}\right] \tag{18.5}$$

The obtained value of the coefficient characterizing the perforation strength properties of St0S steel makes it possible, using Eqs. (18.1) or (18.4), to calculate the thickness of a steel door plate which will prevent their penetration by a given type of bullet fired from a weapon. For example, to prevent the door from being penetrated by a 7.62-mm projectile from the TT-33 pistol, the St0S steel plate must have a minimum thickness of 4.6 mm.

18.3.1   Empirical Evaluation of the Influence of the Shape of the Bullet Tip on the Depth of Penetration

The shape of the tip of the bullet has a strong effect on its ability to penetrate and perforate at speeds where the stresses produced within it are smaller than the

Table 18.4 Limit ballistic velocity [20]

Shape of bullet tip (caliber 6.35 mm)	Limit ballistic velocity [m/s]	
	Angle of impact	
	$\alpha = 0°$	$\alpha = 60°$
Hemisphere	875	1213
Cone	892	1262
Truncated cone	942	1273

dynamic yield of the material. The flatter the bullet tip, the higher the limit ballistic velocity. If the bullet strikes the partition with a speed at which the stresses within it exceed the dynamic yield of the material of which it is made, the shape of the tip has practically no effect on the value of the limit ballistic velocity. The confirmation of this, in Table 18.4 [20], results are given from tests of steel bullets with mass 14.6 g, diameter-to-length ratio 10, and Brinell hardness *HB* of 55.5 MPa. The bullet tips had the shapes of a hemisphere, cone, and truncated cone with a vertex angle of 40°. They were fired into steel plate with a thickness 12.7 mm and Brinell hardness *HB* of 38 MPa. The bullet struck the partition at angles of $\alpha = 0°$ and 60°.

The maximum velocity required to penetrate the tested steel plate was obtained for the bullets with a truncated cone shape, striking at angles of $\alpha = 0°$ and 60°. This velocity exceeds the minimum limit ballistic velocity obtained for the bullets with hemispherical tips by an average of 6.5%. Thus, based on the above empirical evaluation, in testing of the penetration resistance of protective steel doors, the influence of the shape of the bullet tip was not taken into account.

18.4 Testing Impact Resistance of the Structure on an Aluminum Protective Window

The structure of a cash desk window consisted of an aluminum frame and, within it, a three-part pane made of class P4A glass [24]. The middle (inner) pane is placed 30 mm into the interior of the structure and is connected to the edges of the other two extreme (outer) panes via six screwed steel distance sleeves. The height of the outer panes is 105 cm, and their width is 65 cm. The inner pane has a width of 50 cm and a height of 93 cm. The distance between the sleeves is 40 cm horizontally and 35.5 cm vertically. The depth to which the panes were set into the frame, in the case of those supplied for the tests, was 24 ± 2 mm. The structure of the cash desk window placed on a testing stand is shown in Fig. 18.4.

The structure of the cash desk protective window was fastened during the tests in a rigid frame on the testing stand, such thanks to which the conditions of fastening were similar to that occur when the window is in use. The tests were carried out in similar conditions to those in which the window would be used, i.e. at a temperature of 20 ± 20 °C and a relative humidity $50 \pm 10\%$.

Fig. 18.4 Cash desk window fastened on the testing stand. 1 – cash desk window made of three class P4A panes measuring 105 cm × 175 cm; 2 – testing stand frame; 3 – system for applying static load and measuring force and displacement parameters of the middle pane
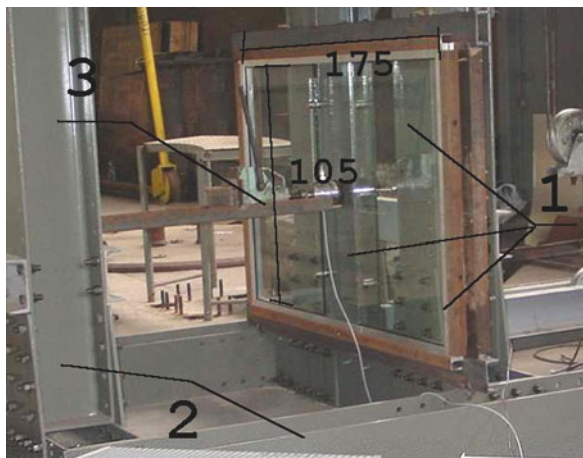
18.4.1   Tests of the Resistance of the Window Structure to a Static Load

This test involved applying a static load to the structure of a cash desk window, followed by visual examination and measurement of the value of the loading force and of displacement (bending) of the tested structure in the middle of the inner pane. The following devices and measuring instruments were used in the tests:

- the testing stand – a rigid steel structure set up vertically, to which the aluminum structure (casing) of the cash desk window was attached;
- a hydraulic servomotor producing a graduated loading from 0 to 5000 N, stepped every 500 N, with an accuracy of ±2%;
- a textolite plate, 100 × 100 × 20 mm, for transferring the load;
- a force measuring instrument – a CL 14 electronic converter with a measuring range from 0 to 5000 N and sensitivity of 1 mV/V;
- an instrument for measuring displacements (bending) – a PTx–100 converter transformer with a measuring range ± 50 mm and sensitivity of 203.39 mV/mm;
- a timer with a scale division not exceeding 1 s.

The positioning of the devices and measurement instruments and the method of fastening the protective window structure on the testing stand are shown in Fig. 18.4.

Methodology   The cash desk protective windows were stored in the room where the testing took place for a period of 5 days, in a vertical position, as they would have when in use in their final position. After this time, for 24 h the window was mounted in the fastening structure of the testing stand (see Fig. 18.4). The zero position of the window and the readings taken from the measuring instruments was established. During the
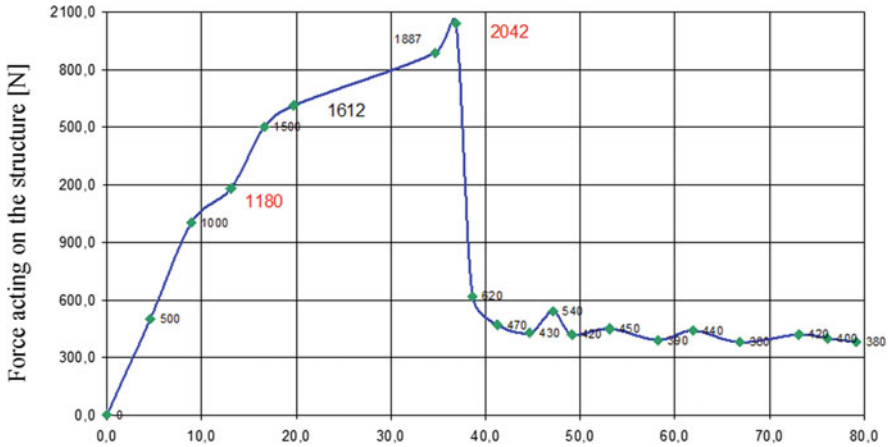
Fig. 18.5 Maximum displacements (bending) of the centre of the inner pane of the cash desk protective window, as a function of static force applied

tests of the resistance of the window structure, a static load was applied in the center of the span of the inner pane through the textolite plate (see Figs. 18.4 and 18.6).

Each loading force, graduated every 500 N, was maintained for 1 min. After this time the readings of the value of the force and the displacement of the center of the inner pane were made. After the pane cracked, readings of the force and displacement were carried out at characteristic points, but not less frequently than every 20 s. The total time of the test of the resistance of the window structure was 8 min 20 s. The test was taken to have completed at the moment when the outer panes were ejected from the window frame at a width of at least 30 mm.

Results of the Experiments The values for the displacements (bending) of the centre of the inner pane, recorded during the experiment, are shown as a function of the applied force in the graph in Fig. 18.5

With the load of 1180 N, horizontal cracking of the panes occurred, passing through the central fastening sleeve on the left-hand side as viewed from the direction of loading. The displacement value of the loaded (middle) pane at this force, was 13.08 mm. The graph clearly shows that at a maximum, the panes can withstand a static force of approximately 2042 N. At this force, severe cracking of the inner pane occurred (see Fig. 18.6), but thanks to the bonding of two layers of P4A glass with a nominal thickness of 4 mm and four layers of plastic sheet with a nominal thickness of 0.38 mm, the structure of the desk window still retains its protective properties. The steel sleeve attachments were not torn off from the panes despite of numerous local cracks in the glass surfaces. A further displacement of the center of the inner pane took place as the static force applied varied over the range

Fig. 18.6 Cracked panes of the cash desk window at maximum static load 2042 N – view from the side where the load was applied

Fig. 18.7 Cracks in the pane of the cash desk window at a maximum displacement in the central part, observed from the opposite side from the site of the place of load application

380 ÷ 620 N. When the inner edges of the panes were ejected from the window frame structure over a width of at least 30 mm, the displacement of the center of the cash desk window structure was 79.16 mm, and the displacement force was 380 N.

When the experiment ended, the extreme left lower edge of the pane (viewed from the side on which the load was applied) was ejected over a width of 31.2 mm. In spite of a large number of small cracks in the regions of the steel sleeves fastening the central pane to the extreme panes, the sleeves were not torn off – the initial spacing of 30 mm did not change significantly within a radius of around 80 mm. Cracks in the glazing of the cash desk window structure are shown in Fig. 18.7.

18.4.2   Tests of Window Structure Resistance to Soft Impacts

Methodology The tests involved applying a dynamic load to the structure of a cash desk window, followed by a visual examination and measurement of the value of permanent displacement (bending) of the tested structure in the center of the inner pane. Dynamic resistance testing of the window structure was carried out on the same stand as the static testing. To apply the impacts, a standard leather load bag with a diameter of 300 ± 20 mm was used, filled with dry sand to a total mass of 30 ± 0.2 kg (see Fig. 18.8). Due to the lack of relevant standards and regulations regarding the testing of such structures as cash desk windows with burglar-resistant panes, the tests were conducted in accordance with the methodology found in [13, 15, 17]

In the tests of dynamic resistance of the cash desk window, the dynamic load was applied in the center of the inner pane using a free pendulous movement of a bag suspended on a rope with of length of $l = 1500$ mm (see Fig. 18.8). The bag was released from a height of h $= 800$ mm, giving an impact energy E of 230 J.

The dynamic load was applied four times: three times until the moment when the panes were ejected from the pane groove over a width of at least 30 mm (the cash desk window suffered such damage that it could not provide anti-burglary protection), and a fourth additional time in order to check the dynamic resistance of the fastenings of the extreme panes and the middle pane using steel sleeves.

Results of the Experiments After each impact, a visual observation was made and the value of the center of the inner pane displacement was read. The results of the

Fig. 18.8 Testing stand for tests of dynamic resistance to soft impacts. 1 – leather bag containing sand, 2 – rope fastening the load bag, 3 – window protective structure of the cash desk
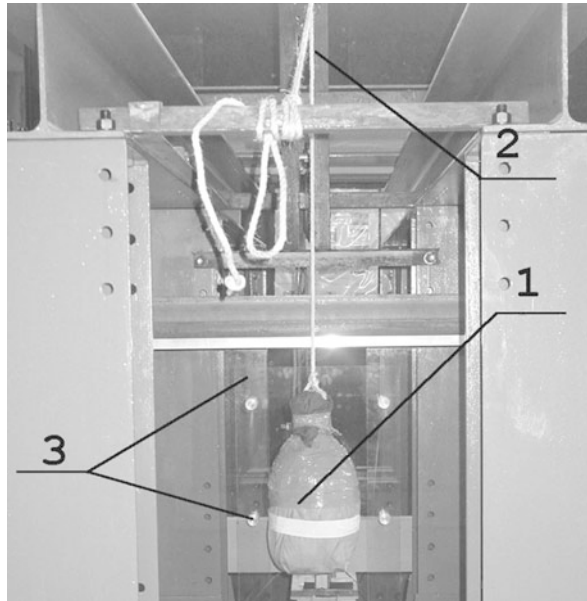
Table 18.5 Maximum displacements of the center of the middle pane of the cash desk window under dynamic load

No.	Load bag impact	Displacement [mm]
1	First impact	35.36
2	Second impact	71.40
3	Third impact	129.20
4	Fourth impact	179.50

readings are contained in Table 18.5. Following the first impact by the bag released freely from a height of 800 mm, a more extensive cracking occurred than under a static load of 1612 N.

After the second impact, the displacement of the center of the inner pane was close to the value obtained at the maximum static displacement (static bending 79.16 mm, dynamic bending after the second impact 71.40 mm). Inside, the outer panes at the bottom and the top of the frame were ejected over a length of 19–21 mm. The panes were 2–4 mm shorter than complete ejection from the frame structure in the central part of the desk window.

After completing the third impact, it was found that on both sides the inner edges of the panes were ejected from the groove of the lower pane of the frame on 65–90 mm sections and up to a height of 3.6 mm measured at the extreme point of the pane from the vertical axis of the window.

According to the adopted methodology, three bag impacts are considered a determinant of the resistance of the cash desk window structure to dynamic load – the displacement of the center of the inner pane was 129.20 mm. Since no layer separation of the panes was observed, and there was a negligible quantity of glass splintering, a fourth load was applied to the cash desk window structure. As a result, the panes underwent further arch deformation by 50.30 mm. The length of total ejection of the panes from the pane groove increased to 120–160 mm on each side. In the side grooves, 1–3 mm more was needed for the panes to be completely ejected from the aluminum frame. The damage to the panes of the cash desk window following the fourth impact is shown in Fig. 18.9.

In the region of the steel sleeves connecting the panes, very minor radial cracking can be observed. Despite this cracking, the sleeves were not detached from the panes and continued to perform their function as a connector between the inner pane and the outer panes mounted in the aluminum window frame. During the loading, the entire three-pane structure of the window underwent deformation as a arch shape.

18.4.3   Tests of the Resistance of Window Structures to Explosion

This test involved applying an explosive load to the structure of a cash desk window, followed by a visual examination and measurement of the values of the overpressure of the air shock wave on the structure and the displacement (bending) of the tested

Fig. 18.9 The nature of
cracking of the panes of the
cash desk window following
the fourth impact – view
from the side where the load
was applied. 1 – the pane
ejected from the frame
groove over the width of
140 mm, 2 – bending of the
window panes

structure at the center of its span. The testing stand, in the form of a rigid steel
structure, was set up vertically in a testing area and anchored, and then the aluminum
frame (casing) of the cash desk window was attached to it. Measurement of the
parameters of the air shock wave was made using M102A piezoquartz converters
with a sensitivity of 1437.07 mV/MPa, and recorded with a digital oscilloscope with
a frequency of 10,000 Sa/s. The method of fastening the window structure on the
testing stand is shown in Fig. 18.10, and the digital oscilloscope used in the
resistance tests is shown in Fig. 18.11.

Methodology The protective cash desk window was mounted on the testing stand
(see Fig. 18.10) 24 h prior to being subjected to an air shock wave. The shock wave
was generated using 60 and 100 g spherical charges of PMW-8 explosive meeting
the conditions specified in a PN-V-87003:1999 Polish standard (sections 2.11 and
5.2.2). The charges were always suspended on the stand in such a way that the center
of the charge was at the same height above the ground as the center of the cash desk
window structure. The explosive charges were placed at the same distance from the
middle pane of the desk windows and from the steel plate with a sensor recording the
parameters of the reflected shock wave. After each impact, the window structure was
visually examined and the displacement values were read. The resistance of the cash
desk window structure to shock waves required the development and application of a
separate methodology, because this structure fails to meet the requirements specified
in a PN-V-87003 standard: the ones from section 5.1.1 due to its larger dimensions,
and the ones from section 5.1.2 due to the lack of tightness of the pane surfaces (steel
distance sleeves are placed between the panes).

Results of the Experiments Based on section 3 of the PN-V-87003:1999 standard,
in the first experiment, a spherical charge of 60 g explosive was used, suspended at a
distance of 130 cm from the middle pane of the cash desk window. The unit impulse

Fig. 18.10 The cash desk window structure on the testing stand. The spherical charge of the explosive is visible
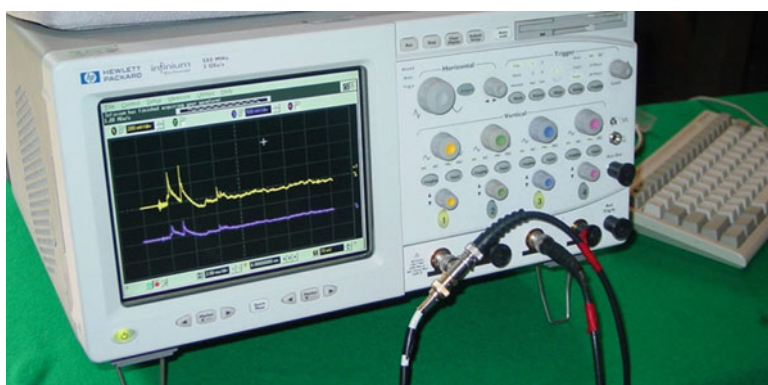

Fig. 18.11 Infiniium oscilloscope, showing a sample graph of pressure at the front of the air shock wave

of the reflected air shock wave produced by such a system corresponds to the parameters of a reflected air shock wave defined for a shock wave resistance class D2 (PN-V-87003:1999, Table 1: $p_{od} = 100$ kPa, $\tau_+ = 10$ ms). During the experiment, an Infiniium digital oscilloscope (Fig. 18.11) was used to record the pressure at the front of the shock wave as a function of time. After the first experiment, radial cracks appeared in the window panes. It was found that the displacement of the pane structure at the center of its span was 5.26 mm. Examples of changes in the value of overpressure of the air shock wave as a function of time, recorded during the third test, are shown in the graph in Fig. 18.12. The nature of the damage and the
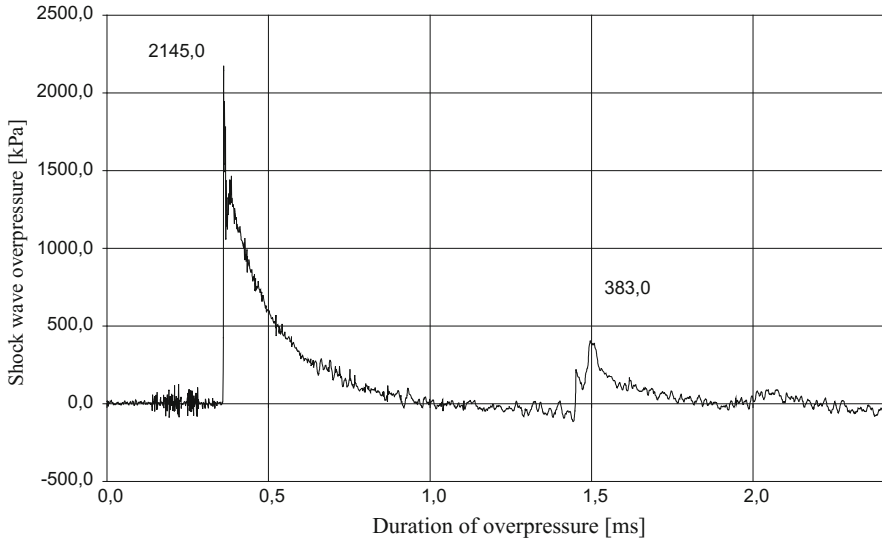
Fig. 18.12 Graph of changes in air shock wave overpressure as a function of time for the third test

directions of the cracks appearing after the cash desk window structure had been subjected three times to the overpressure of the air shock wave can be seen in Fig. 18.12.

Apart from cracking and slight bending of the protective window after the first experiment, no other damage to the tested structure was identified. Comparing the nature of the cracks formed in this experiment and their spatial distribution to those obtained in the dynamic resistance tests after the first bag impact, it can be stated that in the experiment with an explosive the cracks were less numerous and occurred in the outer panes (situated 30 mm closer to the center of the charge). This displacement of the center of the window was 30.1 mm less than in the case of the dynamic testing using the impacts with the bag. This being the case, in the second test, the structure of the cash desk window was subjected to a shock wave from the detonation of an explosive charge of 100 g suspended at a distance of 130 cm. After the explosion, it was found that the displacement at the center of the span increased to 11.87 mm (Table 18.5, No 2), which was accompanied by a slight increase in the number of cracks, particularly in the region of the fastenings using steel distance sleeves. This displacement at the center of the window was still smaller than the one following the first impact from the sand-filled bag: 35.36 mm – see Table 18.5, No 1. Ejection of the panes from the window frame did not exceed 6 mm. In the third test, the cash desk window structure was subjected to a reflected air shock wave produced by the explosion of an explosive charge of 100 g, suspended at a distance of 78 cm from the original plane of the middle pane. As a result of the detonation of the charge, a wave with overpressure of 2145 kPa was created and the duration of the overpressure phase τ_+ was 1.559 ms – see Table 18.6 and Fig. 18.12.

Table 18.6   Maximum displacements of cash desk window panes subjected to an air shock wave

No.	Mass of PMW-8 charge [g]	Distance of PMW-8 charge from pane [cm]	Overpressure p_{od} [kPa]	Duration of overpressure τ_+ [ms]	Maximum displacement [mm]
1	60	130	295	1.780	5.26
2	100	130	412	1.959	11.87
3	100	78	2145	1.559	38.43

Fig. 18.13   Damage to the cash desk protective window following the third application of the air shock wave

The shock wave with the above parameters caused the left pane to be ejected from the lower pane groove along a 130 mm wide section (see Figs. 18.13 and 18.14). There was also a significant bending of the pane structure together with a total breakage in the region of the lower left fastening (distance) sleeve. The bending of fastening points using distance sleeves compared to their initial position prior to the first experiment and the nature of cracking of the panes are shown in Fig. 18.14.

18.5   Tests of Shock Resistance of Laminar Protective Panes and the Structure of a Steel Protective Window Against the Explosion of a Fuel-Air Mixture

The structure of the protective windows consisted of a steel frame with rounded edges, containing a laminar protective pane of type (15 + 1 + 6 =) 22 mm, with dimensions 1048 mm × 2085 mm. In the frame structure the pane was secured with seals of 3.5 mm thick, glued at a distance of 20 mm from the outer edge of the pane [24]. The impact resistance of two types of laminar protective panes consisting of
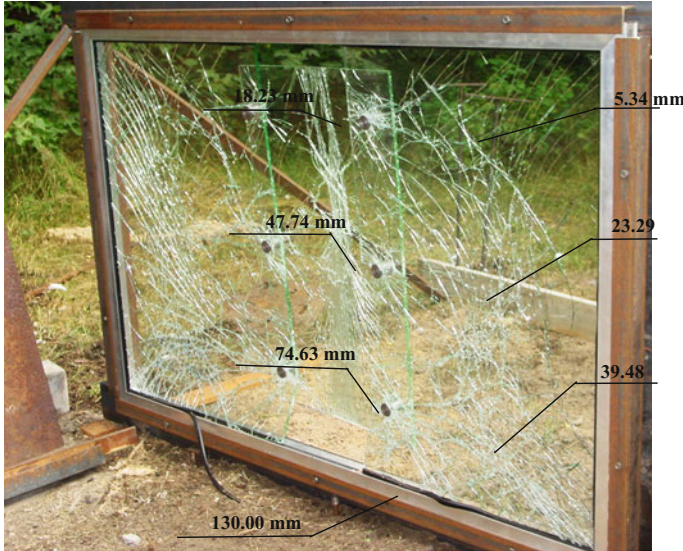
Fig. 18.14 Values of displacements of the cash desk window panes at the points of fastenings by means of distance sleeves following the third shock wave impact

Fig. 18.15 The steel protective window placed on the testing stand. 1 – chamber for generation of load with a fuel-air mixture, 2 – laminar protective pane, 3 – steel window frame, 4 – testing stand fastening frame, 5 – testing stand support structure
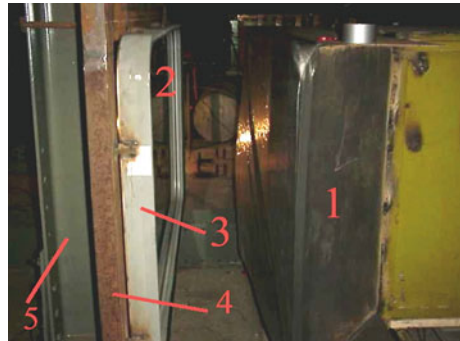

two layers of tempered glass stuck together were also tested. Dimensions of the laminar protective panes: $(15 + 1 + 6 = 22)$ mm $\times$ 1088 mm $\times$ 2125 mm and $(13 + 1 + 6 = 20)$ mm $\times$ 1102 mm $\times$ 1152 mm. The overpressure of the shock wave was applied to the thicker layer (15 or 12 mm). The total thicknesses of the tested laminar panes were therefore 20 and 22 mm, respectively. The panes and the window had been stored for 10 days in a vertical position at the temperature at which the physical experiments were carried out.

The method of fastening the structure of the steel protective window and the laminar protective pane on the testing stands is shown in Figs. 18.15, 18.16 and 18.17. During the tests the panes were fastened to a supporting frame made of steel shaped sections. The tested pane, on the attack side, was fastened to that frame with

Fig. 18.16 The laminar protective pane (1088 mm × 2152 mm) placed on the testing stand. Symbols 1–5 like in Fig. 18.15

Fig. 18.17 Fastening of the laminar pane on the testing stand. 1 – shaped steel section of the support frame, 2 – tested protective pane, 3 – seal glued on the surface of the support frame, 4 – support structure of the testing stand, 5 – fastening clamps
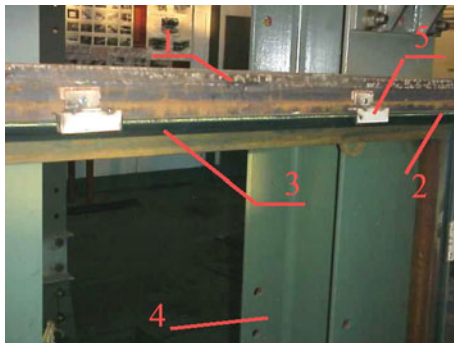
clamps spaced every 400–500 mm. Between the clamp structure and the pane, a seal was placed over the entire clamped area – see Fig. 18.17.

18.5.1   System Generating the Explosive Load

In order to create conditions for the explosive load for the tested laminar panes and protective window – a minimum overpressure of 30 kPa with a duration of at least 200 ms was generated by the explosion of a fuel-air mixture. The explosion in the course of the experiments took place in a specially constructed explosion chamber (see Fig. 18.18.) The size of this chamber was selected so that the load on the tested pane and window was uniform evenly distributed over the entire surface. The loaded surface included practically the entire area of the pane fastened in the structure of the support frame.

The explosive load on 1088 mm × 2125 mm panes was generated using a chamber extended to these dimensions, so that the side of the chamber in contact with the tested pane had dimensions of at least 1040 mm × 2000 mm.

The open side of the chamber in contact with the tested pane or protective window, placing a container with the appropriate quantity amount of fuel had been

Fig. 18.18 Explosion chamber (for generating the explosive load). 1 – explosion chamber, 2 – stand structure, 3 – explosion initiation point, 4 – fuel container

Fig. 18.19 Location of pressure measuring elements. 1 – pressure measurement point on the front of the shock wave, 2 – fuel container, 3 – structure of chamber for generating the explosive load

in the changer, was closed a plastic sheet with a thickness of 50 μm. The fuel-air mixture contained hexane, with a concentration of no more than 2.0% in the mixture. Initial tests demonstrated a repeatable relationship between the maximum value of the overpressure wave and its duration on the one hand, and the fuel concentration on the other hand. Based on this information, a main testing program was designed. The testing system used to control the process of applying an explosive load on the panes and protective windows with a precision of up to 10% in the range from 50 to 900 kPa of the maximum overpressure of the wave reflected from the attack surface.

18.5.2 Methodology

The test involved applying a force from an explosion of fuel-air mixture to the laminar panes and the entire structure of a protective window, followed by a visual examination and measurement of the value of the maximum pressure of the reflected shock wave (see Fig. 18.19), namely recording both the varying value of the pressure on the attack surface of each pane and the displacement (bending) of the tested pane at the centre of its span (see Fig. 18.20) as a function of time. Figures 18.21 and 18.22 show the applied measurement circuit and the devices recording the measured physical values on the testing stand during the experiment.

Fig. 18.20 Location of displacement measuring elements. 1 – stand support structure, 2 – displacement sensor bracket, 3 – PSx-20 converter
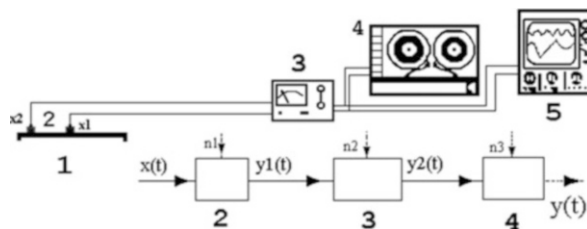

Fig. 18.21 Diagram of measurement circuit used to record pressure and displacement as a function of time. 1 – tested pane or protective window, 2 – PSx–20 sensor for displacement measurement and M102 sensor for pressure measurement, 3 – measurement amplifiers, 4 – V-STORE recorder, 5 – Infiniium digital oscilloscope – see Fig. 18.11

Fig. 18.22 Recording devices on the testing stand. 1 – Infiniium oscilloscope, 2 – V-STORE recorder, 3 – 482A17 amplifier, 4 – MPL-108 carrier wave instrument, 5 – PSx-20 converter

Before filling the container with the fuel, the chamber was heated for 30–40 min until the air temperature inside the chamber was approximately 600 °C. Before the heating began, the open side of the chamber was closed with a plastic sheet along the three edges. After reaching the required temperature, the container filled with the quantity amount of the fuel determined in the trials, was placed centrally on the bottom of the chamber (Fig. 18.19), and then the fourth edge of the chamber side was glued up – see Fig. 18.23. The heating of the chamber continued until the fuel completely evaporated and a fuel-air mixture was produced in the chamber, in practice for 18–20 min.

Fig. 18.23 Closing the chamber side which was to be in direct contact with the attack side of the tested protective pane, using a plastic sheet with a thickness of 50 μm

Fig. 18.24 Testing system at the moment before the explosion. 1 – plastic-covered edge of the chamber; 2 – tested glass sample; 3 – explosion chamber; 4 – clamp attaching the pane to the support frame; 5 – support frame
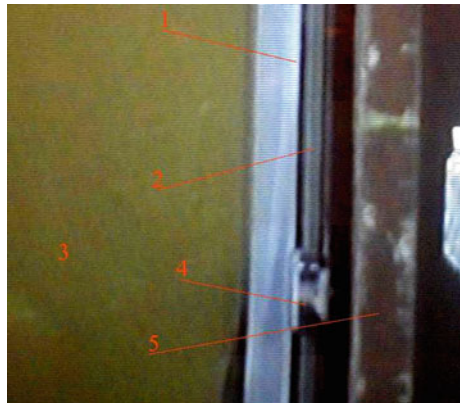
After being prepared in this way, the explosion chamber was moved up to the pane secured on the testing stand, achieving direct contact with the attack surface of the tested sample (see Fig. 18.24).

Then the process of explosive combustion of the fuel-air mixture was initiated – the start of the process is shown in Fig. 18.25. The air shock wave produced in the chamber struck the attack side of the tested pane, applying an impulse of overpressure to it, while at the same time the chamber began to move in the opposite direction – see Fig. 18.26. The values of pressure and displacement as a function of time were recorded simultaneously on the screen of the oscilloscope and on the magnetic tape of the V-STORE recorder – the measurement circuits are shown in Figs. 18.21 and 18.22. After the experiment was complete, a visual examination of the state of the pane surface, and of the fastening and sealing systems was made.
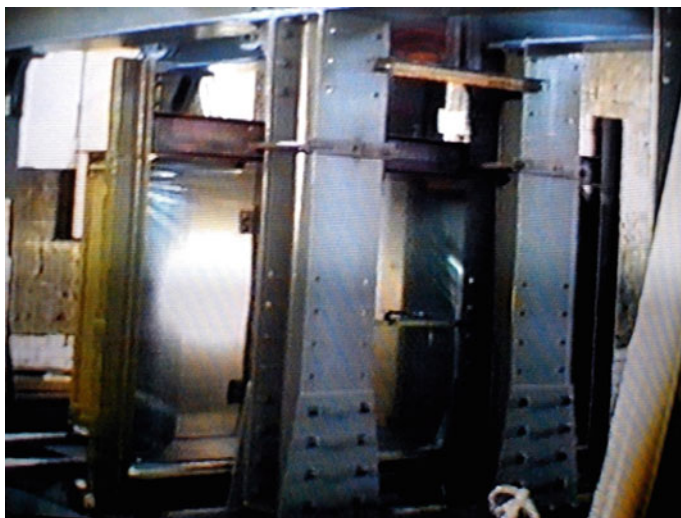
Fig. 18.25 Testing a laminar protective pane – start of the explosion of the fuel-air mixture in the explosion chamber
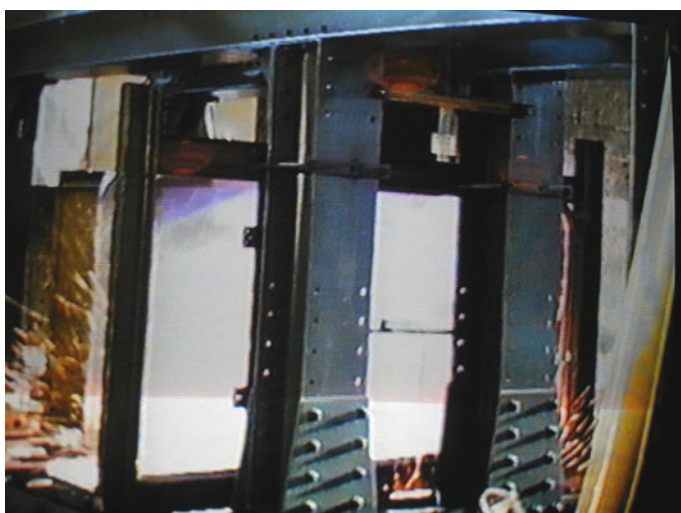

Fig. 18.26 The moment directly following the impact of the shock wave on the tested pane

18.5.3   Theoretical Prediction of Maximum Permissible Overpressure

A prediction of permissible overpressure values was made based on the results of the tests on the protective panes with various thicknesses and dimensions subjected to explosions of fuel-air mixtures, using the formula below:

$$p_p = (\sigma_w/0.684) \cdot (h/b)^2 \cdot (1+\alpha)^2 / (1+0.22\alpha^2) \qquad (18.6)$$

where:

p_p is the destructive pressure of the air shock wave in kPa;
h, b are the thickness and width of the pane in mm;
α is the ratio of the length of the pane to its width;
σ_w is the destructive stress under dynamic load; σ_w taken to be 90 MPa.

For the tested laminar protective panes, the following was obtained from the above formula:

– 139 kPa for a 1102 mm × 1152 mm pane with a thickness of 20 m,
– 116 kPa for a 1088 mm × 2125 mm pane with a thickness of 22 mm.

Hence, based on the above calculations, in the physical experiments, at the first load, a pressure with values not exceeding 80% of the above estimates was applied.

18.5.4   Results of the Experiments

The results for the maximum measured values in the dynamic tests using hexane fuel are presented. In each experiment, pressure changes over time were recorded in the center of the pane. In addition, in selected experiments, the displacement of this point of the pane was also measured over time.

Neither the laminar panes nor the protective window suffered damage. There were no visible signs of breach of the structure of the construction material. The tightness of the protective window was also maintained. Moreover, the system fastening the pane in the window frame continued to function properly after the tests and did not suffer any external damage.

It should be mentioned that during the experiment, apart from the shock wave, the panes and the window were subjected to the action of an intense flame. On the surfaces of the tested panes there is local damage occurred which slightly reduced the transparency of the glass, but did not deteriorate the general technical condition of either the panes or the window to such an extent as to prevent their continued use.

18.6   Conclusions

I. The analysis of the comparative results of the resistance of the structure of the protective door leaves to the projectile strike and the analyzes carried out lead to the following conclusions:

1. The tested protective door leaf structures do not provide full protection against the bullets fired from typical basic types of firearms.
2. The structural material (St0S structural steel) of the tested doors does not provide protection against the penetration by the projectiles fired from long firearms.
3. To make the doors bullet-proof against the projectiles fired from a short distance from a long firearm, the thickness of the steel sheet used should be increased to 5 mm.
4. The protective effect of existing door leaves (their resistance to bullets) can be obtained by introducing a new type of structural steel or by using layered structures, for example with ceramic inlays.
5. In order to determine the perforation properties of the sandwich door structures (and their resistance to bullets), it is necessary to carry out experimental studies, primarily perforation tests to determine the values of the necessary empirical coefficients.

II. Conclusions from the tests of the resistance of the structure of a cash desk protective window to soft impact, air shock wave and static force:

1. The structure of the cash desk window in static resistance tests withstands a force of 2042 N. The panes are ejected from the pane groove of the aluminium frame of the cash desk window only after the displacement of the center of the window by a minimum distance of around 80 mm.
2. In the dynamic resistance tests, even at the first impact with a load bag (impact energy $E = 230$ J) the panes crack, although the entire structure of the window retains its protective properties.
3. Following the third impact with the load there partial (over a width of up to 90 mm) ejection of the panes from the frame structure, at a displacement of the center with the window center displaced by about 130 mm.
4. Following the fourth impact, although the centre of the window is displaced by around 180 mm from its initial position, the cash desk window structure still retains its protective properties, preventing a break-in.
5. The structure of the cash desk window subjected to a reflected air shock wave with a unit impulse of 166 Pas retains its protective (anti-burglary) properties in spite of the cracking of a large area of the panes.
6. On application of the 380 Pas pulse, the panes were ejected from the pane groove of the aluminium frame over a width of at least 130 mm.

7. Because the unit impulse corresponding to the load conditions defined in the PN-V-87003:1999 standard (Table 1 for class D2) is 345 Pas, based on the above tests, the structure of the cash desk window made of P4A class panes should be classified in class D2 for air shock wave resistance.

III. Conclusions from the tests of the resistance of laminar protective panes and the structure of a steel protective window to the explosion of a fuel-air charge:

1. All tested panes and the window were subjected to an explosive overpressure of the shock wave with a maximum value of 30 kPa for a duration of 200 ms. The tested items were not destroyed and could continue to perform their protective functions.
2. Laminar panes of (13 + 1 + 6) mm × 1102 mm × 1152 mm transfer a dynamic load ten times greater than required by the user.
3. Laminar panes of (15 + 1 + 6) mm × 1088 mm × 2125 mm transfer a dynamic load seven times greater than required by the user.
4. A steel protective window with a laminar pane of (15 + 1 + 6) mm × 1048 mm × 2085 mm transfers a dynamic load 17 times greater than required by the user.
5. The action operation of the flame as a result of the explosion of the fuel-air mixture only slightly worsens the transparency of the panes and does not affect the protective function of the window.

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