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METRO- Calculated Explosion Structural Damage

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Sammanfattning

FOI deltar i projektet METRO med studier av generering och skador av tryck efter en explosion i en tunnelbanevagn.

Denna rapport presenterar principer för hur skador på strukturer kan beräknas vid explosionsbelastning. Framför allt fokuseras på skador på fönster, samt skador på människor av glassplitter från fönster och från direkt tryckverkan.

Nyckelord: Explosion, stukturskador, fönster

Summary

FOI participates in the project METRO in studies of the generation and damage of pressure after an explosion in a subway carriage.

This report presents principles for how damage to structures can be calculated. The main focus is on damage to windows, and damage to people due to broken glass from the windows and from the direct blast effects.

Keywords: Explosion, structural damage, windows

Content

1 Introduction

FOI participates in the METRO project with studies of pressure generation and damage from explosions in a subway carriage. This memo presents principles for structural damage from dynamic load such as explosions. It also presents results of calculated or estimated damage to windows in a subway car and to people from the glass shards and from the blast wave of an explosion.

2 General simplified principle for determination of damage to structures from explosive loading

The response of structures loaded by blast waves from explosions is determined not only by the maximum pressure but of the characteristics of the whole pressure-time history. When evaluating the response, it is common to convert the actual structure, for example a plate or a beam, to an equivalent single- degree- of-freedom system (SDOF system). A SDOF system is a mathematical model where the structure only moves along one axis.

To convert a structure to an equivalent SDOF system, equivalency factors for load, mass and resistance are needed. The determination of these factors is based on equal energy of the load, of the resistance and the equal kinetic energy for the real system and the SDOF system. An important factor needed for the transformation of a structure, e.g. a plate or a beam, is the shape deflection. In most cases, this parameter has to be assumed.

Once the SDOF system is defined the deflection versus time can be determined by solving the differential equation for the system.

This methodology is frequently presented in the literature and simplified solutions are given for standardized structures, deformed shapes and loadings.

Example of references presenting methods of work for analyzing dynamically loaded structures using SDOF systems are Biggs (1964), Baker et al. (1983) and Balazs (1997).

Pressure-Impulse (P-I) diagrams (or iso-damage plots), are often used to illustrate the response of structures to dynamic loads. P-I diagrams present combinations of peak pressure and impulse density causing a certain level of damage. The construction of P-I diagrams can be based on calculations with SDOF idealization, finite element analysis or by other methods such as empirically based.

Examples of P-I diagrams for building structures are found in for example Baker et al. (1983) and Forsén (1985), for generic structures such as plates and panels in Aitken-Cade (1974) or Schleyer and Langdon (2006) and for window structures in ESTC (2002), respectively. In the following chapter, examples of P-I diagrams for windows are presented and injury to people behind broken windows are discussed.

3 Damage to windows and humans from glass shards

There are descriptions in literature of the explosion loads that cause damage to glazed surfaces and windows. Such descriptions can be based on calculations as well as on experiments.

It is common to rate the damage in three levels:

- Crack threshold or break safe
- Low Hazard
- High Hazard

The levels of damage are connected to a standardized test procedure (Johnson and Smith 1998). The window is mounted in the wall of a 3 m deep test cell. If the glass shards are thrown longer than 1 m into the room it is considered as low hazard and if the shards are thrown higher than 0.5 m above floor level onto the opposite wall with the window it is considered as high hazard (Figure 1).

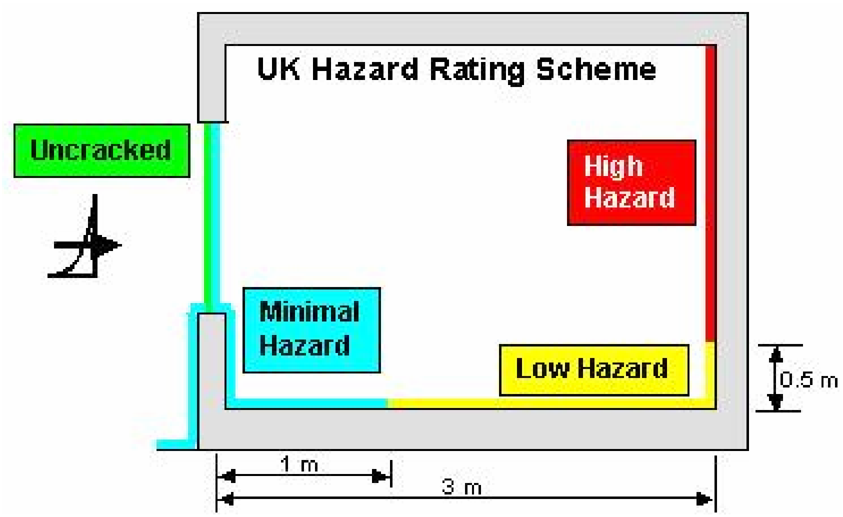

Figure 1. Damage levels according to ”British Glazing Hazard Guide”.

Previous work at FOI (Lööf 2006) has concluded that at the threshold of low hazard the probability of window breakage is 100% and that this will cause minor injury to all persons at the inside of the room (within 3 m), 10% severe injury and 1% fatalities.

ESTC (2002) contains a compilation of various windows’ resistance to explosion load. Tables are presented that give the hazard threshold distances for various glazing types (face-on to the detonation) and charge weights. The following sections demonstrates how P-I diagrams can be evaluated for different window structures based on ESTC.

First three different types of comparatively strong windows were chosen:

1. 8 mm toughened, small pane (1.25 x 0.55 m)
2. Double glazed (sealed unit), 6 mm toughened + 6 mm toughened, small pane (1.25 x 0.55 m)
3. Double glazed (sealed unit), 4 mm annealed + 6.4 mm laminated (normal fix), small pane (1.25 x 0.55 m)

Hazard threshold distances for different charge weights for the different windows and also calculated (BEC 2006) peak pressure and positive impulse densities connected to the pairs of charge weight and distance are presented in Table 1, Table 2 and Table 3.

Table 1. Hazard threshold distances and evaluated peak pressure and impulse densities for 8 mm toughened glass pane with dimensions 1.25 x 0.55 m.

Charge (kg)	**Crack**			**Low haz**			**High haz**		
	Dist (m)	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**
3	9	66,5	142	8	82,4	162	6	148	222
15	18	51,1	205	17	56,1	218	12	106	319
100	40	39,3	323	35	48,4	372	26	80,9	514
500	70	38	538	65	42,5	583	48	70,3	808
2500	125	35,6	879	115	40,4	961	85	66,1	1331

Table 2.Hazard threshold distances and evaluated peak pressure and impulse densities for double glazed (sealed unit), 6 mm toughened + 6 mm toughened glass pane with dimensions 1.25 x 0.55 m.

Charge	**Crack**			**Low haz**			**High haz**		
	Dist (m)	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**
3	6	148	222	5	228	274	4	409	355
15	14	79	269	12	106	319	10	157	392
100	31	59	424	27	75	493	22	112	619
500	55	55.6	697	50	65	773	40	99	988
2500	100	50.3	1116	90	60	1250	70	95	1647

Table 3. Hazard threshold distances and evaluated peak pressure and impulse densities for Double glazed (sealed unit), 4 mm annealed + 6.4 mm laminated (normal fix) pane with dimensions 1.25 x 0.55 m.

Charge	**Crack**			**Low haz**			**High haz**		
	Dist (m)	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**
3	14	32.9	88	11	48.0	114	5,5	181	245
15	35	19.4	101	25	31.0	144	15	70	250
100	80	15.0	155	60	22.0	210	40	39.3	323
500	150	13.3	241	110	20.0	334	80	31.2	467
2500	250	13.8	424	200	18.5	535	150	27.3	724

In order to facilitate an easy determination of the probable hazard level for different combinations of peak pressure and impulse density, the evaluated combinations of peak pressure and positive impulse density values were used to draw P-I diagrams (Figure 2).

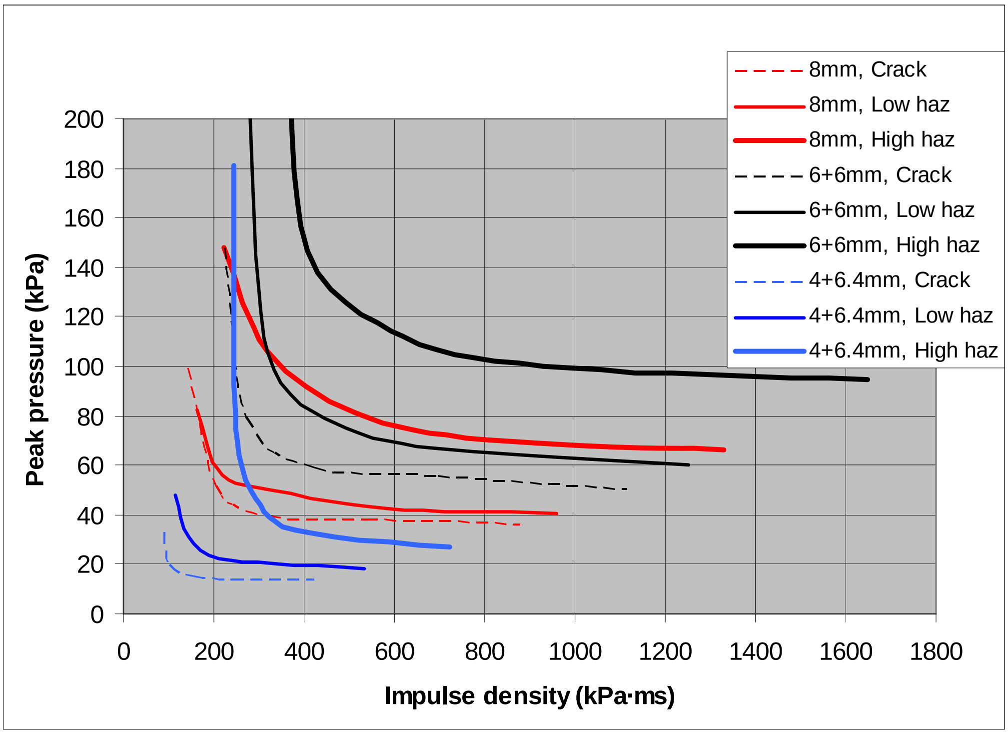

Figure 2. P-I diagrams for three different windows.

As can be seen in Fig. 2, the strongest structure of the three considered is the double glazed (sealed unit) with 6 mm toughened + 6 mm toughened glass. The weakest structure of the three is the double glazed (sealed unit) with 4 mm annealed + 6.4 mm laminated. The 8 mm toughened has strength in between. Based on the latter one may conclude that combinations of blast load above approximately 40 kPa and also above approximately 150 Pas will cause 100% window breakage and this will cause at least minor injury to all persons at the inside of the window (within 3 m), at least 10% severe injury and at least 1% fatalities.

The dimensions of windows in a performed full scale test (Meyer and Berglund 2012) were 1 m width and 0.85 m height and with a thickness of 5 mm. The glass was toughened. This dimension is not present in the ESTC (2002). The two closest are toughened 4 mm and toughened 6 mm panes with dimension 1.25m x 0.55m.

In Table 4 and Table 5 are compiled hazard threshold distances for different charge weights for the different windows and also calculated (BEC 2006) peak pressure and positive impulse densities connected to the pairs of charge weight and distance.

Table 4. Hazard threshold distances and evaluated peak pressure and impulse densities for a 4 mm toughened pane with dimensions 1.2 x 0.55 m.

Charge	**Crack**			**Low haz**			**High haz**		
	Dist (m)	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**
1.5	11	33.4	70.9	9	45.3	87.8	7	68.9	115
3	17	25.0	71.9	14	32.9	88.3	10	55.6	127
15	40	16.3	88.0	32	21.9	111	22	37.3	165
100	90	12.9	137	70	17.9	179	50	28.4	255
500	160	12.3	226	130	16.1	280	90	26.4	412
2500	300	10.9	351	230	15,4	463	160	25.0	677

Table 5. Hazard threshold distances and evaluated peak pressure and impulse densities for a 6 mm toughened pane with dimensions 1.25 x 0.55 m.

Charge	**Crack**			**Low haz**			**High haz**		
	Dist (m)	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**	**Dist (m)**	**p+ (kPa)**	**i+ (kPams)**
1.5	7	68.9	115	6	91,8	136	5	133	167
3	10	55.6	127	9	66.5	142	7	107	187
15	23	34.9	158	20	43.2	183	15	69.6	250
100	50	28.4	255	42	36.6	306	33	53.3	397
500	90	26.4	412	80	31.2	467	60	48.3	635
2500	160	25.0	677	140	30.2	779	100	50,3	1116

In Figure 3 the evaluated combinations of peak pressure and positive impulse density values are displayed as iso-damage curves together with an estimated curve for a 5 mm thick pane that was tested in a full scale test (Meyer and Berglund 2012).

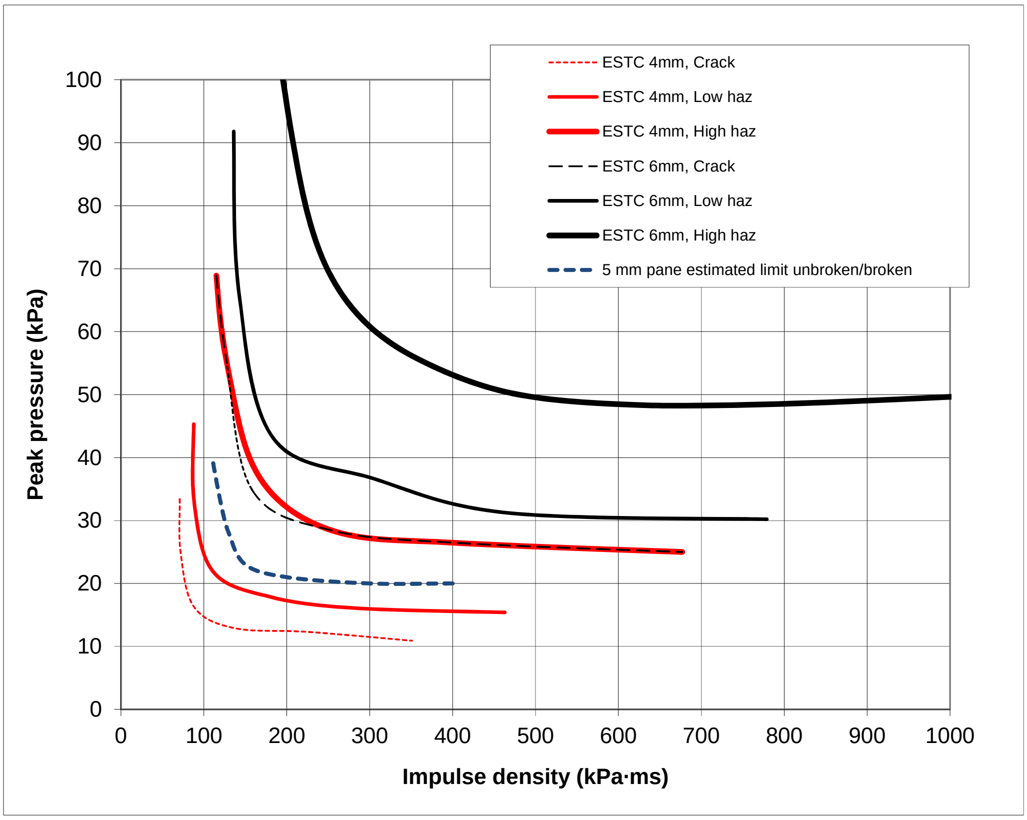

Figure 3. Iso-damage curves for 4 and 6 mm toughened pane with dimensions 1.25 x 0.55 m. Also marked is an estimated Iso-damage curve defining limit for breakage for a 5 mm pane.

4 Damage to humans from blast loads

Humans exposed to blast waves may experience damage ranging from temporary or permanent hearing loss, lung damage or lethality. Several references present criteria for damage to humans based on incident (long durative) pressure levels. Values found in Glasstone and Dolan (1977) and TM 5-1300 (1990) are:

- 35 kPa (5 psi) blast overpressure will cause eardrum rupture in about 1% of subjects
- 310 kPa (45 psi) overpressure will cause eardrum rupture in about 99% of all subjects
- 100 kPa (15 psi) overpressure is reported as the threshold for lung damage
- 240-310 kPa (35-45 psi) overpressure may cause 1% fatalities
- 380-450 kPa (55 to 65 psi) overpressure may cause 99% fatalities.

The pressure levels stated above are incident levels (assuming a free stream situation) while the pressure values calculated (Bryntse and Meyer 2011) are load against the surfaces of the carriage. Although this difference in assumptions, it is considered that an approximate estimate of human damage may be done by comparing the values.

As comparison to the conditions inside the carriage – an estimate is made about damage levels for personnel standing in the open close to a detonating high explosive charge. The estimate is based on Richmond and Fletcher (1971), see Table 6.

Table 6. Distance to different damage level to people versus charge weight.

Charge weight (kg)	**1 % eardrum rupture (m)**	**Lung damage limit (m)**	**1 % fatalities (m)**
1	7	2	0,8
5	12	4	2
10	15	6	3

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