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Analysis of the Resistance of Structural Components to Explosive Loading by Shock-Tube Tests and SDOF Models

Alexander Stolz, Oliver Millon, Arno Klomfass

Fraunhofer Institute for High-Speed Dynamics, Eckerstraße 4, 79104 Freiburg, Germany
stolz@emi.fraunhofer.de

The analysis of the resistance of structural components to explosive loading conditions is important for the design and assessment of buildings which are potentially exposed to explosions. Explosive loading conditions may arise from sabotage, terroristic attacks or accidental explosions and pose a significant hazard. The characteristics of explosive loading differ entirely from those of ordinary static or dynamic loading to which structures are regularly exposed. Reliable methods for the analysis of explosively loaded structures are thus required to design safe buildings and reliably assess existing buildings and thereby minimize the consequences of explosions. Experimental testing is a mandatory step towards a reliable analysis of explosively loaded structures and provides validation data for further simulation-based analysis.

Shock-tube testing offers several advantages over range testing of explosively loaded structural components. This paper describes the shock-tube facility Blast-STAR of the Fraunhofer EMI, which is capable of replicating detonations of high explosives and gas explosions. Besides the presentation of the adjustable range of blast parameters and the installed diagnostic equipment, it is explained how shock-tube tests are used for the derivation of dynamic resistance parameters of building components. These resistance parameters are used in single-degree-of-freedom (SDOF) models, which permit an assessment of the structural response of components and entire buildings under various explosive loadings conditions.

1. Introduction

The knowledge of the behaviour of building structures exposed to explosive loading conditions is essential for the proper design of a new structure or the assessment of an existing structure which may be exposed to such loadings. Explosive loading is characterized by high overpressures, which act in a short duration. They can cause enormous damage, particularly to brittle materials like glass, masonry and concrete, which show a high sensitivity to such loading conditions. Depending on the degree of damage of a structural component and its function in the overall construction, a partial or complete failure of a building (progressive collapse) can occur as a result of a local damage. The correct prediction of the structural resistance and the appropriate design of components thus is the main purpose of the research in the field of protective structures.

The most extreme loading conditions with respect to the exerted overpressure are typically caused by detonations of high explosives such as C4, TNT or other similar substances often used in sabotage or terroristic attacks. Accidents with explosive substances used in the chemical industry can also cause significant blast loadings, particularly as often very large amounts of these substances are involved. In the public media large accidental explosions in industrial facilities are consistently reported as they often cause lots of victims and destructions not only on the site but also in surrounding areas. They can be regarded and must be treated as a significant hazard. Appropriate testing methods are thus not only needed for detonations of high explosives but also for gas or dust explosions and other explosion scenarios that might occur in industrial facilities. Blast waves caused by gas or dust explosions differ from those of TNT or other high explosives as they generate smaller overpressures and larger impulses in the near field. The experimental simulation of a large scale gas or dust explosions with high explosives would therefore require large amounts of explosives (often tons) and large distances (several hundred meters) to the structure under test. Such tests are in general prohibitive. An alternative approach for testing the blast resistance of structural components is the usage of a shock-tube, where the blast wave is generated by compressed gas. In a modern shock-tube

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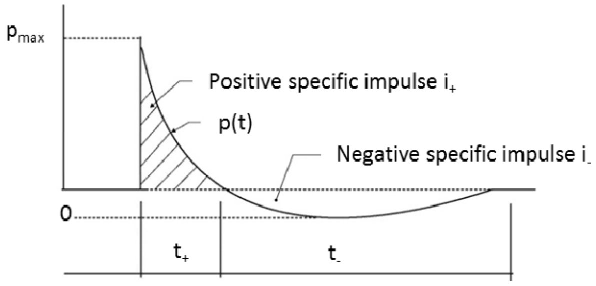
the blast wave parameters (peak overpressure and overpressure-impulse) can be adjusted in a certain range to simulate various explosive sources and distances. In this paper we give a brief introduction to the shock-tube facility BLAST-STAR which was designed and is operated by Fraunhofer EMI. Furthermore we explain the process how shock-tube tests are used to develop resistance parameters for SDOF models.

2. Blast parameters and existing standards for blast testing

A blast wave generated by an explosion takes on a spherical or hemispherical shape at some distance from the explosion source. The loading of an object by such a wave can be approximated reasonably well by the overpressure-time curve shown in figure 1, described by the Friedlander equation (1). The initial shock wave causes the peak overpressure p_{max} after which the overpressure smoothly decays. Subsequently a suction phase with negative overpressure is formed until the overpressure finally decays. Beside the peak overpressure this model blast wave is characterized by the positive overpressure impulse i_+, which is the hatched area below the positive overpressure in figure 1. The duration of the positive phase is specified by the parameter t_+. This simplified model is applicable to both detonations of high explosives and gas or dust explosions. The values of the aforementioned blast parameters depend on the energy of the explosion source and the distance to the loaded object. Gas or dust explosions may generate relatively low overpressures in the far field but can exhibit long positive (and negative) durations up to some seconds resulting in large overpressure impulses. Detonations of high explosives tend to generate higher peak pressures, particularly in the near field, but have shorter durations in the order of tens of milliseconds. These differences must be taken into account in the investigation of explosively loaded structures. Accepted standards for testing methods and resistance classifications are available for security glazing, windows and further components exposed to detonations of high explosives (ISO16934, EN13541 and EN13123-1). Standards for other explosive sources such as gas or dust explosions are presently not defined. Table 1 summarizes the blast parameters required for a certain classification of security windows.



$$p(t) = p_{max} \cdot \left(1 - \frac{t}{t_+}\right) e^{-A \cdot \frac{t}{t_+}} \tag{1}$$

Figure 1: Load-time function of a blast load according to (EN13123-1).

Table 1: Classification of blast resistance of windows, doors, shutters and security glazing (EN13123-1).

Blast load class	Loading pressure [kPa]	Pos. specific impulse [Pa s]	Positive duration [ms]
EPR1	50 – 100	370 – 900	> 20
EPR2	100 – 150	900 – 1,500	> 20
EPR3	150 – 200	1,500 – 2,200	> 20
EPR4	200 – 250	2,200 – 3,200	> 20

3. Shock-tube facility Blast-STAR

Shock-tube facilities have been used to classify and scientifically investigate the response and the resistance of structural components against blast loading for many decades (Kranzer, 2009; Stolz, 2013). Shock-tubes offer several advantages in comparison to range tests: the handling of high explosives is avoided, testing can be performed under laboratory conditions, a high reproducibility of the generated blast waves is achieved and the generated blast waves are nearly perfectly planar in a well-designed shock tube. However, the size of the test object is limited by the cross section of the tube and the attainable blast parameters (mainly the positive durations) are typically within a small range, as they are coupled to the dimensions of the shock tube.

The shock-tube Blast-STAR (figure 2) is a gas driven shock-tube with a two-chamber design, consisting of a high pressure filling chamber and a low pressure expansion chamber. Figure 3 illustrates the conceptual design in a longitudinal view. Further details are given by (Klomfass, 2012).


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Figure 2: View on expansion chamber of the Blast-STAR facility with the end-section wall (grey) for the integration of test samples.

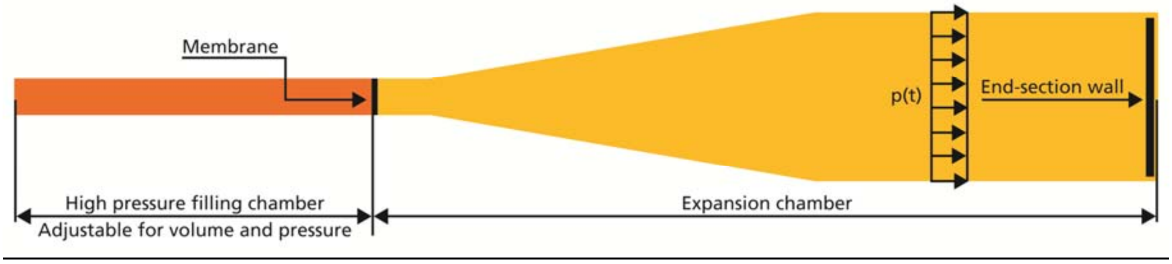

Figure 3: Schematic visualization of the longitudinal profile of the shock-tube Blast-STAR.

The end-wall section of the expansion chamber has a quadratic cross-section with size 3 m x 3 m. Modular rigs permit the fixation of test objects of various sizes up to about the full cross section. The filling pressure and the volume of the high pressure chamber are the mechanically adjustable parameters of the shock-tube, which control the resulting blast parameters on the test sample fixed in the end-wall section. For the simulation of blast waves generated by gas or dust explosions a long high pressure filling chamber with variable length up to 22 m is attached to the shock tube. This filling chamber is operated with comparatively low pressures. A short high pressure filling chamber with a variable length of up to 2 m and high filling pressures is used to generate blast waves, which replicate the far field of high explosive detonations. Figure 4 summarizes the range of blast parameters which can be generated in the Blast-STAR in an overpressure-impulse diagram. The diagram roughly indicates the different loading conditions arising from gas or dust explosions and detonations of high explosives and the separation into far-field and near-field loading conditions. The standardized classification levels for security windows are marked with EPR1 to EPR4 for shock-tube tests and EXR1 to EXR5 for range tests.

Figure 5 shows exemplary test data. On the left side a blast wave replicating a high explosive detonation is shown and on the right side a blast wave representing a gas or dust explosion. Each graph includes the time histories of overpressure and overpressure-impulse. The overpressures were recorded on a planar solid test object (the closed end-wall) by two independent pressure gauges mounted at different positions R1 and R2. The overpressure impulses are obtained by numerical integration of the recorded overpressure transients. The fact that both gauges nearly show identical curves indicates that the incident waves are practically planar and the loading is uniform. In both cases the loading replicates the typical blast wave profile, although the low-pressure, long-duration case (left diagram) is marked by superposed low frequency oscillations. The temporal rise of the overpressure-impulse is however not significantly affected by these oscillations and takes on a rather smooth shape.

The standard diagnostic instrumentation of the shock tube facility includes high-speed video and laser-optical deflection measurements. High-speed video recordings provide the essential information about the global motion and possibly the failure development. Laser-optical measurements are applied to determine local deflections on points of interest. Especially these measurements are important for the determination of dynamic resistance parameters.

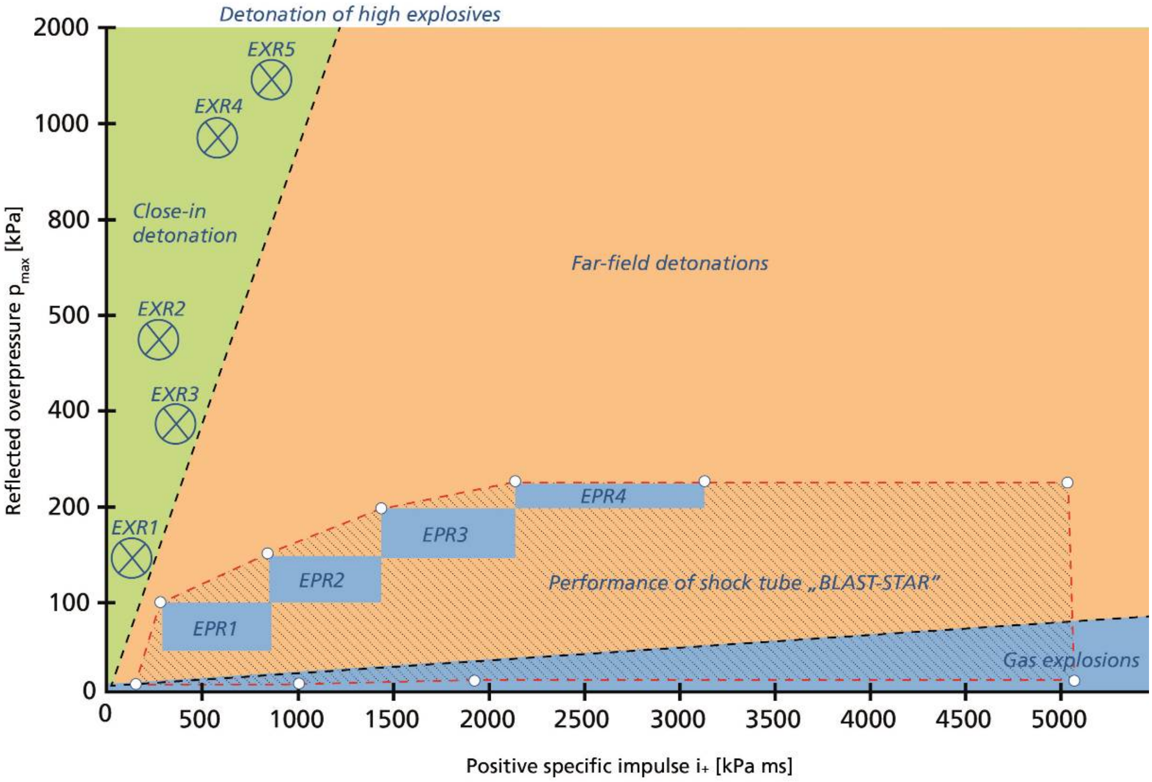

Figure 4: Performance of the shock-tube facility "BLAST-STAR" with respect to loading scenarios defined by pressure and impulse.

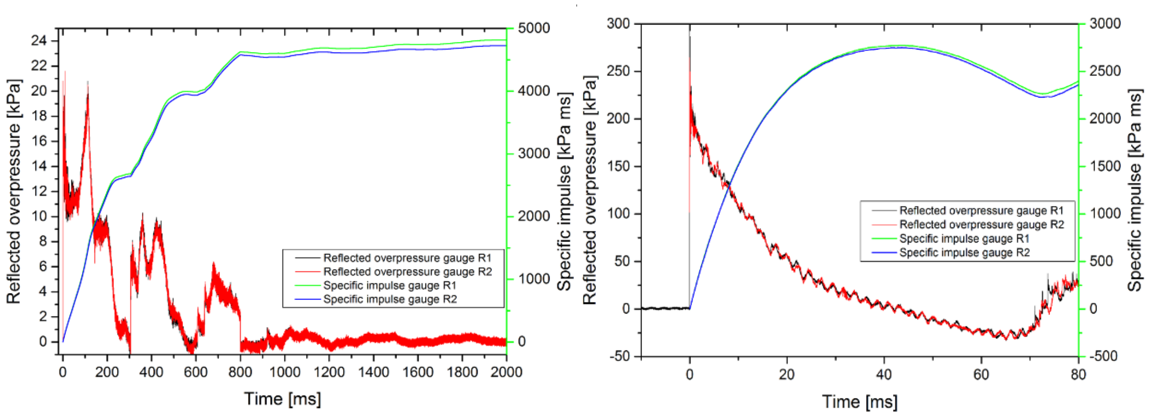

Figure 5: Example of overpressure-time histories generated in the shock tube; left: example of a blast wave representing a gas or dust explosion, right: example of a blast wave from a high explosive detonation.

4. Development of resistance functions for structural components

The analysis of building safety against explosive loading conditions typically requires the evaluation of a broad range of loading conditions (different explosive energies and distances). Such an analysis requires a reliable and efficient computational model, which predicts the structural damage of a component for the considered range of loading conditions. A single degree of freedom model (SDOF) gives a simplified but useful description of the dynamic behaviour of a considered structure. It considers the transient deflection of a single characteristic point of the structure under the effects of the external loading, the effective structural mass, the elastic-plastic properties and the failure limits of the structure. Equation (2) gives the general equation of a SDOF model according to the illustration in figure 6. The time dependent deflection, the velocity and the acceleration of the reference point are expressed by *x* and its first and second derivatives, respectively. The external force is considered as the product of the loaded surface *A* of the structural component and the overpressure-time history *p(t)* of the blast wave. The elastic plastic properties and the failure limits are expressed by the resistance function *R(x)* which relates force to deflection. It depends on the design of the component, its size and material properties. A critical review of SDOF models showed, that the accuracy of SDOF models strongly depends on the chosen resistance function. Equation (3) gives a resistance function suggested by Stolz (Stolz, 2013). In this definition the area specific stiffness c_0 of the component and the reference loading pressure p_{ref} are the free parameters of the function. The viscous damping term *D* is typically neglected for explosive loading conditions, as the maximum deflection (and thus the damage) occurs in the early stage of the response (Biggs, 1964).

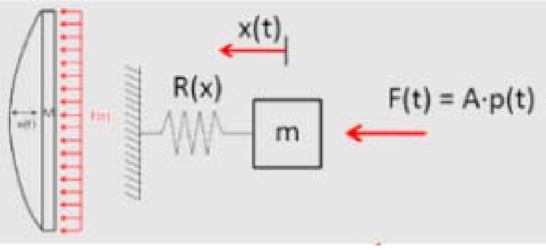

Figure 6: Definitions of the single degree of freedom (SDOF) model with regard to equation (2).

$$m \cdot \ddot{x}(t) + D\big(\dot{x}(t)\big) + R\big(x(t)\big) = A \cdot p(t) \tag{2}$$

$$R(x) = A \cdot \frac{2 \cdot p_0}{\pi} \cdot \arctan\left(\frac{\pi \cdot c_0 \cdot x}{2 \cdot p_{ref}}\right) \tag{3}$$

In shock-tube experiments the transient loading and the transient deflection of the structural component are recorded. The reference point used for the definition of the deflection is usually located in the centre of the element (point of expected maximal deflection) on its outer surface (opposite to the loaded surface). The modelled deflection as solution of equation (3) is compared with the measured deflection of the shock-tube experiment and an optimization procedure is applied to calibrate the free parameters of the resistance function (Fischer, 2009). For a reliable identification of the resistance function and the failure limits a certain number of experiments have to be carried out with different loading conditions. The number of experiments is related to the number of free parameters in the resistance function. The free parameters typically represent the stiffness, the elastic limit, the maximum response pressure and the critical deflection where the structure fails. Shock-tube tests can provide the majority of the data required for the derivation of an SDOF model. Additional data can be gained from range tests if possible and necessary or from high-fidelity computational finite-element models, which in turn can be validated by the shock tube data.

For a simplistic waveform as the one in figure 1 it is sufficient to characterize a loading condition in terms of the peak overpressure and the overpressure-impulse. For such cases the calibrated SDOF model can be used to derive iso-damage curves in p-i diagrams (figure 7). Iso-damage curves are obtained as the set of all possible combinations of peak overpressure and overpressure impulse which lead to the same deflection amplitude i.e. to the same degree of damage. The iso-damage curve permits a simple and direct assessment of the damage in terms of the peak overpressure and the overpressure impulse. Complex waveforms can occur when the loaded object is not in direct line of sight to the explosions centre and the blast wave interacts with other objects on its propagation path. In such cases the SDOF model must be solved by numerical integration using the actual overpressure transient independently for each loading condition. SDOF models and iso-damage curves are common practice for the prediction of structural response due to blast loading, (Morison, 2006). Until today, wide applications can be found for the prediction of the structural resistance of different materials and structural members, like masonry walls (Mayrhofer, 2002), reinforced concrete columns (Shi, 2008) or glazing facades (Smith, 2001). Thus, all structural components of a building for all essential construction materials can be analysed with the described method for a prognosis of the resistance of complete building structures.

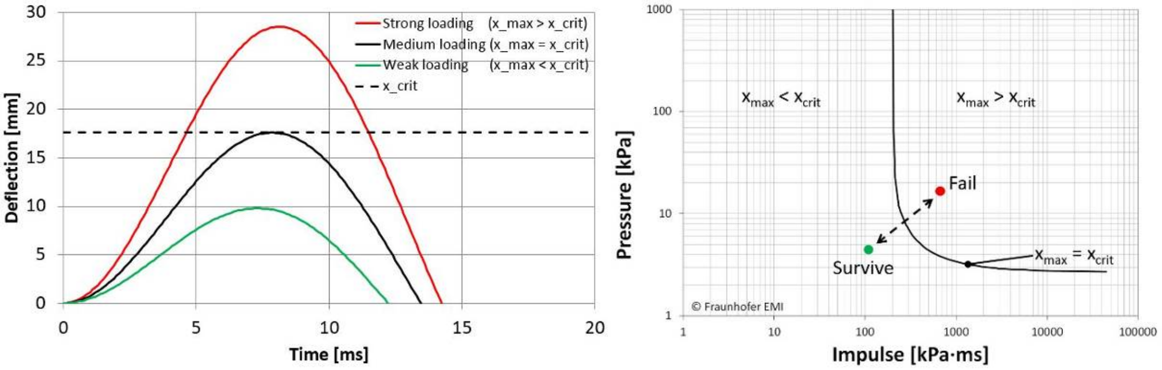

Figure 7: Effects of different blast loading intensities in a SDOF model (left) and an example of a pressure impulse diagram with an integrated iso-damage curve for a specific structural component (right).

5. Conclusions

A modern shock-tube facility can generate a wide range of relevant blast loading conditions. It can be used for testing and certification of components in accordance with existing norms and also for engineering investigations into new concepts of protection and retro-fitting measures. Shock-tube data can be used to calibrate SDOF models, which permit an assessment of the structural safety under a broad range of possible loading conditions. This holds for explosive loading from the detonation of high explosives and also for loadings from other explosive sources like gas or dust explosions.

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