Numerical Simulations on Close Range Blasts Against Light Steel Based Building Facade

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Abstract

External explosions, either accidental or intentional, pose a serious threat to the communities but also a challenge to the structural engineers. Such threats include detonation of high energy explosives (e.g., improvised explosive devices), which can cause structural failures (local damage of structural/nonstructural members or even global failures) and serious injuries or deaths. This risk can be minimized by increasing the standoff distance, but also through structural conception and design, e.g., avoiding brittle materials especially on the facades, adopting specialized construction techniques and detailing. The study investigates the capacity of light steel building facades to resist the effects of close-range explosions and main parameters affecting the ultimate strength and deformation capacity. Pressure-impulse P-I curves are derived from numerical analyses performed with Etabs finite element based structural analysis and design program. Numerical models are calibrated against benchmark tests obtained in a full-scale experimental program.

Keywords: external blast, light building facade, robustness, numerical simulation.

1. Introduction

Steel liner trays, or cassettes, are widely used for exterior wall systems of commercial, industrial, or other kinds of buildings. The common arrangement is made as a double skin system, with a liner tray at the interior, mineral or glass wool as insulation, and weather sheet (the layer at the exterior). Liner trays span horizontally between the main perimeter columns, without any secondary framing support provided by side rails. The common fasteners used to connect the liner trays to the supporting columns are self-tapping and self-drilling screws. Horizontal liner trays are mostly designed as single-span structures. In this case, sagging bending moment acting together with curling of the wide flange is usually critical in design. Up to now, most research activities and code developments on liner tray walls were focusing on the operational performances, including thermal transfer ([1]) and mechanical performance under normal conditions (e.g., design wind pressure/suction) [2], [3], [4]. However, new goals rapidly emerged in the construction industry, focusing not only on individual/single performances of construction products and systems, but on a more holistic approach, which looks at resilience and one of its key components, i.e., the response under extreme loads. Thus, according to [5], the response under extreme loads makes reference to:

a) Safety, which addresses the ability of the building enclosure to resist natural hazards (e.g., strong winds) and continue to operate.
b) Security, which addresses the ability of a building to resist a man-made event (e.g., external explosion) and continue to operate. The steel-based enclosure systems have inherent properties that help satisfy the demands from the first attribute, i.e., safety, and make the building more resilient, e.g., good deformability (and ductility when appropriate), high strength-to-weight ratio, and good connection strength. However, there is less experience associated with the security attribute, and the capacity of liner tray walls to resist extreme accidental loads, e.g., due to external blast.

In a recent study [6], [7], the response of steel liner tray panels under static and blast loading has been investigated and compared in terms of ultimate capacity and failure mode. Numerical models were also calibrated using test data and were further used to obtain more information about liner tray behavior at large deformation stages. However, the results are not entirely practical as the loading conditions may be different, e.g., blast charge weight and distance to the building. To add more complexity, the short duration of the load makes the response more dependent in terms of impulse rather than pressure, which requires dynamic modeling to determine the maximum response. Instead, for assessing the performance of liner trays, but in general of any building component, the so-called pressure-impulse (P-I) diagram may be used [8]. The P-I diagrams may be derived using different methods, such as experimental models, analytical models and finite element analysis [9]. Recently, a new tool to preliminarily estimate the protection level of given structures/components against given blast loadings has been developed at JRC [10]. The Blast Load Assessment and Damage Evaluation tool (BLADE) may be used for structural elements of various types, like slabs, beams and columns, but also building envelope elements made of different kinds of walls, windows and side panels. The included structures and components cover a wide

variety of materials: standard and special concrete types, masonry, steel and glass. The P-I curves are then used to evaluate the respective structure/component damage level against the blast pressure and impulse combination.

This study presents the derivation of P-I curves for steel liner trays using experimental results and numerical models calibrated against test data [6], [7]. The results cover the 115 mm deep webs and 600 mm wide flange (known as MBS KS100/600), with 0.88 mm wall thickness liner trays, made from S320GD steel and connected with six 5.5 mm S-MD55Z fasteners.

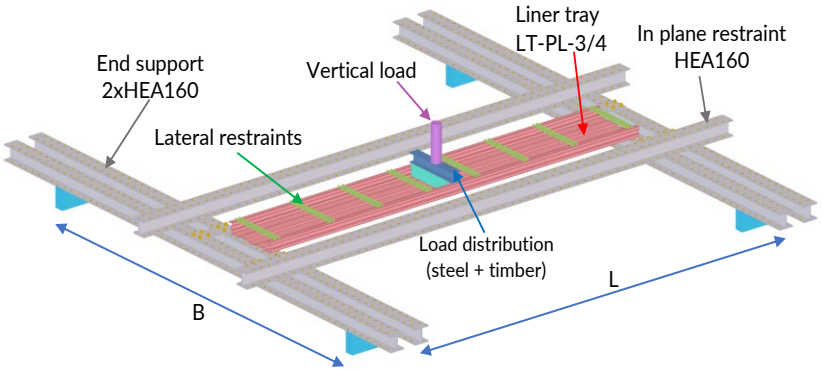
2. Tests On Steel Liner Trays

2.1 Description Of The Experimental Program

The experimental program investigated the ultimate capacity and failure mode of steel-based liner tray panels under quasi-static transverse loading (Fig. 1a) and close range blasts (Fig. 1b), and was developed within the SAFE-WALL project [11]. MBS KS100/600 liner trays with 0.88 mm thick walls, S320 GD steel (see [12] for Technical delivery conditions), spanning 4.5 m were considered. The panels were fixed with six 5.5 mm S-MD55Z fasteners at each end. To account for in-plane stiffness of the supporting structure, two experimental set-ups were considered in the static tests, i.e., low stiffness configuration and high stiffness configuration, respectively. More details about test setup, geometrical and material characteristics, and loading protocols are given in [6], [7]. Results of shear tests on connections are also detailed in [6].

As may be seen from Fig. 2 showing the results of static tests, after the peak flexural load is attained, all specimens show a drop in capacity, followed by a second increase due to the development of catenary forces. Also, failure is ultimately given by the capacity of end fasteners (Fig. 2).

In the case of blast tests, as may be seen from Fig. 3a-b, panels suffer heavy distortions, with more damage in the panel placed normal to the point of detonation. The failure is also caused by the tearing of the liner wide flange around end fastenings (Fig. 3c). If we compare the results of the static and explosion tests, we can see that the maximum residual deformations at failure measured in the two types of tests are very close, see Fig. 4.



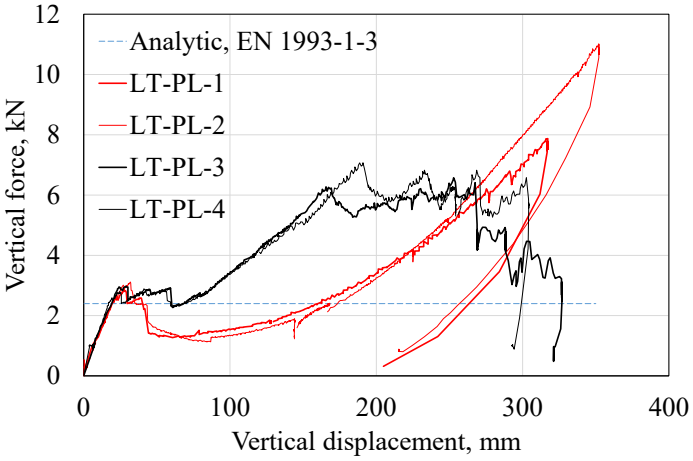
a)

b)

Fig. 1. Full-scale test set-up for static test (a) and photo with the blast model during construction (b).

a)

Fig. 2. Static tests: a) failure mode with complete tearing of the panel wide flange; b) vertical force versus vertical displacement curves.



b)

Fig. 2. Continued

a) b) c)

Fig. 3. Blast test T4: a) snapshot with transient deformations in panels; b) residual deformations in the panels; c) tearing of large wide flange at end fastening.

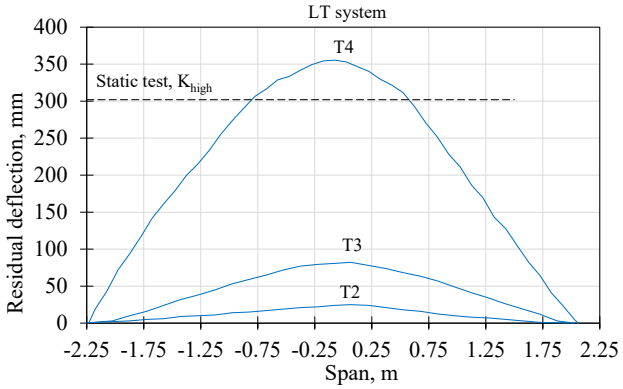


Fig. 4. Maximum residual deflections along panel span.

2.2 Numerical Model Validation

The numerical modelling was done using Etabs software [13], which has advanced features for Nonlinear Dynamic (Time-History) analysis. The model included wall panels and the supporting steel frame structure (Fig. 5a). The consideration of the main steel frame structure allows for more realistic modelling of boundary conditions, mainly the in-plane stiffness of the steel frame, which directly affects the development of catenary action in panels at large deformation stage [14]. Based on observations from the explosion tests, which showed that the panels work independently (seaming connection is lost), but also to reduce the computational demands, a single panel has been considered in the model. The wall panel was arranged as single span. To reduce the numerical computation demand, the liner tray cross section profile was simplified, and was modelled with continuous plane surfaces, without corrugations (ridges and valleys) (Fig. 5b). Four-node quadrilateral nonlinear shell elements were used to simulate the nonlinear response of the panels. The behavior of the end fastenings, six at each end, was modelled using link elements connecting the wide flange to the supporting column (Fig. 5c). The shear link behavior was characterized using a multilinear plastic law on *x* direction, calibrated using static shear test results on identical fasteners and end details (more details can be found in [6], [7]). The directional properties of the link on *y* and *z* were considered fixed. The blast pressure history was modelled using an equivalent triangular function *f(t)*, characterized by an instantaneous rise in pressure (peak reflected pressure, P_r) followed by a linear decay to zero in the time t_{rf}. To reduce the modeling complexity and the computational demand, the variation of the pressure on the wall panel was done

using 20 equal segments, 10 on each side of the midspan. Also, the same arrival time is considered for all segments. Fig. 6 shows a snapshot with the maximum transient deformations of the liner tray during T3, which is well approximated by the numerical simulation.

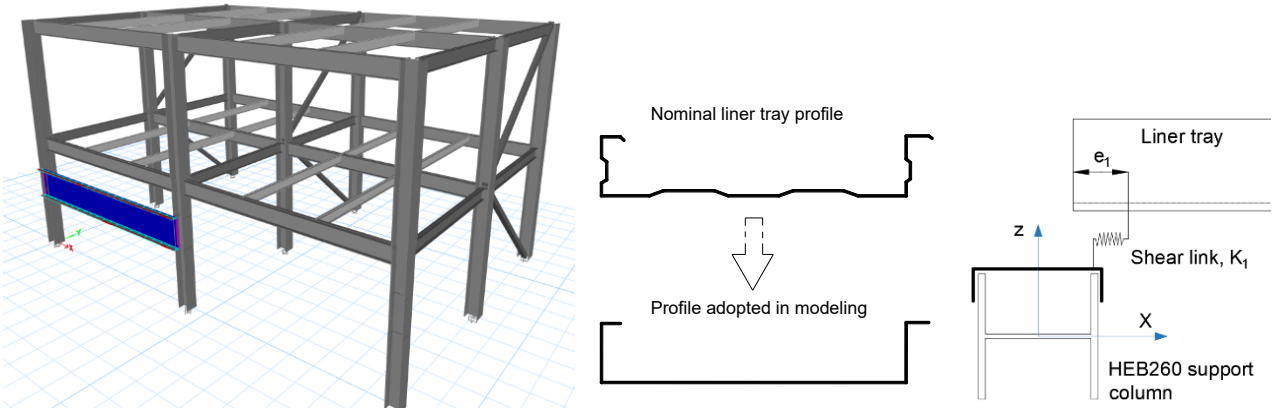


Fig. 5. Numerical model: a) general view with a single liner tray positioned at 1.5 m from column base; b) simplified liner tray profile; c) multilinear plastic link K_1 used for end fasteners.

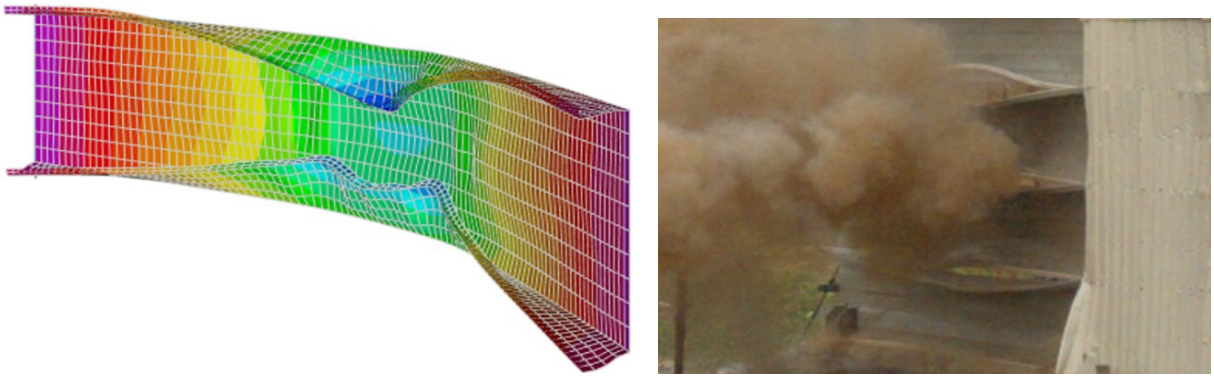


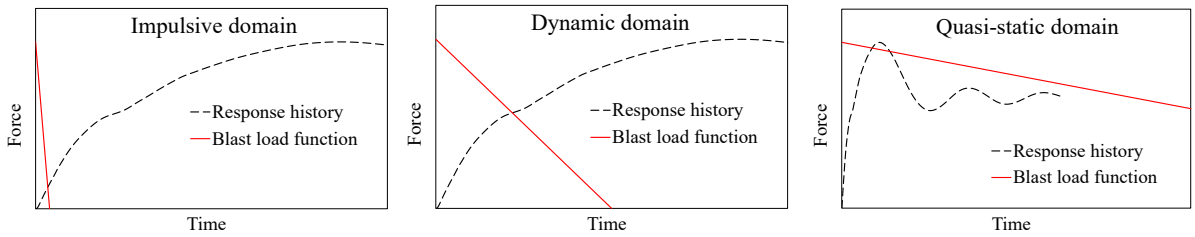
Fig. 6. Maximum transient deformations, test T3, numerical (left) vs experimental (right)

3. Derivation of P-I Diagrams

For extreme loading characterizing a blast event, there are several methods to verify structural response and design adequacy, i.e., experimental methods, numerical methods, engineering approaches and empirical methods. Due to the lack of sufficiently validated calculation methods, the experimental testing, which can be done either using free field test or shock tube tests, is still necessary [15]. For structural dynamic analysis in general, and for blast analysis in particular, the designer is more concerned with the final states rather than a detailed knowledge of the response history [8]. Thus, for assessing the performance of liner trays, but in general of any building component, the so-called pressure-impulse (P-I) diagrams may be used [8]. The P-I diagrams may be derived using different methods, such as experimental models, analytical models and finite element analysis.

For assessing the performance of steel liner trays subjected to a range of detonations produced by different blast charges and different standoff distances, a numerical model calibrated against test data has been employed. The results cover the 115 mm deep webs and 600 mm wide flange (known as MBS KS100/600), with 0.88 mm wall thickness liner trays, made from S320GD steel and connected with six 5.5 mm S-MD55Z fasteners. As seen from previous studies on similar systems, when the ultimate capacity at catenary stage is of interest, the span of the element has small influence. Thus, the increase in span reduces the initial stiffness and load corresponding to bending capacity. However, there is a small influence on the contribution of catenary action [16]. Therefore, the results may be used with some approximations for other span dimensions. To produce the P-I diagrams, the vertical and horizontal asymptotes that differentiate between impulsive and quasi-static domains were first defined, see Fig. 7. Then, two boundaries may be used to check if the P-I combination represents “failure”, i.e., the failure point associated with the impulsive response, i.e., the blast test T4, and the failure point associated with the quasi-static response, i.e., the static test, see Fig. 8.

The procedure detailed in Fig. 8 continued with several trials, until the boundary at failure is defined, see Fig. 9. It is necessary to note that the duration of the positive phase of the blast wave has been limited to 0.5 ms, which is beyond the most possible blast conditions. Further on, two more boundaries associated with minor and moderate damage have been derived. While first one is associated with the presence of some incipient residual deformations, i.e., conditions associated with test T2, the second one is associated with a state of moderate damage, and moderate residual capacity in the end fasteners, i.e., conditions associated with test T3, see Fig. 3 and Fig. 4 [7].



a) b) c)

Fig. 7. Typical response domains: a) impulse; b) dynamic; c) quasi-static.

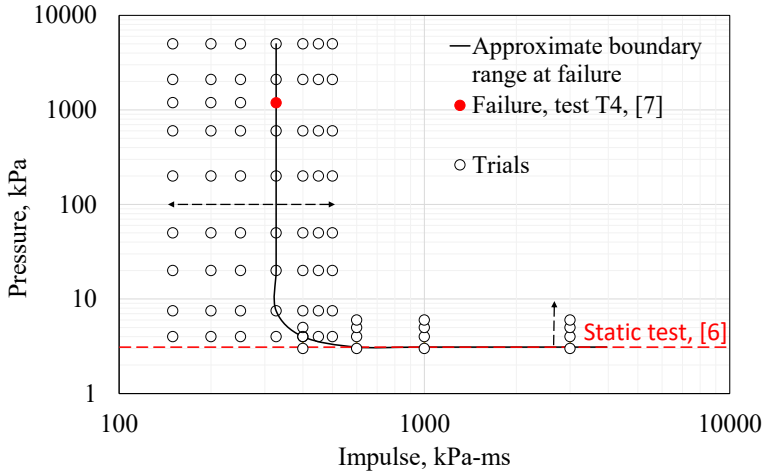


Fig. 8. Search algorithm for deriving the P-I diagrams

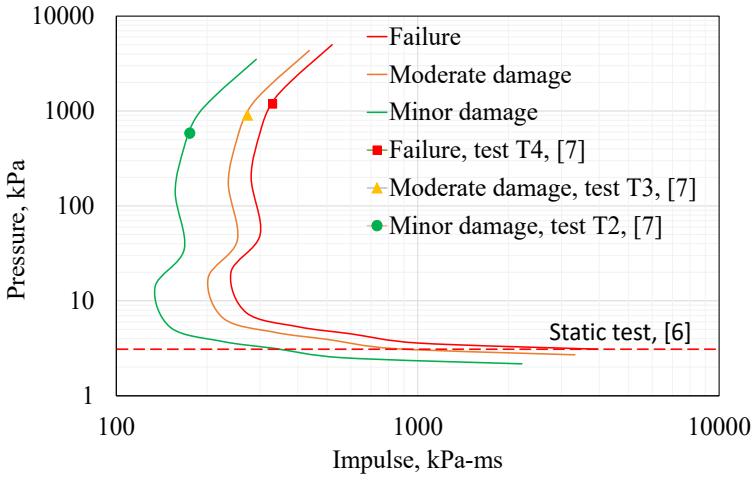


Fig. 9. P-I diagrams for 3 levels of damage: minor, moderate and failure

4. Conclusions

This study presented the derivation of P-I curves for steel liner trays using experimental results and numerical models calibrated against test data. The results cover the 115 mm deep webs and 600 mm wide flange (known as MBS KS100/600), with 0.88 mm wall thickness liner trays, made from S320GD steel and connected with six 5.5 mm S-MD55Z fasteners.

The following main conclusions may be drawn:

- The P-I diagram method provides valuable information for many practical applications.
- The results may be used for preliminary design of the facade, but also the configuration of the safety parameter, if possible.
- Considering the ultimate resistance of the liner trays depends on the shear capacity of end fasteners at large deformation stage, the results may be used with some approximations for other span dimensions but same number and type of fasteners.
- For more complicated geometrical or loading conditions, structural engineers still need to rely on other methods to predict the maximum response due to blast.
- The study will continue by considering other liner tray typologies, number of end fasteners, and blast loading conditions.

Acknowledgement

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