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Efficiency of blast walls for protection of soft targets

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Abstract

The recent trend of terrorist attacks on civilian targets, including transportation systems, resulted in efforts to harden and strengthen these objects which previously were not designed to cope with this kind of threat. The blast mitigation strategies traditionally used in industrial facilities may provide an additional safety. One such solution is a blast wall that could be used for façade systems or for protection of muster areas and evacuation routes of metro and train stations or airports.
This paper deals with the assessment of the blast response of protection walls. The typical types of blast walls commonly used in practice in industrial sector are described. The behavior of blast walls is characterized using simple analytical approach and finite element modelling. The advantages and limitations related to each of these characterization techniques are discussed compared with findings of other authors. Furthermore, a parametric study is performed through extrapolation of numerical models. Two common types of panels with both fixed and pinned boundary conditions are subjected to directly defined pressure loads. Their responses are compared in order to evaluate the effects on the primary steelwork. Possible benefits deriving from typological and geometrical modifications of the local element are also presented. Particular emphasis is given to the importance of the estimation of the reaction forces, displacements and energy dissipation.

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Keywords: soft targets; blast response; blast walls

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1. Introduction

Most of the documents dealing with blast resistance of structural systems are recent and the conclusions reached depend on the soft target type. Detailed documentation on security upgrade options for specific soft target is still rather limited in the European Union, Karlos et al. (2018). This paper represents an effort to improve the blast protection of soft targets by resourcing to the structural blast mitigation solutions already used in oil and gas industrial facilities, as well as to innovative solutions used in earthquake design.

Soft targets indicate vulnerable places that may be selected by terrorists in their effort to maximize casualties, thus inflicting fear to the population and attaining media coverage, Karlos et al. (2018). These may include critical infrastructure, key resources or key assets which are usually without a proper protection and that are open to public by their purpose, Bennett (2018). Critical infrastructure, according to the PATRIOT Act, is any physical or virtual system which destruction would undermine security, economic stability and public health or safety. An example of such infrastructure is the petroleum refinery.

Blasts are unexpected events that may result in catastrophic consequences. There are various solutions that can help reduce the chances of occurrence of these events or that may reduce their severity. The risk is usually managed through control, mitigation and emergency response, UKOOA and HSE (2003). The mitigation measures can be either structural or non-structural which may be active in the case that they require an operator or passive if the mitigation measure acts independently. These measures reduce the probability of occurrence of a certain accidental scenario and reduce the intensity of a hazardous event that may occur. Structural measures focus on structural measures that need to be adopted in order to protect specified areas against explosions and fire. According to Hamdan (2006), the structural safety can be improved by improving the ductile capacity of areas where stress concentrations are expected and through use of blast resisting walls and strengthening of secondary structures so that they can carry part of the blast load.

Having a reliable and a simple assessment tool that can evaluate the response of local members to accidental actions is very important. This design issue is related to the assessment of the actual dynamic response of the structure under impact. This response can be determined either using a simplified calculation models based on a Single Degree of Freedom (SDOF) systems combined with elastic-plastic methods of analysis or using Multi Degree of Freedom, non-linear dynamic finite element analysis. The SDOF for blast analysis is also known as Biggs method, Biggs (1964). The method was further used and improved by various authors Clough and Penzien (1975) and Baker, et al. (1983). In order to take account of moment capacities of the supports, catenary action and material strain rate sensitivity in the case of beams and one-way slabs improved methods were proposed by FABIG (2002, 2007) and U.S Army Corps of Engineers (DoD) (2008) as well as by various standardization organizations and recommended practices API (2006), DNV (2010) and NORSOK (2013). On the other side, even the most recent DoD report UFC 3-340-02 method for two-way elements still do not integrate the catenary effects and the results for thin two-way elements are not accurate. The only way to obtain a realistic response of such elements is to use the specialized finite element software, such as Abaqus.

2. Numerical modelling

In order to study the behaviour of thin two-way elements that are prone to large deformation, it was decided to use finite element modelling software Abaqus. This software allows the use of both implicit and explicit dynamic solution methods, Chen, et al. (2015). The explicit solution is recommended for brief non-linear transient analyses, particularly when large deformations are involved. This approach is chosen for the study due to its computational efficiency. The model is meshed using the first order reduced integration shell elements S4R are appropriate for general blast assessment purposes, Louca and Boh (2004). These elements are recommended for large deformations and finite membrane strains. A fine uniform mesh over the entire part with the element size of 10 mm is chosen. According to DNV, such mesh also allows for the sufficient number of elements to capture the relevant buckling modes, DNV (2013). The adopted meshes are shown in the Fig. 1 both for the bulkhead and for the corrugated plate.

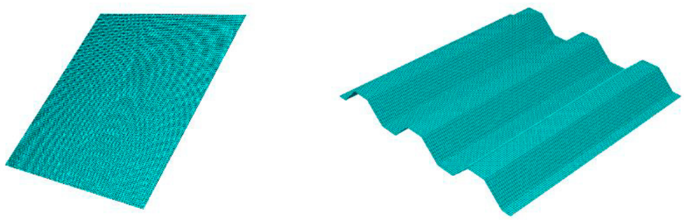

Fig. 1 Adopted mesh for bulkhead (left) and corrugated plate (right)

2.1. Material modelling

Lighter protection barriers used in petroleum industry are often made of either carbon steel or stainless steel. Herein, the structural steel S355 was adopted. The dynamic behaviour of this material is well documented in the literature which allowed the modelling that integrates the strain rate effect and strain hardening, as well as damage evolution. The parameters used for this purpose are taken from the experimental study, Ribeiro, et al. (2016a, 2016b). The authors of these works describe the material stress-strain response based on the Johnson-Cook law, Johnson and Cook (1983). The strain hardening was defined directly using a multi-linear curve whereas the sotftening was disregarded. The strain rate constant for the second part of the equation is defined as C = 0,039 for the strain rate $\dot{\varepsilon} = 600$ s-1. According to Ngo et al. (2007), the strain rate enters the explosion domain since it falls in between the 100 s-1 and 10000 s-1. Also, the proposed model integrates ductile fracture. The damage evolution was defined by linear displacement and no temperature dependancy was adopted. The plastic displacement was defined as:

$$\bar{u}^{pl} = L\bar{\varepsilon}_f^{pl} \tag{1}$$

The Eq. 1 is dependent on the mesh size L and on the equivalent plastic strain at failure which is here defined as $\bar{\varepsilon}_f^{pl} = 20\%$. This value is defined according to recommendation from CEN (2005).

2.2. Load description

In the case of this study the interaction between the load and the element was not taken into account. The load was defined directly by specifying the pressure variation. This assumption is in line with recommended practices DNV (2010), API (2006). According to several authors and recommended practices, the pressure resulting from the explosive event can be realistically simplified using the triangular shape load representation. The deflagration type of explosion can be satisfactorily approximated by taking into consideration only the positive phase duration which is characterized by the higher peak overpressure. This simplification is shown in Fig. 2, corresponding to the time period t^+ and maximum overpressure P_{max}. The real positive interval is defined by the $0 < t \leq t_3$. The triangle which simplifies this interval is defined by $t_1 < t \leq t_3$.

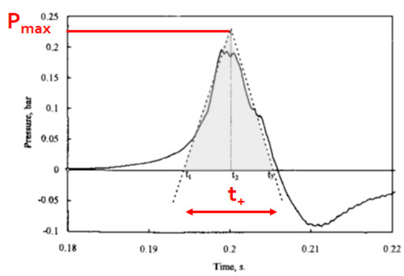

Fig. 2 Positive duration phase of an explosion (Puttock, 1995)

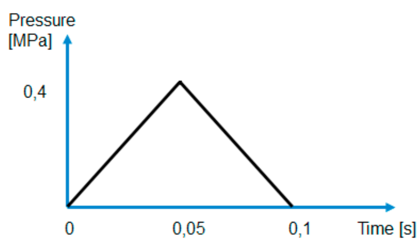

Fig. 3 Pressure-time curve

The recommended practices offer some values of pressures and simplified formulations that can be used for load definition in the early design phases. According to API (2002), the blast overpressures on a platform can vary from near zero on a small, open platform to more than 2 bars (0.2 MPa). According to more recent publication by Louca and Mohamed Ali (2008), overpressures resulting from the deflagration type of explosion may be as high as 8 bar (0.8 MPa). The intensity of 4 bar (0.4 MPa) can be anticipated in the case of fully confined space. It is suggested that it is not economical to design the primary members for overpressures above 4 bar (0.4 MPa). Therefore, the maximum overpressure was chosen having in mind these recommendations. It was assumed that the pressure is the result of the bang-box ignition in the small and confined space and the maximum peak overpressure was adopted as 4 bar (0,4 MPa). The positive phase duration is taken equal to 100 ms based on the Hoiset formulation, as it is schematically represented in Fig. 3.

2.3. Validation of the modelling approach

The numerical approach described in the previous sections was assessed considering the results of another numerical study by Tavakolia and Kiakojouri (2014). The material properties, loading and boundary conditions were defined as in the reference study, according the procedures described in the previous chapters. The detonation type of pressure curve was used for the validation of the model. The simplified, triangular pressure diagram is frequently used in practice.

The original study analysed the effect of various stiffener typologies. For the purpose of the validation of the approach, only the results for the unstiffened plate (Model 1), the plate with one stiffener (Model 2) and the plate with two stiffeners (Model 3) were considered. Fig. 4 compares the deflection obtained by Tavakolia and Kiakojouri and using the previously described numerical approach. Table 1 summarizes the maximum displacements obtained for these three cases. The results show a very good agreement between the developed model and the results of the reference study.

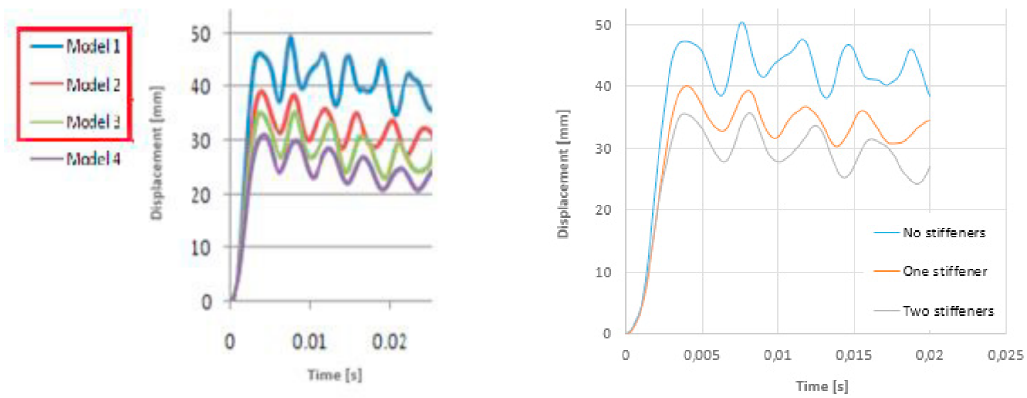

Fig. 4 Displacements obtained in (Tavakolia & Kiakojouri, 2014) (left) and using the described approach (right)

Table 1 – Comparison of maximum displacements

Type of plate	Current study [mm]	Tavakolia and Kiakojouri [mm]
Without stiffeners	50,4	49,2
With 1 stiffener	40,1	39
With 2 stiffeners	35,6	35,5

3. Results and discussion

The set of results obtained by numerical analysis is presented, first for the fixed and then for the pinned boundary conditions. The following discussion is aimed at identifying the most favourable plate type regarding the blast response of the member and compares the findings with those by other authors. This study of two-way elements was performed with an emphasis on the estimation of displacements, distribution of the reaction forces and evaluation of energy dissipation. Fig. 5 identifies the element sections which were analysed.

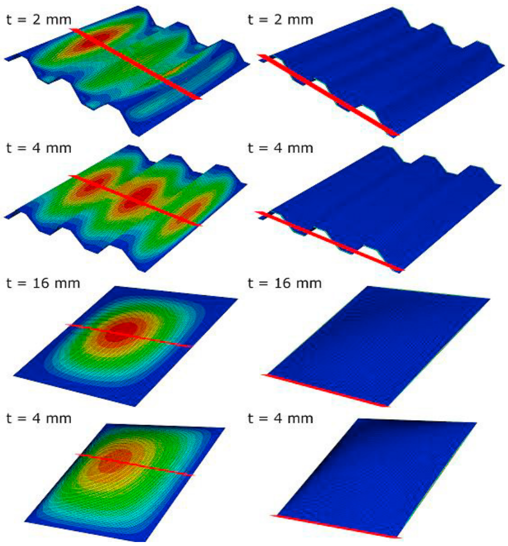

Fig. 5 Sections in which the results were analyzed: Displacements (left) and reactions (right)

All the results, except for the displacement of the central node of the plates, were analysed considering the time frame in which the maximum displacement of the time-displacement response was obtained. The displacements in the central node are given in time. The analysis was run during 300 ms in order to characterize the free vibration stage of the plate.

Considering the reduced time durations involved, the damping effect was neglected in agreement with the procedures adopted by several authors including Biggs. Figs. 6 to 9 show the responses obtained considering fixed support conditions along all four sides. The results show, particularly Fig. 7, that there is a clear difference between the time-displacement responses obtained for flat and corrugated plates, showing the first ones, in general, a much greater oscillation of the displacement values registered during time, probably due to their reduced flexural stiffness.

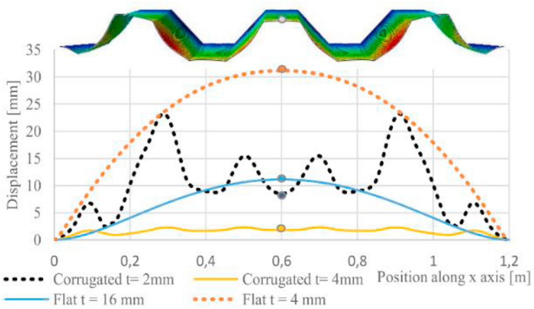

Fig. 6 Displacements of fixed plates in the section according the Fig. 5

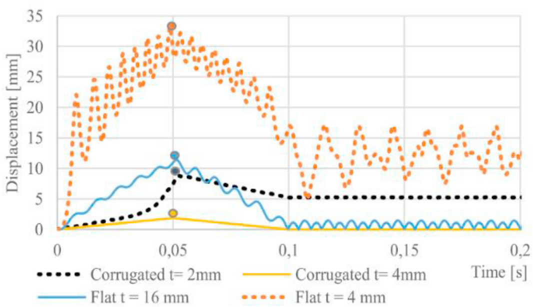

Fig. 7 Displacements of fixed plates in the central node with maximum displacements corresponding to the Fig. 6

According to the general FEM framework, reaction forces are computed in the nodes of the elements, therefore the magnitude of the reaction force will depend on the size of the mesh element. For this reason, the value of the horizontal reaction forces was factored by the ratio of the element size and the length of the support. This way, the magnitude of forces is comparable. This was important mostly because the nodes on the inclined part of the corrugated plate were refined in order to coincide with those of flat plates.

Furthermore, the results shown in Figs. 6 to 9 demonstrate that corrugated plates reach much lower deflections than the flat ones. The maximum deflection of the 4 mm thick corrugated plate is almost five times lower than the maximum deflection reached by the bulkhead with a thickness of 16 mm. Compared to the 'thick' bulkhead, which remains practically in elastic domain during the entire response, the thin corrugated plate is characterized by larger permanent deflections when the maximum deflection reached by the same node is compared. According to Fig. 8, the thinner corrugated plate showed maximum reaction forces in the nodes which were approximately 20% lower than the ones in the thick corrugated plate, but higher reaction forces than the ones in the thicker bulkhead. Thin corrugated plates allowed for significant plastic dissipation, approximately two times more than the thin bulkheads, Fig. 9. Figs. 10 to 13 show the responses obtained for all plates considering pinned connection at the supports along all four sides. The displacements, reaction forces and plastic dissipation are evaluated and presented as before. In the case of pinned plates, the time-displacement responses showed that, in general, higher displacements have been reached in all cases, as expected. Once again, corrugated plates outperform the bulkheads, since the lighter elements are characterized by significantly lower deflections. Corrugated plates have reached higher peak reaction forces, but the average reaction forces are lower than the ones obtained for the thin bulkhead. On the other hand, the difference between the reactions of the two bulkheads is not as significant as in the case of fixed boundary conditions. This remains to be verified in the future, by representing the interaction between the plate and the adjacent structure more realistically. Plastic energy dissipation for thin corrugated plates was three times higher than the one for the thin bulkhead, and around 40% higher than for the thin fixed corrugated plate.

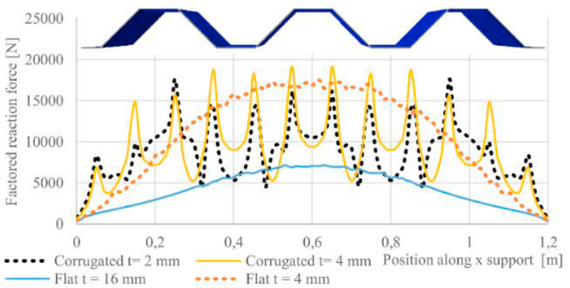

Fig. 8 Factored reaction forces for fixed plates in the section shown in the Fig. 5

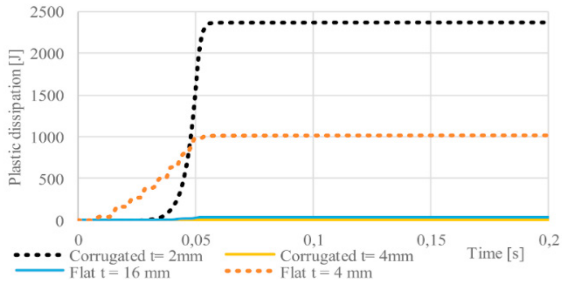

Fig. 9 Plastic dissipation of fixed plates

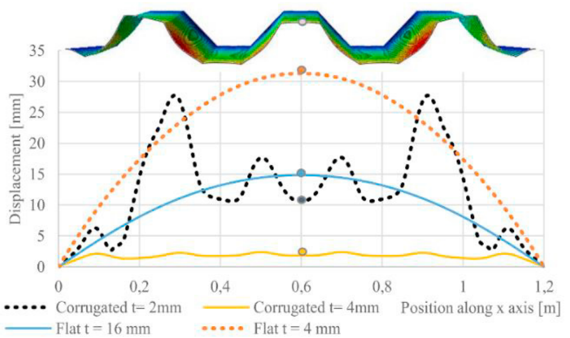

Fig. 10 Displacements of pinned plates in the section according to Fig. 5

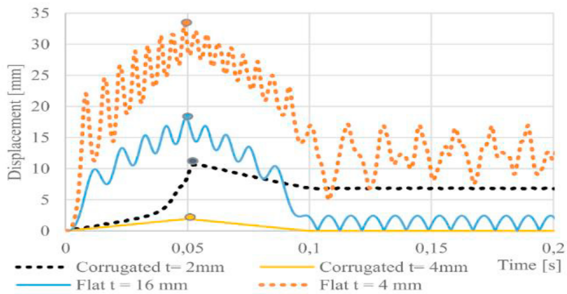

Fig. 11 Displacements of pinned plates in the central node with maximum displacements corresponding to the Fig. 10

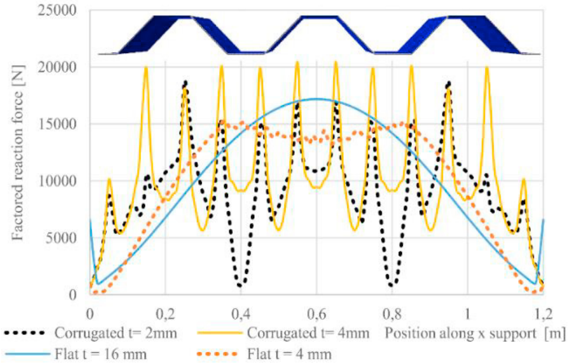

Fig. 12 Factored reaction forces for pinned plates in the section shown in the Fig. 5

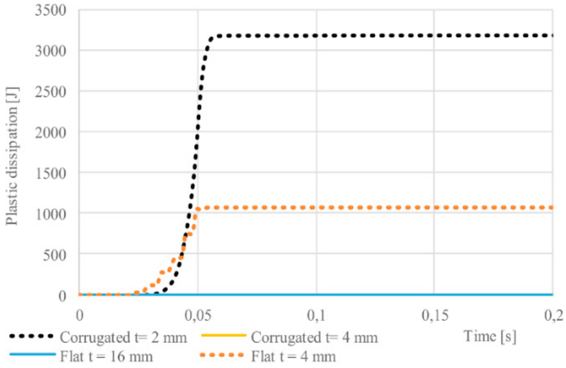

Fig. 13 Plastic dissipation of pinned plates

4. Conclusions

The presented study recognizes the need for improvement of safety measures of soft targets. It introduces blast protection practices adopted in oil and gas sector and proposes the implementation of these practices for protection of public spaces and objects that were not previously designed for this type of action. It was possible to analyse the time-displacement response of blast walls against deflagration-type of blast loading representative of explosions resulting from hydrocarbon gas ignitions. It was shown that the design process of the blast wall, regarding its dynamic response, greatly benefits from detailed FEM analysis. This analysis integrates the non-linear behaviour of the materials and the detailed design requirements can be more precisely accounted for. The results of FEM analysis demonstrate the importance of the studied parameters, such as member geometry and boundary conditions, for the safer design of supporting structure. In general, it was possible to conclude that, for the type of blast action considered, it is more economical to use corrugated plates instead of bulkheads if the deflection of the element is the relevant design criterion. In this case, it appears to be more reasonable to allow some flexibility in the edges since the overall response of the plate would be more favourable due to the much higher energy dissipation. On the other hand, even though much heavier, the thick bulkhead seems to perform better if the magnitude of the reaction forces is the primary design criterion.

As previously mentioned, the present study may be extended by analysing the interaction of the plate and the neighbouring structure. This means that the connection between them should be represented more realistically. Additionally, blast load description may be improved by including the negative phase of the time-pressure curve and the interaction between the load and the structure may be taken into account. Also, other sizes and geometries of the plates, as well as other material combinations, should be considered in order to understand the importance of the scale and whether the better performing solutions can be attained.

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