Finite Element Analysis of Blast Resistant Structures in the Oil and Gas Industry

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Abstract: *A common requirement in the oil and gas industry is to design structures that are adequate against the effects of accidental gas explosions. This paper presents an overview on the methodologies involved in the study of the response of structures to resist blast and explosion, focusing on the use of nonlinear finite element analysis (NLFEA). NLFEA can be used to overcome the limitations of commonly used analytical methods which are predominantly developed for elastic response or limited plastic response and do not allow for large deflection and unstable responses. More importantly, the use of NLFEA can pave the way towards a more rational performance-based blast resistant design, since the current criteria as set out in the design guides can be inadequate*

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1. Introduction

Protection of a structure and its occupants against any form of blast loadings requires a detailed assessment on the characteristics of the loading and the subsequent structural response. Historically, the subject of blast analysis has been largely ignored in many of the structural design codes and much of the work that has been done is not readily available in the public domain. The consequences of this lack of knowledge can be costly, such as the complete loss of the Piper Alpha oil rig platform and many lives following an accidental explosion [1].

The best form of protection against any blast loading is prevention, and when this is not possible or cannot be anticipated, a detailed assessment on the survivability of the targeted structure must be performed. In other words, the robustness of the structures against such loadings must be evaluated. In analogy to earthquake analysis, two levels of assessment, strength and ductility, can be identified [2] for any blast resisting structure. The strength level analysis relates performance of structures in terms of strength and the ductility level analysis allows a certain amount of permanent damage (provided that this does not lead to an escalation of events). Performance is thus based on deformation limits, rupture and ductility. Proper connections need to be provided so that there is adequate strength or ductility for the transfer mechanism of the blast load to take place. It is also reasonable to expect that expensive shutdown of facilities must be prevented or limited and that repair can be carried out as quickly as possible.

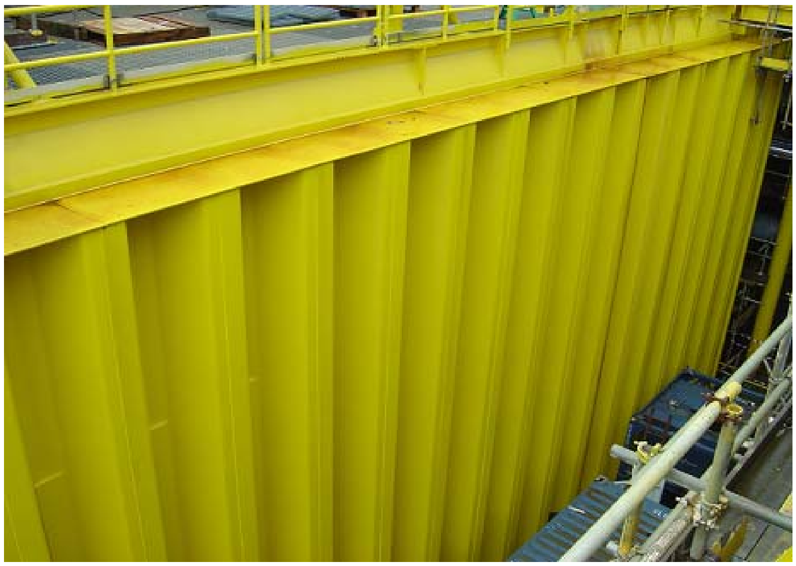

Figure 1. Typical blast wall.

Traditionally, concrete has been used for land based blast protective structures, due to its massiveness and ability to absorb large amount of energy. In offshore and marine environments, different structural schemes are needed since weight is an important factor in design. Consequently, the blast barriers to separate zones with an explosion risk and protected areas, such as living quarters, must be light, robust and should not participate in an escalation of events following the blast. A suitable design fabricated in steel is an obvious choice to meet these requirements. Another class of material, the so called advanced composites, has also been extensively studied in recent years to take advantage of its superior specific strength and stiffness.

A typical profiled steel blast wall used in offshore topsides is shown in Figure 1. The height of the blast wall spans from floor to ceiling , which can be up to 10 metres depending on the primary framing and they can run many metres in the transverse direction. Blast walls are usually fabricated from mild steel, but stainless steel is increasingly common because of its ductility and corrosion resistance. The thickness of the blast walls depends on the anticipated blast pressure and the slenderness limits of the corrugation web and flange and its column slenderness. It must also be mentioned that flange to web ratio and corrugation angles are important design parameters.

This paper will review finite element techniques using ABAQUS to analyse the response of structures subject to blast, in particular for corrugated blast walls. Methodologies involving the simplification of blast loadings and some analytical techniques for blast response will also be briefly discussed.

2. Analytical Methods

Accurate modelling of blast loads is extremely complicated especially when the blast loads are derived from a hydrocarbon explosion in offshore topsides. This requires an understanding of the complex combustion process and its interaction with the surrounding, typically congested facilities. Therefore, application of blast prediction models that are predominantly developed for high explosive charges may not be applicable in an offshore accidental gas explosion. Deterministic methods such as empirical, phenomenological and computational fluid mechanics models, are often employed for blast load prediction [3].

Biggs method [4] is probably one of the most widely used Single Degree of Freedom (SDOF) models used to assess blast response, in particular when the structures can be conveniently idealized as a simple beam or plate for which design charts are readily available. The method involves the idealization of the load and resistance functions, as well as converting the real system to an equivalent system so that the displacement time response of the equivalent system is exactly the same as that of a particular point of interest in the real system. This is achieved through the use of transformation factors which are obtained by equating the energies of both the real and equivalent systems. The schematic diagram of idealizing the real system into an equivalent spring mass model is shown in Figure 2.

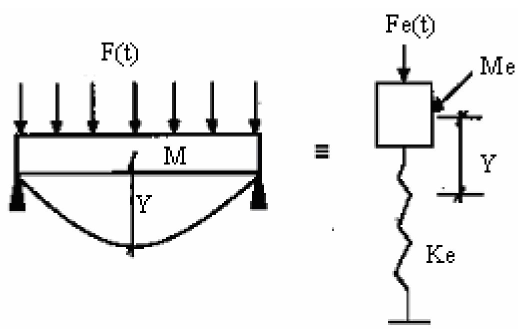

Figure 2. Equivalent spring mass model.

Although the Biggs method is a relatively simple approach for solving transient dynamic problems, there are some inherent limitations which have been discussed in the literature [2, 4]. Technical Note 5 (TN5) [5] for design of stainless steel blast wall has recommended the use of the finite element method if the ductility factor (ratio of maximum and elastic limit deflections) of the response exceeds 1.5.

3. Finite element method

An explosion is a low probability event and therefore large deflection and permanent deformation are usually allowed. Therefore, nonlinear geometrical and material behaviour should be accounted for in an efficient design. This is suitably considered in a nonlinear finite element analysis (NLFEA) such as ABAQUS [6]. NLFEA also allows accurate modelling of the supports which is vital in a blast response assessment. In essence, the finite element method attempts to discretize a continuous structure into finite elements that can be represented by a displacement function:

$$x = \sum_{i=1}^{n} N_i x_i \tag{1}$$

where N_i is the interpolation function, x_i is the basic nodal degree of freedom at node *i*, *n* is the number of degree of freedoms being considered. The finite element method is a very versatile analysis tool and it has the added advantages of addressing some inherent limitations of the SDOF as noted above. For example, there are no particular restrictions on the use of complex material response data, loading profiles and boundary conditions. A comparative drawback of the method is the time and expertise required in pre and post processing for a given structural system, although this should improve with the analyst's experience. It is also necessary to provide detailed checks on the generated results since the method inherently underestimates the displacement response if there is inadequate discretization of the real system, resulting in too stiff a response. The following discusses some principles of the finite element method relating to blast analysis.

3.1 Characterization of loading

There are, in general, two types of blast loadings as shown in Figure 3. Figure 3A shows a typical hydrocarbon explosion due to the ignition of flammable vapour clouds and Figure 3B shows a typical shock loading that may be due to high explosives detonation or far field loading from a hydrocarbon explosion. It can be seen that the loading experienced by the structures typically has a complex variation with time, involving many oscillations of varying frequencies. If blast pressure data is available, it can be fed directly into the finite element model. Otherwise, the guidelines given in Table 1 [7] can be used to simplify the pressure profiles. Further guidelines on characterization of blast loading can be found in [8].

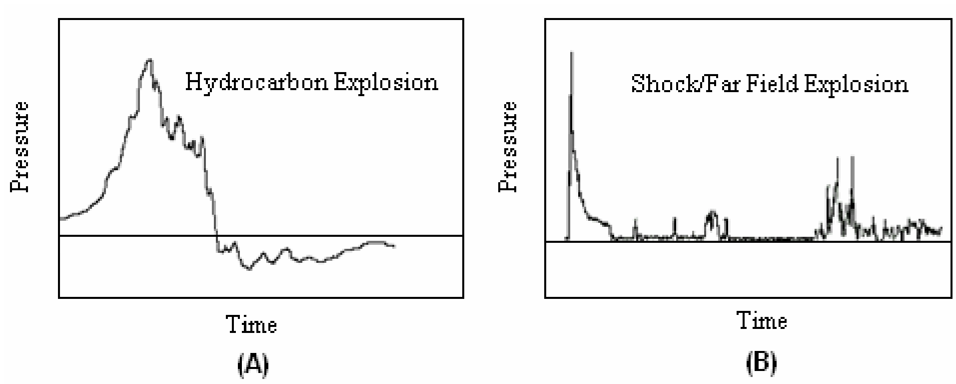

Figure 3. Typical pressure profiles.

3.2 Characterization of material

The constitutive relationship of the material and rate effects have a direct and significant influence on the response and subsequent failure modes of a blast resisting structure. For example, coupon test certificates often report yield strength that is 10-20% higher than minimum guaranteed values, and also report upper yield strength for carbon steel – designs may be based on these values but really it is the lower yield strength which is of interest in inelastic analysis. It is recommended to use actual stress strain curve material data in the model if available, or otherwise an appropriate idealized stress strain curve. Traditionally, for analysis purposes steels have been assumed to possess behaviour of rigid plastic, elastic perfectly plastic, or linear hardening post yield response up to ultimate stress. However, a more realistic stress strain curve for stainless steel can be obtained by the modified Ramberg and Osgood formulation [9] given below.

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \qquad for \sigma < \sigma_{0.2}$$

$$\varepsilon = \frac{\sigma}{E_0} + 0.002 + \left(\frac{\sigma - \sigma_{0.2}}{E_{0.2}}\right) + \varepsilon_{pu}\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m \qquad for \sigma > \sigma_{0.2} \tag{2}$$

where $E_{0.2} = \frac{\sigma_{0.2}}{(\sigma_{0.2}/E_0) + 0.002n}$ and n, m = 5, 2.5 respectively.

Equation 2 describes a nonlinear response of the material at all strain levels and a continuous reduction in the plastic modulus with increasing straining. However, nonlinearity is significant only after 0.2% proof stress. The effects of the strain hardening are shown in Figure 4. The elastic perfectly plastic model under predicts the static capacity by approximately 5% and the ductility before instability by 100%. The modified Ramberg and Osgood formulation also predicts a more ductile failure response. It is also often necessary to apply strain rate effects for typical blast response due to an accidental gas explosion [10].

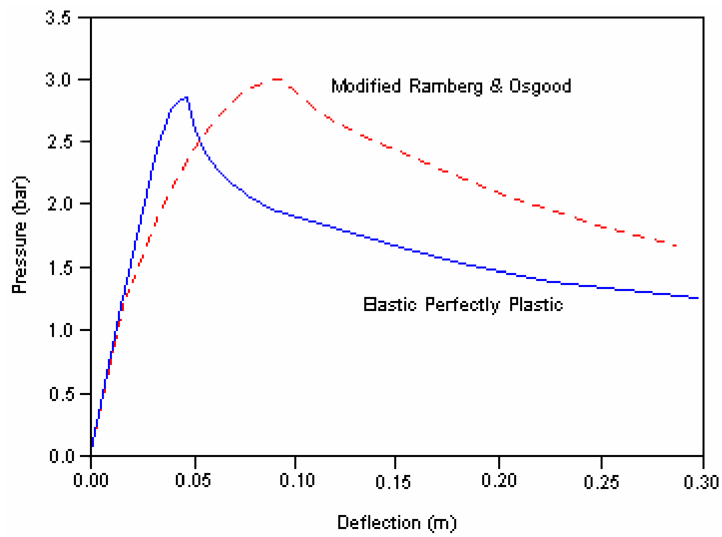

Figure 4. Effects of material models.

3.3 Finite element mesh

Inappropriate meshes can sometimes lead to the masking of other failure modes such as buckling which may otherwise dominate the blast response. A fine mesh is often needed to capture the onset and spread of plasticity accurately. It is difficult to establish guidelines on the appropriate number of elements but prior experience based on an experimental investigation of blast response for a corrugated panel indicates that approximately 3000 and 8000 first order shell elements in ABAQUS may be appropriate to achieve satisfactory results for shallow and deep corrugated profiles respectively. In the absence of prior modelling experience on similar systems, mesh sensitivity studies should be carried out. Figure 5 shows the mesh sensitivity response of a typical corrugated blast wall commonly used in offshore facilities – mesh details are shown in Figure 6.

The strain fields at the connecting regions can be highly sensitive to the mesh density. These regions may exhibit large strain gradient and strain singularity behaviour as shown in Figure 7. To ensure an adequate mesh density, the strain values at the Gauss (integration) points should remain relatively close to that obtained from the nodal points of the element. Abrupt changes to the mesh densities will represent a poor discretization resulting in artificial wave reflections and should be avoided. Where mesh density is graded, adjacent elements should not vary by more than a factor of 2. In addition, the aspect ratio of the elements should be no greater than 2. Distorted elements can be excessively stiff and unreliable results may be obtained especially at high ductility levels.

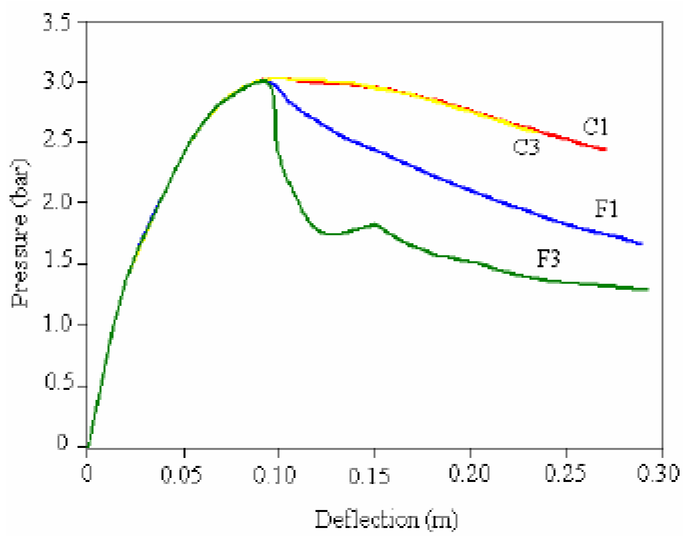

Figure 5. Mesh sensitivity study for corrugated blast wall

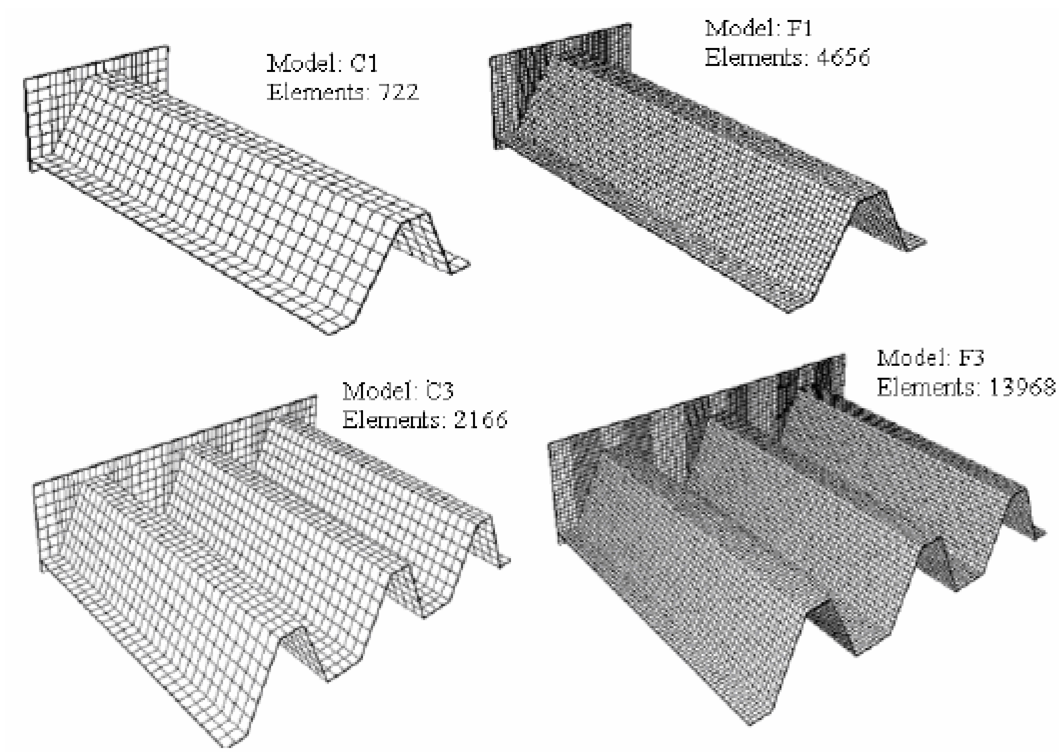

Figure 6. Finite element model for corrugated blast wall.

A uniform mesh consisting of small and low order elements has been found to be suited for use with the explicit numerical scheme. For efficiency and adequate accuracy, first order reduced integration shell elements such as S4R elements in ABAQUS are appropriate for general blast assessment purpose. However, adequate mesh refinement and constraints to the model may be required if hourglassing is significant. For detailed analysis, a local model using solid elements can be set up where its initial boundary and kinematics conditions are obtained from a global analysis of the entire model.

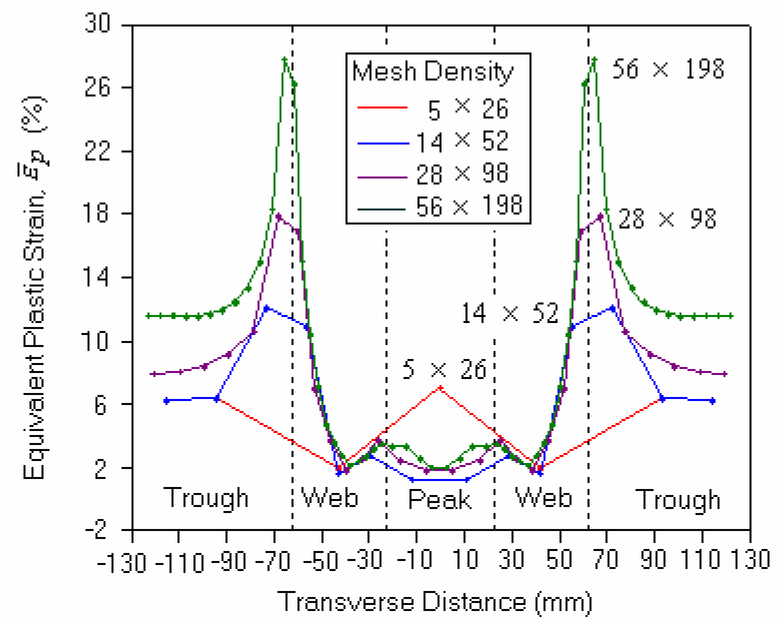

Figure 7. Strain singularity at connecting ends of a corrugated panel.

3.4 Response limits

Another advantage of using the finite element method is the relatively ease in carrying out parametric studies so as to develop an envelope of blast response. At extreme values of loading, the ductility will become sensitive to the loading distribution [11] which often cannot be precisely determined. Coupled with the sensitivity of the mesh density, it may be appropriate to carry out a parametric study to establish the likely limits of containment pressures for the blast resistant structure. A typical response envelope developed using a series of finite element analyses, based on an equivalent plastic strain (PEEQ) limit of 18%, is shown in Figure 8. Such a plot is very useful to determine the containment pressure for a given structure and to assess the sensitivity of the structural response to blast load and duration.

It should be noted that at high ductility values, the dynamic response of such structures can be very sensitive to the rise time of the pressure profiles. In some cases, where the actual pressure time profiles are available, they can be directly fed into the finite element analysis to provide a more realistic spatial and temporal load distribution on the structures. Sensitivity to any spikes in the pressure profiles, where the magnitudes of such spikes can be several orders of magnitude greater than the design overpressure, can also be assessed [11].

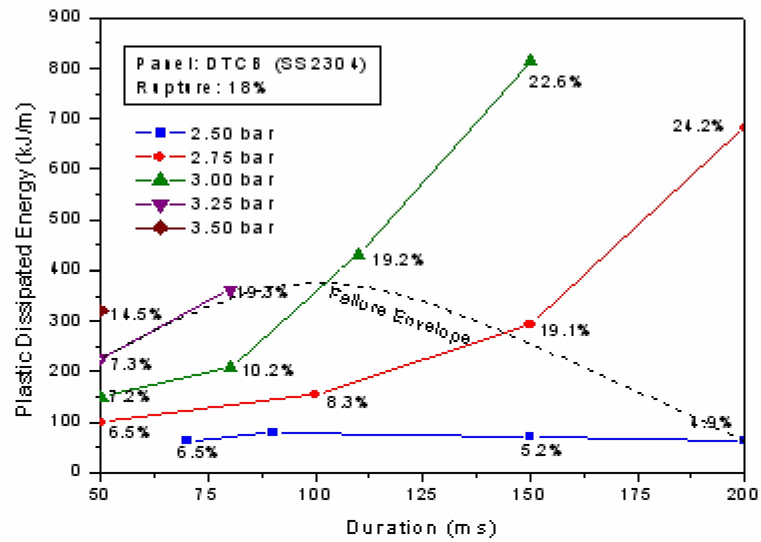

Figure 8. Response envelop for a typical blast analysis

3.5 FE procedures

Both implicit and explicit codes are available in ABAQUS and can be used for blast analaysis. ABAQUS/Explicit is commonly used for brief nonlinear transient analysis, particularly when large deformation is involved since the advantage of a bigger time step offered by the implicit scheme cannot be realized. ABAQUS/Explicit allows nonlinearities arising from contact and tearing to be handled in an efficient manner. The explicit scheme also has the added benefit of automatically accounting for local buckling effects due to the inherent influence of the inertia, which is considered in the analysis. Implicit schemes on their own are not capable of capturing the sudden drop in the load displacement relationship unless some forms of stabilizing algorithms are incorporated. A very stable algorithm, Riks, is available in ABAQUS/Standard [6] that deals with such global instabilities (see Figure 9 below). Nevertheless, for mild dynamic response and static analyses, the implicit schemes may still provide a more economical solution.

Depending on the objective of the study, several and various types of analyses may be performed. Most commonly, a static analysis will be carried out, to validate the finite element model and carry out sensitivity studies to establish a suitable meshing scheme. This approach will provide confidence in the responses obtained from a fully nonlinear dynamic analysis. If a quasi-static analysis is used to replace a dynamic analysis, then kinetic energy must be small (say 10%) when compared to the internal energy in order for the solution to be valid. A linear dynamic analysis can also be carried out to extract the natural frequencies and its corresponding deformation modes for subsequent imperfection studies. Figure 9 shows the influence of various FE procedures on the predicted response of a stainless steel blast wall. It is obvious that for a given deflection limit above 0.1% proof stress, a linear elastic analysis based on a typical design code methodology can give a grossly non-conservative prediction of the static capacity of the blast wall and its use is very limited. On the other hand, geometric linear analysis has completely missed the instability mode. Even if geometric nonlinearity is considered in the analysis, some form of stabilization energy needs to be imposed to obtain a full solution as illustrated by the Riks analysis.

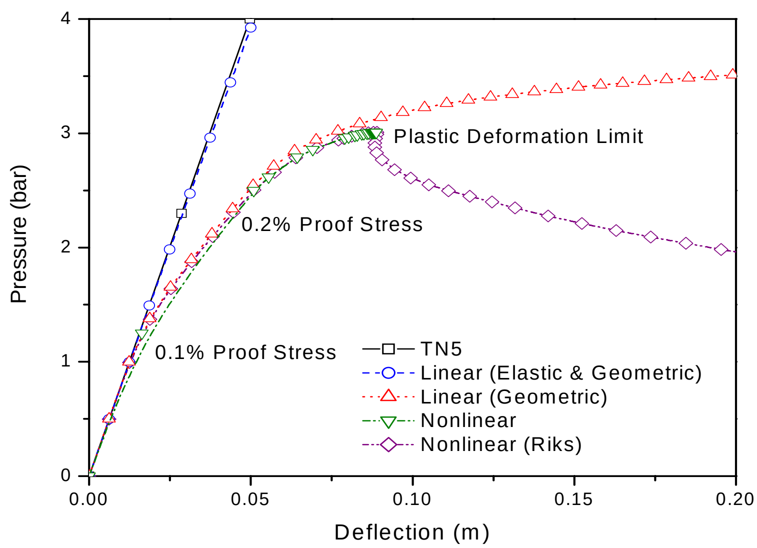

Figure 9. Types of FE analyses for blast response assessment.

3.6 Buckling and imperfections

Care needs to be taken in modelling the end connection details as this can affect the degree of mobilization of the membrane effects. An under prediction of the membrane effects can over predict the response of the blast panel and lead to low unsafe predictions of the reaction forces, while an over prediction of the membrane action can prevent or delay the onset of buckling in the model and over predict the stiffness of the blast wall. It is proposed that adequate structural details beyond the blast resistant structure should be included in the model so that a more representative restraint and stiffness condition can be modelled. Imperfections may also be required for slender sections in the finite element model. It is recommended in Technical Note 5 [5] to study the effect of imperfections in a sensitivity study using NLFEA. An element size of less than 1/6 to 1/8 of the local buckling length is also proposed. An exaggerated imperfect stiffened panel based on the interaction of first 10 buckling modes is shown in Figure 10. It is clear that one of the instability modes is web buckling of the stiffener. This model is subsequently fed into a general static analysis and its response is shown in Figure 11. As expected, the imperfect structure demonstrates a lower initial stiffness.

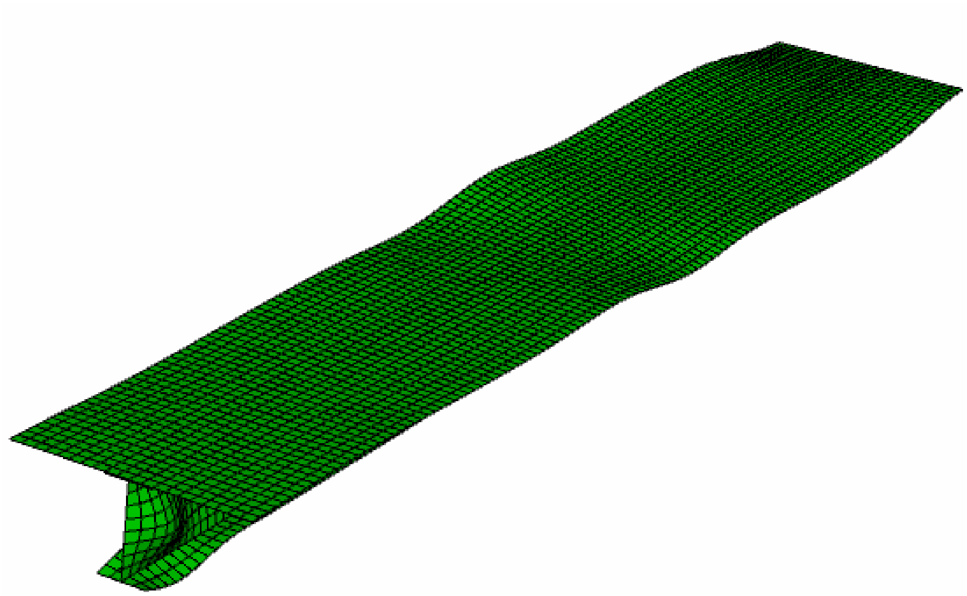

Figure 10. Buckling modes (first 10 modes) of a stiffened panel.

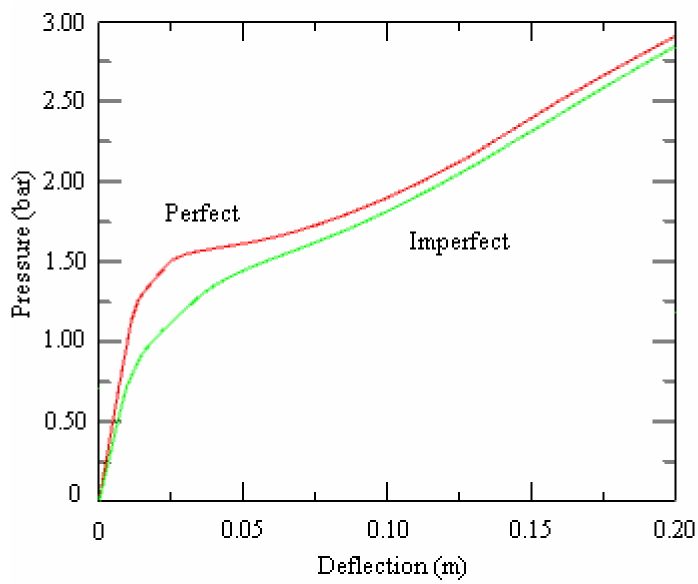

Figure 11. Comparison of perfect and imperfect stiffened panel subject to blast.

Symmetry conditions should be used sparingly whenever possible in a blast analysis. These boundary conditions will impose constraints to the model, restricting its buckling modes which may not be intended. In some cases, initial symmetry conditions may result in antisymmetric buckling response as in the case of a shallow arch subjected to uniform pressure [12]. The effects of imperfections for corrugated blast walls commonly used in offshore topside have been investigated in [11] although more studies are needed for these thin wall structures.

3.7 Material failure

Material failure may need to be assessed to ensure rupture does not occur during an explosion and prevent an escalation of events. This may be achieved by modifying the constitutive relationships such as using a strain based failure criteria [13] given in Equation 3.

$$\sum \bar{\varepsilon}_p \geq \varepsilon_{crit} \tag{3}$$

where $\bar{\varepsilon}_p$ is the equivalent plastic strain and ε_{crit} is the user input rupture strain which can be regarded as the ductility of the material. Figure 12 illustrates the failure of a shallow corrugated blast wall that is able to qualitatively describe the weld failure.

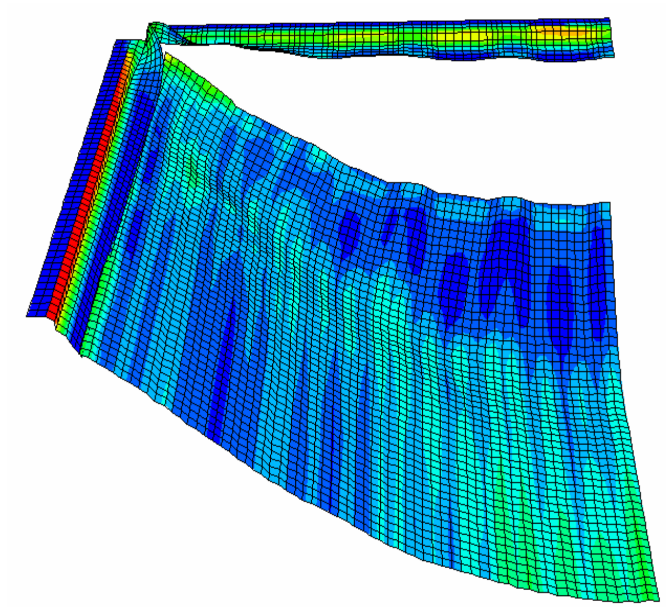

Figure 12. Failure of weld in a finite element model.

However the problem of strain singularity, illustrated in Figure 7, means that a strain based failure model may be highly mesh sensitive when used to predict weld failure at the connecting ends. Therefore efforts were also taken to look for alternatives to describe the weld failure. One such failure criterion is by means of an attachment algorithm of the elements such as a nodal force based failure criteria [14-15]. In ABAQUS, this is described by the spot weld failure model,

$$\left(\frac{F_{N,\max}}{F_{N,ult}}\right)^2 + \left(\frac{F_{S,\max}}{F_{S,ult}}\right)^2 \leq 1.0 \qquad (4)$$

where $F_{N,\max}$ = maximum tensile force (Mode I)

$F_{S,\max}$ = maximum shear force (Mode II)

$= \sqrt{(F_{1,\max})^2 + (F_{2,\max})^2}$

$F_{N,ult}$ = ultimate force causing failure in tension

$F_{S,ult}$ = ultimate force causing failure in shear = $F_{N,ult}/\sqrt{3}$

There is scope to include the postfailure energy dissipation mechanism in Equation 4. It may also be appropriate to carry out a separate detailed analysis of the regions of interest using a fracture mechanics approach. For example the submodeling technique can be employed where the solutions (boundary and kinematics conditions) obtained from the global model are used to drive the solutions of a more detailed local sub model to investigate local crack propagation. Alternatively, the solutions from the submodels can also be used as the performance criteria for the global models.

4. Conclusion

This paper has given an overview on the methodology involved in performing a blast analysis resulting from an accidental gas explosion. Some commonly used simple analytical techniques for blast analysis are briefly reviewed. Although these methods are still valuable in many instances, there are some inherent limitations. For this purpose and when detailed study of the blast response is required, emphasis is placed on the use of nonlinear finite element method to predict the structural blast response representatively. Several considerations discussing its use in blast response prediction are presented.

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