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A PARAMETRIC STUDY FOR THE EFFICIENT DESIGN OF CORRUGATED BLAST WALL PANELS USED IN PETROCHEMICAL FACILITIES

M. A. Faruqi[1], J. Grisel[1], A. Salem[2] and J. Sai[1]
[1]Department of Civil and Architectural Engineering, MSC, Texas A and M University- Kingsville, TX, USA
[2]Consultant in Stress Analysis, Corpus Christi, TX , USA
E-Mail: m-faruqi@tamuk.edu

ABSTRACT

Corrugated panels are currently used in petrochemical facilities as an economic means to provide blast protection to personnel and other valuable assets. In this paper, parametric studies were conducted on the various elements (e.g., compression flange, depth, angle of corrugation, etc.) of a corrugated blast wall using static nonlinear finite element analyses and dynamic nonlinear single degree of freedom analyses. During the static analyses, panel characteristics such as ductility and strength were explored and nonlinear load-deflection curves were generated. The load-deflection curves were then used to observe the response of each wall using a single degree of freedom time-step integration method. Results showed that some blast wall profiles have a greater ability to limit reaction loads transferred to the primary structure, reduce material cost / panel thickness, and/or protect nearby assets (deformation control). The results contained herein define specific dimensional ratios for elements that will result in a favorable response. Understanding how the different elements of a corrugated blast wall affect its structural response to a blast enables the engineer to design efficient passive protection systems that dissipate blast energy efficiently.

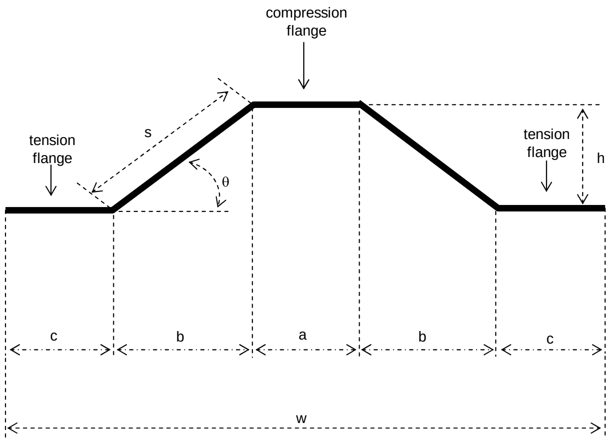
Keywords: blast wall, corrugated panel, energy absorption, flexural efficiency.

1. INTRODUCTION

Corrugated blast walls are among some of the common passive protection systems that have been developed to protect personnel and/or important assets from hydrocarbon explosion. Whether the maximum blast wall deflection needs to be limited to protect nearby process equipment or expected presence of personnel, the material weight needs to be minimized to reduce project cost, or standardized profiles need to be considered due to fabrication limitations, understanding the effects of the different elements of a corrugated profile on blast response will result in a blast design that is economically efficient. This paper investigates the effect of the elements that make up a blast wall profile. The impact that these parameters have on characteristics such as total material weight, plastic ductility, and energy absorption are identified and efficient cross-section dimensional ratios are discussed.

2. ANALYSIS METHODS

This research uses parametric studies to investigate the components of a corrugated blast wall panel that are most influential when optimizing the design. The components investigated are the compression flange, tension flange, depth, angle of corrugation, and plate thickness. A standard industrial base model 4m in span is used and each parameter of interest is varied by sweeping it through a series of values less and greater than the dimension from the base model. Figure-1 defines the starting blast wall dimensions referenced throughout this study, and Table-1 summarizes how each parameter is varied.



a = 160 mm
b = 160 mm
c = 160 mm
h = 200 mm
thickness = 9 mm
s = 226 mm
θ = 45 deg
w = 800 mm
z, longitudinal span = 4000 mm

Figure-1. Base model for comparison.

In these studies, a, c, h, and wall thickness are the independent parameters varied. The dimension "c" represents half of the tension flange, so the figure above represents one unit corrugation.

Table-1. Variation schedule for blast wall parameters.

Parameter range for studied elements				
a (mm)	c (mm)	h (mm)	θ (deg)	thickness (mm)
80	40	120	30	7
100	60	140	45	8
120	70	160	51.3	9
140	80	180	55	10
145	100	200	60	11
150	120	220	65	-
155	140	240	70	-
160	160	260	80	-
165	180	-	85	-
170	-	-		-
175	-	-		-
180	-	-		-
200	-	-		-
220	-	-		-

* Base model dimensions shown in red.

Static analysis (MDOF Model)

A static analysis provides information about the inherent ductility and strength of the geometric section of interest. The Plastic Deflection Limit (PDL), Elastic Deflection Limit (EDL) and Ductility Ratio (μ) are three important indications of the energy absorbing capabilities of a blast wall [1]. For a static analysis, the PDL can be defined as the maximum deflection before the wall becomes unstable. American Society of Civil Engineers (ASCE) and the Department of Defense [1 and 7] provide some basic limits for the PDL. In this research, the PDL is the point where either the slope of the load-deflection curve becomes negative (an indication of global instability) or the membrane stiffness generates unacceptable reaction loads and strains at the connections. The latter limit is somewhat subjective, because it is dependent upon the ability of the connection detail and backing structure to transfer and/or absorb the membrane reactions. The EDL is the maximum deflection when the wall reaches 0.2% proof stress or yield stress, depending on how the stress-strain curve is defined. The ratio of the PDL to EDL is the Ductility Ratio (μ).

This research uses ANSYS, a commercial finite element software package widely accepted for this type of analysis, to calculate accurate load-deflection curves. The models are built using 4-node higher order shell elements with 6 degrees of freedom at each node. These elements are suitable for nonlinear applications involving plasticity, large strain, and large deflection.

To capture nonlinear effects (i.e., local buckling effects), a mesh size of 20 mm (approximately 2t) is used and 3 unit corrugations are modeled [2].

Selecting realistic boundary conditions is an essential consideration when using any method to simulate blast response. To provide consistent comparisons, all models in this research are subject to the same boundary conditions. Symmetry is applied along the outer edge of the corrugations, out-of-plane translational restraint is applied at the end plate edges, and in-plane restraint is treated as a "free roller" as shown in Figures 2 and 3. Modeling the appropriate connection details on the surrounding support structure will provide a project-specific look at how the failure of the wall will behave, so it is critical to include this information if optimization is desired. Achieving a near-fixed connection can greatly increase the capacity of the wall, and accounting for this in the model can be beneficial. On the other hand, if the wall is stiffer and has a higher capacity than the model, end connections could be under designed and maximum reactions will be underestimated.

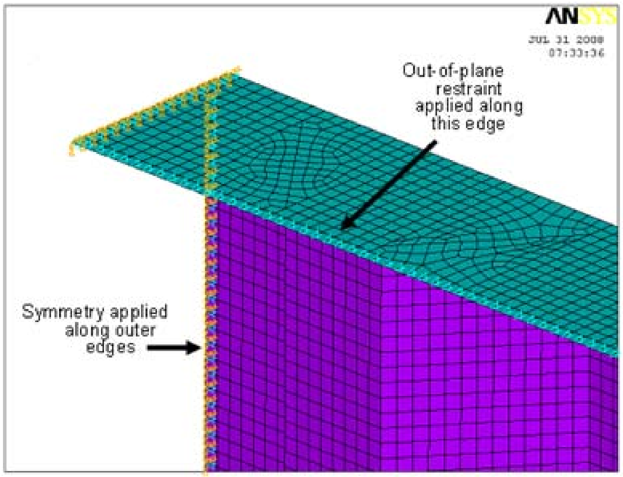


Figure-2. Model boundary conditions (top connection).

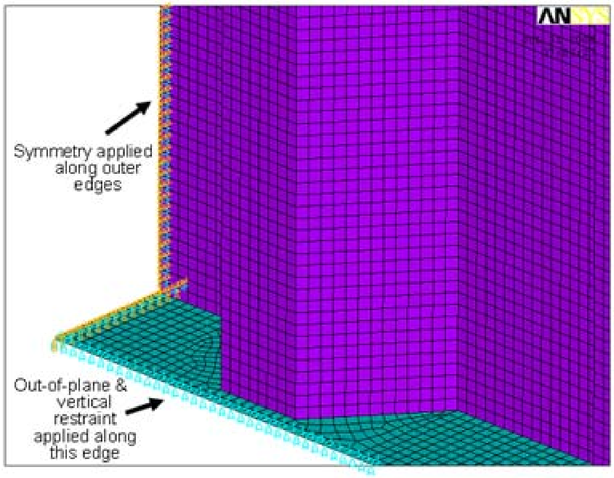


Figure-3. Model boundary conditions (bottom connection).

The material model selected in a nonlinear finite element analysis will affect the ductility of a blast wall, because accounting for strain hardening significantly adds to the plastic deflection limit and contributes little to ultimate strength [2]. These investigations take advantage of this benefit by adopting the modified Ramberg and Osgood formulation to account for the material stress-strain relationship [3]. This formulation accounts for stress-strain relationships beyond 0.2% proof stress and can be derived based on the material yield and ultimate strength. In this paper, a 0.2% proof stress of 220 MPa and ultimate tensile strength of 530 MPa are assumed for 316ss material (commonly used in offshore petrochemical practice). It has been previously shown that extremely high localized strains can be obtained at mid-span and the connections if the wall and details are properly designed [4 and 5].

A Multi Degree Of Freedom (MDOF) analysis may use implicit or explicit algorithms. The static analyses in this research employ the modified Newton-Raphson method that is updated with a tangent stiffness matrix upon each load increment (implicit method). The load step increments used are relatively small so that nonlinear behavior is closely followed. Automatic Time Stepping can be implemented in ANSYS, which is a technique that divides the load step increment and rescales the applied load accordingly if convergence difficulties occur. Under the Automatic Time Stepping algorithm, the analysis is performed again and the analysis is repeated until a minimum load step increment is reached or the solution is completed. If the load step increment is a small enough value and convergence has not been achieved, the analysis is stopped and the last solution to converge is reported. For the purposes of these analyses, divergence is also an indication of global instability.

Dynamic analysis (SDOF Model)

The varied parameters statically analyzed for the compression flange, section depth, corrugation angle, and wall thickness are also varied with a Single Degree of Freedom (SDOF) dynamic analysis. The SDOF procedure [6] is a time-step integration scheme (linear acceleration method) that can account for plastic deformation. The nonlinear curves from the static analyses are incorporated into the scheme so that the stiffness consistently reflects that of the finite element model.

While the Dynamic Increase Factor (DIF) is not explicitly considered, a factor of 1.12 is applied to the strength [1] to account for material rate sensitivity. Figure-4 shows an illustration of the SDOF model constructed to incorporate the static load-deflection curves. The initial load-deflection curve is nonlinear, and the unloading / reloading behavior is given by the elastic stiffness, K_{EL}.

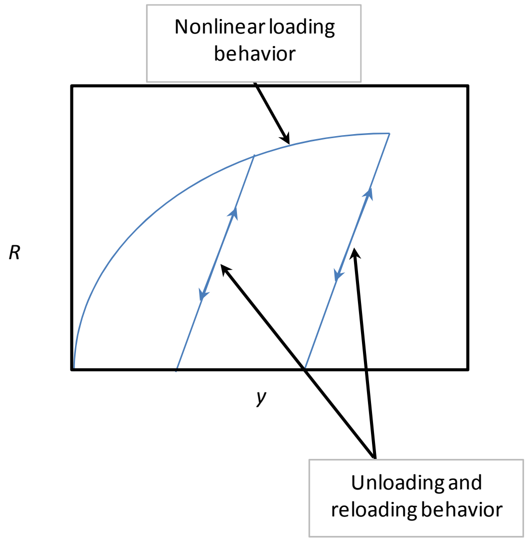


Figure-4. SDOF load-deflection model.

There are many methods used in industry to characterize the load in a blast analysis. If available, a Computational Fluid Dynamics (CFD) analysis of potential blast scenarios should be performed so that pressure-time histories for walls of interest can be measured and the complete transient loads captured. An actual explosion is often represented by a triangular pulse load, similar to the one shown in Figure-5. Instead of a triangular pulse load with an equal rise and fall time, the rise time may be very short or effectively instantaneous if the nature of the explosion is better described in this manner. This research assumes the triangular pulse load shown in the Figure, with a rise time (t_R) equal to half the load duration (t_D), and t_D equal to 150 msec. For a blast impulse, local structural components are typically influenced considerably by the energy they must absorb as well as the peak overpressure. Even if the load duration is near the elastic natural frequency of the component being analyzed, the stiffness will change with the onset of inelastic deformation and the energy will be dissipated in the form of plastic strain.

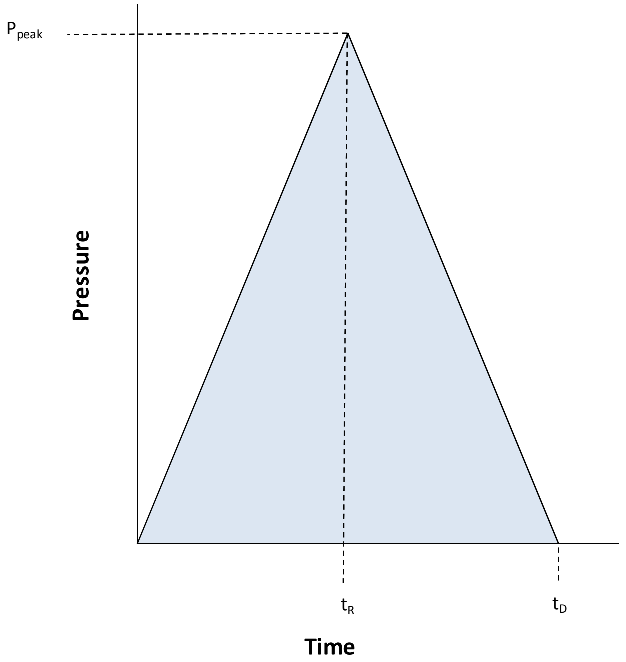


Figure-5. Idealized triangular pulse load.

Two different peak pressures are used to provide different levels of plastic mobilization in this study. The peak pressure of 1.0 bar and 1.5 bar are used to show the difference between the levels of plasticity they generate. The two pressure levels allow the influence of the parameter under investigation to be revealed more clearly. The results from analysis on each specimen in this research were used to investigate their performance with respect to the ductility usage and DLF variation.

The ductility usage is defined here as the maximum dynamic deflection divided by the plastic deflection limit, and it quantifies how much of the allowable deflection has been used. Calculations resulting in a ductility usage greater than unity are considered inadequate for the design [1].

The DLF is important because it identifies which specimens will generate higher reaction loads on the connections and supporting structure. It will also be shown that maximizing the static PDL helps to reduce the DLF because the kinetic energy is absorbed and dissipated by plastic deformation.

3. COMPARISON OF RESULTS

Panel weight sensitivity

For weight-sensitive structures in the offshore industry (e.g., spars, semi-submersibles, etc.), weight is often identified as a critical component of design that must be limited for stability of the vessel. Aside from reducing material costs for the panel itself, minimizing the weight of a proposed blast wall profile can also reduce the global weight impact when there is a significant portion of the facility that must implement a blast wall design. If there are many walls throughout the facility that require blast resistance, corrugated paneling can offer an efficient method of passive protection if properly designed. Figure-6 summarizes the weight of each blast wall profile presented in this paper in terms of percent deviation from the base model. The features that influence the weight of the blast wall can readily be identified by inspection of the curves in the plot. In the figure, zero percent represents the original base model. As the compression/tension flange, thickness, depth, or corrugation angle is varied, the weight increase or decrease is represented by a percentage.

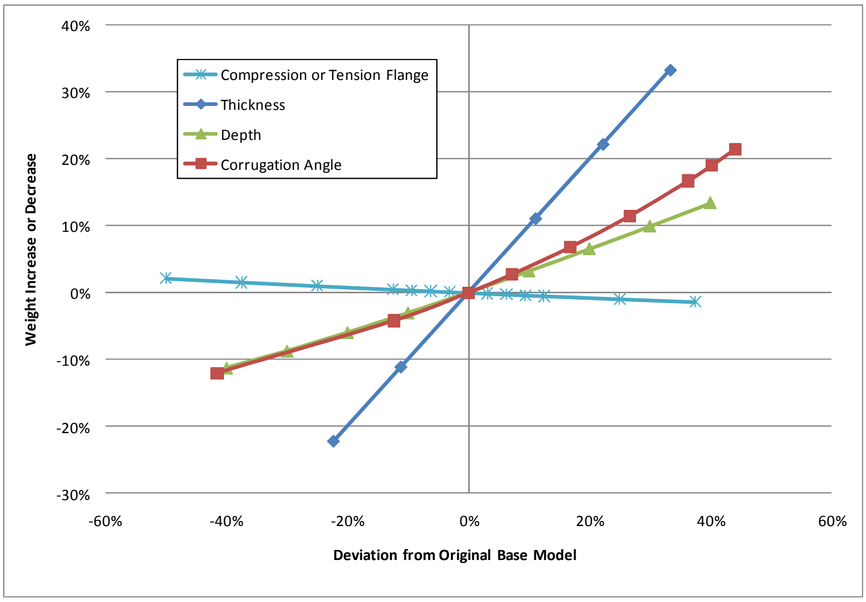


Figure-6. Weight sensitivity of different blast wall features.

The thickness of the blast wall has the most dramatic effect on its weight. It is clear that the material volume can be minimized by designing an efficient profile that allows the thickness to be reduced. The corrugation angle and depth have a similar effect on the panel weight, and the width of the compression or tension flange have the smallest effect. Varying the flange lengths to attain the desired capacity will generally result in a more efficient use of the steel, especially if the depth can be reduced or the thickness can be decreased.

Influence of panel compression/tension flange on blast response

The width of the compression flange has a significant influence on the plastic deflection limit and hence the static ductility ratio of a blast wall. As the compression flange increases, it reaches a point where it will begin to buckle before it can reach its full plastic capacity. The ductility ratio peaks at a a/t (ratio of compression flange to wall thickness) value between 16 and 18 (Figure-7), after which flange buckling or instability begins to dominate the failure and limit ductility. The pressure capacity has a similar peak because of the buckling behavior (Figure-8).

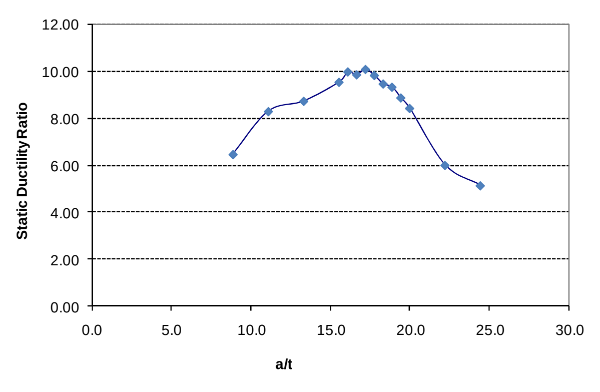


Figure-7. Static ductility ratio as compression flange varies.

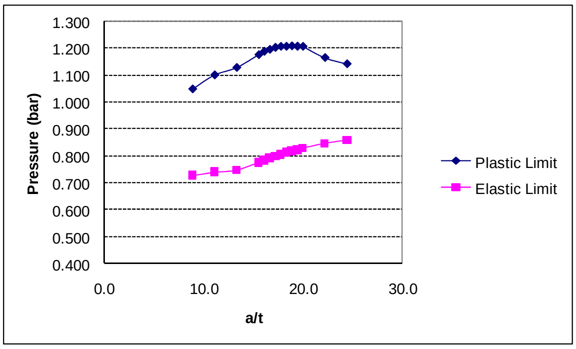


Figure-8. Pressure capacity as compression flange varies.

The dynamic analyses of the compression flange results in a ductility usage that supports the static behavior above. For the peak pressure of 1 bar in Figure-9, none of the specimens experience enough plastic mobilization to come close to the plastic deflection limit. However, the dynamic analyses that use the higher peak pressure of 1.5 bar reveal a similar optimum peak as the static analyses. In this case, the sections that have the highest ductility ratio and pressure capacity are the only sections able to absorb 1.5 bar while maintaining a ductility usage less than unity.

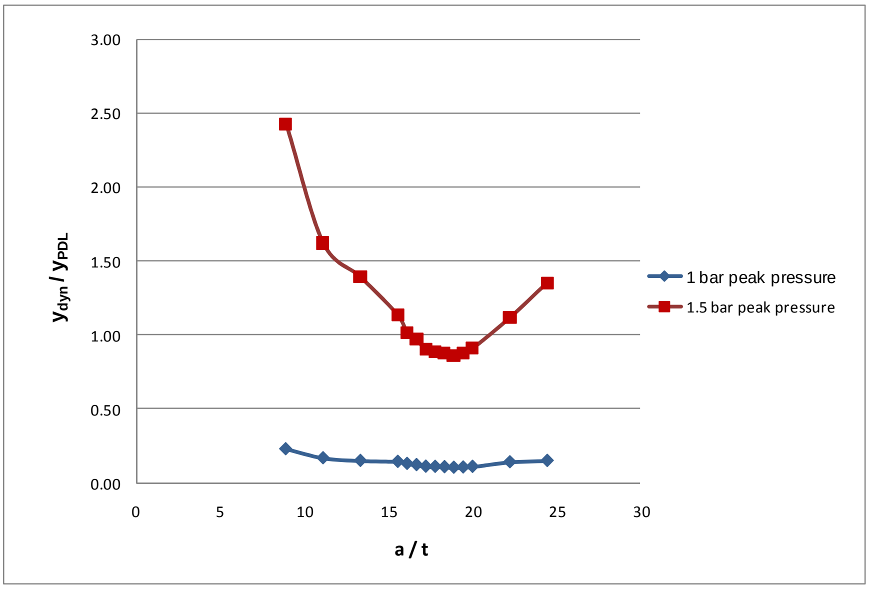


Figure-9. Dynamic ductility usage as compression flange varies

For these analyses, the dynamic response is sensitive to the level of plasticity encountered. The DLF increases and peaks in the region where the static ductility ratio is greatest and the plastic deflection limit has not been reached (Figure-10). In addition, the DLF for all sections is reduced when the peak pressure is increased. This is directly related to the fact that energy is being absorbed through inelastic deformation. Inelasticity becomes the means whereby the energy is dissipated and the DLF will in general be reduced as long as membrane action does not begin to dominate wall stiffness.

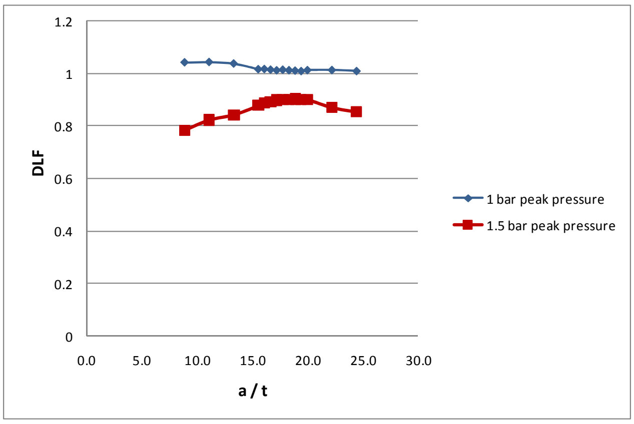


Figure-10. DLF as compression flange varies.

Variation of the tension flange does not have a buckling state, so its ductility ratio is more dependent on section symmetry (Figure-11) with respect to the compression flange. After the tension flange becomes greater than about 80-90% of the compression flange, failure in the compression flange dominates limits the wall capacity. This is because for these specimens the compression flange begins to locally distort and cause global instability before the tension flange can fail.

In practice, the section should be symmetric unless quality control of the installation can be ensured. A symmetric section simplifies the design process and reduces the risk of installation mistakes (i.e., the wall may be installed backwards) that are costly to correct.

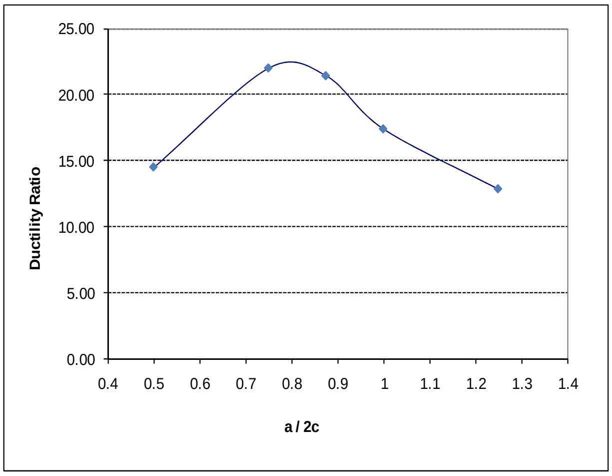


Figure-11. Static ductility ratio as tension flange varies.

Influence of panel depth

As the depth of the base model is swept through the prescribed values from Section 4, the static ductility ratio exhibits a clear peak that suggests a more energy-absorbent value for this geometric element (Figure-12). In other words, deepening the section does not necessarily mean that more energy will be absorbed by the blast wall. Making the wall too deep can overly stiffen the wall and increase the reaction loads on primary structure.

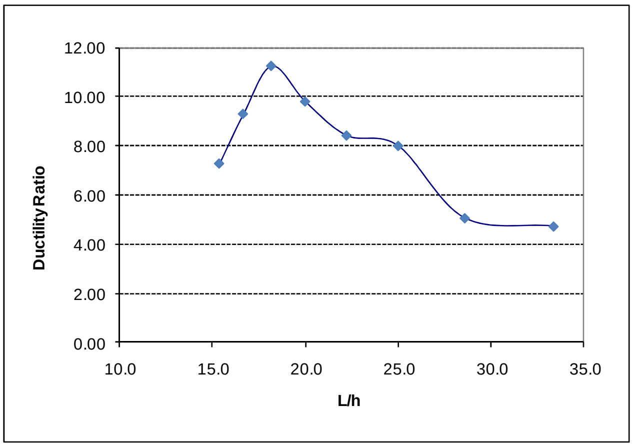


Figure-12. Static ductility ratio as depth varies.

Although the static ductility ratio has a distinct peak, the moment and pressure capacity continues to increase as the wall is deepened (Figure-13). Comparing the increase in capacity to the static ductility ratio peak, energy absorption is achieved at the expense of increased reaction loads. If there is critical equipment sitting in way of the blast wall, deflection requirements may need to be limited to keep the wall from causing damage. This approach is valid as long as the design of the primary structure accounts for the increased energy transferred from the blast wall.

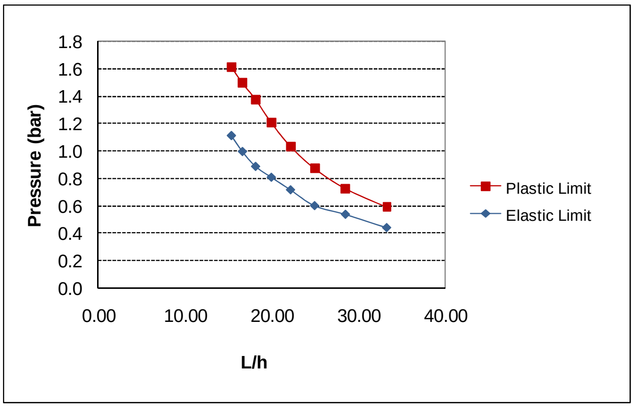


Figure-13. Pressure capacity as depth varies.

The dynamic ductility usage of the section improves as the depth increases (Figure-14) similar to the static pressure capacity shown above. Even if the stiffer section is required to limit deflections and prevent process equipment or other assets from being impacted, in general the stiffness will also increase the DLF and create an even higher demand on the supporting structure (Figure-15).

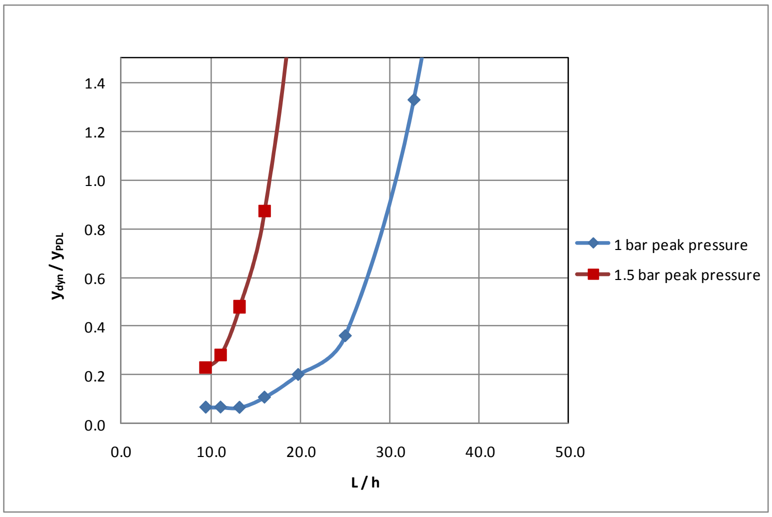


Figure-14. Dynamic ductility usage as depth varies.

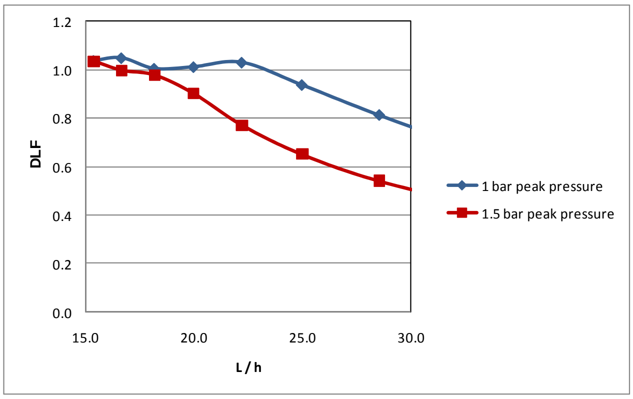


Figure-15. DLF as depth varies.

Influence of panel thickness

Increasing the wall thickness significantly increases the energy the blast wall can absorb. Because thickness has the greatest impact on the wall weight, optimizing the profile shape in an effort to minimize thickness will result in a more material-efficient wall. In general, the thickness should be increased when the profile shape becomes unworkable for the premised blast loads. Figures 16 and 17 show this.

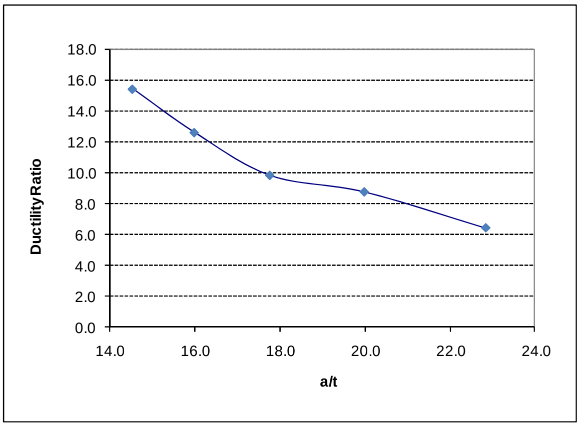


Figure-16. Static ductility ratio as thickness varies.

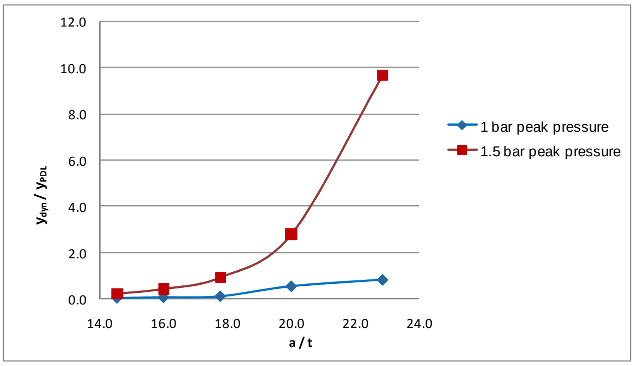


Figure-17. Ductility usage with varying thickness.

4. CONCLUSIONS

By understanding the effect different elements have on the performance of a blast wall, the analyst can select panel dimensions efficient in absorbing the energy from an explosion. It has been shown by this research that for a blast wall made of 316ss having a span of 4m, optimum ductility ratios can be achieved if the profile is properly proportioned. Keeping the ratio of the compression flange to the wall thickness between 16 and 18 will result in a section that results in an efficient static ductility ratio. It is also reasonable and practical to maintain a symmetric cross-section, thereby simplifying the design and construction process. The optimum depth of the section is somewhat subjective depending on the project requirements for deflection control. If the deflection must be significantly limited to protect nearby assets, the resulting section will be deeper and stiffer. The stiffer section will be accompanied by higher reactions on the primary structure, increasing the cost and weight of the overall passive protection system. If deflection limits are not an issue, keeping the ratio of the span length to panel depth between 17 and 20 will result in an optimized static ductility ratio. It has also been shown that the static ductility ratio directly impacts the dynamic performance of the blast wall. While there is room for refinement to the parametric studies performed in this research, understanding the general effect of different corrugated blast wall elements can provide general guidance when the engineer is faced with the different project requirements. As with the case of panel depth variation, understanding the different elements of a corrugated blast wall can also help the engineer be informed of the compromises that must be made or side effects that must be accepted once a corrugated panel is optimized to meet specific project requirements.

5. FUTURE WORKS

One limitation of this research is the lack of restraint at the connection details. The models in this research were analyzed using a simple support, but in reality the connection details will provide additional rotational and catenary action. A similar study using common connection details and local backing structure would provide the level of detail required to develop some standard blast wall systems that are efficient in absorbing impact energy.

Only 316ss material was used in this research because it is commonly used in offshore petrochemical practice. For very thin-walled cold-formed panels, other steel grades (e.g., A446) may be more common. This is especially true for onshore construction where corrosion is not an issue and the inherent designs are not as robust as offshore construction. Studies similar to the one in this research could use other common steel grades found in onshore facilities. The different material hardening characteristics exhibited under high strain levels for different steel grades may not have a significant effect on panel wall strength, but the panel ductility will show dramatic variations.

Notations

A	Compression flange width
b	Projected web width
c	One half the tension flange width
h	Blast wall depth
EDL	Elastic Deflection Limit
MDOF	Multi-Degree Degree Of Freedom
NFEA	Nonlinear finite element analysis
PDL	Plastic deflection limit
SDOF	Single degree of freedom
W	Overall width of three unit corrugation panels.
Z	Blast wall span length
θ	Angle of corrugation
μ_{max}	Static ductility ratio = PDL / EDL
μ_{dyn}	Dynamic ductility ratio = (peak deflection during dynamic analysis) / EDL

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