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EFFECT OF FINITE ELEMENT FORMULATION TYPE ON BLAST WALL ANALYSIS SUBJECTED TO EXPLOSIVE LOADING

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ABSTRACT

This study suggests relevant finite element (FE) formulation types for the numerical simulations of a stainless steel offshore blast wall subjected to seven (7) blast loading scenarios. These structures are typically modelled by solid and shell finite elements considering the thicknesses of the structural parts. The FE simulations have been conducted in LS-DYNA and the results were validated by the experimental results by HSE [1]. The influence of strain rate has been considered to assess the dynamic responses of the blast loaded structure. Recommended FE types were discussed based on statistical analyses, which would provide broad insights into the influence of FE formulations on the blast response as well as the selection of FE formulations.

Keywords: Hydrocarbon, explosion, blast wall, HSE, finite element formulation.

INTRODUCTION

Hydrocarbon explosions are accidental events in the offshore industry which exert extreme blast loadings on offshore topsides. These events often lead to disastrous consequences which include loss of human lives, irreversible environmental impacts, as well as huge financial losses. To date, the explosions of the Piper Alpha and the Deepwater Horizon platforms in 1988 and 2010, respectively remain the most destructive ones in history.

Blast walls are basically an integral part of the topside modules that act as passive protective barriers to mitigate the effect of explosion loading and to protect the personnel and critical equipment on board. Thus, the integrity of these structures is critically emphasised throughout the design life of the entire platform. Though the Technical Note 5 [2] issued by the Fire and Blast Information Group (FABIG) has been generally referred to, there is no universally agreed guideline for the design of stainless steel corrugated blast walls. In practical industrial design, numerical finite element analysis (FEA) has been widely adopted as the most cost-effective approach in modelling complex structural problems, unlike the experimental studies which often incur high capital investments or the analytical methods with limited applicability.

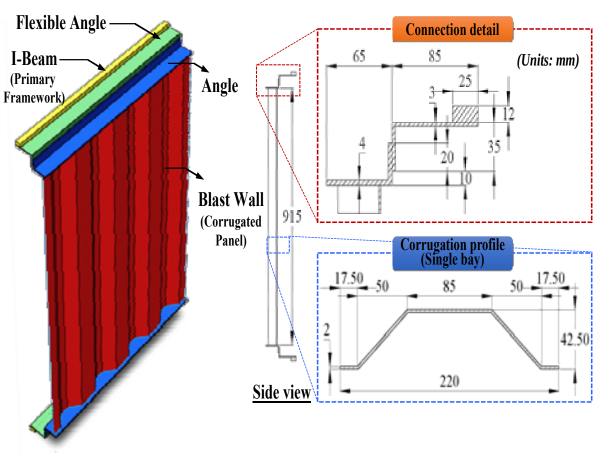
Intensive studies have been conducted by Langdon and Schleyer [3-5] on the experimental, analytical, and numerical techniques to assess the structural responses of stainless steel corrugated blast walls under up to 2 bar of peak pressures. Related studies on the FE approach have also been addressed by [6-8]. Nevertheless, despite the technological advancement in the FE techniques, the quality of the output from FEA are strongly dependent on the skills and experience of the user. Decent engineering judgements, which include consideration of material models, mesh sizes, load and boundary conditions, as well as element formulations are essential to ensure the representability of the FE model to the real structure of interest.

Present study aims to investigate the performance of solid and shell FE formulations associated with hourglass control functions on a stainless steel corrugated blast wall using LS-DYNA explicit finite element solver.

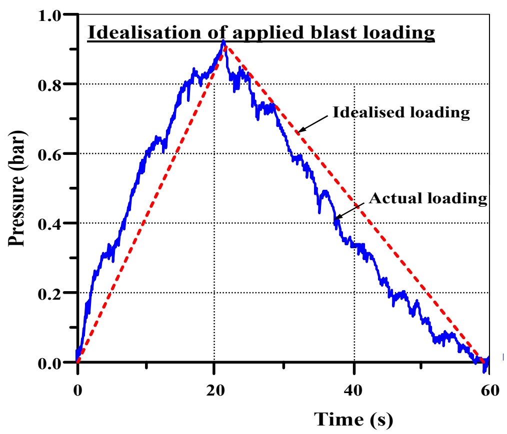
NUMERICAL MODELLING OF BLAST WALL SUBJECTED TO HYDROCARBON EXPLOSION

Structural and applied loading data

Figure-1 (a) provides the schematic diagram of the target blast wall structure with dimensions, load idealisation (Figure-1(b)), and seven blast loading scenarios by [1] (Figure-1(c)).



(a)Configuration



(b)Load idealization

Blast loading scenario No.	Peak pressure (bar)	Rise time (ms)	Duration time (ms)
1	●: 0.51	16.7	38.0
2	●: 0.57	30.7	57.5
3	●: 0.76	25.9	63.0
4	●: 0.91	21.7	59.1
5	●: 1.04	31.0	83.0
6	●: 1.21	26.1	73.4
7	●: 1.92	59.7	125.7

(c) Applied loadings

Figure-1. Configuration and FE modelling of blast wall with applied loading.

FE modelling

To reduce computational cost, finite element (FE) model of the reduced-scale (quarter model: one quarter of a single corrugation bay) blast wall with integrated supporting structure was adopted as shown in Figure-2(a) for the condition assessment of blast wall structures under hydrocarbon explosion. The typical deformed shape of blast wall subjected to blast loading is also presented in Figure-2(b).

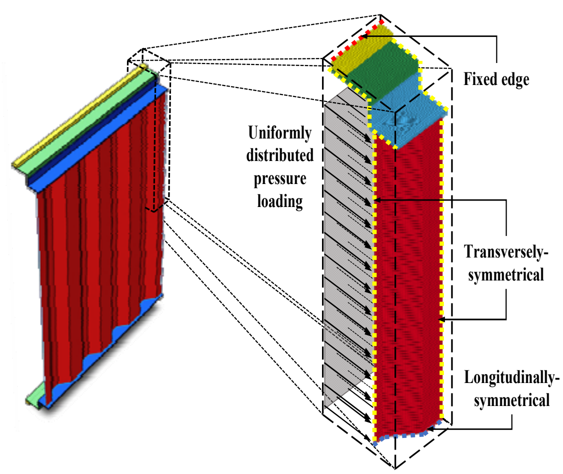
LS-DYNA explicit FE solver was used to perform the numerical simulation, through which the structural responses of the blast wall model subjected to a range of pulse pressures were evaluated. With regards to boundary conditions, the upper edge of the model was fixed, both sides of the model set to be symmetrical in the transverse direction, and the bottom edge set symmetrical in the longitudinal direction illustrated in Figure-2(a). Uniformly-distributed time-dependent idealised pulse pressure loading was applied all over the surface of the corrugated panel. Four-node shell elements were used to model the thin corrugated panel and eight-node solid elements were employed to represent the connection angles considering the shear effect across the plate thicknesses. Mesh sizes of approximately 4-mm [9], were applied to the entire FE model. Material model No. 24 in LS-DYNA material library was used to represent the nonlinear dynamic behaviour of the structure by specifying the material failure strain and strain rate parameters. The strain rate effect is accounted for in the Cowper-Symonds constitutive equation as shown in Table-1.

Experimental test results

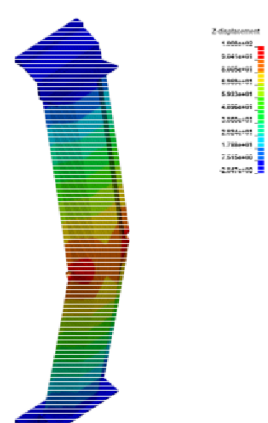
Table-2 shows the summary of pulse pressure tests on a corrugated blast wall conducted by [1]. A total of 7 applied loading scenarios as illustrated in Figure-1(c) are considered for the testing and obtained outcomes, i.e., the maximum and permanent deflections from FEA as defined in Figure-4 will be used for standard of comparison.

Numerical simulation results

Three (3) FE models such as Type I, II, and III were constructed under combinations of reduced- and fully-integrated solid and shell element formulations, as detailed in Table-3, to validate the effect of FE formulation on the structural responses, i.e., maximum- and permanent-displacements at mid-span of the corrugated panel under 7 applied loading scenarios.



(a) 1/4 FE modelling with boundary condition



(b) Buckled shape (after explosion event)

Figure-2. Finite element modelling with boundary conditions.

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Table-1. Material properties of the blast wall obtained tensile tests [1].

Part	t (mm)	Material type	ρ (kg/m^3)	E (GPa)	σ_Y (MPa)	Cowper-Symonds coefficients $\sigma_{Yd}/\sigma_Y = 1+(\dot{\varepsilon}/C)^{1/q}$	
						C (1/s)	q
Corrugated panel	2	AISI 316L	7970	200.0	293.7	1522	5.13
Angle	4				283.3	2720	5.78
Flexible angle	3				276.2	429	4.08
I-beam	12	Mild steel		205.8	235.0	40.4	5.00

Comparisons with test results [3] showed that the result discrepancies increase exponentially with increasing peak pressure. The time-displacement plots of all models (Types I, II, and III) are compared in Figure-4 for the most extreme peak pressure (loading case No. 7), which clearly prompts the capabilities of these FE formulations for estimating the blast wall dynamic responses. From the Type I mode, the excessively over predicted response was due to the hourglass deformation modes that produce zero energy in the affected solid elements, which cause the supporting members to lose stiffness hence falsifying the computation of the maximum displacement. As hexahedral solid and quadrilateral shell Fes have high tendencies for hour glassing, the Type II model could be opted to relieve the undesirable elemental "defects" in most loading cases with lower peak pressures. For instance, the fully integrated solid elements have underestimated the permanent displacement due to the shear-locking effect. On the other hand, little deviation has been observed between the Type II model and the Type III model, which consists mainly of fully-integrated solid elements. This may imply that the influence of shell elements is relative insignificant. The hour glassing phenomenon can be clearly observed from the solid elements in the Type I model in Figure-4.

The addition of hourglass control functions in Type I and Type II models, according to Table-3, can be classified as viscous and stiffness forms. These functions introduce internal resistance forces proportional to the components of nodal velocity and nodal displacements, respectively, to compensate the zero-energy deformation modes [10]. It is evident that the selection of relevant hourglass control functions could enhance the result accuracies, by rectifying the individual elemental distortions in reduced-integration solid elements in the Type I model, as shown in Figure-5(a). On the contrary, such approach is not as effective to the situation with reduced-integration shell elements as in the Type II model, as shown in Figure-5(b).

Table-2. Pulse pressure test results on a corrugated blast wall by [1].

Blast loading scenario No.	Testing	
	w_{max}	w_p
1	4.8	0
2	4.9	0
3	7.5	0
4	7.5	0
5	9.0	0
6	-	4.0
7	-	69.0

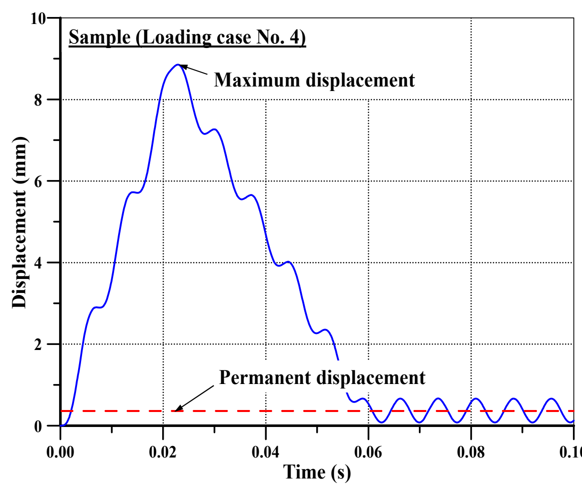

Figure-3. Sample of displacement-time plot from LS-DYNA.

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Table-3. Selected scenarios to check the effect of FE formulation type on blast wall simulation.

FE Formulation	Type I		Type II		Type III	
	Supporting member (Solid element)	Corrugated panel (Shell element)	Supporting member (Solid element)	Corrugated panel (Shell element)	Supporting member (Solid element)	Corrugated panel (Shell element)
Reduced integration	√ (ELFORM = 1)	-	-	√ (ELFORM = 2)	-	-
Fully Integrated	-	√ (ELFORM = 16)	√ (ELFORM = 3)	-	√ (ELFORM = 3)	√ (ELFORM = 16)
Hourglass control	Viscous form (IHQ = 3) Stiffness (IHQ = 5)				-	-

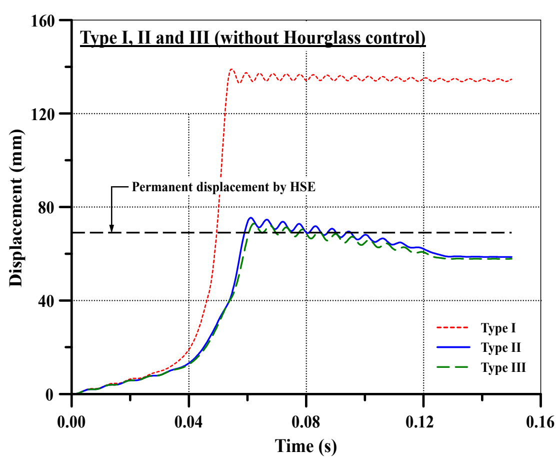
Note: supporting member = modelled by solid element, corrugated panel = modelled by shell element, ELFORM = element formulation in LS-DYNA, IHQ = Hourglass viscosity type in LS-DYNA.

DISCUSSION AND RECOMMENDATION

In explicit finite element analyses, reduced-integration elements are generally preferred due to their time-effectiveness and robustness in cases of high structural distortion, in addition to their ability to withstand shear-locking, which can suppress the true response. However, the downside of these elements is their tendency to introduce the hourglass modes of deformation, through which neither stresses nor strains are generated in the affected elements, thus ill-defining the resulting structural response.

While fully-integrated elements can be effective in dealing with hourglass instabilities, their major drawback is, as opposed to that of the reduced-integration element, over-stiffening of the response by shear-locking, e.g. when the material behaviour becomes incompressible. However, as may be difficult to eliminate the effects of hourglass, some forms of hourglass control technique may be required to enhance the FEA solutions. Based on Figure- 6(a) and (b), following outcome can be proposed as a recommendation for the numerical simulation of blast wall.

- **Accuracy:** Type I < Type II ≈ Type III
- **Computational cost:** Type III < Type II < Type I
- **Hourglass:** without ≈ IHQ 3 < IHQ 5



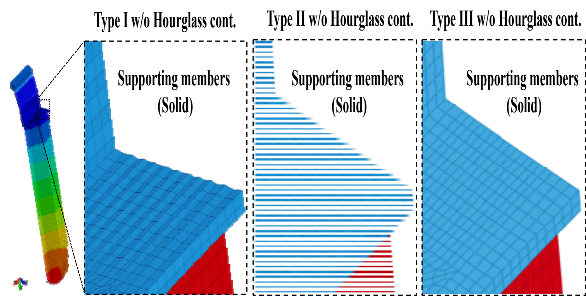
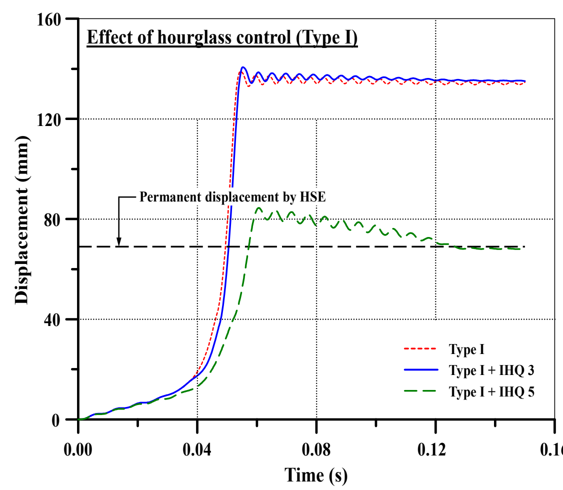


Figure-4. Outcome of type I, Type II, and type III models with the effect of hourglass (Loading case No. 7).



(a)Type I

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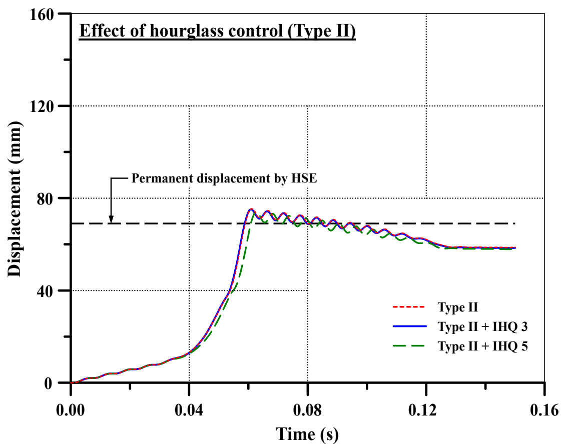
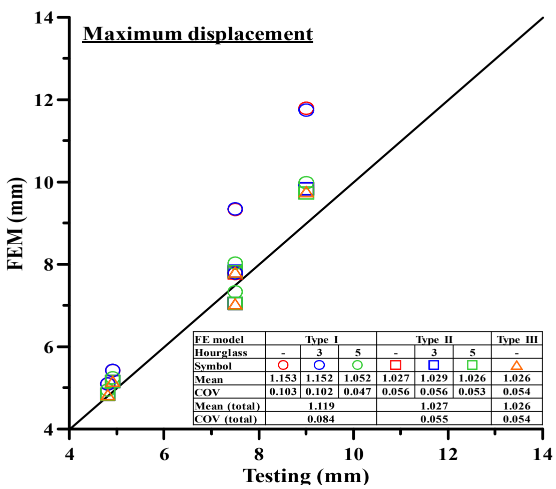


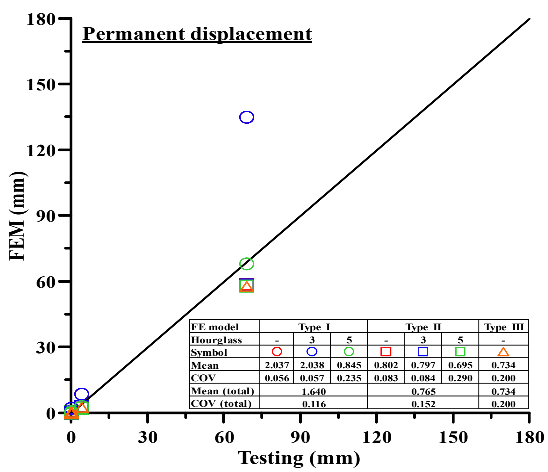
(b)Type II

Figure-5. Effect of hourglass control options (Loading case No. 7).



FE model	Type I			Type II			Type III
Hourglass	-	3	5	-	3	5	-
Symbol	○	○	○	□	□	□	△
Mean	1.153	1.152	1.052	1.027	1.029	1.026	1.026
COV	0.103	0.102	0.047	0.056	0.056	0.053	0.054
Mean (total)	1.119			1.027			1.026
COV (total)	0.084			0.055			0.054

(a)Maximum displacement



FE model	Type I			Type II			Type III
Hourglass	-	3	5	-	3	5	-
Symbol	○	○	○	□	□	□	△
Mean	2.037	2.038	0.845	0.802	0.797	0.695	0.734
COV	0.056	0.057	0.235	0.083	0.084	0.290	0.200
Mean (total)	1.640			0.765			0.734
COV (total)	0.116			0.152			0.200

(b)Permanent displacement

Figure-6. Statistical analysis results between testing and obtained outcomes.

CONCLUDING REMARKS

The influences of solid and shell element formulations with additional hourglass control functions on the maximum responses of corrugated blast wall were investigated in LS-DYNA explicit finite element solver. It is generally suggested that the fully-integrated solid element be applied only on cases of lower peak pressures as the fully-integrated solid element formulation could over-stiffen the response, as compared with the experimental observations. On the other hand, appropriate hourglass control functions can be added to the FE models to mitigate the zero-energy deformation modes to determine the true structural responses. The findings from present study may be applied in other structural dynamics FE studies.

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REFERENCES

[1] HSE (2003). Pulse pressure testing of 1/4 scale blast wall panels with connections (Research Report 124 edited by G.K. Schleyer and G.S. Langdon). Liverpool University, Health and Safety Executive, Liverpool, UK.

[2] Brewerton, R. (1999). Design guide for stainless steel blast walls (Technical note 5). Fire and Blast Information Group, Berkshire, UK.

[3] Langdon, G. and Schleyer, G. (2005a). Inelastic deformation and failure of profiled stainless steel blast wall panels. Part I: Experimental investigations. International Journal of Impact Engineering 31(4), 341-369.

[4] Langdon, G. and Schleyer, G. (2005b). Inelastic deformation and failure of profiled stainless steel blast wall panels. Part II: Analytical modelling considerations. International Journal of Impact Engineering 31(4), 371-399.

[5] Langdon, G. and Schleyer, G. (2006). Deformation and failure of profiled stainless steel blast wall panels. Part III: Finite element simulations and overall summary. International Journal of Impact Engineering 32(6), 988-1012.

[6] Boh, J., Choo, Y. and Louca, L. (2004). Design and numerical assessment of blast walls subjected to hydrocarbon explosions. The 14th International Offshore and Polar Engineering Conference (ISOPE 2004), 23-28 May, Toulon, France (ISOPE-I-04-439).

[7] Louca, L.A., Boh, J.W. and Choo, Y.S. (2004). Design and analysis of stainless steel profiled blast barriers. Journal of Constructional Steel Research 60(12), 1699-1723.

[8] Sohn, J.M., Kim, S.J., Kim, B.H. and Paik, J.K. (2013). Nonlinear structural consequence analysis of FPSO topside blastwalls. International Journal of Ocean Engineering 60, 149-162.

[9] Sohn, J.M., Kim, B.H., Paik, J.K. and Schleyer, G.K. (2012). Nonlinear structural consequence analysis of blast wall structures under hydrocarbon explosive loads. The 31st International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2012), 1-6 July, Rio de Janeiro, Brazil (OMAE2012-83521).

[10] LS-DYNA (2016). LS-DYNA Theoretical Manual, Livermore Software Technology Corporation, Livermore, CA, USA.