Structural Engineering and Mechanics, *Vol. 51, No. 5 (2014) 755-771*
DOI: http://dx.doi.org/10.12989/sem.2014.51.5.755

Structural impact response characteristics of an explosion-resistant profiled blast walls in arctic conditions

Jung Min Sohn[a], Sang Jin Kim[b], Dong Jin Seong[c], Bong Ju Kim[d], Yeon Chul Ha[e], Jung Kwan Seo[*] and Jeom Kee Paik[f]

The Korea Ship and Offshore Research Institute (The Lloyd's Register Foundation Research Centre of Excellence), Pusan National University, Busan, Korea

(Received May 21, 2012, Revised April 22, 2014, Accepted June 19, 2014)

Abstract. Environmental changes, especially global climate change, are creating new challenges to the development of the Arctic regions, which have substantial energy resources. And attention to offshore structures has increased with oil and gas development. The structural impact response of an explosion-resistant profiled blast walls normally changes when it operates in low temperatures. The main objectives of this study are to investigate the structural response of blast walls in low temperature and suggest useful guidelines for understanding the characteristics of the structural impact response of blast walls subjected to hydrocarbon explosions in Arctic conditions. The target temperatures were based on the average summer temperature (−20°C), the average winter temperature (−40°C) and the coldest temperature recorded (approximately −68°C) in the Arctic. The nonlinear finite element analysis was performed to design an explosion-resistant profiled blast wall for use in Arctic conditions based on the behaviour of material properties at low temperatures established by performing a tensile test. The conclusions and implications of the findings are discussed.

Keywords: offshore structures; arctic conditions; structural impact response characteristics; blast walls; nonlinear finite element analysis

1. Introduction

World energy consumption is on the increase due to the economic growth of BRICS (Brazil, Russia, India, China and South Africa) which an association of five countries (Enerdata 2013), and energy shortages are on the rise. These energy shortages have shifted global attention to oil and gas development in the oceans, which has in turn led to an increase in offshore installations, including FPSOs (floating production and storage units) in the ultra-deep ocean. This has naturally

∗Corresponding author, Professor, E-mail: seojk@pusan.ac.kr
[a]Ph.D. Student, E-mail: jminz@pusan.ac.kr
[b]Ph.D. Student, E-mail: sangjin@pusan.ac.kr
[c]Master Student, E-mail: seong_dj@pusan.ac.kr
[d]Professor, E-mail: bonjour@pusan.ac.kr
[e]Professor, E-mail: ycha@pusan.ac.kr
[f]Professor, E-mail: jeompaik@pusan.ac.kr

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

given rise to concerns about accidents (explosion, fire etc.) on installations. Accidents, such as the Piper Alpha accident (6th July 1988) and Deepwater Horizon accident (20th April 2010), have caused property loss, serious casualties and unrecoverable environmental pollution. The Piper Alpha accident, which left 167 people dead, triggered the establishment of regulations about the use of risk-based design for offshore structures to reduce the risk (frequency x consequence). In European countries, risk assessments are now a legislative requirement for all new and existing installations, and several other countries are implementing similar regulations. As a result, QRA (Quantitative Risk Assessment) is used worldwide by designers, operators, consultants and offshore industries.

Resistant profiled blast wall is one of the safety systems to decrease the consequence from hydrocarbon explosion and usually used on the topsides of offshore installations to protect people and vital equipment. Blast walls are divided into three types; flat plate type (with or without opening), stiffened-plate and corrugated plate type. The stiffened-plate blast walls have a strong stiffness and strength. Whereas, corrugated blast walls are usually used for safety system on offshore installations due to benefit of cost, manufacture and energy absorbing system.

Previous studies on corrugated type of blast walls have covered two main topics (1/4 and full scale blast walls at room temperature). For 1/4 scale blast walls, Schleyer *et al*. (2006, 2007) performed the shock pressure test by experimental and structural response analysis of target structures by FEA (finite element analysis). Structural response characteristics of 1/4 scale blast walls with various connection and length were defined by Langdon and Schleyer (2005a, b, 2006). And HSE (Health and Safety Executive) (2003, 2006) obtained the dynamic structural response of 1/4 scale blast walls using experimental, numerical (Finite Element Analysis, FEA) and analytical method (Single Degree of Freedom, SDOF) with P-I (Pressure-Impulse) charts.

For full scale blast walls, Louca *et al*. (1998) reported results for the response of a corrugated blast walls and a tee-stiffened panels (stiffened plate type of blast walls). FABIG (Fire and Blast Information Group) (1999) provides the design guide for design, construction details, and structural response of stainless steel blast walls with numerical solutions. And Paik (2011) performed nonlinear structural analysis of blast walls on topside of FPSO with P-I diagram using FEA and SDOF. Most of studies provided massive material for explosion loads and structural response characteristics of blast walls at room temperature.

As the Arctic sea-ice cover decreases due to global warming, the oil and gas industries are increasingly focusing on petroleum exploration and development in the Arctic region, which is estimated to hold about 25% of the earth’s oil and gas. Given this trend, the design of operation and production facilities to suit Arctic conditions has become an important topic. According to LR (Lloyd’s Resister) report (2012), environmental changes, especially those linked to global climate change, have given rise to a broad set of economic and political developments in the Arctic. Resource exploitation in the Arctic requires robust risk management frameworks and processes that adopt best practice and cover worst-case scenarios, crisis response plans and full-scale exercises. It is thus important to study and develop methods to deal with the behaviour of the target structures under Arctic conditions. Paik *et al*. (2011) investigated the effects of low temperatures on the crushing characteristics of thin-walled steel structures. They calculated the temperature and strain rate dependent strength and ductility of tested representative materials for offshore structures, and used the findings to analyze their mechanical properties and to establish a database for structures installed in the Arctic.

Research has not been conducted on FPSO blast walls subjected to explosion accidents under Arctic conditions. The aims of this study are to examine the effects of low temperatures on the structural impact response characteristics of explosion-resistant profiled blast walls and generate Pressure-Impulse diagram with upper and lower bound. The target temperatures were chosen based on the average summer temperature (−20℃), the average winter temperature (−40℃) and the coldest temperature recorded (approximately −68℃) in the Arctic. A series of tensile coupon tests and nonlinear FE simulations were performed at low temperatures ranging between 0℃ and -80℃, which is equivalent to temperatures in the Arctic environment. The insights gained from these tests and numerical simulations are discussed.

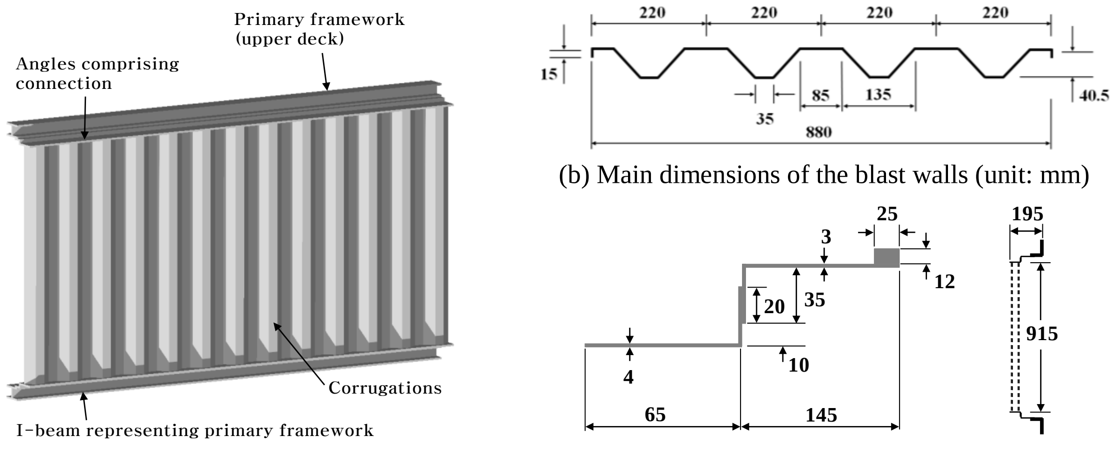
For the first step, design of 1/4 scale blast walls obtained by Schleyer *et al*. (2006, 2007), Langdon and Schleyer (2005a, b, 2006) and HSE (2003, 2006) were used for target structure. And many things in this paper are adopted from HSE reports and, papers by Langdon and Schleyer.

2. Numerical modelling

2.1 Target structure (blast walls) and extent of analysis

Typical type of 1/4 scaled blast walls obtained by HSE (2003) consist of steel profiled corrugated plates and connection parts, as shown in Fig. 1(a). In general, the blast walls of offshore installations are connected to the top and bottom of the primary steelwork by angles, and are normally free at the sides. Fig. 1(b), (c) presents a schematic diagram of the connection and corrugated plates of the structure considered in this study. A 1/2 symmetry model of corrugated blast walls is adopted for the extent of analysis, as shown in Fig. 2.

In the previous papers, the material of blast walls was stainless steel. And stainless steel blast walls are introduced in the FABIG (1999) report. But, nowadays some heavy industries, which are building ships and offshore installations in Korea, are using a carbon steel (mild or high tensile steel) to manufacture the blast walls due to reason of cost and welding problem. So, high tensile steel (Grade DH) was used for material of blast walls (corrugated plates and connections) in this study.



(a) Corrugated type of 1/4 scaled blast walls

(b) Main dimensions of the blast walls (unit: mm)

(c) Details of the connection and side view of the panel (unit: mm)

Fig. 1 1/4 scaled blast walls and profile dimension (HSE 2003)

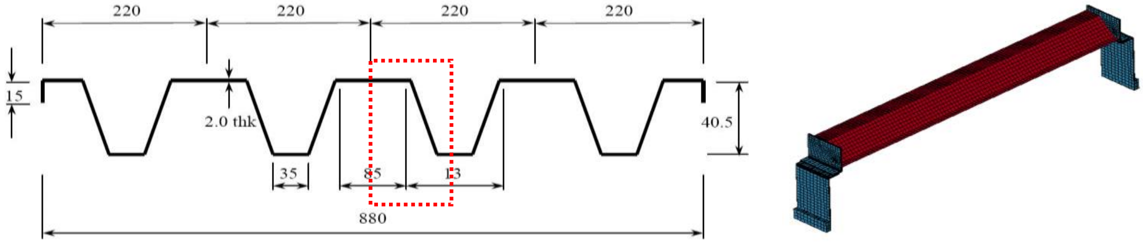


Fig. 2 The extent of analysis

2.2 Finite element modelling

2.2.1 Applied mesh size

A FE (finite element) model was employed in the structural response study to generate accidental design curves for nonlinear structural behaviour and obtain the suitable characteristics for a corrugated blast wall under an explosion load. Nonlinear FEA is the most refined method among those currently available, and is believed to provide the most accurate solutions. However, the FEA modelling technique applied must be capable of representing the actual structural behaviour associated with geometrical nonlinearity, material nonlinearity, the boundary conditions, the loading conditions, the mesh size, and so on.

Because the thin steel plate elements of a blast wall are subject to local buckling and the plates and stiffeners are subject to in- and out-of-plane buckling effects, the element chosen must be capable of modelling these buckling phenomena and their associated behaviour. It must also be capable of modelling the structural behaviour in both linear and nonlinear regions, including large displacements, elasto-plastic deformations and associated plasticity effects. ANSYS/LS-DYNA (2013) nonlinear FEA was employed in present study for the nonlinear structural dynamic analysis of blast walls subjected to explosion loads.

The shell elements in the ANSYS/LS-DYNA element library generally satisfy the criteria, and can thus be employed to model the steel plate elements of a blast wall. Of the various types of shell elements available in the library, iso-parametric quadrilateral elements with four nodes and six degrees of freedom per node were used to model the corrugated steel plate elements. The connections were modelled using eight-node solid elements. The bending and large strain deformation behaviour of the connections with material nonlinearity must be simulated while the plate is under explosive loading.

In the current analysis, detailed convergence studies were conducted to determine the appropriate number of elements for both the corrugated plates and the connections to obtain sufficiently accurate results without the need for excessive computation time. And Fig. 3 shows the results of mesh convergence studies. From the convergence studies, the element size of 4×4 mm (width×breadth) for corrugated plates and 4×4×4 mm (width×breadth×height) for connections were selected as shown in Fig. 4.

2.2.2 Boundary and loading conditions

Fig. 5 shows the boundary and loading conditions used in the study. Symmetry conditions were applied to the two edges of the blast wall, and the connections were fully restrained along the bottom face. It was assumed that the dynamic pressure loads were applied to the corrugated panel

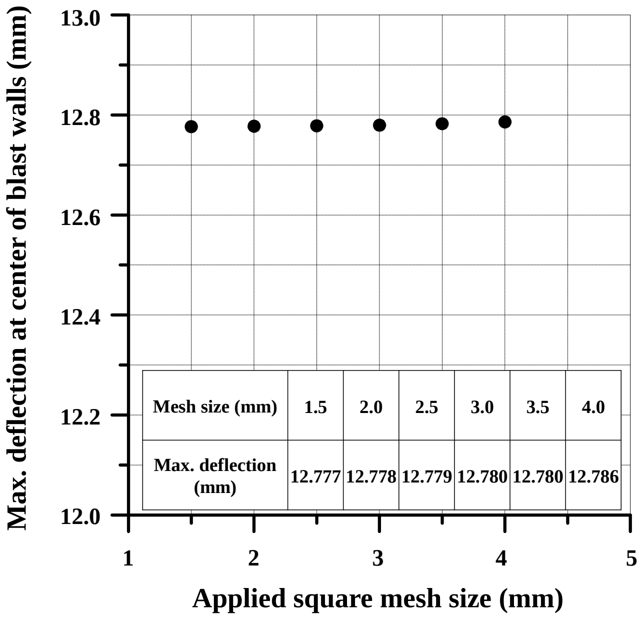


Fig. 3 Results of mesh convergence studies of the blast walls

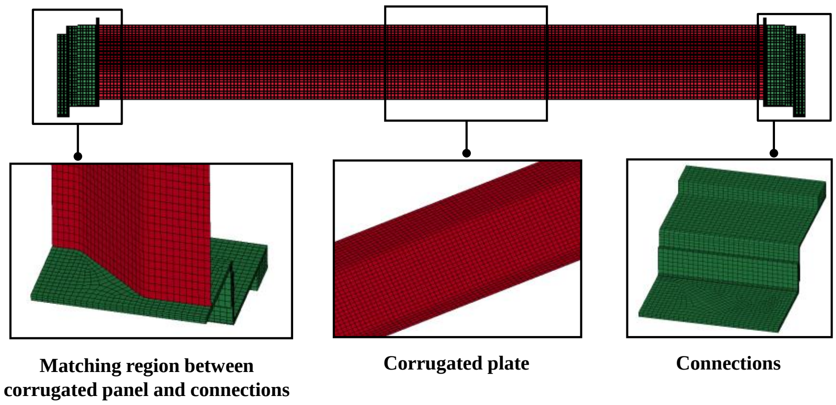
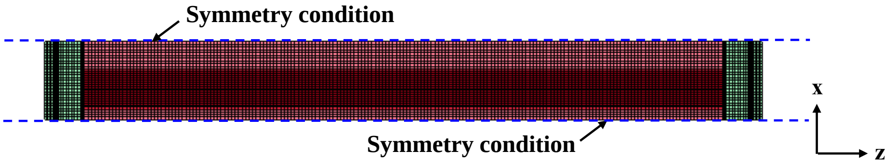


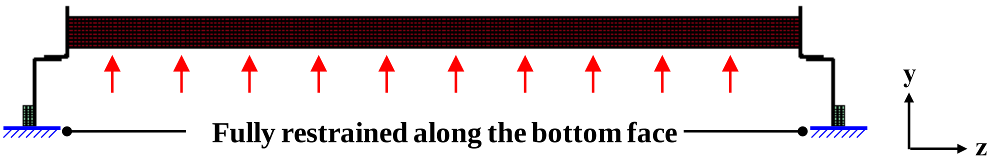
Fig. 4 Finite element models (Applied mesh) of the blast walls

as uniformly distributed loads, because the whole of the blast wall except for the connections would be exposed to an explosion if one occurred.

The explosion pressure loads have a very high peak value that lasts for a very short time. There are also many uncertainties in explosion accidents on FPSO topsides. One of the main uncertainties is the shape of the loading pulse. The loading pulse shape in many experiments and numerical analysis is taken as the actual load (FABIG 1999, Czujko 2001, Paik and Czujko 2010) as shown in Fig. 6. The realistic characterization of blast pulse pressure action requires the pressure-time history to be traced, including the rise time, peak pressure, duration and type of pressure decay. Blast pressure can be idealized as an impulsive loading that is characterized by peak pressure and duration time. To simplify the structural analysis, the time history of the panel



(a) Plan view



(b) Side view and loading direction

Fig. 5 Boundary conditions and loading direction

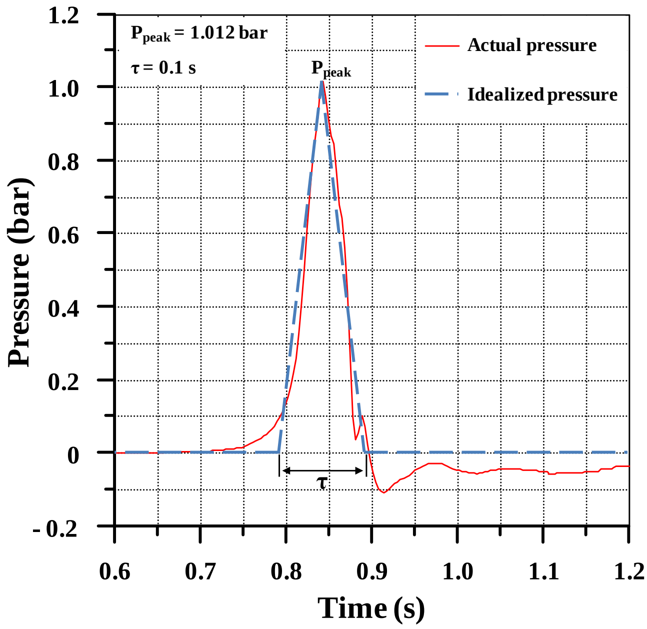


Fig. 6 An example of actual and idealized pressure-time history by CFD simulation (Paik and Czujko 2010)

load around its peak was idealized as a triangular impulse, as shown in Fig. 6. The triangular type was defined as the time history of the pressure to a symmetric triangular impulse of a short duration, from which it is possible to generate the triangular impulses of the duration and the rise time, which is an integer multiple of the short duration. The maximum response time is then taken as half of the duration.

A series of ANSYS/LS-DYNA computations were carried out to assess the dynamic strength performance of the corrugated blast wall under explosion action. Eigen value analysis is usually performed to determine the loading conditions in nonlinear dynamic structural analysis. According to NORSOK (1999), structural behaviour can be idealized within three domains of behaviour

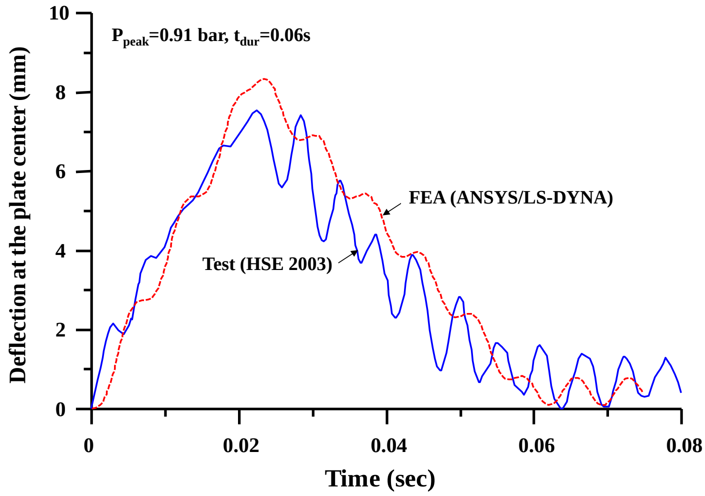


Fig. 7 Validation of FE modelling technique with test by HSE (2003)

depending on the ratio of the duration of impact to the natural period of the structure; the quasi-static domain, dynamic/impact domain and impulsive domain. The eigenvalue analysis was used to investigate the dynamic behaviour of the structure under different characteristic frequencies. The natural period of the global mode was 0.007sec. After eigenvalue analysis, 1.0 to 5.5bar of peak pressure and 0.0050 to 0.0225bar·s of impulse were selected for loading conditions.

2.2.3 Validation of FE analysis with test

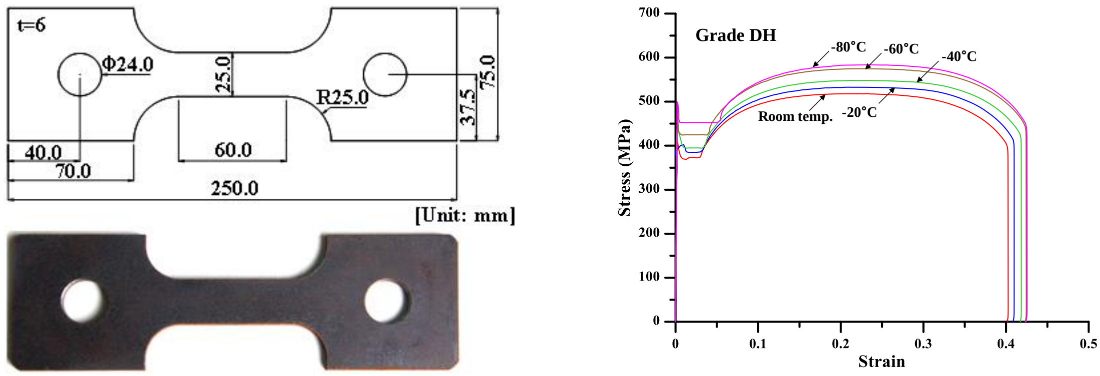
The modelling technique (extent of analysis and boundary conditions) used in this study was validated with PPLR (Pulse Pressure Loading Rig) test (HSE 2003). And Fig. 7 shows that the modelling technique is correct.

2.3 Material model and properties

The material model or the corrugated plate and connections was piecewise linear plastic. This material model in ANSYS/LS-DYNA includes a true stress-true strain curve. The material properties at various temperatures for both parts of blast wall structure as obtained from the tensile tests were used and subsequently employed in the FEA. The Poisson’s ratio, density and Young’s modulus were taken as 0.3, 7850 kg/m^3 and 205,800 MPa, respectively. Details of the tensile testing and material modelling are provided in the following sections.

2.3.1 Tensile coupon test

Metallic materials for offshore structures must comply with the specific requirements of their classification. These requirements are almost all the same as ASTM (2008) Standard Specification for Structural Steel for Ships. The blast wall was assumed to be made of Grade DH steel, which is commonly used in ships and offshore structures in Arctic conditions. The tests were conducted by Park *et al*. (2011) and the tensile coupons were cut off from the plate in a longitudinal direction with a width of 25 mm and a gauge length of 50 mm, as shown in Fig. 8(a). The specimen and test method satisfied ASTM (2009) and ISO (2000).



(a) Test specimen (b) Stress-strain curves

Fig. 8 Tensile coupon tests results at different temperatures (Park *et al*. 2011)

Table 1 Tensile coupon test results (nominal stress and strain) (Park *et al*. 2011)

Temperature (℃)	*E* (MPa)	Density (kg/m^3)	σ_Y (MPa)	σ_T (MPa)	ε_f
RT			368.699	518.58	0.4014
-20			384.881	532.790	0.4084
-40	205,800	7,850	394.802	548.274	0.4171
-60			424.588	574.708	0.4231
-80			454.067	583.727	0.4240

Note: *E*: elastic modulus, σ_Y: yield stress, σ_T: tensile stress and ε_f:fracture strain.

Table 2 Material properties of the blast walls used in the nonlinear FEA

Temperature (℃)	*E* (MPa)	σ_Y (MPa)	Cowper-Symonds Coefficient	
			C (1/s)	*q*
RT		368.88		
-20		390.08		
-40	205,800	399.00	3200	5
-60		427.18		
-80		455.14		

The temperature at three measured points of the specimen was set as the criteria for the surface temperature during the test. Five minutes of temperature adaption was allowed. Once the temperature had reached the target, it was kept at ±3C. Five temperature cases were considered - −80℃, −60℃, −40℃, −20℃, and room temperature - to identify the material behaviour of Grade DH at those temperatures. It was observed that a temperature decrease caused an increase in strength and a uniform trend of fracture strain, as shown Fig. 8(b). The tensile coupon test results are presented in Table 1.

2.3.2 Material model for the FEA

For the FE analysis, the material behaviour obtained from the tensile tests as shown in Fig. 8 is needed to convert to true stress and strain. Because elasto-perfectly plastic model were used for

Table 3 Selected duration time at a constant peak pressure of 2.5 and 4.0bar

Pressure=2.5bar		Pressure=4bar	
Impulse (bar·s)	Duration time (s)	Impulse (bar·s)	Duration time (s)
0.0050	0.004	0.0050	0.00250
0.0075	0.006	0.0075	0.00375
0.0100	0.008	0.0100	0.00500
0.0125	0.010	0.0125	0.00625
0.0150	0.012	0.0150	0.00750
0.0175	0.014	0.0175	0.00875
0.0200	0.016	0.0200	0.01000
0.0225	0.018	0.0225	0.01125

Table 4 Selected duration at a constant impulse of 0.02 and 0.0075bar·s

Impulse=0.02bar·s		Impulse=0.0075bar·s	
Peak pressure (bar)	Duration time (s)	Peak pressure (bar)	Duration time (s)
1.0	0.0400	1.0	0.0150
1.5	0.0267	1.5	0.0100
2.0	0.0200	2.0	0.0075
2.5	0.0160	2.5	0.0060
3.0	0.0133	3.0	0.0050
3.5	0.0114	3.5	0.0043
4.0	0.0100	4.0	0.0038
4.5	0.0089	4.5	0.0033
5.5	0.0073	5.5	0.0027

material model, only yield stress was converted to true stress for FE simulations. Table 2 shows converted material properties and it was used for structural analysis

In an impact load case such as explosion load, the effect of the strain-rate must be significant in the FE material model. Cowper-Symonds (1957) suggested the Eq. (1) for considering dynamic effect.

$$\frac{\sigma_{Yd}}{\sigma_Y} = 1.0 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/q} \tag{1}$$

where C and q are coefficients that are determined based on the test data. And C and q for high tensile steel are 3200 and 5 (Paik and Chung 1999). It is evident that coefficients C and q are dependent on the material type, among other factors. Material type 24 is elasto-plastic, and the strain rate can be accounted for by using the Cowper and Symonds model, which scales the yield stress with factors C and q in numerical studies.

3. Structural impact response analysis

3.1 Details of the parametric study

Although there are various types of blast walls available for use in Arctic conditions, only those that are most likely to be used in explosion-resistant profiled blast walls were selected for this study. Impulse, dynamically and pressure sensitive regions were included based on the pressure-impulse damage curves (Abrahamson and Lindberg 1976). As noted by Abrahamson and Lindberg (1976), pressure-impulse diagrams can be used to assess the structural dynamic response. It illustrates that the combination of pressure and impulse produces an equal structure response. Pressure-impulse diagrams can be divided into three categories - impulse sensitive range, dynamic range and pressure sensitive range - as shown in Fig. 10. A variety of pressures and duration times were selected to estimate the effect on sensitive regions. Tables 3 and 4 summarise the specific values for the parametric studies.

3.2 Results of the numerical study

Tables 5(a) and (b) summaries the permanent deflections obtained from the numerical study toinvestigate the effect of temperature on the blast walls. The results show elastic behaviour when the applied pressure is under 1.0bar. In contrast, when the pressure is above 1.5bar, the blast wall presents a plastic response regardless of the temperature. An increase in pressure and impulse corresponds to an increase in the permanent deflection. This tendency should relieve the impulse increases (the area under the time-pressure curve). A small permanent deflection occurs with lower temperatures. This occurs because the permanent deflection is closely related to the material characteristics, which vary with the temperature. The yield stress of grade DH tends to strengthen as the temperature decreases. This causes an increase in the structural strength and a decrease in the absorbed energy. Figs. 10 and 11 show the dynamic structural response of the blast wall as calculated by ANSYS/LS-DYNA based on the modified material properties as shown in Table 2.

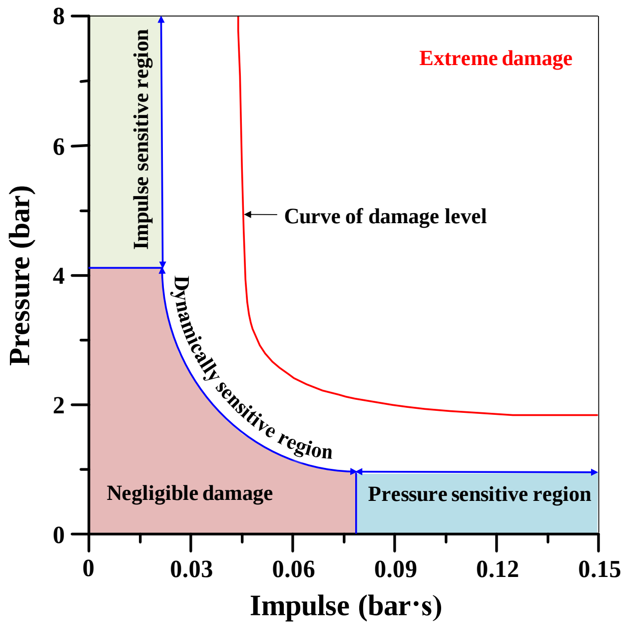


Fig. 9 Description of the pressure-impulse damage curve (Abrahamson and Lindberg 1976)

Table 5(a) Results obtained from the numerical study (impulse=0.0075 and 0.02bar·s)

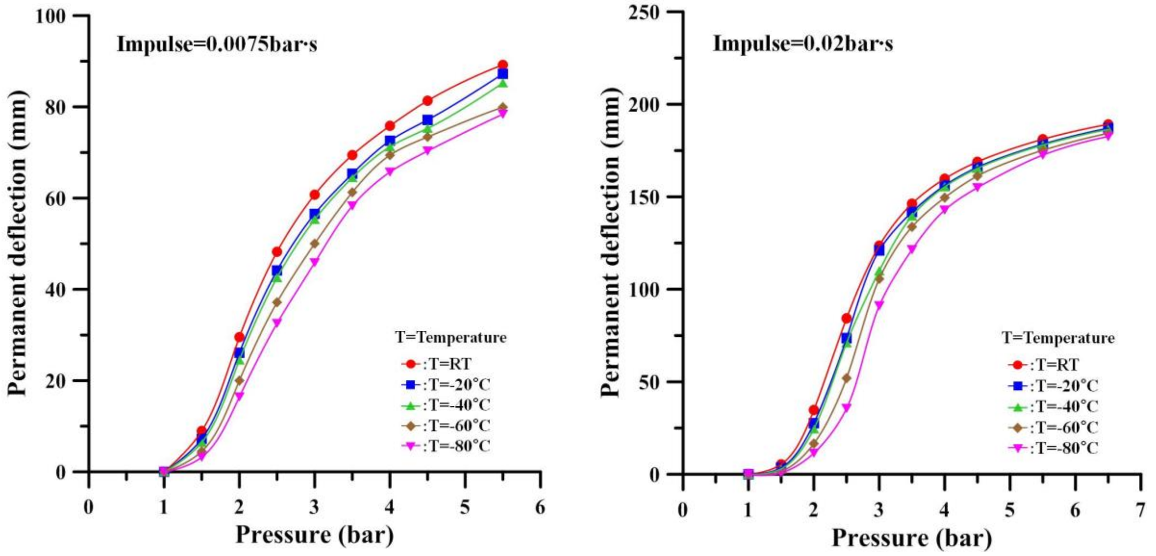
Pressure (bar)	Permanent deflection (mm)									
	Impulse=0.0075bar·s					Impulse=0.02bar·s				
	RT	−20℃	−40℃	−60℃	−80℃	RT	−20℃	−40℃	−60℃	−80℃
1.0	0	0	0	0	0	0	0	0	0	0
1.5	9.0	7.2	6.5	4.5	3.2	5.4	3.6	2.9	1.5	0.8
2.0	29.5	26.1	24.5	20.0	16.4	84.3	27.7	24.6	16.6	11.5
2.5	48.2	44.1	42.6	50.0	32.5	123.6	73.6	71.1	52.0	35.6
3.0	60.7	56.5	55.3	61.3	45.8	146.3	121.0	110.0	105.7	91.1
3.5	69.4	65.3	64.5	69.4	58.3	159.7	141.7	139.6	133.8	121.4
4.0	75.8	72.6	71.3	69.4	65.7	168.9	156.1	155.4	149.5	142.8
4.5	81.3	77.2	75.3	73.4	70.3	181.1	166.0	165.4	161.2	154.9
5.5	89.2	87.2	85.3	79.9	78.4	189.1	178.5	178.0	175.1	172.5

Table 5(b) Results obtained from the numerical study (peak pressure=2.5 and 4.0bar)

Impulse (bar·s)	Permanent deflection (mm)									
	Peak pressure=2.5bar					Peak pressure=4.0bar				
	RT	−20℃	−40℃	−60℃	−80℃	RT	−20℃	−40℃	−60℃	−80℃
0.0050	29.1	26.9	25.9	22.5	19.4	39.9	37.7	36.7	33.2	30.1
0.0075	48.2	44.1	42.6	37.2	32.5	75.8	72.6	73.1	66.1	64.2
0.0100	64.0	56.7	54.3	46.6	39.5	115.4	110.7	112.0	99.7	95.0
0.0125	71.5	63.3	61.6	53.4	41.4	138.2	133.0	131.3	127.3	119.9
0.0150	77.0	68.2	66.1	51.4	39.8	152.4	147.5	147.0	140.8	136.1
0.0175	81.2	72.6	69.1	51.5	37.0	158.1	154.7	152.9	149.3	143.0
0.0200	84.3	74.6	71.1	52.0	35.9	159.9	156.4	155.4	152.9	146.8
0.0225	86.8	76.2	72.4	53.4	36.8	159.9	156.8	155.5	152.4	148.7

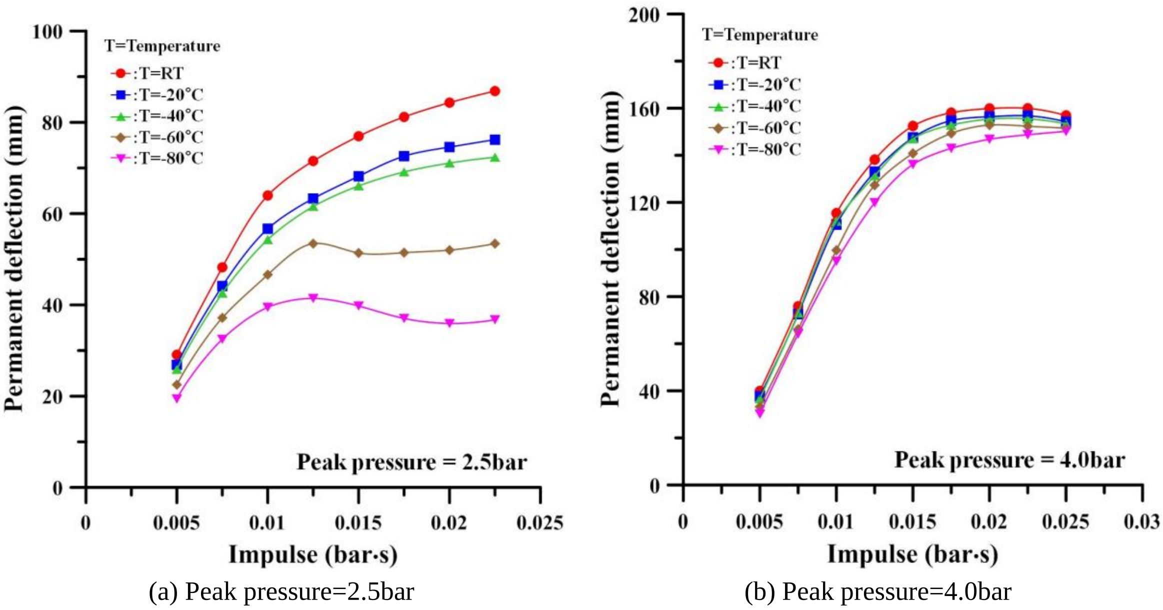
Fig. 10 presents the pressure versus permanent deflection curves with varying temperature and a constant impulse. The low impulse is at 0.0075bar·s and the high impulse is at 0.02bar·s. The quasi-static region occurs at a relatively lower pressure, as can be see from a comparison of Fig. 10. There is a sensitive response between 2.5 and 4.0bar depending on the temperature under a high impulse, but the permanent deflection converges at around 180mm as the high pressure is applied. When a low impulse is applied to the impulse/dynamic regions, the permanent deflection gradually increases as the pressure increases.

Fig. 11 presents the impulse versus permanent deflection curves with varying the temperature and a constant pressure. The relationship between the impulse and permanent deflection indicates the effect of duration and temperature on the behaviour of the structure when the same pressure is applied. It is well known that the permanent deflection increases as a high pressure is applied to impulse/dynamic regions, whereas the permanent deflection converged at a certain value in quasi-static regions. This trend is also shown in the graphs in Fig. 11. Fig. 11(a) displays the interesting result that the permanent deflection increases as the impulse increases at room temperature, −20℃ and −40℃ whereas nonlinear behaviour is dominant at −60℃ and −80℃ under a pressure of 2.5bar. The permanent deflection under 4.0bar shows similar temperature-dependent behaviour.



(a) Low impulse (I=0.0075bar·s) (b) High impulse (I=0.02bar·s)

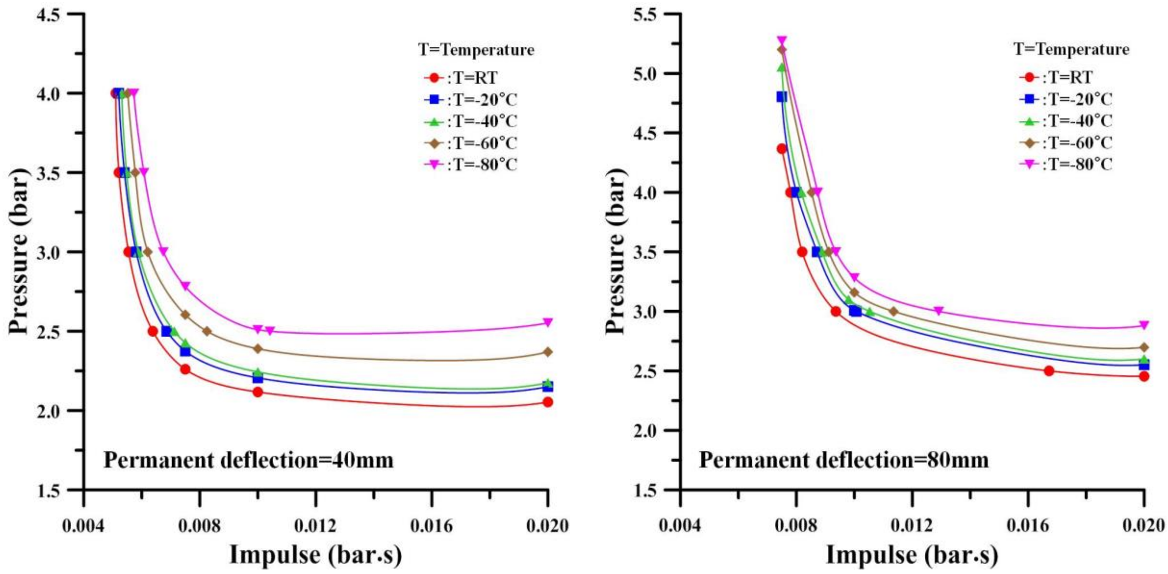
Fig. 10 Pressure versus permanent deflection curves with varying temperature



(a) Peak pressure=2.5bar (b) Peak pressure=4.0bar

Fig. 11 Impulse versus permanent deflection curves with varying temperature

It can be concluded that the effect of decreasing temperature on the permanent deflection is more sensitive to a change in pressure than a change in impulse. Fig. 12 shows the pressure-impulse damage curves with temperature at the same permanent deflections (40 and 80mm). The permanent deflection at 40 mm has a linear tendency, whereas the permanent deflection at 80 mm is the initial deflection of the buckling behaviour of the blast wall. These curves are similar to the



(a) Permanent deflection=40mm (b) Permanent deflection=80mm

Fig. 12 Pressure-impulse curves obtained from the FEA results

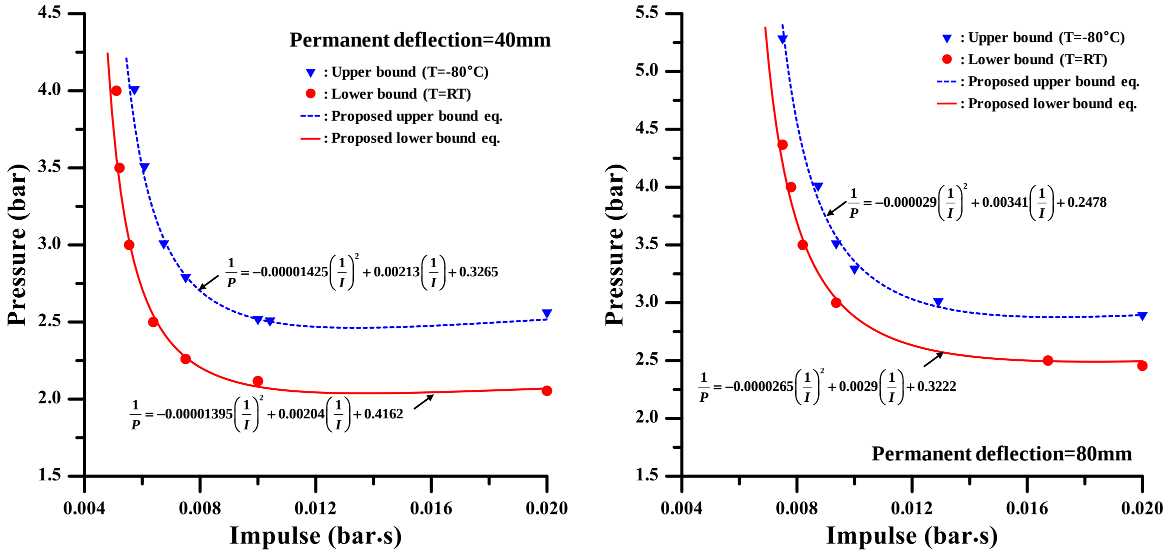
general pressure-impulse curves in that they are divided into three regions - an impulse sensitive region, a dynamically sensitive region and a pressure sensitive region - which describe the temperature-dependent characteristics. The effect of temperature on the dynamic structural behaviour of the blast wall is inappreciable in the impulse sensitive region, but becomes gradually more prominent in the pressure sensitive region through to the dynamically sensitive region. This suggests that pressure is an important cause of the differences in permanent deflections. The effect of pressure is more remarkable at lower damage levels. In other words, lower damage levels are more sensitive to temperature differences.

3.3 Proposed P-I design curve

Curve fitting is a process of making a useful curve or mathematical function that has the best fit to a series of data points. A smooth function was constructed based on the FEA results reported in Fig. 13 that approximately fits the data. Fig. 13 shows the pressure-impulse curves that are the best fit of the FE results. The proposed equation is as follows

$$\frac{1}{P} = a\left(\frac{1}{I}\right)^2 + b\left(\frac{1}{I}\right) + c \tag{2}$$

where a=−0.00001425, b=0.00213 and c=0.3265 for the upper bound solution; a=−0.00001395, b=0.00204 and c=0.4162 for the lower bound solution at δ_p=40 mm; and a=−0.000029, b=0.00341, c=0.2478 for a=−0.0000265, b=0.0029, c=0.3222 for the lower bound solution at δ_p=80 mm. The proposed equation is recommended for use with a pressure of 5.0bar and between 0.0045bar·s and 0.02bar·s. Fig. 14 shows the proposed pressure-impulse curves of blast walls subjected to blast loading. The upper and lower limits of the permanent deflections are 40 mm and 80 mm. The upper bound represents the behaviour of the blast wall at −80℃ and the lower bound



(a) Permanent deflection=40 mm (b) Permanent deflection=80 mm

Fig. 13 Proposed pressure-impulse curves with the FEA results

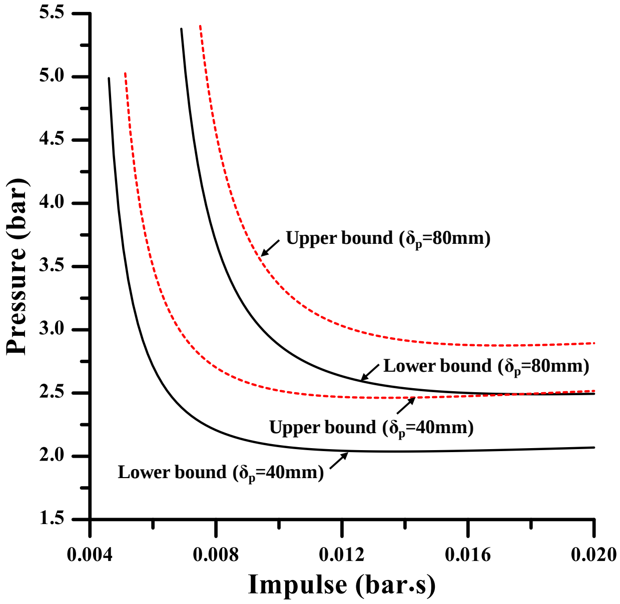


Fig. 14 Proposed pressure-impulse curves of the blast wall subjected to blast loading

indicates the deflection at room temperature. The results indicate that a larger pressure and impulse are required to create a permanent deflection at low temperatures. The proposed pressure-impulse curves can be used to examine the effect of low temperature on the structural impact response characteristics of explosion-resistant profiled blast walls. The graph shows the range of limit at certain deflections and other deflections that are predicted using extrapolation and interpolation.

Table 5 Comparison of the results of the FEA and proposed equation at δ_p=40mm

Permanent deflection=80 mm	FEA		Proposed eq.		Propose Eq./FEA	Sensitive region
	Impulse (bar·s)	Pressure (bar)	Impulse (bar·s)	Pressure (bar)		
Upper bound (*T*=−80℃)	0.0058	4.00	0.0056	4.00	0.97	Impulse
	0.0061	3.51	0.0061	3.48	0.99	
	0.0067	3.00	0.0068	3.02	1.01	
	0.0075	2.78	0.0075	2.80	1.00	Dynamic
	0.0100	2.51	0.0100	2.51	1.00	
	0.0104	2.50	0.0105	2.50	1.00	
	0.0200	2.55	0.0200	2.51	0.98	Pressure
Lower bound (*T*=Room temp.)	0.0051	4.00	0.0049	4.00	0.96	Impulse
	0.0052	3.50	0.0052	3.49	1.00	
	0.0056	3.00	0.0056	3.00	1.00	
	0.0064	2.50	0.0064	2.52	1.01	Dynamic
	0.0075	2.26	0.0075	2.26	1.00	
	0.0100	2.11	0.0097	2.08	0.99	
	0.0200	2.05	0.0200	2.06	1.00	Pressure
					Mean	0.99
					COV	0.0144

Table 6 Comparison of the results of the FEA and proposed equation at δ_p=80mm

Permanent deflection=80 mm	FEA		Proposed eq.		Propose Eq./FEA	Sensitive region
	Impulse (bar·s)	Pressure (bar)	Impulse (bar·s)	Pressure (bar)		
Upper bound (*T*=−80°C)	0.0072	4.33	0.0072	4.34	1.00	Impulse
	0.0084	3.38	0.0083	3.35	0.99	
	0.0090	3.01	0.0091	3.03	1.01	Dynamic
	0.0097	2.84	0.0098	2.86	1.01	
	0.0126	2.63	0.0124	2.60	0.99	
	0.0197	2.54	0.0197	2.54	1.00	Pressure
Lower bound (*T*=Room temp.)	0.0072	3.65	0.0071	3.60	0.99	
	0.0075	3.37	0.0074	3.35	0.99	
	0.0079	3.00	0.0079	3.01	1.00	Dynamic
	0.0090	2.62	0.0091	2.64	1.01	
	0.0164	2.25	0.0164	2.25	1.00	
	0.0197	2.22	0.0197	2.24	1.01	Pressure
					Mean	1.00
					COV	0.0079

Tables 5 and 6 compare the FEA and proposed equation based on the sensitive region of the pressure-impulse curves, and show good agreement between them. The results in the graph should thus be implemented in the design of DH steel corrugated blast walls. However, defining more of the material properties would be helpful to fully investigate the effect of low temperature on the structural behaviour. In addition, further study is recommended to apply a variety of the designs of DH steel corrugated blast walls with different sensitive regions, damage criteria and temperatures.

4. Conclusions

The objectives of this study were to investigate the effect of temperature differences on the structural impact response characteristics of explosion-resistant profiled blast walls subjected to explosion pressures in Arctic conditions. The nonlinear finite element method was used for the investigations, which were performed based on the material characteristics for Grade DH steel at specific temperatures using ANSYS/LS-DYNA. The finite element structural modelling techniques for blast walls were studied in terms of the strain-stress relation at several temperatures, the extent of the analysis, the loading conditions and the boundary conditions. Based on the numerical computations, the structural impact responses of a DH steel corrugated blast wall at different temperatures were examined, and design curves for impact/pressure and permanent deflection were developed. The results should be implemented in the design of DH steel corrugated blast walls.

The change in strength with temperature significantly influenced the permanent deflection of the blast wall. Further, the temperature-dependent permanent deflection was more sensitive to a change in the pressure value than a change in the impulse value. These insights should be a useful guide for the design of corrugated blast walls subjected to potential explosion action. However, further studies under different conditions, loading conditions, damage criteria, blast wall type and material properties should be carried out to further improve the design of explosion-resistant profiled blast walls.

Acknowledgments

The authors of this paper quoted the design of 1/4-scale blast wall panels in HSE reports (HSE, UK) and some papers by G.S. Schleyer (University of Liverpool, UK) and G.K. Langdon (University of Cape Town, South Africa). This research was supported by Leading Foreign Research Institute Recruitment Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (MSIP) (Grant no.: 2013044761), and this work was also supported by the Components & Materials Technology Development Program (Grant no.: 10043799) funded By the Ministry of Trade, industry & Energy (MI, Korea). And the study was undertaken at the Lloyd's Register Foundation Research Centre of Excellence at Pusan National University, Korea. The Lloyd's Register Foundation supports the advancement of engineering-related education, and funds research and development that enhance the safety of life at sea, on land and in the air.

References

Abrahamson, G.R. and Lindberg, H.E. (1976), "Peak load-impulse characterization of critical pulse loads in structural dynamic", *Nucl. Eng. Des.*, **37**, 35-46.

ANSYS/LS-DYNA (2013), *User's manual (version 14.0)*, ANSYS Inc., Canonsburg, PA, USA.

ASTM (2008), *ASTM A131/A131M-08: Standard specification for structural steel for ships*, American Society for Testing and Materials International, Conshohocken, PA, USA.

ASTM (2009), *STM E8/E8M-09: Standard test methods for tension testing of metallic materials*, American Society for Testing and Materials International, Conshohocken, PA, USA.

Cowper, G. and Symonds, P.S. (1957), *Strain-hardening and strain-rate effects in the impact loading of cantilever beams*, Technical Report 28, Department of Applied Mathematics, Brown University, RI, USA.

Czujko, J. (2001), *Design of offshore facilities to resist gas explosion hazard: Engineering handbook*, CorrOcean ASA, Oslo, Norway.

Enerdata (2013), *Global energy statistical yearbook*, Enerdata, London, UK.

FABIG (1999), *Technical note 5: Design guide for stainless steel blast walls*, Fire and Blast Information Group, Berkshire, UK.

HSE (2003), *Pulse pressure testing of 1/4 scale blast walls panels with connections*, Health and Safety Executive Research Report, RR124, Health and Safety Executive, London, UK.

HSE (2006), *Pulse pressure testing 1/4 scale blast wall panels with connections - phase II*, Health Safety Executive Research Report, RR404, Health and Safety Executive, London, UK.

ISO (2000), *ISO 15579 - Metallic materials: Tensile testing at low temperature*, International Organization for Standardization, Geneva, Switzerland.

Langdon, G.S. and Schleyer, G.K. (2005a), "Inelastic deformation and failure of profiled stainless steel blast wall panels. Part I: experimental investigations", *Int. J. Impact Eng.*, **31**(4), 370-399.

Langdon, G.S. and Schleyer, G.K. (2005b), "Inelastic deformation and failure of profiled stainless steel blast wall panels. Part II: analytical modelling considerations", *Int. J. Impact Eng.*, **31**(4), 341-369.

Langdon, G.S. and Schleyer, G.K. (2006), "Inelastic deformation and failure of profiled stainless steel blast wall panels. Part III: finite element simulations and overall summary", *Int. J. Impact Eng.*, **32**(6), 988-1012.

Louca, L.A., Pan, Y.G. and Harding, J.E. (1998), "Response of stiffened and unstiffened plates subjected to blast loading", *Eng. Struct.*, **20**(12), 1079-1086.

LR (2012), *Arctic opening: opportunity and risk in the high north*, Lloyd's Register, London, UK

NORSOK (1999), *Design of steel structures*, Norwegian Standards, Oslo, Norway.

Paik, J.K. (2011), *Explosion and fire engineering of FPSO (Phase III): Nonlinear structural consequence analysis*, Report No. EFEF-04, The Ship and Offshore Research Institute, Pusan National University, Busan, Korea.

Paik, J.K. and Chung, J.Y. (1999), "A basic study on static and dynamic crushing behavior of a stiffened tube", *Tran. Korea Soc. Automobile Eng.*, **7**(1), 219-238. (in Korean)

Paik, J.K. and Czujko, J. (2010), *Explosion and fire engineering of FPSOs (Phase II): Definition of fire and gas explosion design loads*, Report No. EFEF-03, The Ship and Offshore Research Institute, Pusan National University, Busan, Korea.

Park, D.K., Kim, D.K., Jang, B.S, Park, D.H., Kim, D.H., Kim, B.J., Seo, J.K. and Paik, J.K. (2011), "The Effects of low temperature on the material properties and plated structures", *Annual Spring Meeting of The Society of Naval Architects of Korea*, Busan, Korea, June. (in Korean)

Schleyer, G.K., Kewaisy, T.H., Wesevich, J.W. and Langdon, G.S. (2006), "Validated finite element analysis model of blast wall panels under shock pressure loading", *J. Ship Offshore Struct.*, **1**(3), 257-271.

Schleyer, G.K., Langdon, G.S., Martland, R., Lowak, M. and Polcyn, M. (2003), "Pulse pressure testing of 1/4 scaled steel blast panels", *Proceedings of 12th Major Hazards offshore Conference*, ERA Technology, London, UK, December.