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Response of Vertical Wall Structures under Blast Loading by Dynamic Analysis

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Abstract

This paper studies the dynamic response of vertical wall structures under blast loading. Blast loading is simulated by the form of dynamic excitation in time based on some assumptions to assure physical nature of dynamic problems. The vertical wall structure is modelled by plates restrained in an edge and fixed in four edges is surveyed both linear and nonlinear response under explosion. The nonlinear dynamic analysis is considered with cracked behavior of the plate. The governing equation of motion of the structure is established by Finite Element Method with quadrilateral 4 nodes elements and integrated by constant acceleration method of Newmark's family. BLASTSHELL program which analyzed the behavior of shell under blast loading is built on MATLAB software. The numerical results show that the effect of damping ratio, location and pressure of blast loading is sensitive to response of the wall structure. Conclusions have practical applications in design of protective buildings in both civil and defense areas.

Keywords: Dynamic analysis, Wall structure, Plate, Blast loading.

1. INTRODUCTION

Research has been undertaken over the past half a century on the modelling of blast pressure on objects and structures (Brode 1955; Henrych 1979; Smith 1994). The recommended expressions for the blast generated maximum (peak) static over-pressure enable predictions to be made in the open field for any given stand-off distance and blast load expressed in terms of TNT equivalence. The reflected over-pressure resulted from interaction of the blast wave with a stationary target surface has also been modelled (Smith 1994). Each rectangular wall is treated as a single degree of freedom system in the

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dynamic analyses (Lam, Mendis and Ngo 2004). The analysis and design of structures subjected to blast loads require a detailed understanding of blast phenomena and the dynamic response of various structural elements.

The objective of this paper is to determine the dynamic response of the vertical wall structures due to blast loading. The pressure of the explosion is approximated as the negative exponential form in time. The structure is idealized as multi degrees of freedom system and governing equation of motion can be established by finite element method and balance of a forces. The nonlinear dynamic analysis is considered with cracked behavior of the plate when the maximum moment of elastic plate element equals the critical moment.

2. FORMULATION

2.1. Blast pressure

To simplify the analysis, a number of assumptions related to the response of structures and the loads has been proposed and widely accepted as follows: the form of wave is the common "hemispherical" blast scenarios; explosions are "far enough" to ensure the physical root of dynamic analysis. Estimations of peak overpressure due to spherical blast based on scaled distance $Z = R/W^{1/3}$ is introduced as (Brode 1955)

$$p_s = \frac{670}{Z^3} + 100 \, \text{kPa} \, (p_s > 1000 \, \text{kPa});$$

$$p_s = \frac{97.5}{Z} + \frac{145.5}{Z^2} + \frac{585}{Z^3} - 1.9 \, \text{kPa} \, (10 < p_s < 1000 \, \text{kPa}) \tag{1}$$

where R is the stand-off distance in metres; W is the charge weight of the blast in kg based on TNT equivalence. Transformation of this pressure is approximated as the negative exponential form as follows (Bulson 1997)

$$p(t) = p_0 + p_s \left(1 - \frac{t}{T_s}\right) \exp\left(-\gamma \frac{t}{T_s}\right) \tag{2}$$

where $p(t)$ is the pressure in time; γ is the parameter controlling the rate of wave amplitude decay; T_s is the time which the pressure can return to atmospheric pressure $p_o = 101$ kPa. The parameters γ and T_s are defined as (Lam 2004) and (Smith 1994)

$$\gamma = Z^2 - 3.7Z + 4.2 \qquad T_s = W^{1/3} 10^{\left[-2.75 + 0.27 \log\left(\frac{R}{W^{1/3}}\right)\right]} \tag{3}$$

The coefficient for the reflected over-pressure C_r is approximated by (Lam 2004)

$$C_r = 3\left(\sqrt[4]{\frac{P_{s\max}}{101}}\right) \qquad P_{s\max} \text{ - the peak static pressure in unit of kPa} \tag{4}$$

Refer to (2), the blast pressure expression is rewritten to C_r as

$$p(t) = p_0 + C_r p_s \left(1 - \frac{t}{T_s}\right) \exp\left(-\gamma \frac{t}{T_s}\right) \tag{5}$$

2.2. Models of wall structures and material

The vertical wall of H_0 high by B_0 wide and thk thickness is subjected by blast pressure functions defined. They are divided by $m \times n$ elements ($B_0 = mB$ and $H_0 = mH$).
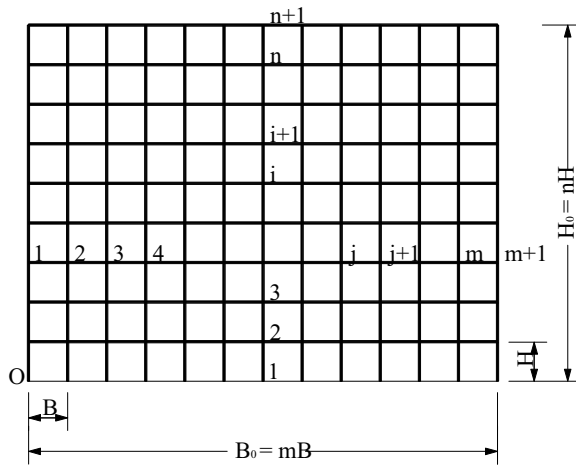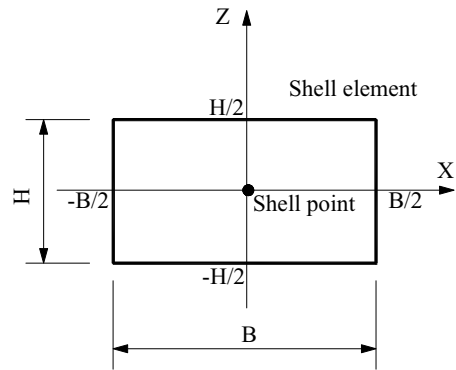

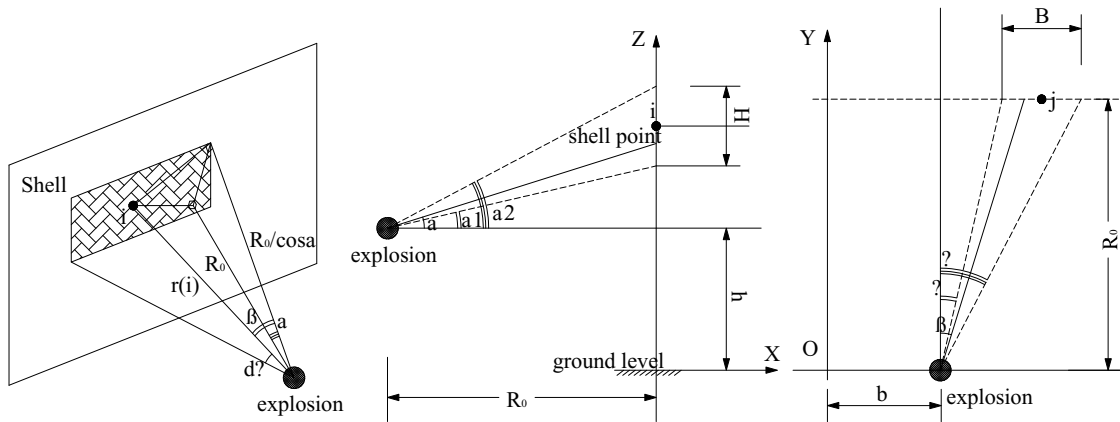Figure 1: Mesh areas

Figure 2: Shell element

Figure 3: Determine distance $r(i)$ and angle α and β

Blast loading on each node i, j of the plate is given as

$$P_{ni,mj} = \int_{\alpha_i}^{\alpha_j} \int_{\beta_i}^{\beta_j} p(t) d\alpha d\beta \tag{6}$$

The bending rectangular shell element has 12 degrees of freedom on the local axis system xyz as Figure 4.
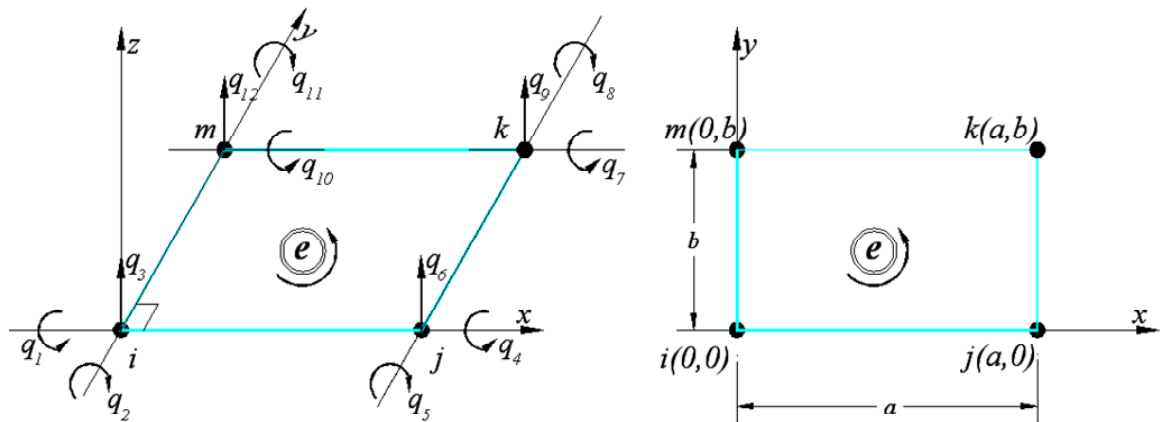

Figure 4: The degree of freedom of the bending rectangular shell element

Figure 4: The degree of freedom of the bending rectangular shell element

The parameters of this model for response of walls have been established (Nguyen and Tran 2009). The equation of deflection $w(x, y)$, displacement vector of the bending rectangular shell element q_e, the stiffness matrix of rectangular shell element (12x12) $[K]_e$, the mass matrix $[M]_e$, strain matrix $[B]$ are also derived. The damping matrix Rayleigh $[C] = \alpha[M] + \beta[K]$ can be applied in these problems. Finally, the constant acceleration method of Newmark is used for integrating the equation (Nguyen 2008). The material property is shown in Figure 5 to apply in the analysis. The maximum moment M_{max} of elastic plate element is solved. It is easy to determine the critical moment M_{cr} of the reinforcement concrete shell element. BLASTSHELL program in Figure 6 which analyzed the dynamic behavior of shell under blast loading is built on MATLAB software.
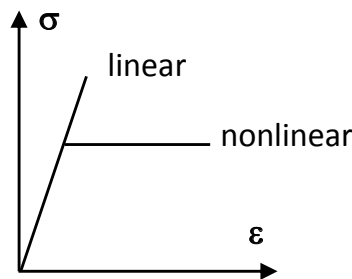

Figure 5: Material model

3. NUMERICAL RESULTS

Vertical walls of $H_0 = 3000mm$ high by $B_0 = 1000mm$ with various thicknesses are divided by $m \times n = 16 \times 16$ elements with fixed in four edges in Figure 7 and restrained in an edge in Figure 8.
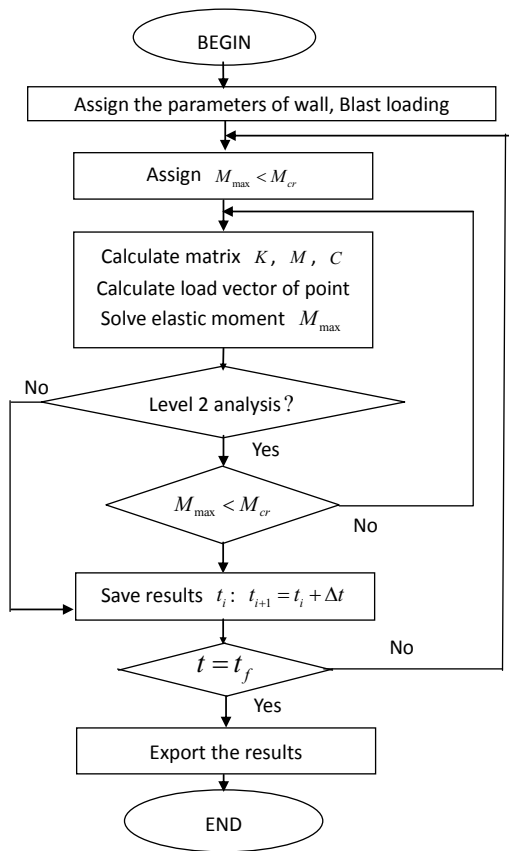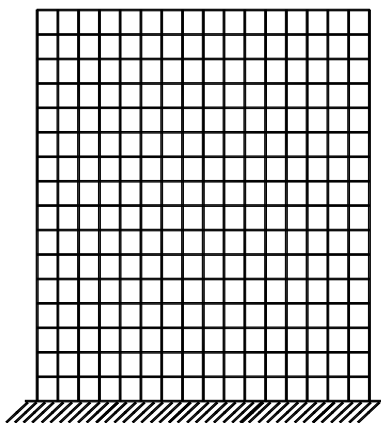
Figure 6: Algorithm chart
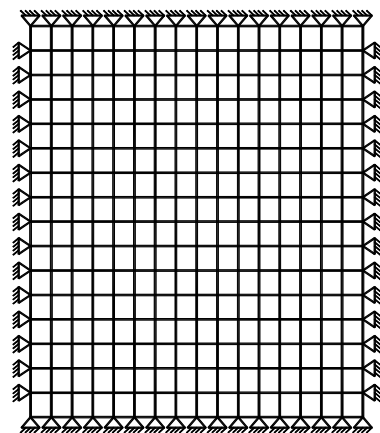

Figure 7: Plate restrained in an edge

Figure 8: Plate fixed in four edges

3.1. The static and free vibration analysis

The reliability of BLASTSHELL program is verified by SAP2000 software in static analysis and eigenvalue analysis. Table 1 presents the comparison of peak displacement of wall panels restrained in an edge due to a static load 1 kN at the top wall. Relative errors of peak displacement from the BLASTSHELL and SAP2000 are very small. It reveals the accuracy of BLASTSHELL program. The natural periods of first and second modes of the structures are expressed in Table 2. Relative errors of the natural periods are negligible when meshing area is smooth.

Table 1: Results of static analysis

Wall Dimension (mm)	Mesh area	Horizontal disp. of top point of wall (cm)		Relative Error (%)
		BLASTSHELL	SAP2000	
1000x3000x100	8x8	0.124994	0.12503	0.0288
	16x16	0.437210	0.43725	0.0091
	32x32	1.630850	1.63082	0.0018
1000x3000x150	8x8	0.037035	0.03704	0.0130
	16x16	0.129544	0.12956	0.0123
	32x32	0.483216	0.48321	0.0012
1000x3000x200	8x8	0.015624	0.01563	0.0371
	16x16	0.054651	0.05466	0.0157
	32x32	0.203857	0.20385	0.0034
1000x 3000x250	8x8	0.007999	0.00800	0.0050
	16x16	0.027982	0.02798	0.0054
	32x32	0.104375	0.10437	0.0048

Table 2: Results of free vibration analysis

Mesh area	Period (s)	BLASTSHELL	SAP2000	Relative Error (%)
4x4	T_1	0.17000	0.17490	2.80
	T_2	0.02712	0.02980	8.99
6x6	T_1	0.17008	0.17220	1.23
	T_2	0.02718	0.02840	4.31
8x8	T_1	0.17011	0.17140	0.75
	T_2	0.02719	0.02780	2.19
12x12	T_1	0.17013	0.17069	0.33
	T_2	0.02720	0.02747	0.97
16x16	T_1	0.17014	0.17046	0.19
	T_2	0.02721	0.02734	0.49
32x32	T_1	0.17015	0.17022	0.04
	T_2	0.02721	0.02722	0.04

3.2. The dynamic analysis

The dynamic response of vertical wall structures due to blast loading is solved by BLASTSHELL program. The parameters of blast loading consist of $R_0 = 10$ m, $W = 625$ kg, $h = 1.5$ m, $b = 0.5$ m and the structure is given as: thickness of wall of 100mm, grid lines $m \times n = 16 \times 16$, plates restrained in an

edge with time step $\Delta t = 0.001$ s. The variation of blast loading is plotted in Figure 9 and peak displacement is also expressed in Figure 10.
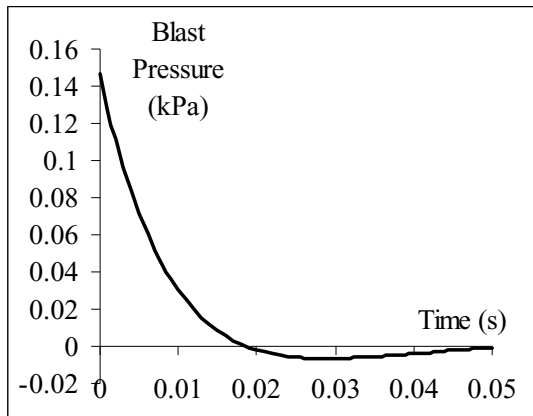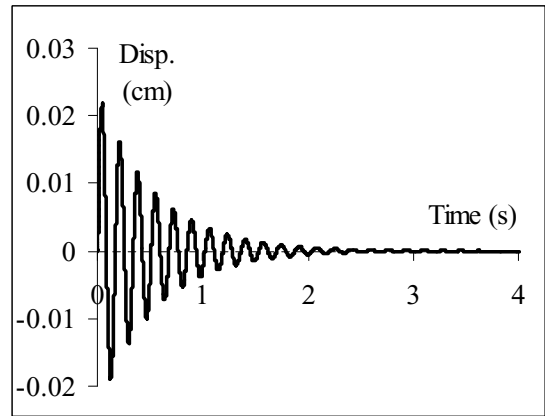

Figure 9: Variation of blast loading

Figure 10: Time history of peak displacement

3.3. . Influence of parameters

In this section, the influence of the parameters of the plate restrained in an edge to dynamic response is considered. The parameters consist of damping ratio ξ, thickness of plate, distance from explosive to ground h, distance from explosive to center point of plate R_0, and explosive mass W. The numerical results are shown in following Figures from 11 to 16.

In Figure 11, the effect of damping ratio is negligible. When the thickness of plate is increased steadily, displacement is dropping slowly in Figure 12. Dynamic response of structures linearly varies explosive mass as figure 16. In Figures 13, 14, and 15, the effect of location of explosive is sensitive to displacement of the plate. All Figures show that displacement of wall structures in the case elasto plastic behaviour are higher than elastic one about 30 - 40 percents.
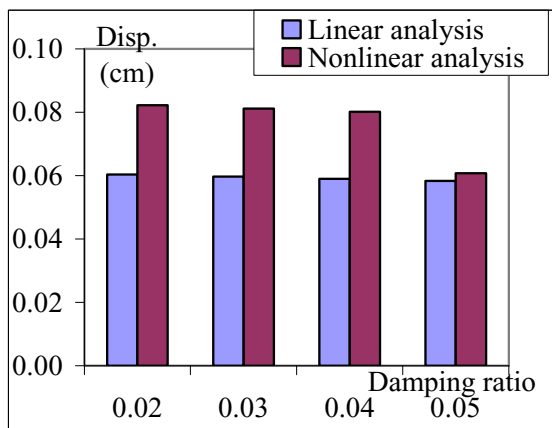

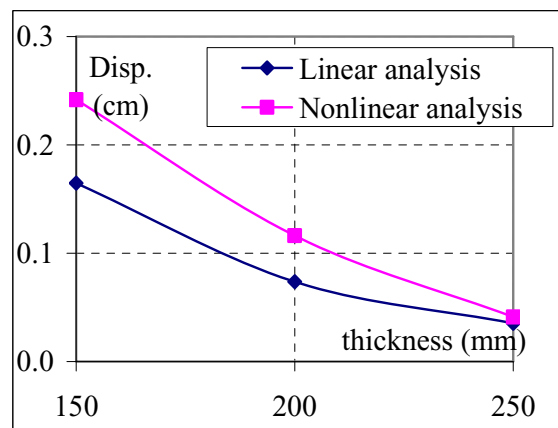Figure 11: Influence of damping ratio
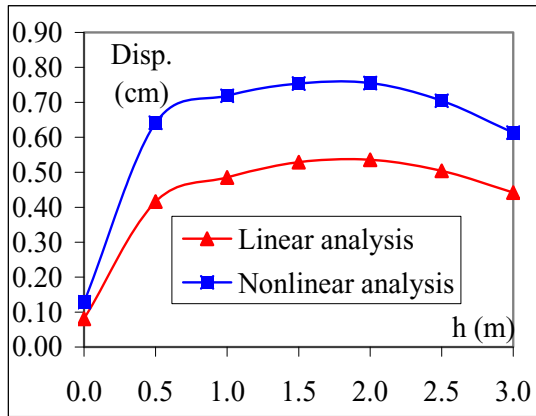

Figure 12: Influence of thickness
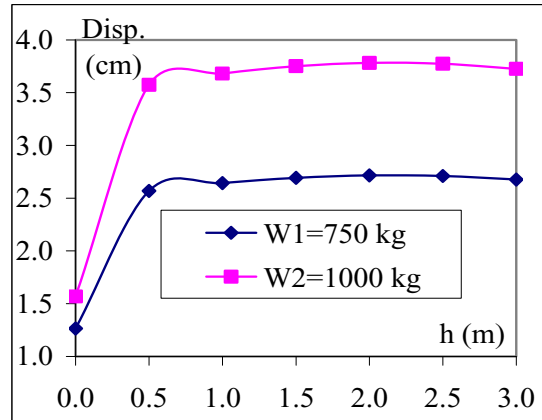
Figure 13: Influence of distance *h*
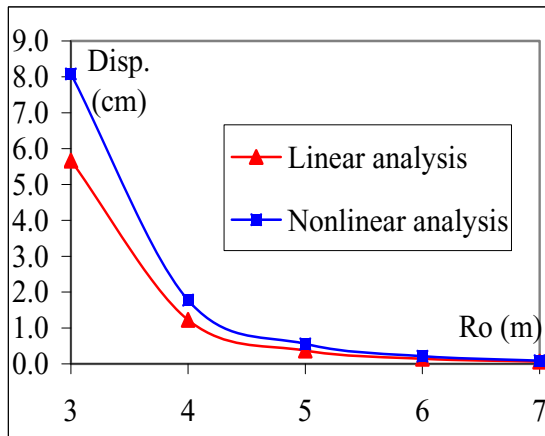
Figure 14: Influence of distance *h*

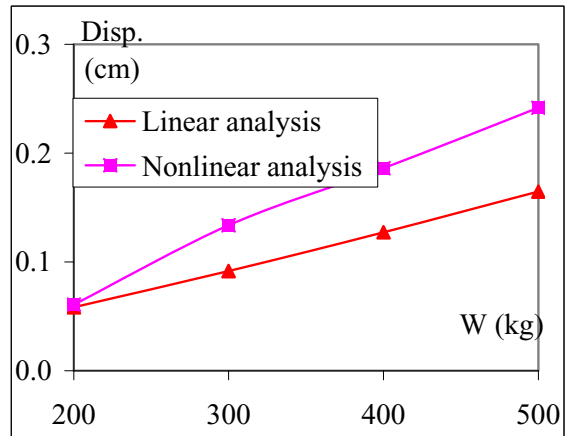Figure 15: Influence of distance *R₀*

Figure 16: Influence of mass *W*

4. CONCLUSIONS

The problem of vertical wall structures with various boundary conditions due to blast loading simulated by negative exponential function and elasto - plastic model of material has been analysed. The BLASTSHELL program is helpful for the needs of design work. The results show that the effect of loacation of explosive as stand-off distance, high and volume of TNT is sensitive to dynamic responses of wall structures.

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