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
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)

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

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

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)

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

where $p(t)$ is the pressure in time; $\gamma$ 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 $\gamma$ and $T_s$ are defined as (Lam 2004) and (Smith 1994)

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

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

$$C_r = 3 \left(\frac{p_{r_{\text{max}}}}{101}\right) \quad P_s_{\text{max}} - \text{the peak static pressure in unit of kPa} \quad (4)$$

Refer to (2), the blast pressure expression is rewritten to $C_r$ as
\[ p(t) = p_0 + C_r p_s \left( 1 - \frac{t}{T_s} \right) \exp \left( -\gamma \frac{t}{T_s} \right) \]  \hfill (5)

2.2. Models of wall structures and material

The vertical wall of \( H_0 \) high by \( B_0 \) wide and \( \text{thk} \) 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](image1)

![Figure 2: Shell element](image2)

![Figure 3: Determine distance \( r(i) \) and angle \( \alpha \) and \( \beta \)](image3)

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

\[ P_{n,i,j} = \int_{\alpha_i}^{\alpha_j} \int_{\beta_i}^{\beta_j} p(t) \, d\alpha \, d\beta \]  \hfill (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](image)

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 $(12 \times 12) [K]^e$, 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 $M_{\text{max}}$ of elastic plate element is solved. It is easy to determine the critical moment $M_{\sigma}$ 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](image)

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.
BEGIN

Assign the parameters of wall, Blast loading

Assign $M_{\text{max}} < M_c$

Calculate matrix $K$, $M$, $C$
Calculate load vector of point
Solve elastic moment $M_{\text{max}}$

Level 2 analysis?

Yes

$M_{\text{max}} < M_c$

No

Save results $t_i$: $t_{i+1} = t_i + \Delta t$

$t = t_f$

No

Yes

Export the results

END

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

<table>
<thead>
<tr>
<th>Wall Dimension (mm)</th>
<th>Mesh area</th>
<th>Horizontal disp. of top point of wall (cm)</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000x3000x100</td>
<td>8x8</td>
<td>0.124994</td>
<td>0.0288</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>0.437210</td>
<td>0.0091</td>
</tr>
<tr>
<td></td>
<td>32x32</td>
<td>1.630850</td>
<td>0.0018</td>
</tr>
<tr>
<td>1000x3000x150</td>
<td>8x8</td>
<td>0.037035</td>
<td>0.0130</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>0.129544</td>
<td>0.0123</td>
</tr>
<tr>
<td></td>
<td>32x32</td>
<td>0.483216</td>
<td>0.0012</td>
</tr>
<tr>
<td>1000x3000x200</td>
<td>8x8</td>
<td>0.015624</td>
<td>0.0371</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>0.054651</td>
<td>0.0157</td>
</tr>
<tr>
<td></td>
<td>32x32</td>
<td>0.203857</td>
<td>0.0034</td>
</tr>
<tr>
<td>1000x3000x250</td>
<td>8x8</td>
<td>0.007999</td>
<td>0.0050</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>0.027982</td>
<td>0.0054</td>
</tr>
<tr>
<td></td>
<td>32x32</td>
<td>0.104375</td>
<td>0.0048</td>
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</table>

Table 2: Results of free vibration analysis

<table>
<thead>
<tr>
<th>Mesh area</th>
<th>Period (s)</th>
<th>BLASTSHELL</th>
<th>SAP2000</th>
<th>Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4x4</td>
<td>T₁</td>
<td>0.17000</td>
<td>0.17490</td>
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</tr>
<tr>
<td></td>
<td>T₂</td>
<td>0.02712</td>
<td>0.02980</td>
<td>8.99</td>
</tr>
<tr>
<td>6x6</td>
<td>T₁</td>
<td>0.17008</td>
<td>0.17220</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td>T₂</td>
<td>0.02718</td>
<td>0.02840</td>
<td>4.31</td>
</tr>
<tr>
<td>8x8</td>
<td>T₁</td>
<td>0.17011</td>
<td>0.17140</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>T₂</td>
<td>0.02719</td>
<td>0.02780</td>
<td>2.19</td>
</tr>
<tr>
<td>12x12</td>
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<td>0.17013</td>
<td>0.17069</td>
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<tr>
<td></td>
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<td>0.02720</td>
<td>0.02747</td>
<td>0.97</td>
</tr>
<tr>
<td>16x16</td>
<td>T₁</td>
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<td>0.17046</td>
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<td>0.17022</td>
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</tr>
<tr>
<td></td>
<td>T₂</td>
<td>0.02721</td>
<td>0.02722</td>
<td>0.04</td>
</tr>
</tbody>
</table>

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 consists 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](image1)

![Figure 10: Time history of peak displacement](image2)

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 $\xi$, 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](image3)

![Figure 12: Influence of thickness](image4)
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 location of explosive as stand-off distance, high and volume of TNT is sensitive to dynamic responses of wall structures.

REFERENCES


