Out of Plane Behavior of Reinforced Wall under Blast Loading

by

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Abstract

This paper aims to study the out of plane behavior of a vertical reinforced wall subjected to dynamic blast loading. The reinforced concrete wall is modeled using finite element method with appropriate boundary conditions. A tool was developed to implement the finite element method for a reinforced wall in MATLAB. 3D modeling of reinforced wall is done using 20-noded or 8-noded brick elements. Considering Rayleigh damping, the dynamic equilibrium equations are solved using Gaussian quadrature and Newmark's direct integration scheme. The tool was used to analyze the behavior of reinforced walls under varying percentage steel, damping ratio, standoff distance, reinforcement diameter, charge weight, etc.

1. Introduction

In the recent past, there have been many terrorist and accidental explosions in the world that not only affects the normal human life, but also affects the structural integrity and its performance and resistance to withstand any further damage. Thus, it is important to design a structure taking into consideration the effects of such conditions. It might not be possible to design a structure to sustain a terrorist threat, but it is possible to improve the performance of the structural system by better studying the factor contributing to the resistance offered by structure under such loading conditions.

In case of such incidents, walls are the first structural element exposed to blast loading. Thus they become crucial to mitigate the effects of explosions. Mays et al. [1] studied the blast load effects on concrete wall panels with openings. Olson [2], Yuan and Tan [3] studied the plastic deformation steel plates due to blast loads.

Ngo and Mandis et al. [4] compiled various methods which could be used to estimate blast pressure and predict structural response due to such loading. In the study, effect of blast load on a RC column, building façade and progressive collapse was analyzed. Concluding that the guidelines on blast load cases and provisions on progressive collapse prevention should be included in the building codes.

Luccioni et al. [5] analyzed the behavior of concrete pavement slab under air blast load occurring above it. Experimental analysis was carried out for the study. Comparison of the experimental results was done with numerical modeling using finite element program and the authors concluded that the explicit dynamic analysis approximately reproduced the experimental results. Ganchai et al. [6] carried out an experimental analysis on RC slab under blast loading. Numerical analysis of deflection of slab was carried out in LS-DYNA and the results were approximately matching. Nash et al. [7] studied and predicted spallation occurring in concrete wall using one-dimensional model under blast loading.

Jacinto et al. [8] did experimental analysis on steel plates subjected to blast loading. In the study experimental results were compared with numerical modeling done using finite element program ABAQUS. It was found in the study that blast loads excites higher frequencies.

El Sayed et al. [9] experimentally evaluated the out of plane response of concrete block wall subjected to blast loading. Different wall parameters were used along with 3 different charge weights to cover different threat scenarios. It was concluded that the damage with sanding capacity of wall depends on the reinforcement ratio and scaled distance of the explosion.

Nguyen and Tran [10] worked on studying the dynamic response of vertical walls under blast loading. In the analysis wall was modeled as a plate restrained at an edge and fixed from all sides to carry out the dynamic analysis. BLASTSHELL program was created to analyze the behavior of the wall. The governing equation of motion of the structure was established by finite element method with quadrilateral 4 nodes element and integrated by
constant acceleration method of Newmark's family. The study showed the influence of damping ratio, thickness, standoff distance on the wall.

To study the exact effect of blast loading on any structure, it requires studying the interaction of liquids and gases with structural surfaces applied to proper boundary conditions. Such study is computationally very expensive, requiring huge amount of resources and time to get results. So in this study, we use finite element modeling to get approximate results with acceptable accuracy in a rather short amount of time.

As part of this research, a tool was developed to implement finite element method for a reinforced wall in MATLAB. 3D modeling of reinforced wall is done using 20-noded or 8-noded brick elements. Meshing is done accordingly to give global connectivity and coordinate matrix. Gaussian quadrature is used for numerical integration with 2 or 3 sampling points. Using Gaussian quadrature, element stiffness matrices are calculated for each distinct element. These element stiffness matrices are then assembled globally to get a global stiffness matrix. In similar manner global mass matrix and damping matrix (using Rayleigh damping) are calculated. Global mass, stiffness and damping matrices are all sparse matrices. To calculate the response under dynamic loading Newmark's direct integration scheme is used. The code is optimized to give comparable runtime with any other finite element software. The results from the tool is validated and used in the study.

In case of blast loading over pressure is created which acts in the transverse direction to the incident surface, making it important to analyze the out of plane behavior of the structure. The aim of this work is to study the behavior of a vertical reinforced wall subjected to transverse blast loading using the finite element tool. The behavior of the wall was analyzed by studying the effects of different parameters like increasing percentage steel, damping ratio, standoff distance, charge weight, etc. on the maximum out of plane displacement of RC wall.

2. Blast Phenomenon

In case of an explosion, large amount of energy is released in a short duration (in milliseconds) creating spherical blast wave fronts in its surroundings termed as shock or blast waves. In a detonation, reaction occurs at speed greater than the speed of sound or at supersonic speed towards un-reacted material. Shock waves are generated during a detonation and they propagate at supersonic speed. The Figure 1 shows the pressure time history at a point in the region of the explosion. As it can be seen there is an instantaneous rise in pressure as shock waves hit an object and then rapid decay occurs.

As the wave front moves forward, the over pressure reduces and after one point the interior pressure goes below ambient pressure causing a net negative over pressure in that region. Over-expansion at the center of blast creates a vacuum in the source region and there is a reversal of gas motion. Figure 2 shows the variation of over pressure measured at different times. It shows the drop in pressure with increase in time which reduces below atmospheric pressure and time tₚ creating negative pressure in interior region.

In the event of an explosion over earth’s surface, shock waves travel outwards in spherical wave front. When these blast wave front strikes the earth surface, they are reflected back. This phenomenon is similar to sound wave propagation where echo are produced in similar manner. This reflected wave is capable of causing material damage just like the direct wave. The reflected wave front moves at faster speed than the incident wave front because of the decreased density of interior region of the incident shock front. The reflected wave travels through air which has been heated up and compressed because of the passing direct wave through it so as a result, reflected wave fronts travel faster than the incident wave fronts.
At certain position these two wave fronts, i.e., the direct and reflected wave front merges. This depends on various factors like the explosive charge weight, the distance between the ground and point of explosion, etc. This merging phenomenon is termed as Mach effect. These two wave fronts merge to form a single wave or Mach Stem. Since reflected wave travels at a faster speed, the length of Mach stem increases or the triple point continuously rises upwards as the reflected wave reaches further. For the purpose of this study we just consider the effects of surface blasts on the subjected RC wall.

2.1 Blast Wave Reflection

When the blast wave hits an object, it is reflected back and the pressure noted at any point in front of the reflecting surface is increased. In an ideal scenario the pressure felt should be same but in case of explosion, nonlinear shock waves push the air particle in front of them, which in turn obstructs them during reflection leading to significantly higher overpressure in that region. At a point before the reflecting surface, two separate shocks will be felt. The first shock is felt because of incident shock wave and the other shock is felt because of the reflected wave. The overpressure due to reflected wave is more than the incident wave and it depends on several factors like the geometry of explosive, its weight, distance from ground zero, structure shape, etc.

2.2 Scaling Laws

It has been seen that data of one explosion can be applied to another explosion of similar geometry and in similar environments. So using experimental data, numerical models are compiled which are used to predict blast parameters for different combination of charge weight and standoff distance. Scaling laws provide parametric correlations between a particular explosion and a standard charge of the same substance; it can be extended to other explosives using TNT equivalence.

Scaling laws proposed by Hopkinson [11] and Cranz [12] is widely accepted and is also termed as the cube root scaling. It is based on the theory that two charge weights of similar geometry and under similar environment, with different charge weights will produce almost similar blast waves at an equal scaled distance. According to this, if \( R \) is the distance of the point of interest from a reference explosion of charge weight \( W \), then for any other explosion of charge weight \( W' \), similar blast parameters will be noted at a scaled distance \( R \) is given by:

\[
\frac{R}{W^{1/3}} = \frac{R_1}{W_1^{1/3}}
\]

In general, scaled distance is used to predict different blast wave parameters, is simply given by:

\[
Z = \frac{R}{W^{1/3}}
\]

where \( R \) is the standoff distance and \( W \) is charge weight.

3. Predicting Blast Wave Parameters

Simplified blast load prediction involves usage of several blast parameters. These blast parameters include peak overpressure or side-on pressure, reflected pressure, dynamic pressure, total positive duration, and velocity of sound. The following sections present several empirical relations widely used to predict all these blast parameters.

In the past few decades, a significant amount of data has been published leading to generation of various empirical equations relating different blast wave parameters with scaled distance or charge weight and standoff distance. These empirical methods to predict the blast parameters consists of published equations, graphs, tables that allow one to determine the principal loading of a blast wave on a building or a similar structure. It is convenient to use these methods over comprehensive methods, such as computational fluid dynamics which requires particular software, weeks of work and verifications.

3.1. Peak overpressure

Kinney and Graham [13] using large amount of chemical type explosion data formulated following equation to predict the peak positive overpressure:

\[
P_{o_{max}} = P_0 \frac{808}{\left[ 1 + \left( \frac{Z}{4.5} \right)^2 \right]^{1/2} \left[ 1 + \left( \frac{Z}{0.48} \right)^2 \right]^{1/2} \left[ 1 + \left( \frac{Z}{0.32} \right)^2 \right]^{1/2} \left[ 1 + \left( \frac{Z}{1.35} \right)^2 \right]^{1/2}}
\]

where \( P_0 \) is the ambient pressure in bars, \( Z \) is scaled distance in m/kg\(^{1/3} \) and \( P_{o_{max}} \) is the peak overpressure in bars.

Another widely used relationship was proposed by Newmark and Hansen [14] to predict maximum overpressure in bars, for a high explosive ground burst:

\[
P_{o_{max}} = 6784 \frac{W}{R^3} + 93 \frac{W}{R^5}
\]
where $P_o$ is in bars, $W$ is the charge weight in ton of TNT and $R$ is distance in m.

Hopkins-Brown and Bailey [15] proposed the following equations:

$$P_{so} = -12.45 + \frac{19.35}{Z} + \frac{2.353}{Z^2} - \frac{0.1065}{Z^3} \quad (0.05 \leq Z \leq 1.15)$$

$$P_{so} = \frac{0.707}{Z} + \frac{3.602}{Z^2} - \frac{4.891}{Z^3} \quad (1.15 < Z \leq 40)$$

where $P_{so}$ is in bars and $Z$ is the scaled distance in m/kg$^{1/3}$.

Kingery and Bulmash [11] equations are widely used to predict blast parameters. The primarily used Unified Facilities Criteria (UFC 3-340-02) (2008)[] contains blast wave parameter curves developed by Kingery and Bulmash. Swisdak (1994)[] proposed simplified Kingery equations with average error of less than 1%. Following is the standard polynomial equation used by Swisdak and it is also used for different blast wave parameters prediction:

$$F(Z) = \exp\left(A + B \ln Z + C \ln Z^2 + D \ln Z^3 + \frac{E}{Z} \ln Z^4 + F \ln Z^5 + G \ln Z^6\right)$$

Table 1 shows the constants values for peak overpressure calculation in kPa

### 3.2. Dynamic pressure

The dynamic pressure equation proposed by Newmark[14] is:

$$q = P_o \left(\frac{5P_o}{2(P_o + 7P_s)}\right)$$

where $P_o$ is the peak side-on pressure in bars, $P_s$ is ambient pressure.

### 3.3. Positive Phase Duration

Table 2 provides the constants for polynomial of positive phase duration for Simplified Kingery equations.

<table>
<thead>
<tr>
<th>Z(m/kg$^{1/3}$)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2-1.02</td>
<td>0.5426</td>
<td>3.2299</td>
<td>-1.5931</td>
<td>-5.9667</td>
<td>-4.0815</td>
<td>-0.9149</td>
<td>0</td>
</tr>
<tr>
<td>1.02-2.8</td>
<td>0.5440</td>
<td>2.7082</td>
<td>-9.7354</td>
<td>14.3425</td>
<td>-9.7791</td>
<td>2.8535</td>
<td>0</td>
</tr>
<tr>
<td>2.8-40</td>
<td>-2.4608</td>
<td>7.1639</td>
<td>-5.6215</td>
<td>2.2711</td>
<td>-0.44994</td>
<td>0.03486</td>
<td>0</td>
</tr>
</tbody>
</table>

3.4. Reflected Overpressure

Newmark [14] proposed the following equation for reflected overpressure:

$$P_r = P_{so} \left(\frac{2 + 6P_{so}}{P_{so} + 7P_o}\right) \quad (P_{so} < 10 \text{ bar})$$

$$P_r = P_{so}(4\log P_{so} + 1.5) \quad (P_{so} > 10 \text{ bar})$$

where $P_{so}$ is the peak side-on pressure in bars, $P_o$ is ambient pressure.

It can be seen from the above equation that the reflected overpressure value can approach up to 8 times the maximum side on pressure (theoretically for zero atmospheric pressure) and it is always more than twice the side-on pressure.

Table 3 provides the constant values for reflected overpressure using simplified kingery equations.
Table 3. Constants for polynomial of reflected overpressure for Simplified Kingery equations

<table>
<thead>
<tr>
<th>Z(μy/kg²)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06-2</td>
<td>9.006</td>
<td>-2.6893</td>
<td>-0.6295</td>
<td>0.1011</td>
<td>0.29255</td>
<td>0.13505</td>
<td>0.019736</td>
</tr>
<tr>
<td>2-40</td>
<td>8.8396</td>
<td>-1.733</td>
<td>-2.64</td>
<td>2.293</td>
<td>-0.8232</td>
<td>0.14247</td>
<td>-0.0099</td>
</tr>
</tbody>
</table>

3.5. Front Wall Load

Reflection occurs at the front wall which is facing the point of explosion. As shown in reflected overpressure equations, reflection effect amplifies the blast pressure acting on the front facing side of the building. The reflected overpressure dies out further in time because the overpressure at the top and side edges of the front wall is less than the reflected overpressure thus causing decay in the reflection which starts from the edges and it moves inward. Due to this phenomenon the reflected pressure vanishes and only side-on pressure and dynamic pressure acts on the front face. Reflected pressure is completely removed in clearing time, tC. The clearing time is a function of the height, width of the front wall and velocity of sound in the medium. As per UFC 3-340-02[17] clearing time is given by eq. 10.

\[
t_c = \frac{4 \cdot S}{(1 + \frac{S}{G})} C_r = \frac{4 \cdot S \cdot G}{S + G} C_r
\]

where \( S \) is the minimum of height or width of the building, \( G \) is the maximum of height or width of the building, and \( C_r \) is the velocity of sound in the medium given by UFC 3-340-02.

Figure 3 shows an equivalent triangular pulse which can be assumed to act on the front wall. Here the reflected pressure stays till the clearing time, then the combination of side-on and dynamic pressure multiplied by the drag coefficient (Taking equal to 1.0 for this study) prevails till the end of the positive phase. Using the basic straight line assumption we can formulate the following equation for equivalent loading and its duration:

\[
P_e = P_{so} + C_d \cdot q
\]

\[
t_e = \frac{(P_{so} - P_t) \cdot t_t + P_t \cdot t_t}{P_t}
\]

where \( P_{so} \) is the net overpressure includes side-on \( P_{so} \) and dynamic pressure \( q \), \( t_t \) is the total clearing time calculated using equation , \( t_t \) is the total positive phase duration, \( P_t \) is the peak reflected pressure, \( t_c \) is the equivalent time duration for the equivalent triangular pulse.

4. Finite Element Modeling

A finite element tool was created for this study and it is written in MATLAB. The tool is optimized to run comparable with other finite element software. The finite element analysis followed in the MATLAB tool can be broken down into these three stages/steps:

4.1. Pre-processing

During the pre-processing stage all the input, which includes loads, boundary condition, material properties, dimensions, etc. are collected and defined. It is followed by generating a simple model by considering the inputs like the wall dimensions, loads, etc. Then suitable element type is chosen for the problem (8-node or 20-node hexahedral element). Concrete and steel both are modeled together as 3D brick elements. As per the input dimension and element type, a suitable fine mesh is generated. Mesh is generated in a way that it is sparse near reinforcements and coarse in between. Meshing returns a global coordinate and connectivity matrices containing all the necessary information about the elements created in the process. In pre-processing stage,boundary conditions are also defined along with calculation of load vector based on charge weight and standoff distance of a surface blast.

4.2. Solution

The solution phase consists of deriving the governing global matrices i.e., global mass, global stiffness, global damping and load matrices. Global stiffness matrix is a sparse matrix calculated by assembling element
stiffness matrices. Figure 4 shows the flowchart for global stiffness matrix calculation. Initially, based on element properties like dimensions, modulus of elasticity and Poisson’s ratio, unique elements are compiled. Since element stiffness matrix depends only on these factors, we avoid redundant calculation of such matrices by using calculations of unique matrices.

Shape function is defined based on the selected element type. Jacobian matrix is calculated by differentiating the shape function with respect to the intrinsic coordinate system. Using Jacobian matrix, strain matrix is calculated which then is used to calculate element stiffness matrix using following equation:

\[ K_{element} = \int B^T D B \, dv \]  \hspace{1cm} (12)

This integral over the volume of element is carried out using Gauss quadrature, 3 sampling point integral scheme for 20-node hexahedral elements and 2 sampling point integral scheme for 8-node hexahedral elements. matplotlib Function is used to get the element stiffness matrix in terms of element Meta data i.e. dimension, modulus of elasticity and Poisson’s ratio. For all the elements, stiffness matrix is calculated by substituting the element Meta data into this function.

Global stiffness matrix is assembled using indices and value triplets. For this sparse(i, j, v) is used which adds together elements if duplicate indices are recorded. Similar to stiffness matrix, mass matrix is calculated and global mass matrix is assembled. Damping matrix is calculated based on Rayleigh damping using equation(13). Rayleigh damping coefficients are calculated using two predominant frequencies.

\[ C = \alpha M + \beta K \]  \hspace{1cm} (13)

Then dynamic equilibrium equations solved using Newmark method. For the purpose of our study we used constant average acceleration method to solve the equilibrium equations, which is an unconditionally stable scheme proposed by Newmark.

\[ M \ddot{u} + C \dot{u} + K u = F_{\text{external}} \]  \hspace{1cm} (14)

Using this equilibrium equation is reduced into a system of linear equations which is solved by Cholesky decomposition. Once the displacement vector is calculated, stresses and strains are calculated using it.

4.3. Post-Processing and Validation

The obtained results during the solution process are represented in some user friendly format like deformed shape, contour, etc. Abaqus was used to validate the results generated by the MATLAB tool which is covered in the results sections.

5. Wall Model

A standard wall with a height of 3m, width of 5m and depth of 220mm was used for this work with presence of horizontal and vertical reinforcements with a diameter of 10mm in most cases. The reinforcement in wall is provided based on IS 456 Clause 32. The minimum requirement for reinforcement in walls is provided in clause-32.5 and the minimum ratio of vertical reinforcement to the gross concrete area shall be 0.0012 for bars with diameter less than 16mm and grade more than or equal to 415 N/mm². The reinforcement is provided with a clear cover of 75 mm as per IS-456 and there is no overlap between two layers of horizontal and
vertical reinforcements. Figure 5 shows a general wall model created in the code with two layers of horizontal and vertical reinforcements with clear cover of 75mm on both sides and 300mm centre to center spacing.

Boundary condition: In the created tool, wall could be modeled with fixidity of any combination of faces of the wall. In most of the study the wall was fixed at the bottom face and the assumed damping ratio value is 0.05.

FE-415 is used for reinforcement and M25 grade of concrete is used for the study with concrete Poisson's ratio equal to 0.18 and that of steel is taken to be 0.3. All the rest of material properties used are mentioned below:

Concrete
- Density = 2.4e-9 Mg/mm³
- Young's modulus = 50000 N/mm²
- Poisson's ratio = 0.18
- Yield strain = 0.002, and Yield stress = 50 N/mm²
- Steel
- Density = 8e-9 Mg/mm³
- Young's modulus = 2e5 N/mm²
- Poisson's ratio = 0.3
- Yield stress = 415 N/mm², and Yield strain = 0.002075

6. Results

6.1. Validation of FEM Program

The created finite element program was validated using Abaqus modeling of the same wall. Dynamic and frequency analysis was carried out for this purpose. Figure 6 shows the response of above mentioned standard wall applied with elcentro ground motion using 8-noded hexahedral elements in the program and C3D8 element without reduced-integration in Abaqus. It can be seen here that there is a considerable difference in both the results. One possible reason for such variation is that this is a bending dominant problem and low order finite element like 8-node hexahedral elements are not rich enough to capture the kinematics of the system. Figure 21 shows one face of our element during bending with 2-point gauss quadrature, and it can be seen that the normal plane doesn't remain normal during bending thus a shear stress is developed in the element to counter this deficit. This is termed as shear locking and because of shear locking the overall structural stiffness is more than the actual value leading to reduced displacement which is evident in the Figure 6.

Most finite element software avoids this type of behavior by using reduced integration, which may lead to hourglass modes. Abaqus uses selective reduced integration for C3D8 element thus it performed better than our MATLAB 8-noded hexahedral elements. Table 4 and Table 5 shows the Eigen values and frequency for top 10 modes of the standard wall while using C3D8 and 8-

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>MATLAB (Eigen values)</th>
<th>Abaqus (Eigen values)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>20732.45</td>
<td>17025.2</td>
<td>21.78</td>
</tr>
<tr>
<td>2.</td>
<td>36102.05</td>
<td>31181.9</td>
<td>15.78</td>
</tr>
<tr>
<td>3.</td>
<td>188329.51</td>
<td>148332</td>
<td>26.96</td>
</tr>
<tr>
<td>4.</td>
<td>771621.44</td>
<td>600316</td>
<td>28.54</td>
</tr>
<tr>
<td>5.</td>
<td>829064.16</td>
<td>659789</td>
<td>25.66</td>
</tr>
<tr>
<td>6.</td>
<td>914744.91</td>
<td>698667</td>
<td>30.93</td>
</tr>
<tr>
<td>7.</td>
<td>1019314.43</td>
<td>755401</td>
<td>34.94</td>
</tr>
<tr>
<td>8.</td>
<td>1367017.9</td>
<td>939584</td>
<td>45.49</td>
</tr>
<tr>
<td>9.</td>
<td>2632509.49</td>
<td>1634740</td>
<td>61.04</td>
</tr>
<tr>
<td>10.</td>
<td>2888608.25</td>
<td>2228730</td>
<td>29.61</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>MATLAB (Frequency)</th>
<th>Abaqus (Frequency)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>22.92</td>
<td>20.77</td>
<td>10.35</td>
</tr>
<tr>
<td>2.</td>
<td>30.24</td>
<td>28.1</td>
<td>7.62</td>
</tr>
<tr>
<td>3.</td>
<td>69.07</td>
<td>61.3</td>
<td>12.68</td>
</tr>
<tr>
<td>4.</td>
<td>139.8</td>
<td>123.31</td>
<td>13.37</td>
</tr>
<tr>
<td>5.</td>
<td>144.92</td>
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<td>12.1</td>
</tr>
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<td>6.</td>
<td>152.22</td>
<td>133.03</td>
<td>14.43</td>
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<tr>
<td>7.</td>
<td>160.68</td>
<td>138.33</td>
<td>16.16</td>
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<tr>
<td>8.</td>
<td>186.08</td>
<td>154.27</td>
<td>20.62</td>
</tr>
<tr>
<td>9.</td>
<td>258.23</td>
<td>203.49</td>
<td>26.9</td>
</tr>
<tr>
<td>10.</td>
<td>270.5</td>
<td>237.6</td>
<td>13.85</td>
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</table>
noded hexahedral elements in Abaqus and Matlab tool respectively. The average error in frequency is almost 14.8% in first ten modes and the eigenvalue average error is 32%.

One possible solution to such situation is to use higher order elements as they can capture the element kinematics more suitably. In higher order elements the number of nodes are higher when compared with lower order elements resulting in increase in total degrees of freedom thus providing better kinematics for each element. So, in our study, we proceeded with using 20-node element, which is a second order element. We presented finite element formulations for 20-node element in previous sections. The computation cost for 20-Node is very high as compared to 8-node element because of increasing degrees of freedom. Following Table 6 and Table 7 shows the comparison of eigen values and frequency of our standard wall when using C3D20 element in Abaqus and 20-Node hexahedral element in Matlab code.

As it is clear from the Table 6 and 7 that using 20-node hexahedral elements in Matlab code, the error recorded is almost negligible. Abaqus and Matlab program results are approximately the same with average error in eigenvalues and frequency less than 1e-5%. This can be attributed to floating point error. One more thing to note here is that Abaqus results using C3D8 element and C3D20 elements are not identical and it is because selective reduced integration is not totally accurate, but it is still a reasonable correction over simple linear hexahedral element solution. As mentioned by Benzley et. al [25] that Quadratic hexahedral elements tends to perform superior to Linear hexahedral elements. So for

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>MATLAB (Eigen values)</th>
<th>Abaqus (Eigen values)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
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<td>-0.00006</td>
</tr>
<tr>
<td>7.</td>
<td>680962.1</td>
<td>680962</td>
<td>0.00002</td>
</tr>
<tr>
<td>8.</td>
<td>757490.4</td>
<td>757490</td>
<td>0.00006</td>
</tr>
<tr>
<td>9.</td>
<td>1137135</td>
<td>1137140</td>
<td>-0.00041</td>
</tr>
<tr>
<td>10.</td>
<td>1354393</td>
<td>1354390</td>
<td>0.00022</td>
</tr>
</tbody>
</table>

Table 7. Frequency comparison of Abaqus and Matlab code using C3D20 and 20-noded hexahedral element

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>MATLAB (Frequency)</th>
<th>Abaqus (Frequency)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>12.95</td>
<td>12.95</td>
<td>0.00001</td>
</tr>
<tr>
<td>2.</td>
<td>22.85</td>
<td>22.85</td>
<td>0.00005</td>
</tr>
<tr>
<td>3.</td>
<td>47.78</td>
<td>47.78</td>
<td>-0.00001</td>
</tr>
<tr>
<td>4.</td>
<td>80.29</td>
<td>80.29</td>
<td>0.00005</td>
</tr>
<tr>
<td>5.</td>
<td>91.98</td>
<td>91.98</td>
<td>-0.00007</td>
</tr>
<tr>
<td>6.</td>
<td>98.32</td>
<td>98.32</td>
<td>-0.00003</td>
</tr>
<tr>
<td>7.</td>
<td>131.34</td>
<td>131.34</td>
<td>0.00001</td>
</tr>
<tr>
<td>8.</td>
<td>138.52</td>
<td>138.52</td>
<td>0.00003</td>
</tr>
<tr>
<td>9.</td>
<td>169.72</td>
<td>169.72</td>
<td>-0.00021</td>
</tr>
<tr>
<td>10.</td>
<td>185.22</td>
<td>185.22</td>
<td>0.00011</td>
</tr>
</tbody>
</table>

further study, we used the 20-Node element for carrying out the finite element analysis.

6.2. Parametric Study

Table 8 shows the combination of charge weight and standoff distance blast used for conducting parametric study of a wall subjected to impulsive loading. The table presents the equivalent pressure and time of triangular pulse as shown in Figure 3, UFC-3-340-02 [17] chart was used for the calculation of equivalent pressure and time based on charge weight, and standoff distance.

The following section covers the parametric study of wall subjected to blast loading. In order to study the out of plane behavior of wall subjected to last loading, effect of damping ratio, diameter of steel bars, percentage of reinforcement on the maximum displacement of a wall fixed at base is presented.

Figure 7, 8 and 9 shows the effect of damping ratio on the maximum displacement for load case 1 to 3. With increase in damping ratio the maximum out of plane displacement is observed to decrease. The normalized displacement plot is shown in Figure 10 which compares all three load cases results shows a decreasing trend for

<table>
<thead>
<tr>
<th>Charge Weight(kg)</th>
<th>Standoff Distance(m)</th>
<th>P&lt;sub&gt;Equivalent&lt;/sub&gt; (MPa)</th>
<th>t&lt;sub&gt;Equivalent&lt;/sub&gt; (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>50</td>
<td>0.04413</td>
<td>17.345</td>
</tr>
<tr>
<td>200</td>
<td>22</td>
<td>0.1724</td>
<td>19.23</td>
</tr>
<tr>
<td>125</td>
<td>20</td>
<td>0.1724</td>
<td>16.91</td>
</tr>
</tbody>
</table>
all 3 load cases. The trend is decreasing because of the dissipation of energy in form of damping energy. A 15% difference is seen in maximum displacement when comparing 0% vs. 20% damping. While just 5% of difference is seen if comparing 0 vs. 0.05 damping ratio values. Figure 11, 12 and 13 shows the effect of increasing the percentage steel of wall on the maximum deflection of wall under all the load cases. Figure 15, 16 and 17 shows the effect of diameter while keeping the number of bars in wall constant for all three load cases. As the diameter of bar increases maximum displacement of wall subjected to impulsive loading should decrease since number of bars are kept constant. The trend is almost parabolic in nature for all the considered blast load cases. Figure 14 and 18 shows the normalized trend for diameter and percentage steel respectively. The maximum displacement decreases with increasing percentage steel because of the increasing stiffness of the wall due to reinforcement.

Figures from 19 to 22 shows the study case where we keep percentage steel constant and then increase the number of reinforcement bars in load case-1. Computationally it is not feasible to compare the effect of multiple bars together. If done, the number of bars will increase at rate nt^2, so only two to three diameters are considered for this study. Figure 19 shows the maximum displacement for 4mm and 10mm diameters taken with constant percentage steel value as 0.16%. Figure 20 shows the maximum displacement for 12mm and 16mm diameters taken for constant percentage steel value of 0.39%. When increasing number of bars while keeping the percentage steel constant the maximum
Fig. 11. Max displacement for varying percentage steel subjected to Load - 2.

Fig. 12. Max displacement for varying percentage steel subjected to Load - 3.

Fig. 13. Max displacement for varying percentage steel subjected to Load - 1.

Fig. 14. Normalized maximum displacement for varying percentage steel.

Fig. 15. Max displacement for varying diameter subjected to Load - 2.

Fig. 16. Max displacement for varying diameter subjected to Load - 3.
Fig. 17. Max displacement for varying diameter subjected to Load - 1.

Fig. 18. Normalized maximum displacement for varying diameter.

Fig. 19. Max displacement for 4 and 10 mm diameter bars while keeping % steel value constant.

Fig. 20. Max displacement for 12 and 16 mm diameter bars while keeping % steel value constant.

Fig. 21. Max displacement for 6, 12 and 18 mm diameter bars while keeping % steel value constant.

Fig. 22. Max displacement for 4, 8 and 12 mm diameter bars while keeping % steel value constant.
displacement increases. This decrease in displacement when taking more bars can be attributed to better distribution of stresses through the reinforcement bars.

Figure 23 and 24 shows the effect of blast parameters on the out of plane behavior of the wall. Here overpressure and other blast parameters were calculated using modified Kingery and Bulmesh [18] equations. As the standoff distance increases the maximum displacement is decreasing because the overpressure drops with distance and close to the blast, the maximum displacement shoots up. This asymptotic behavior can be seen in the Figure 23.

Figure 24 shows the effect of variation of charge weight on the wall. With increase in charge weight at a fixed standoff distance the maximum deflection of wall increases.

### 7. Conclusions

In this study, out of plane behaviour of a RC wall was studied under blast loading. A finite element tool was created as part of this study which was validated using existing finite element software. A parametric study of the wall was carried out over multiple blast load cases to study the effect of different parameters on the maximum out-of-plane deflection of RC wall.

1. With the increase in the damping ratio of the wall or percentage steel, the maximum out-of-plane deflection of wall reduced.
2. Effect of diameter of steel reinforcement was similar to percentage steel giving a decreasing maximum deflection with increasing diameter.
3. While keeping percentage of steel value constant, walls with large diameter bars showed relatively higher deflection as compared to walls with smaller diameters.
4. The wall was also sensitive to the charge weight used and showed a parabolic increasing trend to increasing charge weight.
5. As the standoff distance increased, the maximum out-of-plane deflection of wall decreased.

### 8. References


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