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The behavior of Steel Bolted Beam-Column Connection under blast load

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Abstract

Beam-column connections are one of the most critical components of steel structures. They are responsible for transferring the loads from the beams to the columns, and ensuring that the structure remains stable and strong under all loading conditions. This research investigated numerically using the Finite Element Method (FEM) the effect of blast load on a steel beam-column connection. The beam-column connection consists of an I-beam column with a length of 1500 mm and an I-beam beam with a length of 500 mm. The column and the beam are connected together through a steel plate of thickness 10 mm. The plate is welded to the beam and connected to the columns by 4 ordinary bolts of diameter 16 mm. The Coupled Eulerian-Lagrangian (CEL) modeling technique found in Abaqus/CAE was used to perform the analysis. Lagrangian elements were used to simulate the steel elements and bolts. The Eulerian elements were used to model Trinitrotoluene (TNT) and the surrounding air. A parametric study has been performed for the beam-column connection. The TNT charges were placed at a standoff distance from the center front of the connection on the same level as the bottom surface of the column. TNT charges of 10 kg, 50 kg, and 1000 kg with standoff distances of 2.5 m, and 5 m have been used in the analysis. Analysis has been performed to study the deformation, stresses, and damage of the connection. The results showed that blast load has a major impact on steel bolted beam-column connections as they could destroy the connecting bolts or even completely destroy the connection. Also, TNT charges of less than 10 kg and a standoff distance of more than 5 m have a minor effect on steel bolted beam-column connection. While, TNT charges of more than 1000 kg and a standoff distance of less than 5 m cause a catastrophic damage and could completely destroy steel bolted beam-column connection. Moreover, the connecting bolts are the weakest link in steel bolted beam-column connections subjected to blast load as they could be damaged even when subjected to small TNT charges.

Keywords

Steel structures; Beam-column connection; Blast load; Numerical analysis; Finite element analysis.

1. Introduction

Beam-column connections are one of the most critical components of steel structures. They are responsible for transferring the loads from the beams to the columns, and ensuring that the structure remains stable and strong under all loading conditions. Beam-column connections are particularly important in high-rise buildings and other structures that are subjected to large loads, such as wind and earthquakes. In these cases, a failure of a beam-column connection can lead to a catastrophic collapse of the entire structure (Agency, 2002). There are many different types of beam-column connections, each with its own advantages and disadvantages. The type of connection used will depend on a number of factors, such as the loads the connection must carry, the stiffness and strength requirements, and the cost and complexity of fabrication and erection (Salmon, et al., 2009).

Regardless of the type of connection used, it is essential that it is designed and constructed properly. Beam-column connections are often complex and require careful attention to detail. A failure to properly design or construct a beam-column connection can lead to serious problems, such as premature failure, excessive deformation, and even collapse of the structure (Society, 2017). Steel-bolted beam-column connections are widely used in steel structures due to their ease of fabrication and erection. However, they are also more vulnerable to blast loads than other types of connections, such as welded connections. Blast loads are characterized by their high intensity and short duration. They can be caused by explosions from bombs, vehicles, or industrial accidents. Blast loads can cause significant damage to steel structures, including beam-column connections. In recent years many researchers studied the effect of blast load on steel beam-column connections. Xu et al. (2013) conducted an experimental study on the behavior of steel-bolted beam-column connections under blast load. They found that the type of bolt used significantly affected the performance of the connection. High-strength bolts were more resistant to blast damage than standard bolts. Zhao et al. (2014 investigated the behavior of steel-bolted beam-column connections under blast load. They found that the number of bolts used in the connection significantly affected its performance. Connections with more bolts were more resistant to blast damage. Liu et al. (2015) experimentally studied the behavior of steel bolted beam-column connections with end plates under blast load. They found that the end plate thickness significantly affected the performance of the connection. Connections with thicker end plates were more resistant to blast damage. Wang et al. (2016) numerically investigated the behavior of steel-bolted beam-column connections with web cleats under blast load. They found that the web cleat thickness significantly affected the performance of the connection. Connections with thicker web cleats were more resistant to blast damage.

Wang et al. (2017) conducted a numerical study on the behavior of steel-bolted beam-column connections under blast load considering the effect of bolt preload. They found that the bolt preload significantly affected the performance of the connection. Connections with higher bolt preload were more resistant to blast damage. Li et al. (2018) carried out an experimental study on the behavior of steel-bolted beam-column connections with stiffeners under blast load. They found that the stiffeners significantly improved the blast resistance of the connection. Zhang et al. (2019) conducted a numerical study on the behavior of steel-bolted beam-column connections with different bolt arrangements under blast load. They found that the bolt arrangement significantly affected the performance of the connection. Connections with bolts arranged in a diagonal pattern were more resistant to blast damage than connections with bolts arranged in a square pattern. Yang et al. (2021) did a numerical study on the behavior of steel-bolted beam-column connections under blast load considering the effect of bolt pretension loss. They found that the bolt pretension loss had a significant impact on the performance of the connection. Connections with higher bolt pretension loss were more susceptible to blast damage. This research investigated numerically using the Finite Element Method (FEM) the effect of blast load on steel beam-column connection. The Coupled Eulerian-Lagrangian (CEL) modeling technique found in Abaqus/CAE was used to perform the analysis. Lagrangian elements were used to simulate the steel elements and bolts. The Eulerian elements were used to model TNT and the surrounding air.

2. FEM modelling

The FE modeling was conducted using Abaqus/CAE software. The CEL technique was used in the simulation, in this technique the steel elements were modeled using the Lagrangian elements. While the Trinitrotoluene explosive material (TNT) and the surrounding air were modeled using Eulerian elements. This technique allows for a proper interaction between the steel and the TNT in such large strain problems. Also, this technique takes into consideration the reflections of the blast wave which means more realistic simulation. The beam-column connection was subjected to a blast wave resulting from the detonations of 10 kg, 50kg, and 1000 kg of TNT with standoff distances of 2.5 m and 5 m.

2.1. Geometry of the beam-column connection

The beam-column connection consists of an I-beam column with a length of 1500 mm and an I-beam beam with a length of 500 mm as shown in Figure 1 (a). The column and beam sections are shown in Figure 1 (b) and Figure 1 (c), respectively. The column and the beam are connected together through a steel plate of thickness 10 mm and dimensions shown in Figure 1 (d). The plate is welded to the beam and connected to the columns by 4 ordinary bolts of diameter 16 mm.

2.2. Lagrangian modeling of steel

3D eight-node reduced integration Lagrangian elements (C3D8R) were used to model the Lagrangian steel elements (Corporation, 2017). The yield and the ultimate stresses of the steel used for the column, the beam, and the plate are 360 MPa, and 520 MPa, respectively. The used bolts of grade 8.8 of yield and ultimate stresses 834 MPa and 951 MPa, respectively. The used mesh for the column, the beam, the plate, and the bolts are 4 mm, 10 mm, 4 mm, and 2 mm, respectively as shown in Figure 2.

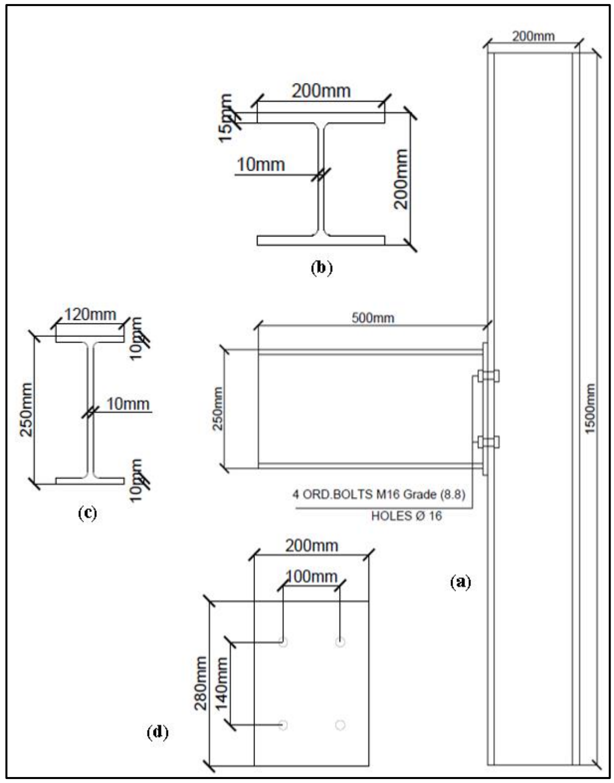


Figure 1. Geometry of the beam-column connection

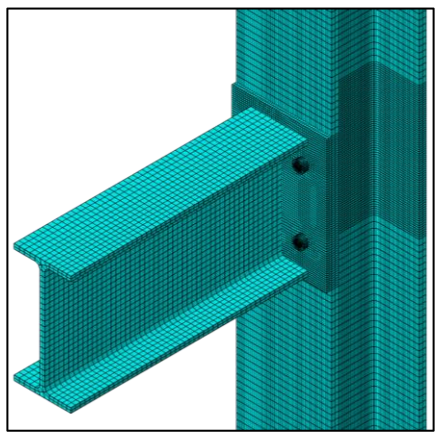


Figure 2. The FE mesh details of the beam-column connection.

2.3. Eulerian modeling of TNT and air

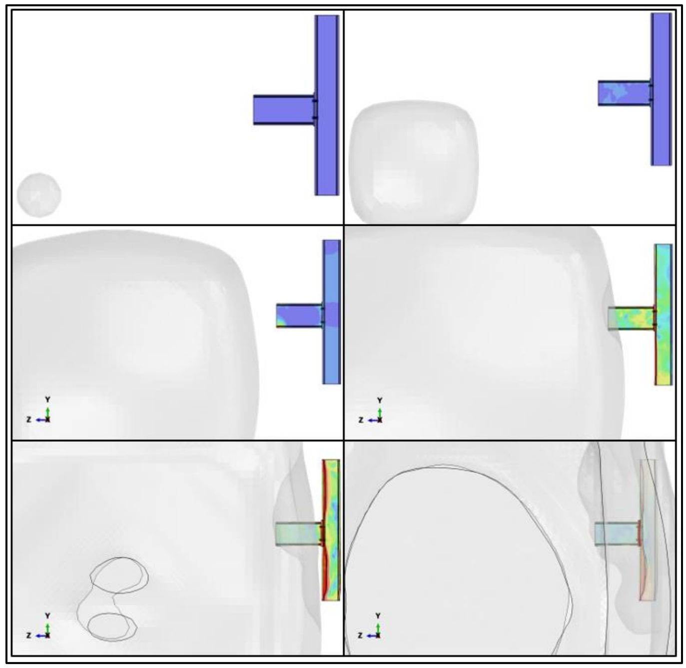
In CEL, the Eulerian material flows through the Eulerian domain and interacts with the Lagrangian elements. Thus, the simulation that generates large deformations and stresses in the Lagrangian elements can be successfully carried out (Abd-El-Nabi, et al., 2022). A big enough Eulerian domain has been modeled and filled with air to contain the TNT blast wave. The TNT and the air have been modeled using eight-node reduced integration Eulerian elements (EC3D8R) (Corporation, 2017). These Eulerian elements can be partially or entirely filled with Eulerian material. The Eulerian domain has been fitted with non-reflecting boundary conditions to prevent any reflections of the blast wave at the Eulerian boundaries. A fine mesh has been applied to track the blast wave propagation through the air accurately. The TNT explosive was modeled using The Jones-Wilkins-Lee (JWL) equation of state (EOS) (Lee, et al., 1968)., where the pressure can be determined using the following equation:

$$P=A\left(1-\frac{\omega}{R_1\bar{\rho}}\right)e^{R_1\bar{\rho}}+B\left(1-\frac{\omega}{R_2\bar{\rho}}\right)e^{R_2\bar{\rho}}+\omega\bar{\rho}e_{int} \quad (1)$$

Where A, B, R_1, R_2, and ω are the TNT material constants. The $\bar{\rho}$ is the ratio of the density of TNT in the solid state to the density of the current state, and e_{int} is the specific internal energy at atmospheric pressure. The equation of state (EOS) for ideal gas was used to model air.

3. FE analysis

The finite element explicit analysis was done using the CEL technique. A parametric study has been performed for the beam-column connection. The TNT charges were placed at a standoff distance from the center front of the connection on the same level as the bottom surface of the column. TNT charges of 10 kg, 50 kg, and 1000 kg with standoff distances of 2.5 m, and 5 m have been used in the analysis. Analysis has been performed to study the deformation, stresses, and damage of the connection. The value of Von-Mises stress in Pascal (Pa) is always positive, while the displacement in meters (m) is considered positive in the positive direction of the X, Y, and Z axes. The analysis time was set to 25 milliseconds (ms), which is enough time for the blast wave to reach the connection and capture all its reflections. Fig**ure** 3. shows the propagation of a blast wave with time for 1000 kg of TNT



with a standoff distance of 5 m.

Figure 3. Blast wave propagation with time for 1000 kg of TNT.

4. Results and discussion

4.1. Standoff distance (2.5 m)

The beam-column connection with subjected to blast wave resulting from the detonations of 10, 50, and 1000 kg of TNT with a standoff distance of 2.5 m. For 10 kg of TNT, as shown in Figure 4 (a), few dents occurred at the plate, local buckling occurred to the flange of the column at the lower part. Also, the bolts were torn apart as shown in Figure 4 (e). Figure 4 (b), (c), and (d) show the displacements in meters of the connection in X-direction (U1), the displacement in Y-direction (U2), and the displacement in Z-direction (U3), respectively. For 50 kg of TNT, as shown in Figure 5 (a), major damage occurred to the connection, and large dents occurred at the plate. The flange of the column experienced large local buckling all over the column's height and part of the flange in the lower part was torn apart. A few dents were found on the flange of the beam.

Also, the bolts were torn apart as shown in Figure 5 (e). Figure 5 (b), (c), and (d) show the displacements of the connection in U1, U2, and U3, respectively. For 1000 kg of TNT, as shown in Figure 6 (a), complete damage occurred to the connection, the flanges of the column and the beam were almost destroyed completely. The plate has undergone severe damage. Also, the bolts were torn apart completely as shown in Figure 6 (e). The steel debris spread around the connection. Figure 6 (b), (c), and (d) show the displacements of the connection in U1, U2, and U3, respectively.

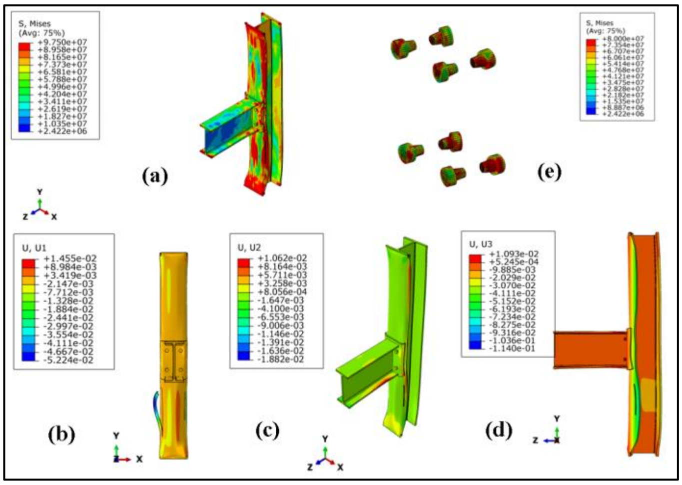


Figure 4. Stresses and deformations of 10 kg of TNT with a standoff distance of 2.5 m.

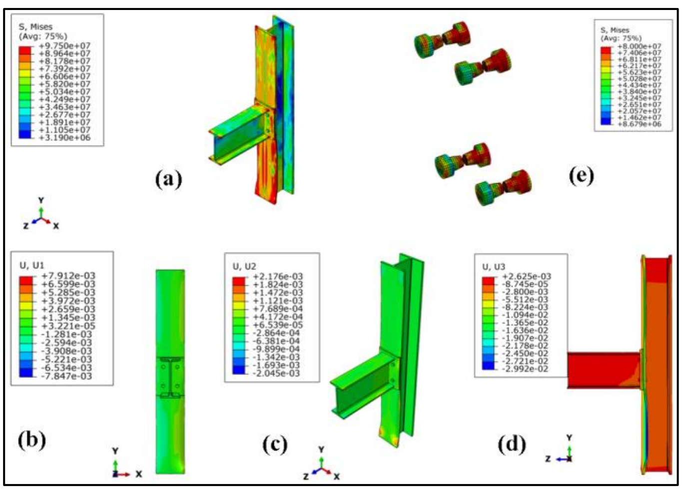


Figure 5. Stresses and deformations of 50 kg of TNT with a standoff distance of 2.5 m.

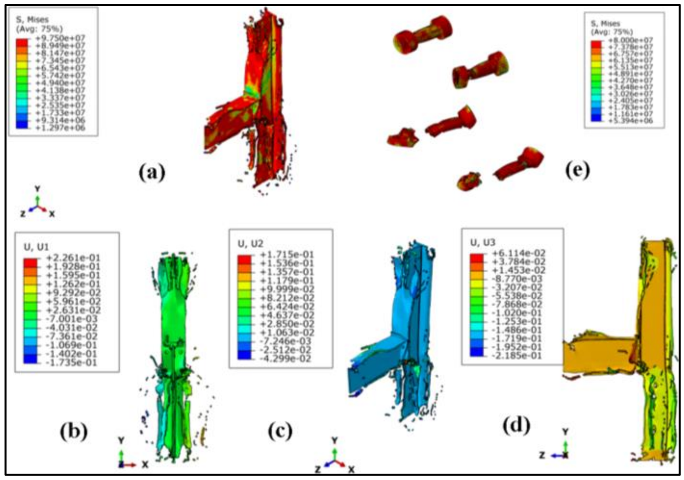


Figure 6. Stresses and deformations of 1000 kg of TNT with a standoff distance of 2.5 m.

4.2. Standoff distance (5 m)

The beam-column connection with subjected to blast waves resulting from the detonations of 10, 50, and 1000 kg of TNT with a standoff distance of 5 m. For 10 kg of TNT, as shown in Fig**ure** 7 (a), no noticeable damage occurred to the connection. Also, the bolts were completely undamaged as shown in Fig**ure** 7 (e). Fig**ure** 7 (b), (c), and (d) shows the displacements in X-direction (U1), the displacement of the connection in Y-direction (U2), and the displacement in Z-direction (U3), respectively. For 50 kg of TNT, as shown in Fig.8 (a), minor damage occurred to the connection, no dents occurred at the plate. The flange of the column experienced minor local buckling at the lower part of the column. No dents were found on the flange of the beam. Also, the bolts were completely undamaged as shown in Fig**ure** 8 (e). Fig**ure** 8 (b), (c), and (d) show the displacements of the connection in U1, U2, and U3, respectively. For 1000 kg of TNT, as shown in Fig**ure** 9 (a), major damage occurred to the connection, the flanges of the column experienced a severe local buckling. Also, the flanges of the beam underwent a severe local buckling. Moreover, the plate has a severe damage. Large dents occurred to the bolts but they didn't tear apart as shown in Fig**ure** 9 (e). Fig**ure** (b), (c), and (d) shows the displacements of the connection in U1, U2, and U3, respectively.

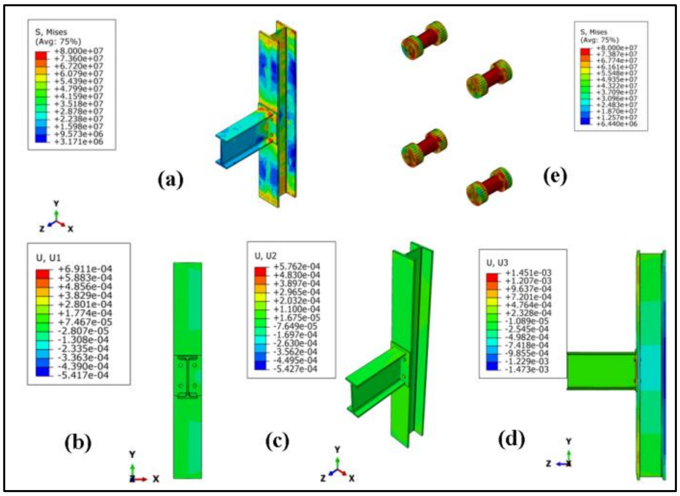


Figure 7. Stresses and deformations of 10 kg of TNT with a standoff distance of 5 m.

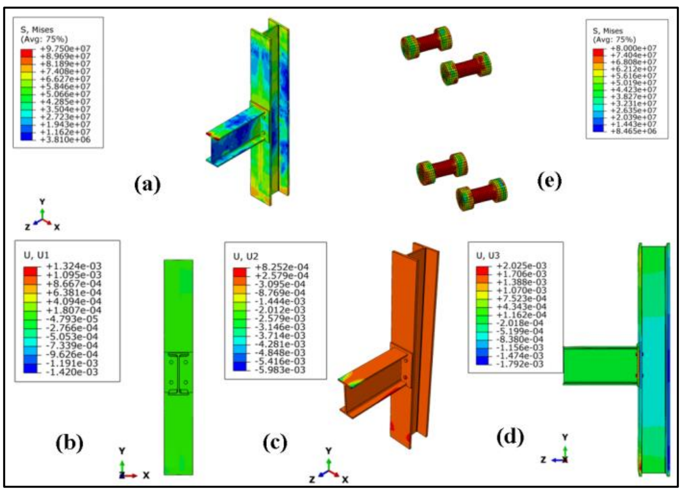


Figure 8. Stresses and deformations of 50 kg of TNT with a standoff distance of 5 m.

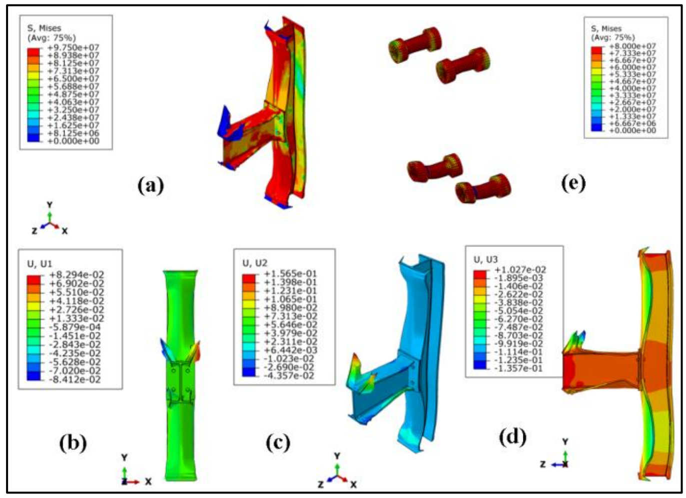


Figure 9. Stresses and deformations of 1000 kg of TNT with a standoff distance of 5 m.

5. Conclusions

Based on the numerical simulation and the result analysis the concluded remarks are as follows:

- Blast load has a major impact on steel bolted beam-column connections as they could destroy the connecting bolts or even completely destroy the connection.
- TNT charges of less than 10 kg and a standoff distance of more than 5 m have a minor effect on steel bolted beam-column connection.
- TNT charges of 50 kg and a standoff distance of less than 5 m could tear apart the bolts and cause large local buckling in steel bolted beam-column connection.
- TNT charges of more than 1000 kg and a standoff distance of less than 5 m cause a catastrophic damage and could completely destroy steel bolted beam-column connection.
- The Connecting bolts are the weakest link in steel bolted beam-column connections subjected to blast load as they could be damaged even when subjected to small TNT charges.

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