Numerical Modeling of Steel Column for its Response to Large Explosive Loading using CEL-FEM Approach

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Abstract. In the past few decades, there has been a growing public concern regarding the protection of infrastructures against extreme events, specifically explosive detonations. Traditional structural design has predominantly focused on accounting for gravity, seismic, and wind loads as the primary factors to consider. The rise in subversive attacks has led to a heightened focus on blast load and its impact on infrastructures. Unconfined, surface explosions are a common type of terrorist attack that occurs outside of buildings. This has necessitated a greater understanding of the effects these explosions can have on structures. A comprehensive numerical model was created in Abaqus for a steel column measuring 2.41m in length and having a W150x24 cross-section. The model was then subjected to a powerful explosion equivalent to 100kg-TNT, with a standoff distance of 10.30m. To achieve this, an Eulerian-Lagrangian approach coupled with the Finite-element method (CEL-FEM) was employed. A thorough investigation was conducted by modifying the explosion's altitude (i.e., blast height), and the subsequent dynamic responses were analyzed and discussed. The outcomes of this investigation significantly enhance our comprehension of how steel columns respond when subjected to intense explosive forces.

1. Introduction

The need to analyze the performance of structures under blast and high-impact loads has become increasingly urgent due to recent global events [1-3]. Modern steel buildings, especially those with non-moment-resisting connections and lighter frame structures, may lack the ability to maintain their structural integrity when subjected to severe blast loads. As a consequence, structures like embassy complexes, significant commercial hubs, essential government edifices, and crucial industrial establishments might necessitate the implementation of blast-resistant architectural design due to assessments of potential blast risks. The paramount objective is to guarantee the protection of these structures by meticulously designing them with adequate fortitude and flexibility to endure the expected level of threat in accordance with designated criteria [4-7].

Columns play a crucial role in the construction industry [8-12]. If any of these elements were to malfunction on a localized level, it could result in the complete failure of the entire framework, especially if the construction does not have redundant load pathways [13-19]. Structural engineers go to great lengths to design columns with an adequate safety factor against service loads. However, they often overlook disaster load cases, such as accidental actions like explosions. As a result, the importance of considering these scenarios cannot be overstated. Investigations have primarily focused on the load capacity of structural elements, specifically plates, in relation to contact charges and near-field detonations [6]. However, there is limited understanding of how steel columns behave under blast conditions. Existing data predominantly revolves around the response of reinforced concrete and concrete-filled steel tubular columns to explosive loads. To address this knowledge gap, this study utilizes an Eulerian-Lagrangian approach, combined with the Finite Element Method in the ABAQUS/Explicit commercial code, to examine the impact of blast height on the dynamic response of a steel column subjected to a substantial explosive load of 100 kg

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TNT at a stand-off distance of 10.30 m. The objective is to acquire a profound understanding of the actions and effectiveness exhibited by steel columns when subjected to explosive situations.
The behavior of the infrastructure when subjected to the force of an explosion can be categorized into three distinct types, determined by the disparity between the natural period of the structure and the duration of the blast load [2, 6]. In the realm of impulse, where the blast load's duration is significantly shorter than the natural period of the structure, the structure's reaction is characterized by an abrupt force. During this phase, the peak pressure of the blast becomes less significant since the structure may not respond quickly enough to reach its maximum deformation once the blast load is complete. Nevertheless, the impulse still imparts a considerable amount of energy to the structure, resulting in damage. Conversely, when the duration of the load is comparable to the structure's natural period, both the peak force and the impulse emerge as crucial factors in determining the structural response. In situations like these, it becomes necessary to conduct a comprehensive analysis to accurately evaluate the performance of the structure when subjected to such specific loading conditions. By considering both the peak force and impulse, a comprehensive understanding of the structural response can be obtained, enabling effective design strategies and mitigation measures to be implemented. It is crucial to note that the response of a structure to blast loads is highly dependent on its natural period and the duration of the applied load. Understanding these relationships and conducting proper analyses are essential for ensuring structural integrity and safety in blast-prone environments.

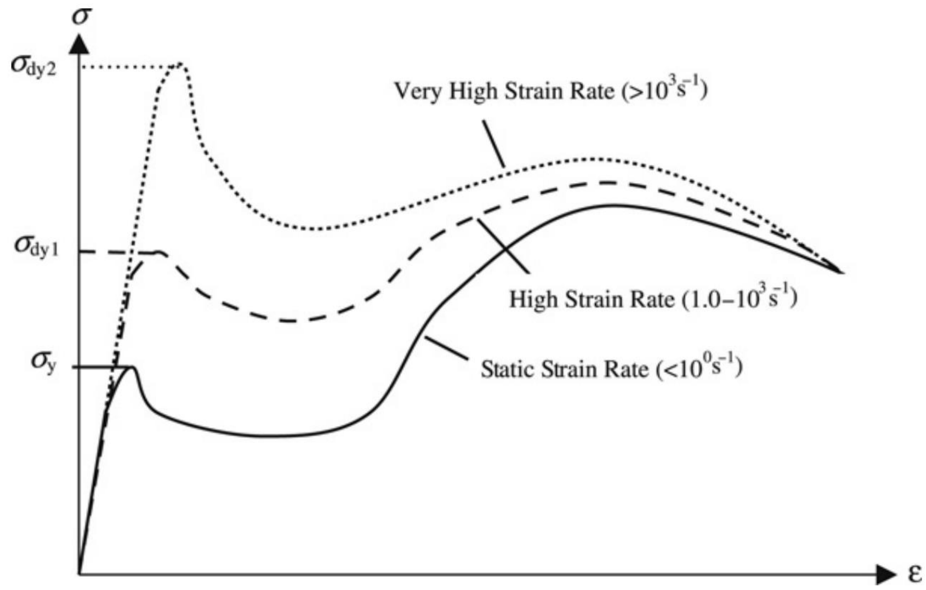

Fig. 1. Steel response under different loading rates

- **Strain rate effect**

The velocity at which deformation takes place plays a crucial role in determining the mechanical characteristics of steel. By examining the mechanical properties under conditions of stationary loading, we can discern the influence of escalating strain rates on the strength of steel, as illustrated in Figure 1. In this illustration, the yield strength (σ_y) experiences a substantial increase, transforming into a dynamic yield strength (σ_{dy}). This highlights the considerable influence that strain rate has on the overall strength characteristics of steel. Experimental findings presented in the research conducted by [6] illustrate that under extremely high loading rates, the dynamic yield strength has the potential to exceed the ultimate strength, as visually represented in Figure 1. The behavior of the elastic modulus, on the other hand, remains relatively unaffected by the rate of loading. Although there is a slight elevation in the ultimate tensile strength, this increase is comparatively smaller than the observed rise in the yield strength. Additionally, the elongation at rupture either remains unchanged or experiences a slight reduction due to the elevated strain rate. The rapid application of force can influence the categorization of cross-sectional shapes, causing a compact steel section to be redefined as a slender section. Consequently, this reclassification can lead to the occurrence of local buckling when subjected to high-speed deformation.
To address the strain-rate effect in steel material, the present study utilizes the Johnson-Cook (J-C) approach in ABAQUS. For in-depth information on this model, refer to the works of [6-9].

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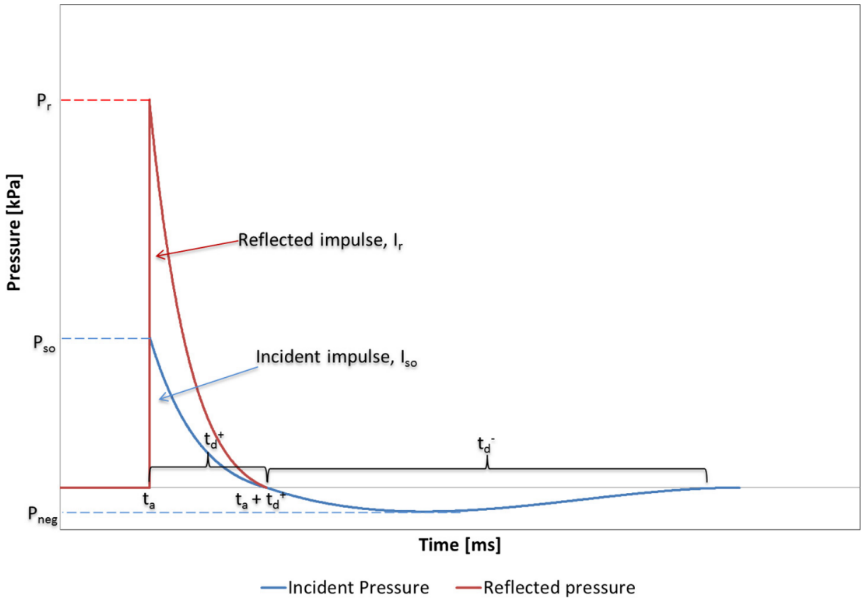

Fig. 2. A standard profile of blast pressure and the associated terminology

- **Explosive detonation load**

Traditional methods of structural design do not take into consideration the effects caused by explosive incidents. Consequently, only a few structures possess the required resilience against blast loading [5, 7]. In certain cases, there are deviations from the standard practice, particularly in buildings situated within petrochemical complexes where there is a pre-existing risk of explosions, as well as in prominent structures like embassies. As a result, the field of structural engineering lacks a comprehensive grasp of the dynamics of explosions, the development of blast waves, and their interaction with structures [6].

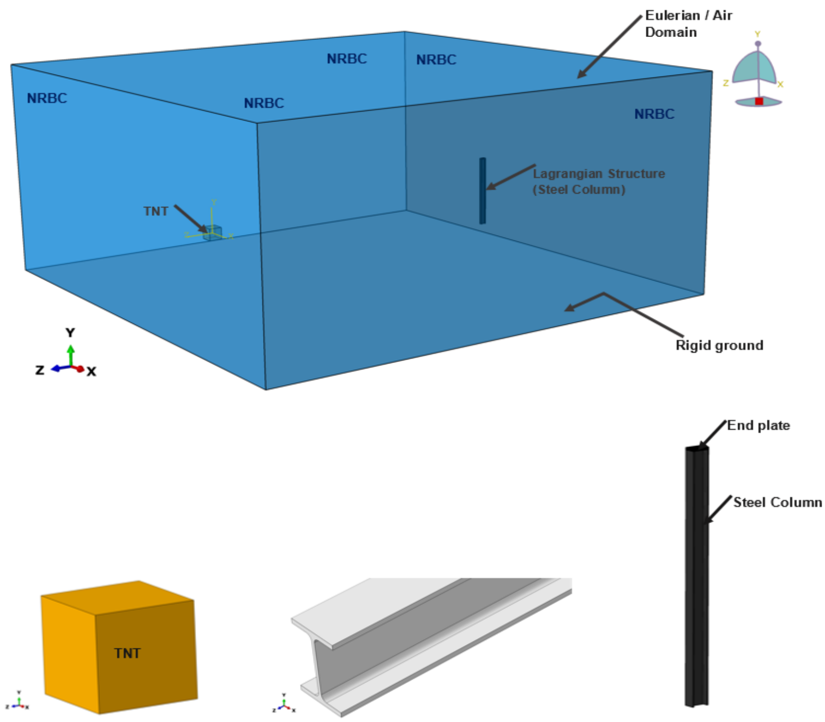

Fig. 3. Numerical model

Chemical explosions take place when a volatile substance experiences a rapid process of oxidation, leading to the emission of a significant quantity of energy in the form of heat and light. This process is known for its quickness and intensity [2, 20-22]. The occurrence of a chemical reaction results in the expansion of the air in its vicinity, leading to a simultaneous rise in atmospheric pressure and temperature. This rapid expansion of the air causes it to compress the air ahead of it, creating a concentrated shock front. As this shock front propagates away from the core of the explosion, it induces a significant increase in atmospheric pressure, aligning with the incident pressure. Subsequently, it exponentially decreases back to atmospheric conditions. The duration and characteristics of the explosion's positive phase are determined by the period in which the pressure remains higher than the surrounding atmospheric levels [7]. When the shock wave encounters a material denser than the medium through which it is propagating, it undergoes reflection. The peak reflected pressure, which exceeds the peak incident pressure, is influenced by both the angle of incidence and the magnitude of the incident pressure. According to sources: [4] [6], the peak reflected pressure can be as much as eight times higher than the peak incident pressure.
Situated at a considerable distance from the central point of the detonation, Figure 2 illustrates a representative representation of the pressure distribution caused by the explosion. The measurement of the blast wave's journey to reach a specific location is determined by the time of arrival (t_a). Instantaneously, the atmospheric pressure reaches its peak incidence pressure (P_{so}) or peak reflected pressure (P_r), depending on whether it encounters a reflecting surface. The blast pressure profile consists of a positive phase with a duration of t_d^+, during which the pressure exceeds atmospheric levels, and a negative phase with a corresponding duration of t_d^-, when the overpressure drops below atmospheric levels. The area beneath the blast pressure profile represents the impulse generated by the blast.

- **Structural response**

The explosion creates shock waves that impose a temporary dynamic burden on buildings and other structures. This impulsive load, which lasts for a short period, along with the inertial forces resulting from the structure's acceleration, are countered by internally produced strain energy [2, 6, 23]. To study how structural components respond to blast loads, one can conduct field tests or employ numerical simulations. In the field of numerical modeling, there are two widely used methods: non-linear FEA and the simpler SDOF analysis. The application of non-linear FE numerical modeling techniques offers a cost-effective solution to study the response of structural elements to blast loading, eliminating the need for expensive experimental field tests. This approach allows for a comprehensive examination of how these elements behave under such conditions. Additionally, numerical modeling affords the opportunity to explore a wide array of design parameters that are crucial to enhancing the blast resistance of structures. The utilization of non-linear FEA, on the other hand, poses distinct obstacles that must be addressed. These challenges encompass the careful selection of an appropriate mesh specific to the problem at hand, the capability to evaluate the stability of the solution procedure, and the comprehensive assessment of all potential sources of errors attributable to modeling assumptions [10, 11, 24-25].

- **Literature Survey**

Blast loads are considered to be highly hazardous due to their potential to deliver a significant amount of energy to structures, which can result in structural damage. Extensive research has been conducted to predict the response of structures to blast loads, aiming to assess the extent of damage and mitigate the associated risks. [26] formulated equations utilizing energy-based methods to predict the enduring distortions of building components when exposed to sudden force. In a comparable manner, [27] along with [28] created a computer software called DYNFA, which facilitates the evaluation of diverse frame structures when subjected to arbitrary explosive loads. Through these innovative approaches, researchers have made significant advancements in understanding and analyzing the behavior of structural elements under impulsive stress conditions. This program allows for a comprehensive evaluation of the structural response, aiding in the identification of vulnerabilities and the implementation of appropriate measures for risk reduction. [29] and [30] conducted extensive field testing on multiple wide flange steel columns subjected to different explosion forces. Their research provided empirical evidence of the experimental findings and the outcomes of numerical calculations. In a separate study, In their study, [31] examined the performance of a W360x347 steel column measuring 5.73 meters in height when subjected to a blast force equivalent to 1818 kilograms of TNT ANFO and placed at a height of 4.75 meters above the ground. Another experimental investigation by [32] focused on 18 RC beams exposed to explosive product detonation, examining their dynamic response. The study aimed to analyze the structural performance of these beams under explosive conditions. The exorbitant expenses linked to performing explosion experiments on complete vertical supports or other materials that bear loads in laboratory or field environments has consistently emerged as a significant subject of conversation and investigation in various literature publications and other sources. Researchers have increasingly turned to numerical studies using equivalent S-D-O-F or more advanced FEM to assess the dynamic response and potential damage of various infrastructural components

subjected to explosive product detonations. This trend has been observed over the course of several decades. To put it differently, an effective alternative to conducting a large number of experiments is to utilize numerical modeling of the structural system, simulate potential outcomes, and establish predictive equations. [33] conducted a study where they utilized LS-DYNA to investigate the characteristic behavior and dynamic response of blast-loaded steel columns with varying cross-sectional shapes through explicit FEA. The researchers revealed that when comparing parametric FE results based on the damage index and support rotation criteria, the projected damage level indicated by the displacement criterion was often exceeded. This suggests that the displacement criterion is a more reliable design assumption. By implementing this approach, it is possible to gain valuable insights into the behavior of structural systems under varying conditions without the need for extensive physical experimentation. Moreover, the study also revealed that the shape of a steel column, specifically when its members are fixed at the ends, has minimal impact on the qualitative response. When comparing identical cross-sections and load conditions, a maximum dispersion of approximately 30-35% was calculated when transitioning from pinned to fixed end support conditions.
There is a lack of comprehensive and sufficient research available regarding the behavior of steel columns when exposed to blast events. This study aims to enhance our understanding of the impact of blast mechanisms and explosion height on steel columns that experience both axial and lateral dynamic blast loads.

- **Explicit platform in Abaqus**

The explicit dynamics procedure is renowned for its ability to efficiently execute numerous small time increments. This technique employs a distinct time integration method called explicit central-difference, which presents a cost-effective alternative to the direct-integration dynamic analysis method offered by Abaqus/Standard. To achieve cost-efficiency, the requirement of solving simultaneous equations is bypassed. At the start of each increment, indicated as "t," the explicit central-difference operator meets the dynamic equilibrium equations. The computed accelerations at time "t" are then utilized to advance the velocity solution until time "t + Δt/2," and the displacement solution until time "t + Δt." This approach ensures efficient utilization of resources while maintaining accuracy in the computations. By avoiding the complexities associated with simultaneous equations, the process becomes more streamlined and effective, resulting in significant cost savings.
The utilization of the CEL method in Abaqus/Explicit involves a two-step procedure. In this approach, all materials undergo deformation using Lagrange treatment within a specified time increment [6-9]. Subsequently, a remapping process is employed for the Eulerian material. Any discrepancies or overlaps between the Lagrangian and Eulerian materials are effectively managed through the implementation of a versatile contact algorithm.
In the CEL-FEM methodology, the Lagrangian structure of interest is encompassed by an Eulerian element-based air volume. At a certain distance, there exists a point that represents the theoretical position of the explosive [6-7]. The objective is to generate a shock wave at the inlet of the air domain, achieved through boundary conditions, which mimics the blast wave that would occur at the actual distance from the detonated explosive. This becomes the starting point for the analysis, eliminating the need to model the explosive's actual detonation. The present study employs ABAQUS Explicit to solve the nonlinear equations of the problem. The CEL-FEM approach is utilized to define the blast loading.

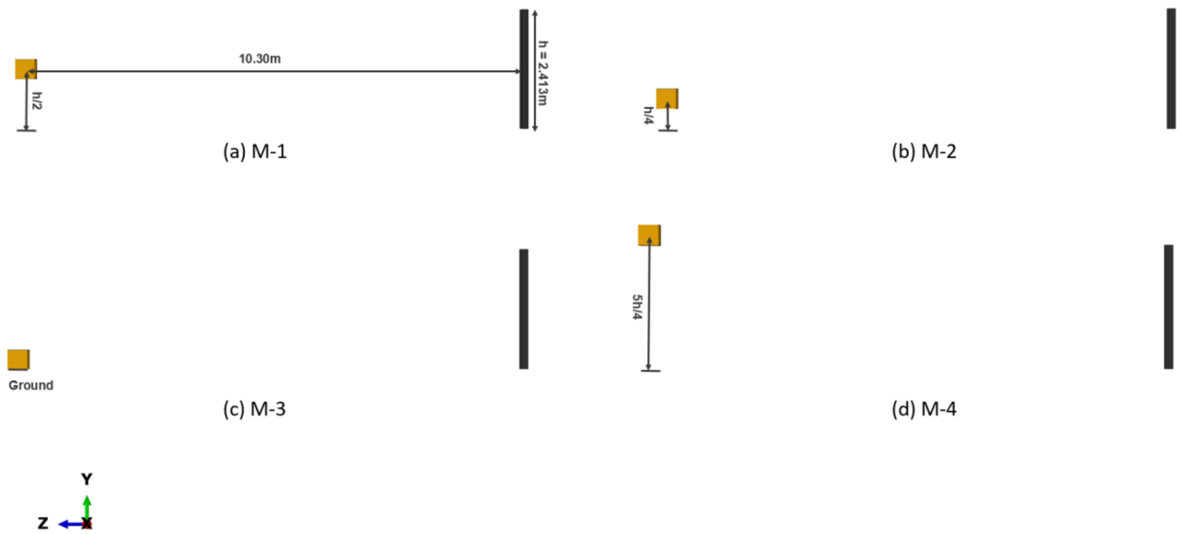

Fig. 4. Considered explosion scenarios (note: all the columns are subjected to axial load of 270kN)

2. Numerical Modeling

Using the ABAQUS/Explicit, we conducted numerical simulations to analyze how a steel column responds to large explosive detonation. In this research, we modeled the steel column as a 3-D solid continuum. In order to break down the steel into smaller parts, we utilized the 8-node hexahedral element. Figure 3 showcases a three-dimensional representation of a wide flange steel column with specific measurements: a length of 2413mm and a section size of W150 x 24. The column was simulated with a finite element size of 5mm. At the lower end of the column, boundary conditions were imposed, allowing all degrees of freedom except rotation in the X-direction. In contrast, the upper end was limited in its movement, except for linear displacement along the Y-axis and rotational motion around the X-axis. To simulate real-world conditions, a 270kN axial force was introduced at the column's upper end through the utilization of an end plate. The visual representation of the numerical model can be observed in Figure 3.

ABAQUS employs a specialized time integration algorithm to effectively solve the equation of motion. This algorithm offers significant benefits when applied to dynamic problems that involve high-frequency content. An example of such a situation would be blast-loaded members. The explicit analysis involves iteratively solving the equation of motion and updating the stiffness matrix after each incremental load and displacement step. The modifications being implemented are a result of changes in the structural configuration and characteristics of the materials involved. To ensure a comprehensive understanding of the column's response, a termination time of 24ms has been established. This timeframe allows for a more thorough examination of the column's behavior. ABAQUS has the capability to automatically determine the appropriate time step by utilizing the J-C model to simulate the speed of sound in steel. When analyzing steel materials, the necessary input properties include the yield stress, density, fracture strain, and Poisson's ratio. For this specific case, these properties are defined as 470 MPa, 7850 kg/m3, 0.20, and 0.30 respectively. The non-linear parameters of this model are obtained from previous studies conducted by [6-7, 30].

The W150x24 section has the following dimensions: Depth measures 160 mm, the Top Width is 102 mm, the Top Flange Thickness is 10.3 mm, the Bottom Flange Width is 102 mm, the Bottom Flange Thickness is 10.3 mm, the Web Thickness is 6.6 mm, and there is a Fillet Radius of 11.7 mm. The density of TNT is 1630 kg/m3. The TNT is simulated using the Jones-Wilkins-Lee Equation of State, with detailed parameters and description provided in the sources [6-7]. All components of the CEL-FEM numerical model are discretized with an element size of 5 mm. Non-reflecting Boundary Conditions (NRBC) are applied to all faces of the Eulerian domain, except for the bottom face. The TNT is positioned at a stand-off distance of 10.30 m, with a mass of 100 kg. Figure 4 illustrates the specific heights considered in relation to different heights but maintaining the same stand-off distance.

The loading procedure for the columns in the numerical simulations consists of two separate stages. In the initial stage, known as phase one, the axial load is incrementally applied to the nodes located on the upper surface. This gradual increase continues until the desired level of axial load is achieved. To accomplish this task, the load is applied temporarily to allow the internal stress to reach a state of stability that corresponds to the axial load factor of 1.0 considered in the simulation. Following this, in the second stage of loading, the column is exposed to lateral blast loading while maintaining a constant static pressure.

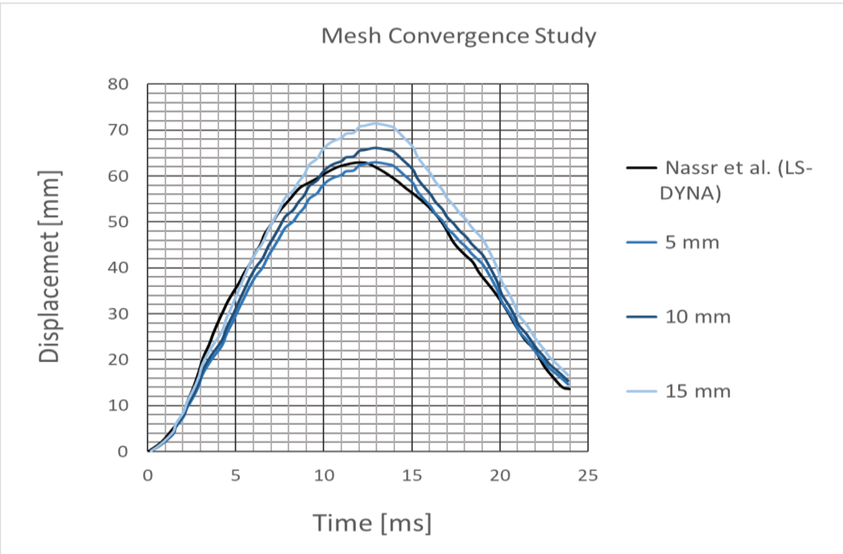

Fig. 5. Model verification

3. Results

The simulation of air blast wave propagation is conducted through the utilization of computational fluid dynamics. The resulting blast wave is then transmitted to the structure, exerting blast loads on the column. This phenomenon arises from the intricate interplay between the fluid component (air) and the structural component (column).

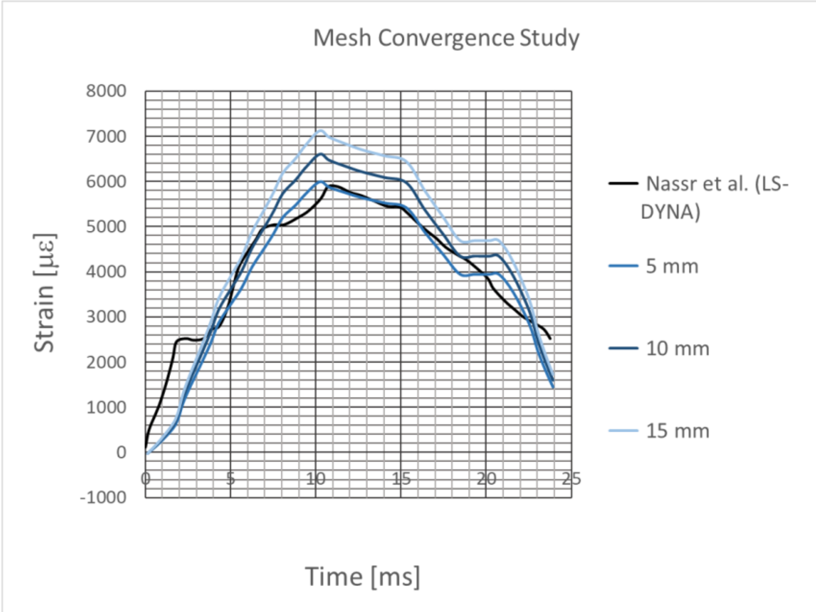

Fig. 6. Comparison of strains

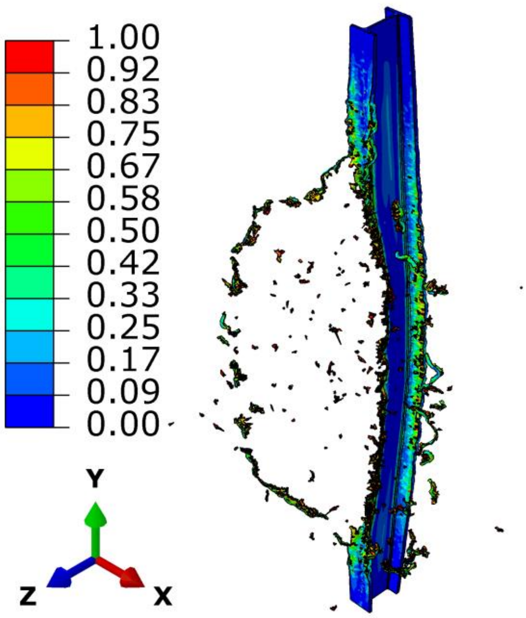

Fig. 7. Damage for M-1

In order to assess the impact of different mesh sizes on the accuracy of the simulation outcomes for modeling steel columns, a series of simulations were conducted using five varying mesh sizes. For the purpose of numerical validation, mesh sizes of 5, 10, and 15 mm were taken into consideration. Figure 5 presents a comparison of the displacements in the -Z direction at the mid-height of the column. The entire analysis was carried out over a duration of approximately 24 ms, which was applied to the ABAQUS model using the Explicit module. According to [30], the peak displacement was reported to be 62.92 mm. However, with the selected mesh sizes, the displacements were found to be 62.35 mm, 66.07 mm, and 71.35 mm, respectively. Based on these results, it can be concluded that the default mesh size of 5 mm is the most appropriate choice.

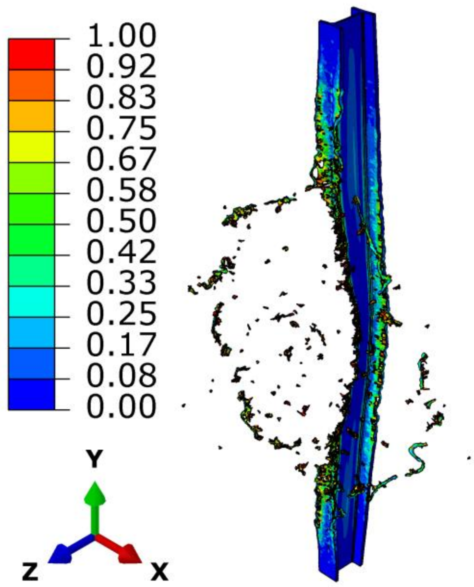

Fig. 8. Damage for M-2

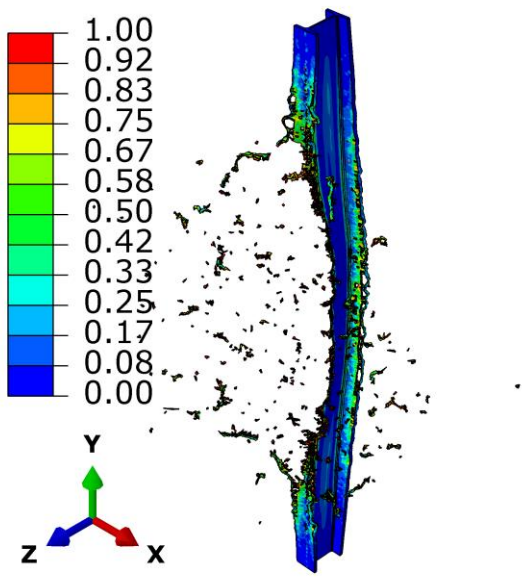

Fig. 9. Damage for M-3

Figure 6 illustrates the comparison of strains, specifically focusing on peak strain values. According to [30], the peak strain reported is 5889.87 με. On the other hand, when considering the meshes being analyzed, the strains are determined to be 5998.65 με, 6598.51 με, and 7126.39 με, respectively. Upon comparing the anticipated strain reactions to a 5 mm measurement, it becomes evident that there is a notable resemblance in terms of both the maximum strain and the overall pattern.

The validation outcomes illustrate the exact precision of the existing finite element model when it comes to forecasting the behavior of columns under blast loads. It is important to note, however, that there exists a discrepancy between the experimental data and the predicted values obtained from the FEA. When the explosion force exceeds a certain threshold, the column experiences instantaneous failure immediately after the blast load is applied. The reason for this failure can be attributed to the substantial distortions caused by the combined impact of the blast force and the initial axial force.

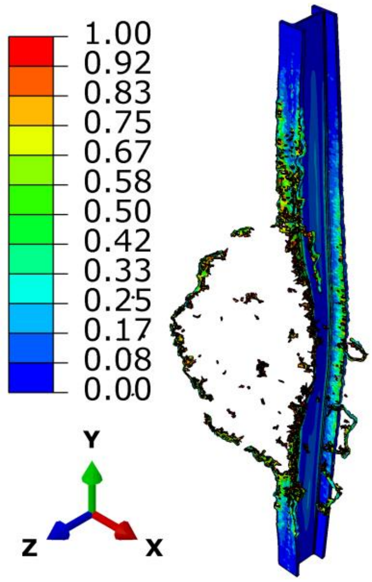

Fig. 10. Damage for M-4

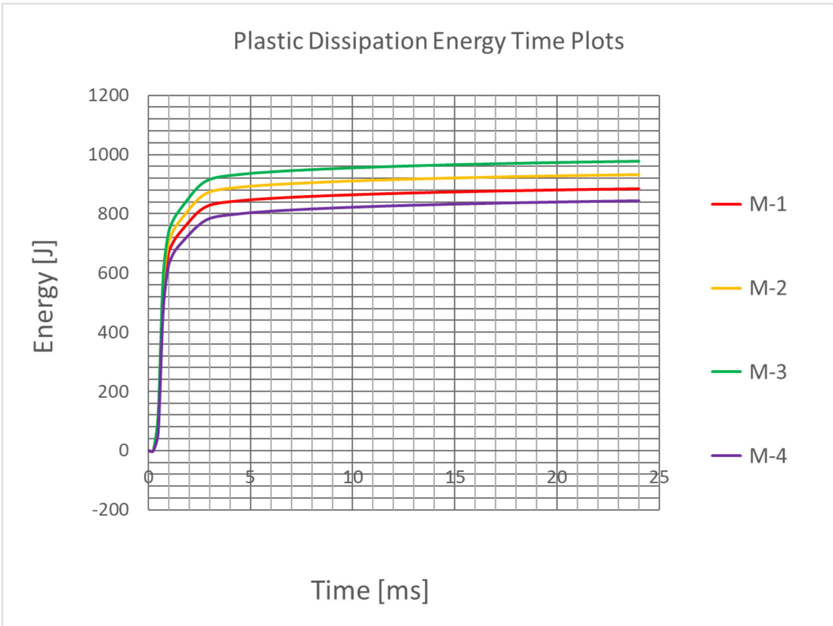

Fig. 11. Damage energy plots

The damage profiles for models M-1, M-2, M-3, and M-4 can be observed in Figure 7, Figure 8, Figure 9, and Figure 10, respectively. The provided figures showcase the fringe levels, which serve as indicators of the extent of harm inflicted upon the column. A fringe level value of 0.0 signifies an absence of damage, whereas a level of 1.0 denotes substantial damage, resulting in a notable decrease in the steel material's strength and rigidity. By examining these figures, one can observe the localization and spread of damage along the length of the column. The provided figures clearly demonstrate that the deformation shapes of the columns closely resemble the first mode shape of static buckling. Furthermore, the data indicates that the areas of deformation are predominantly concentrated at the points of support and where the columns experience the greatest lateral deflection in the elastic buckling mode. These discoveries imply that these columns demonstrate the failure mode of plastic mechanism collapse. Figure 11 displays the plastic energy plots, showcasing the maximum plastic energy values for models M-1, M-2, M-3, and M-4, which are 885.36 J, 931.96 J, 978.56 J, and 844.35 J, respectively. The evident demonstration reveals the impact of blast height on both the damage inflicted and the subsequent plastic energy generated within the material of the column models. It is important to acknowledge that, in the aforementioned cases, the damage to the column is predominantly governed by the flexural mode. As illustrated, blast height exerts a significant influence on the outcomes, particularly within the realm of flexural mode. The maximum displacements observed in the column models are as follows: 62.35 mm, 68.11 mm, 70.05 mm, and 57.01 mm, respectively. Correspondingly, the strains recorded are: 5998.65 με, 6711.05 με, 6995.45 με, and 5597.11 με, respectively. The peak pressure values recorded for the model under consideration at various blast heights are 106.24 MPa, 108.11 MPa, 108.99 MPa, and 100.05 MPa, respectively. Using the ConWep blast code, the same pressures were calculated and resulted in peak values of 103.55 MPa, 106.88 MPa, 107.05 MPa, and 97.12 MPa for models M-1, M-2, M-3, and M-4, respectively. These findings indicate a strong correlation between the measured pressures and the predictions made by the ConWep blast code.

The stress distribution for model M-1 is displayed in Figure 12, illustrating the maximum principal stress. On the remote surface of the pillar, an utmost tensile stress of 508.32 megapascals is detected. In the case of models M-2, M-3, and M-4, these values are 538.11 MPa, 546.11 MPa, and 478.10 MPa, respectively. In contrast, the frontal or explosed surface of M-1 undergoes a peak stress of -635.90 MPa. For models M-2, M-3, and M-4, these values are -689.99 MPa, -695.10 MPa, and -526.10 MPa, respectively. When subjected to dynamic blast loads, the plastic resistance of steel columns increases due to the strain rate sensitivity effect. It is crucial to acknowledge that before the section reaches its maximum dynamic plastic resistance in the collapse mode of the plastic mechanism, there is a possibility of local spallation and buckling of the compression flange.

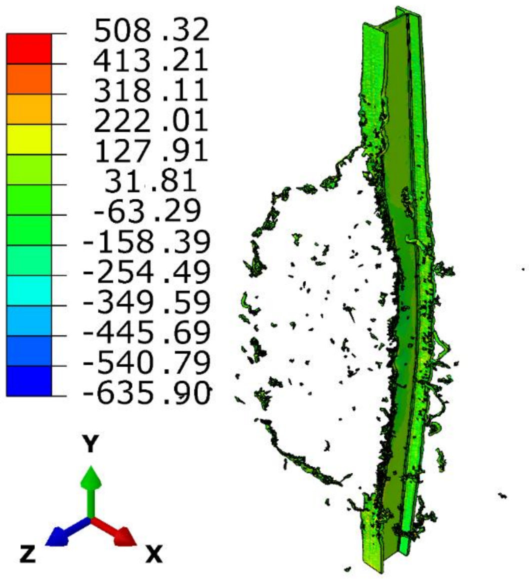

Fig. 12. Principal stress for M-1

4. Conclusions

This paper examines the explosive height effect on a verified steel column subjected to severe explosive detonation. The blast modeling utilizes the CEL-FEM, while the steel material is represented using the J-C approach. The study focuses on columns specifically designed to withstand gravitational loads and allow for lateral deformation, but not classified as part of the Special Moment Resisting Frame (SMRF) systems. By investigating the blast height effects, this research aims to enhance our understanding of how steel columns perform under axial compression in explosive scenarios. The reduction in the height of the explosion has a significant impact on the damage caused and the dynamic responses of the target when subjected to blast loading. As the blast height decreases, there is an increased dominance of flexural damage mode and rupturing of the steel material, accompanied by localized damage along the length of the column. The height of the explosion serves as a crucial parameter in determining the extent of damage and other dynamic responses experienced by the target. When evaluating the optimal parameters of a fixed weight and stand-off distance for an explosive charge, it is crucial to take into account the phenomenon of localized failure, known as spallation, in the column. As the blast height decreases, this localized failure transitions into a more widespread bending deformation, referred to as the flexural damage mode. Through the utilization of the J-C model, simulations have been conducted to accurately replicate the displacement and other relevant parameters within the target column. These simulations have proven effective in predicting the level of damage sustained along the entire length of the column for varying blast heights. Global plastic instability, characterized by the primary failure pattern in steel columns when exposed to dynamic blast loads, is a crucial phenomenon to consider.

The findings of this research demonstrate that the utilization of computational fluid dynamics (CFD) modeling offers a viable and efficient method for comprehending the characteristics of a blast wave and the intricate dynamics between blast loads and the response of a steel column.

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