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Response of A 3-D reinforced concrete structure to blast loading

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ABSTRACT

Major building codes now adopt various measures to address design issues associated with potential blast loading that may result from terrorist attacks. Adoption of these design measures has been gaining momentum, increasing the awareness toward better understanding structural response under blast loads and adoption of existing and new mitigation techniques. Research efforts into improving current design practice makes it incumbent to undertake sophisticated numerical analysis with application to real 3-D structures to identify the structural elements that are most vulnerable and the means to improve their design and performance. In this research, detailed finite element analyses were performed using ABAQUS to assess the structural performance of an existing residential 4-storey, reinforced concrete structure under blast loading. A 3-D model was developed for this structure, which was originally designed for vertical loads only. The response of the original structure under the simulated blast loads is presented. The results show that modifying the design by using a concrete filled steel tube for external columns can increase the blast resistance significantly. The improved performance is a result of the dynamic toughness of the steel material, which reduces the kinetic energy uptake of the structure.

1. Introduction

Ongoing terrorist attacks on many structures around the world have increased the importance of analysis of structures under blast loading. Blast loading from explosives generates pressure waves that impose dynamic loading on nearby structures, which can lead to failure and loss of lives (Baker et al., 1983). Ideally, analysis of the dynamic response of blast-loaded structures includes the effect of high strain rates; non-linear, inelastic behavior of concrete and reinforcement; and time-dependent deformations. These combined effects provide complexity, making 3-D computational analysis inevitable in most cases. Examples of computer codes that can perform 3-D coupled analysis are LSTC (2009) and DSS© (2014).

Many researchers used finite element analysis to assess the structural responses under blast loading. Jayasooriya et al. (2011) used LS DYNA to carry out a non-linear elasto-plastic analysis of a 3-D sub frame considering strain rate effects. They studied the damage mechanisms and the extent of damage to assess the residual strength capacity of the key elements that can cause catastrophic failure of large sections of the building, leading to progressive collapse.

In their research into improving the performance of concrete columns subjected to blast loading, Jayasooriya et al. (2014) evaluated the blast response and safety of a composite column made of a central I-beam section embedded in concrete, as a key element in a structural system. They developed a comprehensive model for the composite column using LS-DYNA to capture its behavior when subjected to blast pressure. They concluded that the structural capacity of the column was enhanced by the central steel core, which provided adequate load carrying capacity in post blast serviceability state.

Fu (2013) studied the robustness of a tall building under blast loading. He conducted a 3-D finite element analysis on a 20-storey building using ABAQUS to study its real behaviour under blast loading. Detonation of a typical package bomb charge of 15 kg was simulated on the 12th floor. The blast loading effect was considered through a sudden removal of certain columns, ignoring the duration of the blast load affecting the structures. It was concluded that, for the buildings designed using available design guidance, a small-scale blast such as

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the package bomb can hardly trigger the collapse of the whole building.

Elsanadedy et al. (2014) studied the progressive collapse of a typical multi-storey steel framed building in Riyadh, KSA, due to blast attacks, using the finite element analysis package LS-DYNA. Different blast scenarios were considered by removing columns at different locations in the ground floor. The results showed that the building may undergo progressive collapse, even for a charge weight of 500 kg, which can be easily carried in a small vehicle.

They recommended strengthening the outer exposed ground floor columns by concrete encasement or addition of steel plates. In case the strengthening of column is not enough for resisting the blast loads due to the possible blast scenarios, they suggested some structural modifications such as adding diagonal braces or shear walls.

Altering the design of the external columns of structures using a concrete filled steel tube can generally improve the response to explosions detonated outside buildings.

For example, Ultra-High performance concrete (UHPC) filled double skin tube columns were experimentally investigated by Zhang et al. (2016a) under blast loads. They tested two types of these columns; square and circular inner and outer steel tubes. Only minor cracks were observed in the core concrete with no visible buckling or rupture of steel tubes. Zhang et al. (2016b) also observed that UHPC filled double skin square tubes subjected to blast loads can withstand large blast loads without failure. No steel buckling or concrete crushing was observed. A parametric study using numerical model of this type of columns revealed that the response is dominated by the shape of the outer steel tube not the inner one.

Xu et al. (2016) conducted experimental tests to compare the response of UHPFRC and high-strength reinforced concrete (HSRC) columns under blast loads. They observed three types of major damage modes including flexural, shear and concrete spalling. The results confirmed the superiority of UHPFRC response in terms of crack patterns, damage levels and permanent deflections.

The flexural behavior of concrete filled steel tubes was numerically investigated by Zhang et al. (2015). The results showed good flexural resistance of these columns under static and dynamic loads. Wang et al. (2017) examined the blast resistance and residual strength of concrete filled square and circular steel tube columns. It was found that these columns were still able to keep most of their axial load capacities even after being subjected to blast loads.

Guidelines for designing frame structures against blast loading have been established by several agencies around the world (U.S. GSA, 2003). The merit of the guidelines includes improving reinforcement details and strengthening joins (e.g., adopting the guidelines established for seismic resistance (Drakatos and Dritsos, 2014). However, in their pursuit for simplicity, existing guidelines ignore the initial damage that occurs by the blast loading. This feature was shown to be critical in the course of post blast assessment (Shi et al., 2010). Accounting for initial damage entails full understanding of the response of the various elements of a frame structure after blast loading. It is such need that invokes the use of complex computational means for the analysis such as the one presented in this paper.

Following from the introduction above and the relative paucity of 3-D case studies, this research was conducted on a real 3-D model of an existing residential reinforced concrete structure using the finite element package ABAQUS to investigate how altering the design of the external columns (using a composite section of steel tube and a concrete core) can enhance the structure's performance under blast loading.

2. Details of the 3-D structure

The structure studied in this research is a real, 4-storey residential building made from normal reinforced concrete (in Egypt), and it was originally designed for vertical loads only (Fig. 1). No shear walls were used in the original design. The structural system of the floors is flat plates, with a slab thickness of 20 cm, with an upper and lower reinforcement mesh of 6 Ø 12/m′. The structure has a storey height of 3.0 m each. Section details of the various structural elements of the structure are summarized in Table 1. The plan of a typical floor of this structure is shown in Fig. 1.

Table 1: Details of the structural elements

Element	Type	Position	Section Dim. (cm)	Main Reinf.
C1	Column	Corners	30×30	8Ø12
C2	Column	Edges	30×30	8Ø12
C3	Column	Center	35×35	4Ø16 + 4Ø12
S	Slab	Slab	100×20	6Ø12/m

Two cases were studied for this structure, as follows:

- Case 1: The original structural design, with a blast load of 1.0 ton (2204 lb) of TNT at a standoff distance of 5 m outside the building;
- Case 2: A revised design using an alternative cross section for all external columns facing the blast load (Fig. 2). This revised section is made of a concrete filled steel tube of 200 mm x 200 mm dimensions and 3.5 mm thickness. The axial load capacity of this alternative design is similar to that of the original design with pure reinforced concrete.

The analysis also considered the original case but with a longer standoff distance of 10 m; however, the results of this case are not presented here.

3. Simulation of blast loading

Various methods of interpretation and conversion of explosions into equivalent blast loads with time history are well established in the literature (UFC, 2002). For the purpose of this research, the intention was to apply a blast load that can purposefully inflict damage to the 3-D structure of the base case (Case 1).

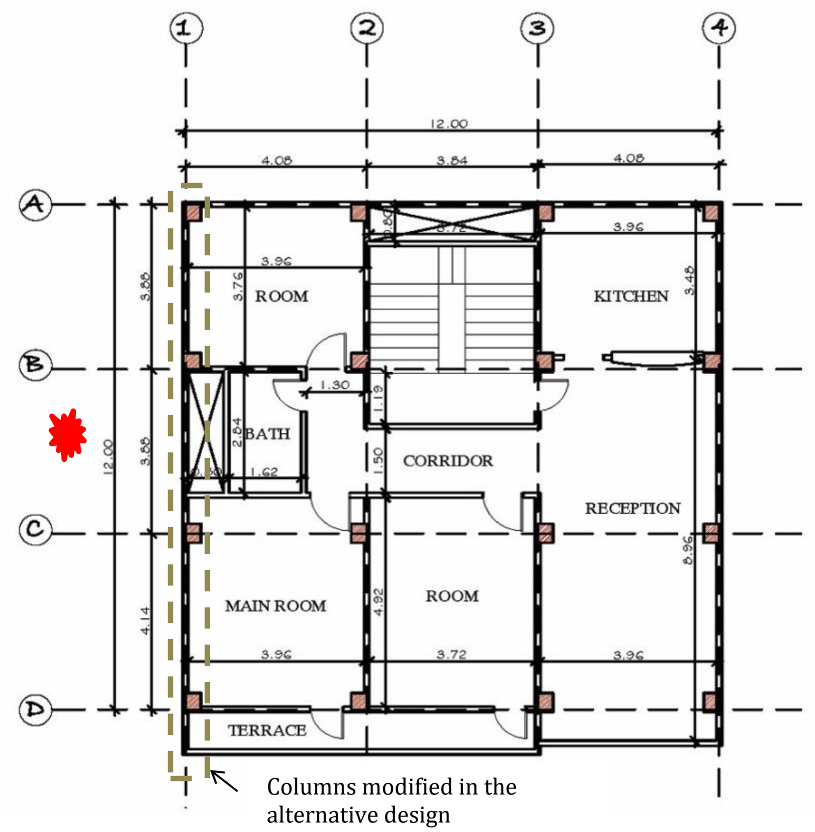


Fig. 1: Typical floor plan of the 4-story structure

To this end, a separate parametric study proved that an arbitrary 1.0 ton (2204 lb) of TNT at a distance 5 m away from the building is adequate. The explosive material was assumed to be at 1 m height from the ground. Different positive phase shock wave parameters for a hemispherical TNT explosion on the surface at sea level were used through the chart developed by UFC 3-340-02. To model the complex pressure-time history resulting from the applied explosion, the idealization depicted in Fig. 2 was made. It simulates the chain of high magnitude shock fronts that become magnified by reflective waves off the building surface.

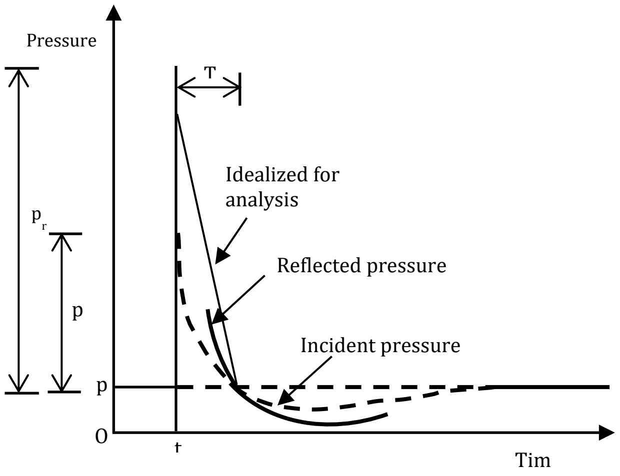


Fig. 2: Incident and reflected pressure (UFC, 2002)

4. Finite element modeling

ABAQUS was used to analyze the behaviour of the 3-D structure presented in Figs. 1-5. The concrete parts were modelled using C3D8/C3D8R elements, which are 8-node solid elements with reduced integration. The rebars in the columns were modelled as truss elements of only axial capacity. ABAQUS constrains the nodes of the truss elements kinematically to the nodes of the contacting solid elements via a fully embedded region algorithm.

The concrete damage plasticity model was used for the concrete material. This model uses the concept of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to model the inelastic behavior of concrete. Fig. 3 shows the stress-strain curves for the concrete damaged plasticity model, for both compression and tension (Martin, 2010). The stress-strain curves are based on the material properties of Chopra and Chakrabarti (1973), which are designed to model the behavior of concrete structures under seismic loading. In the case where the column exposed to the simulated explosion was assumed to be fully damaged (U.S. GSA, 2003), the 'brittle cracking' concrete model in ABAQUS was used to represent column removal. The material parameters of the brittle cracking models were used such that the external columns of the ground floor in the vicinity of the detonation point were removed immediately once the peak wave front reaches the columns after the blast. This treatment was deemed necessary to avoid unrealistic behavior and excessive distortion of the columns, while enabling reliable assessment of the structure's damage.

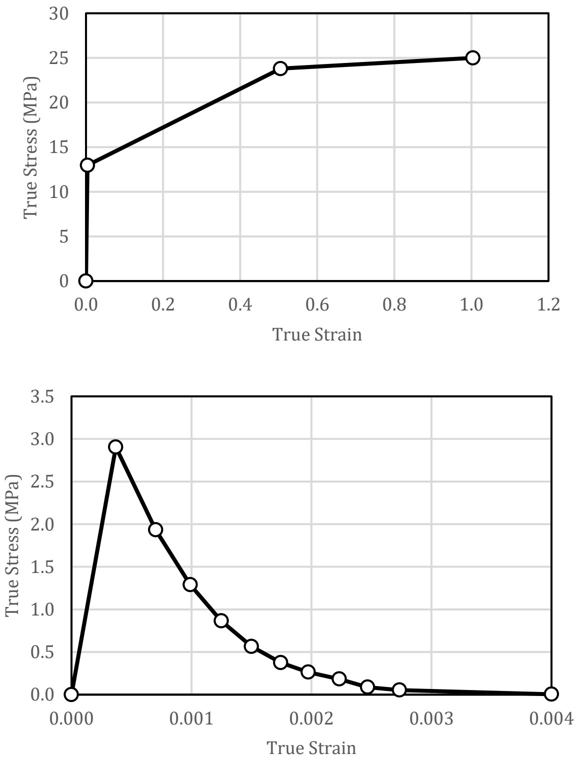


Fig. 3: Stress-strain curve for concrete under compression and under tension (Shi et al., 2010)

The steel used in the model is grade 60 with a yield stress of 420 MPa and an ultimate strength of 700 MPa. The metal plasticity model was used to represent the steel, as shown in Fig. 4.

Blast loading is always associated with high strain rates that can be several orders of magnitude above those resulting from monotonic loading. This rate effect was considered in the current study by multiplying the yield strength by 1.5 for both concrete in compression and steel and by 2 for concrete in tension.

The finite element model of the 3-D structure is shown in Fig. 5.

5. Results

The output parameters chosen to analyze the response of the 3-D structural above are: (1) Von Mises stress, (2) deformations, (3) concrete damage index in compression and (4) concrete damage index in tension. These parameters are presented and discussed below for the 2 cases described above.

Fig. 6 shows Von Mises stress distrubition; for Case 2, the figure shows the stress in both the concrete core and the steel tubes encasing the external columns (i.e. the enhanced design case).

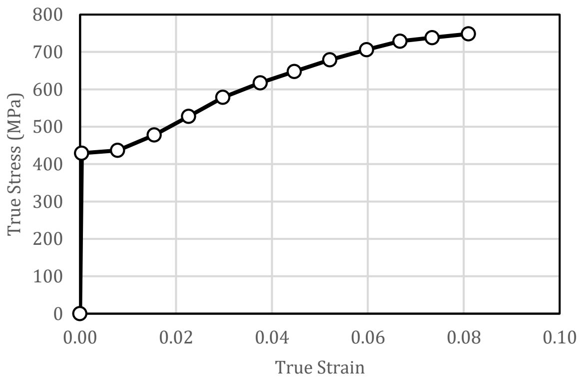


Fig. 4: True stress strain curve for grade 60 steel

The concrete damage index is exhibited in Figs. 7 and 8 for compression and tension, respectively. Fig. 9 shows the time history of the horizontal deformation of certain points on the external columns facing the explosion for the 2 cases. The time history of Von Mises stress for the same points is finally presented in Fig. 10.

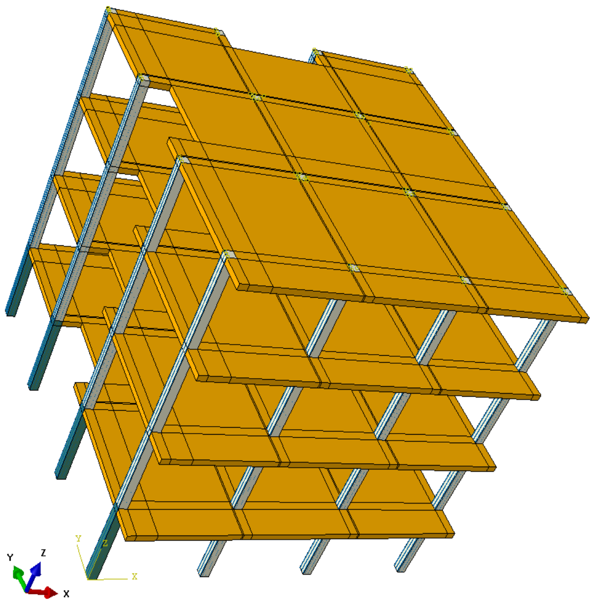


Fig. 5: Finite element model of the structure analyzed in ABAQUS

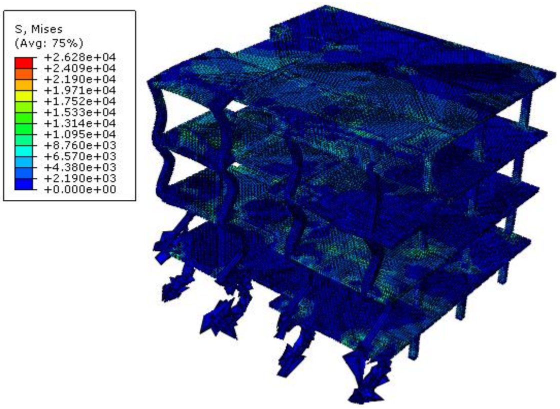
6. Analysis and discussion

As noted earlier, the configurations of the hypothetical blast were chosen to ensure that the original structure (Case 1) undergoes significant damage, especially in structural elements that are in the vicinity of the detonation point. This scenario is actually useful to highlight the benefits that may be imparted by the revised design in which the external concrete columns were replaced by a composite section consisting of a concrete core and a thin steel casing (3.5 mm). However, it should be noted that, even with the latter scenario, the revised columns were intentionally destroyed in the ground floor to eliminate the load path that originally incorporated them. Accordingly, the analysis presented below will focus primarily on the role of the revised external columns. All results presented here are after 200 ms of the load application.

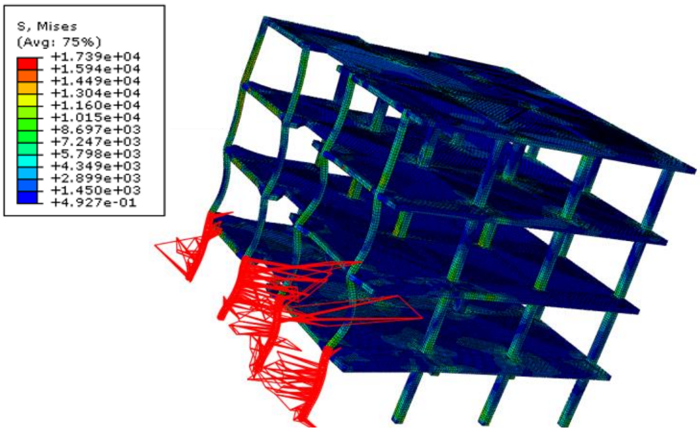
As can be seen from Figs. 6a-10a, under the applied blast load, the original structure indeed experienced high stresses and large deformations, which are a precursor to progressive collapse. As expected, the largest deformation and damage occurred in the exterior columns facing the explosion and within the slab regions behind these columns (Fig. 7a). The progressive nature of the damage was confirmed by analysing the successive frames obtained between time intervals 0 and 200 ms of the output, and this was also confirmed by Ibrahim et al. (2017) for 2D concrete frames. In the base case (Case 1), the size of the damaged zone after 200 ms is substantial, rendering mitigation measures inevitable for the chosen blast scenario. Finally, the seismic effect of the explosion and the resulting out-of-phase behavior is evident from analyzing the deformation diagrams presented in Figs. 10a and 10b (e.g., compare the deformation of Points A to D in these two figures).

The efficacy of the design modifications (i.e. the steel casing around the concrete core) made to the external columns facing the explosion (Case 2) is evident by inspecting the magnitude and extension of the damage index in both compression and tension at 200 ms, as shown in Fig. 7a versus Fig. 7b for compression and in Fig 8a versus Fig. 8b for tension. The significant damage that was experienced by both the external columns above the ground columns and the concrete slabs just behind them is significantly reduced due to the composite effect of the steel tube.

It is now useful to note how the modified design affected the deformation pattern of the structure (compare Figs. 9a and 9b). It is interesting that introduction of the steel casing has changed the mode of deformation dramatically. Specifically, while the deformations of points on the external column facing the explosion in Case 1 increase monotonically from the commencement of the blast loading to the 200 ms interval, the pattern changed in Case 2 with the deformation reversing direction after about 5 ms (refer to Fig. 11 for the loading history of the blast for reference). Within the first 5 ms, the deformation in the blast direction peaks to values much higher than those experienced in Case 1. However, upon reversal of the deformation in Case 2 beyond the first 5 ms, the absolute deformations are very high compared with Case 1 (before they subside again).



a) Case 1

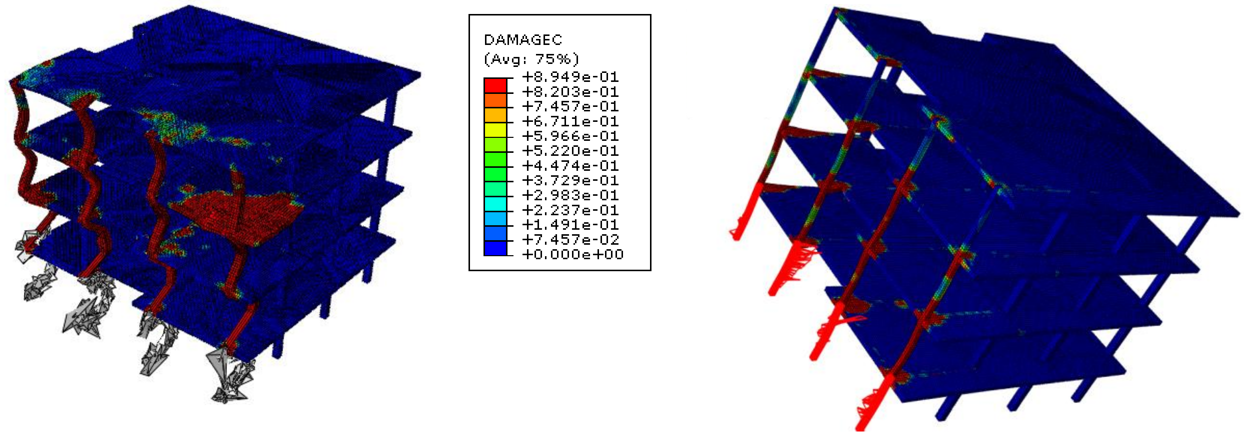


b)Case 2: Concrete core

Fig. 6: Von Mises stress

The observation above is believed to be a result of the high rigidity imparted by the steel tube and the interplay among the various energy components in the structure. This is evident from Fig. 12, which shows variation of the input energy, kinematic energy and internal energy of the structure over time in a normalized fashion for both cases. While the kinetic energy absorbed by the structure reached some 76% of the input energy for the original design in Case 1, the corresponding fraction is only about 35% for Case 1. This is believed to be a result of the higher toughness provided by the steel casing in both tension and compression (evident from the stress-strain curves in Fig. 4). The higher kinematic energy absorbed Case 1 is a strong indicator of the possible overall instability of the original structure and subsequent progressive collapse. Provision of mitigation measures that can reduce this component may be a critical key in designing for blast loading resistance.

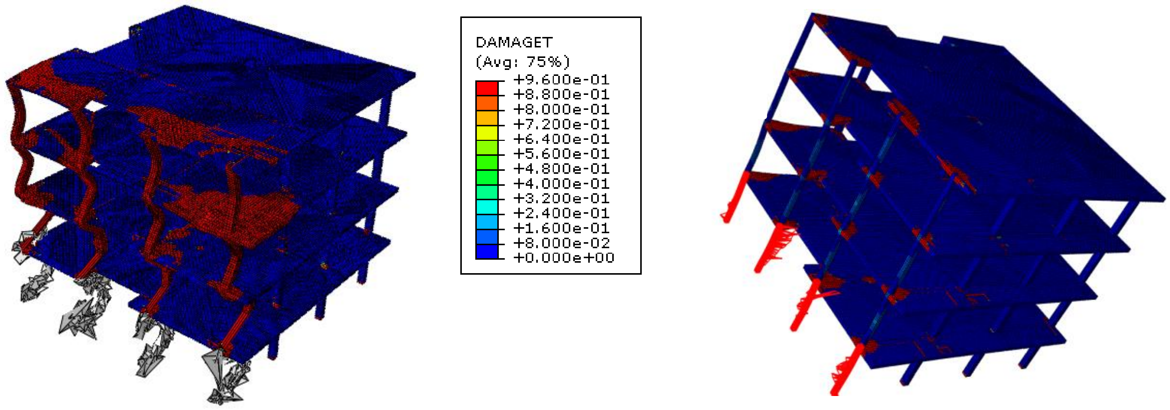
Finally, the time history of Von Mises stresses presented in Fig. 10 indicates that the residual stresses in the case of the composite section are much higher than for Case 1.



a) Case 1

b) Case 2

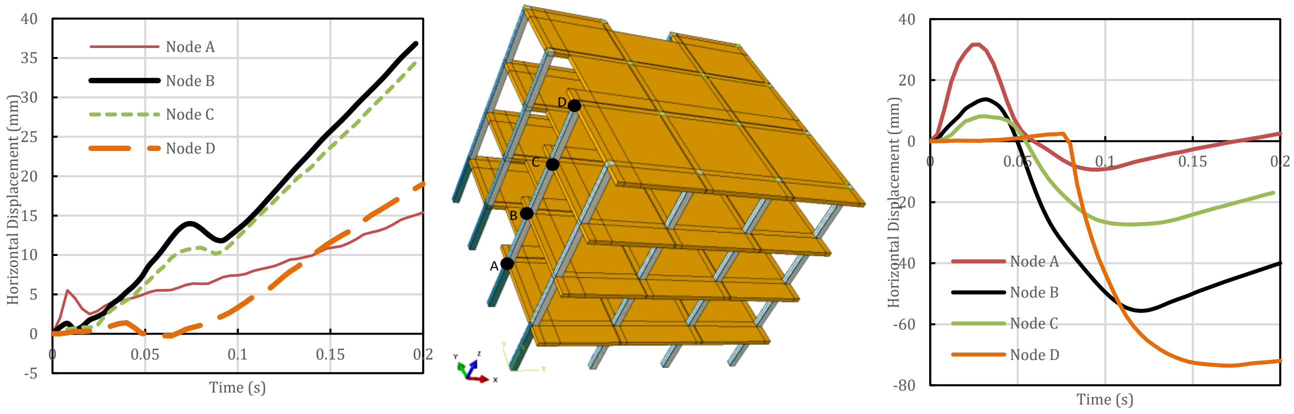
Fig. 7: Concrete damage index in compression



a) Case 1

b) Case 2

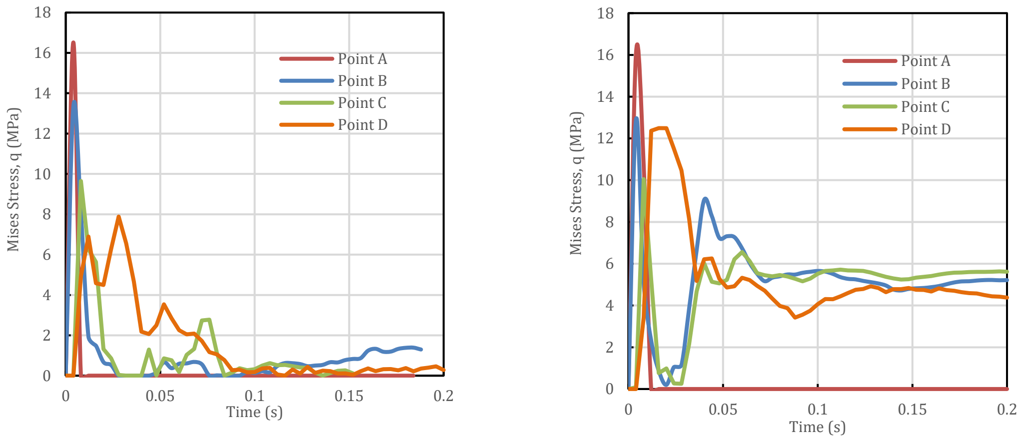
Fig. 8: Concrete damage index in tension



a) Case 1

b) Case 2

Fig. 9: Horizontal displacement at certain points



a) Case 1

b) Case 2

Fig. 10: Von Mises stresses at certain points

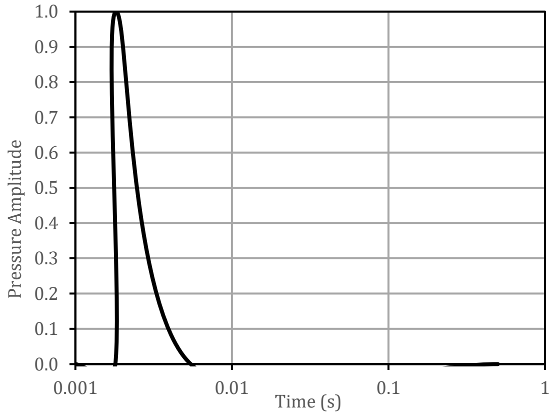


Fig. 11: Blast loading history

7. Conclusion

This paper has presented the results of a series of finite element analyses of a real 3-D structure that was originally designed to resist gravity loads only. The structure is a 4-storey reinforced concrete building, consisting of flat slabs and columns. The software ABAQUS was used to perform the analyses using the explicit dynamic module. The analyses focused on providing insight into the behavior of the original structure before examining the benefit of using an alternative design by encasing each of the external columns facing the blast load into a steel tube. The following conclusions are made from the results and analysis made in this study:

1. Inevitably, the largest possible standoff distance should be selected when designing structures requiring blast resistance to avoid catastrophic collapse.
2. Exterior columns encased in steel tubes can provide tremendous benefits in resisting blast loads and reducing the associated detrimental effects. The improved performance appears to be a result of the dynamic toughness of the steel material, which reduces the kinetic energy uptake of the structure.

Efficiency of mitigation systems can be improved by introducing measures that can reduce the kinetic energy absorbed by the structure due to blast loading.

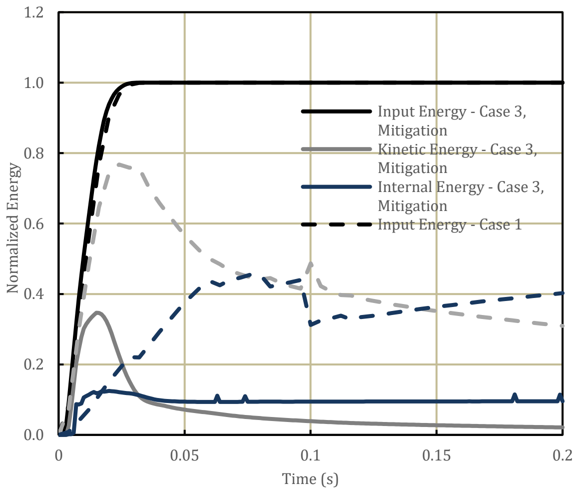


Fig. 12: Energy output: Case 1 and Case 2

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