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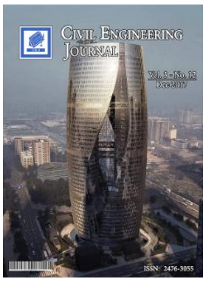

Evaluation of Nonlinear Behavior of Reinforced Concrete Frames by Explosive Dynamic Loading Using Finite Element Method

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Abstract

These days, due to the unpleasant spread of the threat imposed to human life by explosion, the analysis and designating of important structures such as military, governmental and fundamental, and utilities against explosive loading is not anymore a costly conservatism but an inevitable necessity. In this study, the nonlinear behavior of the fortified concrete walls by various carbon fiber reinforced polymers (CFRP) such as glass, carbon and Aramid against the load generated by the explosion wave is investigated by the use of ABAQUS finite element software. In this study, the explosive load, base conditions, wall dimensions, and the features of the material are considered to be the same. The state and the amount of distribution of destruction parameters, tension and displacement in the walls were calculated and the critical areas were identified. Other Two 2 and 4 story models were investigated to examine the frame height and different arrangements of composite fiber reinforcing polymer (CFRP). Similarly, in order to obtain more accuracy in the results, nonlinear behavioral models of concrete and nonlinear plastic damage to concrete have been applied. A 4-node Shell element was used for meshing. The results indicated that, in the reinforced model, about 30% of decrease in the base cutting power is observed, and the reduction of the values for maximum displacement and maximum stress outputs are 30 percent and 45 percent respectively.

Keywords: Reinforcement; CFRP Composite Fiber; Explosion; Concrete Frame; ABAQUS.

1. Introduction

Due to various accidental or intentional events related to important structures all over the world, explosive loads have received considerable attention in recent years. The aim of this study is to further investigate the response of reinforced concrete structures subjected to explosions. Since the capacity of an impulse loaded structure depends on its ability to develop internal work, a parametric study is carried out in order to investigate the important parameters for impulse loaded structures.

Regarding explosive analysis and designing, due to the nature of these charges and applications of the building and also observing economic issues, different levels of performance for the structure under the explosive load are considered. On the other hand, using modern approaches and efficient materials the structure can be reinforced [1].

One of the threats to the urban environment is the explosion. The calculation and estimation of charges caused by the explosion and the conditions under which the charges are imposed on structures is one of the important issues in the

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analysis of the effects of explosions on structures. In order to investigate the effects of explosions on structures, a proper understanding of the effects of explosive loads on materials that are the components of structures must be perceived.

The massive loads imposed to the materials for a short period of time do not fall under the category of the static and dynamic loadings. Due to the impossibility of gaining comprehensive knowledge of the explosion, in many cases, computer-based solutions are well-suited for precise simulation. Knowledge of these cases is useful in analyzes and studies performed in this field [2].

In order to increase the strength of the structure against the explosion-induced loads, there are some commonly applied solutions, among which the most important are the use of local reinforcement such as steel covers and concrete covers for structural sections, as well as adding new structural systems such as a composite cutting steel wall. One of the disadvantages of such methods is that, it imposes significant gravity loads on the structure and ultimately on the foundation, and on the other hand, it requires a lot of time to install, thus it will not be financially favorable. An effective and economical approach to this goal is applying CFRPs to strengthen parts. CFRP composites have been used for about 50 years in structural engineering in the fields of fabrication, retrofit, reinforcement, restoration and refurbishment of existing structures. Over the last decade, a significant growth has been observed in the use of CFRP materials, which are an advanced form of composites. CFRP materials are composite materials which include highly resistant fibers that are put in a polymeric area.

The fibers in a CFRP composite are the main bearer and they exhibit very high strength and stiffness while stretching. CFRP composites are nowadays proposed as a substitute for steel due to their higher resistance, increased corrosion resistance and the convenience of carrying and installing them. Many composites have a very high resistance to fatigue. Unlike steel, CFRP composites do not suffer a gradual softening compared with reciprocating loads or a reduction in hardness prior to any cracking. As a very important advantage, unlike steel, CFRP composites have a high corrosion resistance. Composite materials acts auto tropically under thermal loading due to different thermal expansion coefficients in the same direction with fibers and perpendicular to the fibers. Thus, they stand safe against the thermal activities. But in materials like steel due to their isotropic nature severe destructions take place under thermal pressures. These materials are capable of adapting themselves with the circumstances and they indicate appropriate reaction. Making use of these materials also can lead to considerable increase in the strength of the structure against explosion and decrease of cracking effects by increasing the resistance of the structure.

1.1. Literature Review

An explosion can be characterized as an instantaneous expansion of matter resulting in high pressure and temperature that propagates away from the center of detonation. The result is a load that might differ considerably from the type of static or quasi-static loads normally used for design of structures. Due to the fact that the knowledge of the response of the structures in these situations is limited and the designing methodology often is simplified, there is a great need for further investigations within this subject.

To predict the progressive collapse, few studies have analyzed the effects of column removal under triangular and distributed lateral loads and under external blast load. With respect to column removal scenarios, the corner and external column removal scenarios created higher possibility of progressive collapse under lateral and blast loads [13] and [14].

The impact of blast load on building frames without column removals has also been investigated. One study analyzed the effect of explosion distances on the behavior of a reinforced concrete (RC) frame. Either of explosive quantity or explosion distance affected the damage level of the RC frame [15]. Another study focused on a comparison between a slurry infiltrated fiber reinforced concrete (SIFCON) frame and a regular three-story RC frame under blast load. Using SIFCON improved the response of the frame under blast load [16].

Some studies also have been performed on FRP retrofitting of beams, columns, or beam-column connections and relocating the plastic hinges to improve the load carrying capacity of structures when subjected to earthquake load by pushover analysis. FRP strengthening significantly improved the behavior of these elements and structures [17] and [18].

In the last three decades, researchers imposed requirements for disproportionate collapse prevention, formulated as a result of Ronan Point event. Notes are kept unchanged until these days. Eurocode established different technical regulations regarding the type of structures that should be supplementary checked to progressive collapse [20].

Also, there is a set of governmental documents in the USA, which gives design orientations for structural resistance under extreme loads. Documents are issued by General Services Administration (GSA), Department of Defense and Interagency Security Committee [22]. Those published by GSA provide a detailed methodology in order to reduce the possibility of progressive collapse occurrence for new buildings, using Alternate Path Method and to assess the vulnerability level for existing structures, under extreme loading [23].

The response of reinforced concrete structures due to explosive load has been studied in a long time project performed by Chalmers in collaboration with the Swedish Civil Contingencies Agency (MSB) and Reinertsen [19].

1.2. Methodology

In this study, the issue of the effect of explosion on a concrete frame was simulated using a three-dimensional model of finite element and the ABAQUS / CAE 6.10-1 software. Then, the effects of explosions on CFRP composite fibers and their dynamic response, was investigated based on their features and characteristics. In this model, the beam is modeled using a Wire element. Shell reinforcement sheet with four-sheathed elements, and concrete frame with three dimensional element of Solid were modeled. In this model, the effect of the explosion is put on the frame surface as an external pressure.

In this study, the dynamic behavior of reinforced concrete frame with CFRP coating is studied under explosion charge. Also, concrete modeling of the software is explicitly described and the existed principles and doctrines of the world in the field of structural analysis and structure designing against explosive loads are studied. In order to investigate structural behavior, the spreading of waves caused by the explosion and the interaction of these waves with the structure is analyzed in different models.

2. Explosion

The explosion is a very fast release of energy in the form of light, heat, sound and shock wave. The hit wave consists of a very dense air that moves rapidly from the explosion source to the outside with ultrasonic velocity. With the expansion of the hit wave, the amount of pressure decreases rapidly (proportional to the third index of the distance) and is reflected after reaching a rigid surface, and its amount may increase up to thirteen times. The magnitude of the reflection coefficient is dependent on the proximity of the explosive material and the angle of the collision wave. The Pressure also decreases through time (exponentially). In explosive loading, the loading time is very short and usually expressed in terms of milliseconds (milliseconds).

The analysis of the effect of explosion loading on structures has begun since the 1960s. In 1959, the US Army published an article entitled "structures Resistant to the effects of accidental explosions". The next editions of this work, entitled TM 5-1300 in 1990 and UFC 3-340-02, were presented in 2008 [3]. Crowfsword et al. (1997) studied the columns reinforced by CFRP sheets. In this experimental study, they studied the effect of reinforcing method of concrete columns on CFRP sheets [4]. Luc chini is one of the researchers who have conducted many studies on explosions. In 2006, together with Lewig, he examined the behavior of concrete slabs under the impact of explosion.

In this research, he initially experimented with concrete slabs for explosives, and then compared the results with the modeling obtained by ABAQUS and ANSYS software. After displaying the correctness of the modeling, they tried to determine the relationship between the diameter of the hole induced by the explosion, weight of the explosives and the location, and at the end, they carried out a comparison between the models and the software used and, in each case, they described their weaknesses and strengths [5]. In 2008, Shi et al. reviewed the pressure-shock diagram and predicted the damage rate of concrete columns under explosive loading and they presented their proposed method for predicting damages [6].

3. Damaged Concrete Model

In this model, nonlinear behavior is expressed using elastic damaged isotropic and tensile stresses. This model can be applied in static and dynamic computing.

3.1. Tensile Cracks

Completion of the stretch level is controlled using and the hardening variables $\varepsilon_t^{pl}, \varepsilon_c^{pl}$ which are related to the failure mechanisms under compressive and tensile loading, respectively. In fact, $\varepsilon_t^{pl}, \varepsilon_c^{pl}$ are equivalent to plastic. The concrete stress-strain diagrams are presented in single axis stretching and pressure bellow. Due to uniaxial stretching, the stress-strain curve varies linearly which is associated with the onset and expansion of tiny cracks in concrete. Passing through that point, they appear as visible cracks, which are represented by a softening curve in the strain stress space (Figure 1).

3.2. Pressure Crackups

Under the uniaxial pressure, the response will be elastic to the point of flow, and the behavior in the plastic region is generally expressed as a hardening curve, which ultimately becomes a curvilinear curve by reaching the final stress. In spite of its relative simplicity, this model satisfy the basic concrete properties [7].

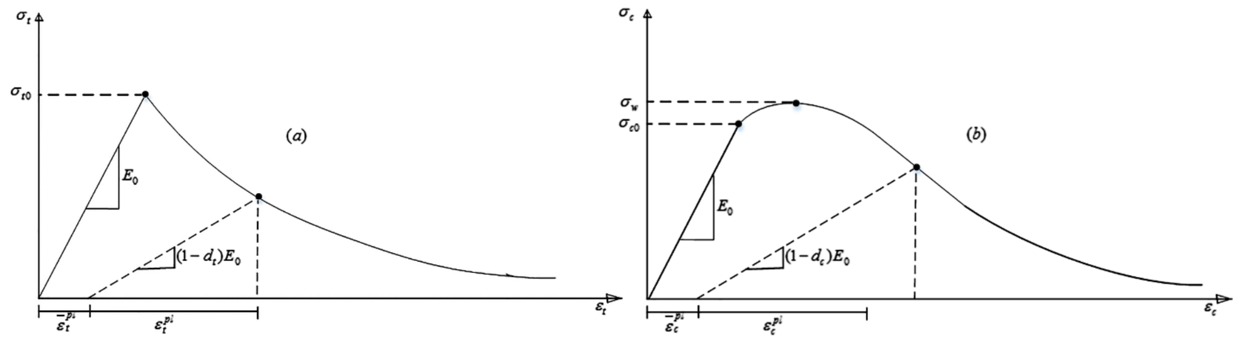

Figure 1. Concrete response under uniaxial loading (a) at strain elasticity, (b) at pressure [7]

Stress-strain diagrams under uniaxial loading have the ability to convert to plastic stress-strain curves, which is done automatically by ABAQUS software using given stresses and non-elastic strains inserted into the software.

$$\sigma_t = \sigma_t\left(\varepsilon_t^{pl}, \dot{\varepsilon}_t^{pl}, \theta, f_i\right) \tag{1}$$

$$\sigma_c = \sigma_c\left(\varepsilon_c^{pl}, \dot{\varepsilon}_c^{pl}, \theta, f_i\right) \tag{2}$$

Where $(\varepsilon_t^{pl}, \varepsilon_c^{pl})$ are the plastic strain equivalent to pulling and pressing. $\varepsilon_t^{pl}, \varepsilon_c^{pl}$ Are the rate of plastic strain equivalent to tension and pressure, as well Temperature and other field variables are defined [8].

4. Loading

Buildings can be effective in decreasing or minimizing damages in terms of behavior against the effects of explosions. Because concrete Reinforced buildings have a massive capacity to absorb more energy than steel buildings, they can indicate better reaction in large bursts; the other advantage of concrete is that it can also withstand compressive loads by itself. On the other hand, the stretch is tolerated by the bars, while in steel buildings steel has the same capacity for pressure and strain.

The explosion wave results from the rapid rise in air pressure from the atmospheric point to the peak explosion pressure, which results in a rapid reduction in the atmospheric pressure of the substrate and then a gradual increase in atmospheric pressure. Therefore, the explosive wave has two phases. The rapid rise in pressure that results in an atmospheric increase in the name of a positive phase or a pressure phase and a decrease in pressure to the atmospheric pressure that leads to a return to the atmospheric state called the negative phase or suction phase.

At a certain distance from the site of the explosion, through time, the pressure of that place suddenly rises to reach its peak. After that, the pressure drops too slowly and goes down to the ambient pressure and even lower.

In the explosion, a law is called the scaled interval is used to find other parameters of these values. The amount of pressure and impact released from the explosion on structures is comparable to empirical formulas, all of which are derived according to the scaled interval law. The relationship between the maximum pressure and the explosion at a given distance is given by the following formula [9].

$$P/P_a = \frac{808\left[1+\left(\frac{z}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{z}{0.048}\right)^2}\sqrt{1+\left(\frac{z}{0.32}\right)^2}\sqrt{1+\left(\frac{z}{1.35}\right)^2}} \tag{3}$$

Where, P stands for the pressure of the explosion and pa stands for the pressure of the atmosphere. Also Z is a scale parameter calculated from the following equation.

$$Z_G = \frac{R}{\sqrt[3]{W}} \tag{4}$$

Where, R is the distance from the explosion and W is the mass of the explosive substance equivalent to the TNT.

5. Numerical Modeling

5.1. Calibration

The results of Chengs experimental test is used for verification of this numerical study [15]. Chen used a test specimen of reinforced concrete with 100*100*7cm in length, width and thickness, respectively. They used 5 specimens without any reinforcement and 13 with CFRP reinforced in tension surface (Figure 2).

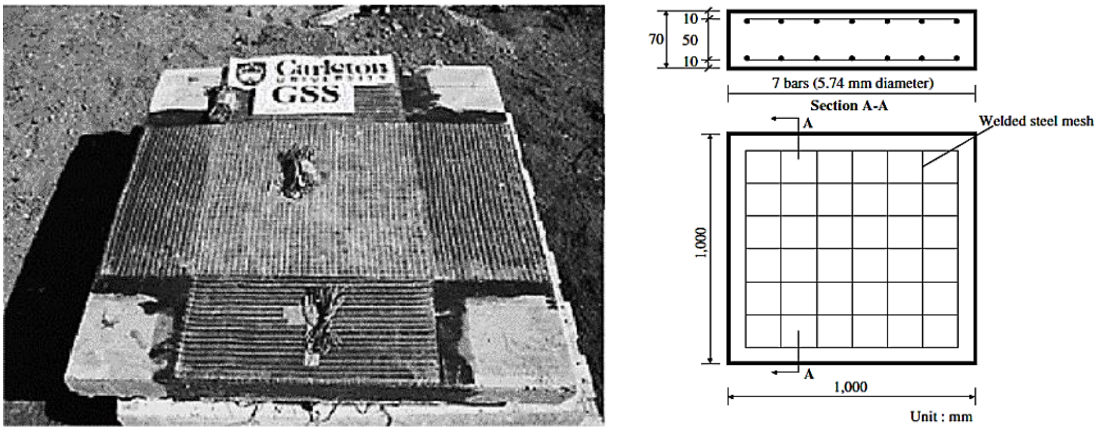

Figure 2. Experimental reinforced slab used for verification [15]

The mechanical properties of CFRP and explosion specification is according to (Table 1 and 2). Also, the results of experiment about respond of CFRP reinforced slab against various blast loading is in (Figure 2). To verify the model, a finite element model is developed according to geometrical and mechanical properties of test specimens. Then, after applying the boundary conditions, the various blasting loading applied to the FE model. Numerical results in compare with experimental results are shown in (Figure 3) which represent the proper FE modeling.

Table 1. Mechanical properties of CFRP

Ultimate strain (%)	E (GPa)	Tensile strength (MPa)	Thickness (mm)	Density (kg/m^3)
2.1	72.5	580	1.2	2100

Table 2. Blasting test specifications

Test No.	Distance (m)	Weight (kg)	Z (m/kg$^{1/3}$)
1	3	18	1.1
2	3	27	1

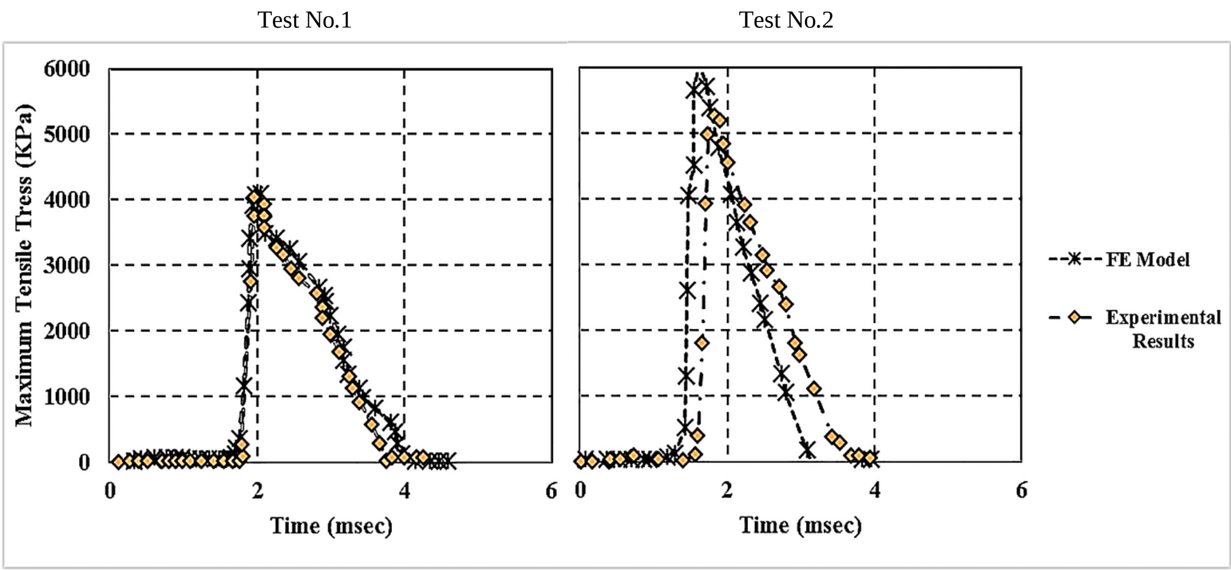

Figure 3. FE results in compared with experimental result for verification of models with blasting loads

5.2. FE Model

This section comprises of details of building model including dimensions of the building frame, material properties considered and details of the frame modeling. The selected model is a reinforced concrete frame with two spans and three floors. Its columns are 40 cm in size. Dimensions of beams like columns are square and dimensions are $40 \times 40\ cm$. The height of the floors is 3 m and the length of the span is 4 m (Table 3).

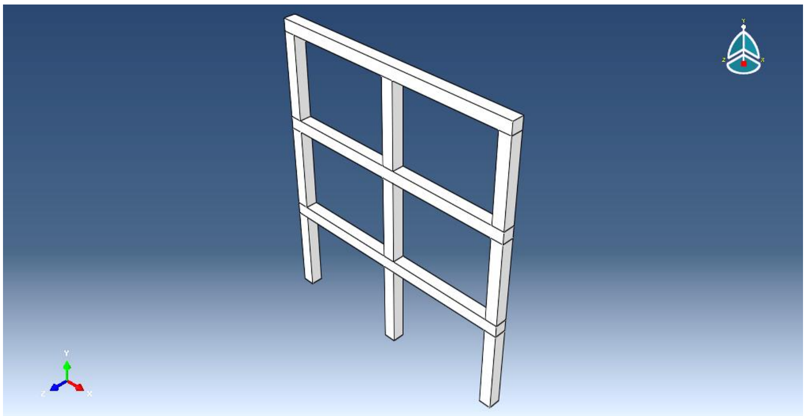

Figure 4. Geometric view of concrete frame

The concrete frame is equipped with longitudinal and transverse reinforcements. The longitudinal reinforcement of the column is of a graded one of size 16, the number of which is 8 at the cross section. The longitudinal reinforcements of the beams were of a size 20, with four armatures placed in four corners of the section. Reinforcements are size 10, which are located in interval of 10 cm in beams and frame pillars.

Table 3. Geometrical properties of concrete frame

Beam reinforcement	Column reinforcement	Opening length	Floor height	Beam dimension	Column dimension
No.20 4@30cm	No.16 8@15	4m	3m	40cm*40cm	40cm*40cm

The columns of Concrete frame are reinforced by 0.44 mm thick CFRP fibers, and in order to ease numerical modeling, they have been considered in integrated forms and completely covered around the pillars. The purpose of this chapter is to investigate the effects of explosions in this strengthened reinforced concrete frame.

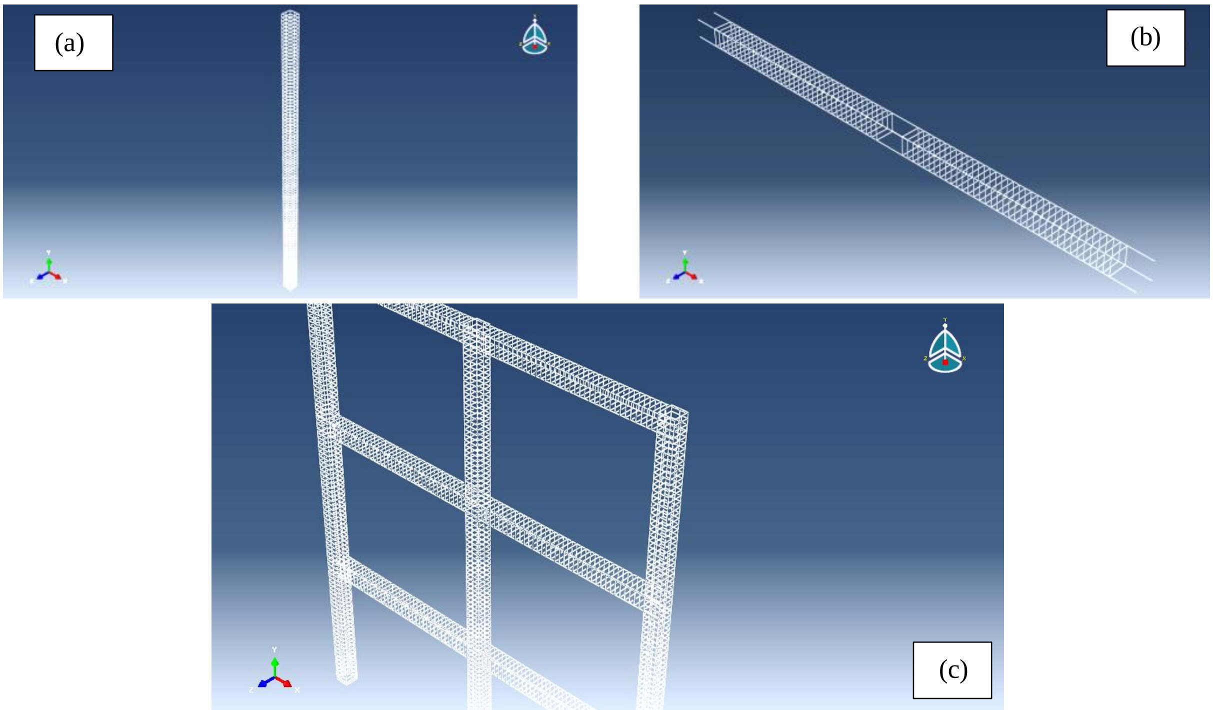

Figure 5. The geometric view of the used rebar; (a) the rebar of the column; (b) the rebar of the beam; and (c) the entire rebar of the concrete frame

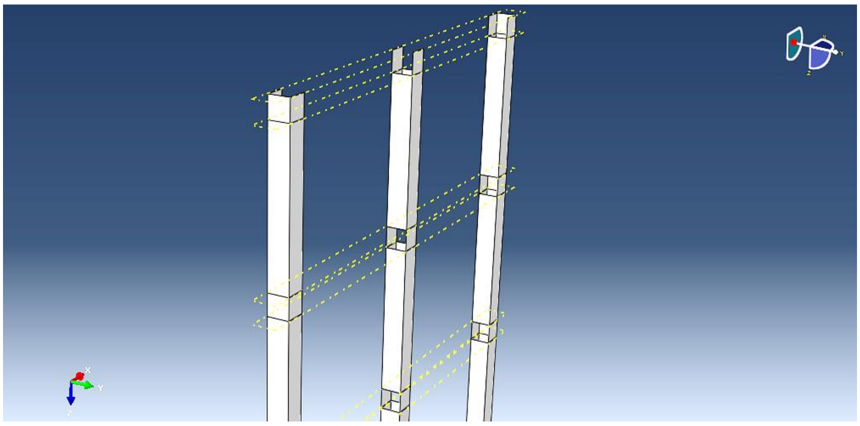

Figure 6. Geometric View of CFRP Composite Hinge Columns

5.3. Mechanical Features of Steel

Nonlinear behavior with kinematic hardening is selected for all species. The plastic behavior of the model is selected based on the Van Maisz fluctuation test and the ASTM A572 stress-strain chart. According to (Figure 7), Young's modulus, the Poisson coefficient of 0.3 and density of 7850 are considered [10]. And nonlinear behavioural model of steel is consistent with (Figure 7).

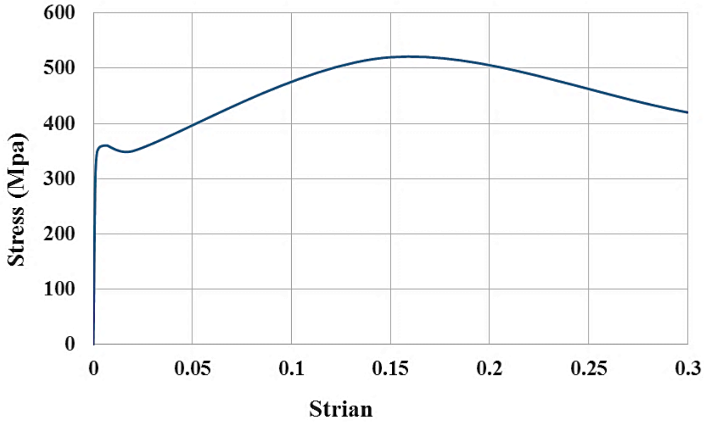

Figure 7. Non-linear behavioral model of steel [11]

5.4. Mechanical Property of CFRP Composite

The density of composite fibers is 1200, the Young's modulus and Poison ratio are 22 Gpa and 0.3 respectively [12].

5.5. Mechanical Property of Concrete

Here, the density of concrete is 2450 kg/m^3, the modulus of elasticity and the Poisson coefficient for mechanical properties in the elastic state are 0.64 and 2.64 MPa, respectively. Also, regarding the definition of the behavioral model of plastic damage model of the concrete, the nonlinear behavioral model of concrete obeys the following figure (Figure 8).

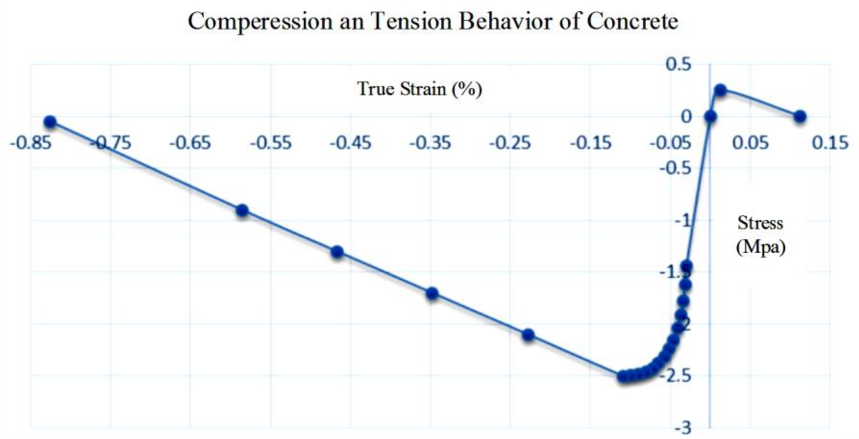

Figure 8. Nonlinear Behavioral Model of Concrete [12]

6. Analyzing the Numerical Model

In (Figure 7), the results of the tensile stress are shown in the last analysis time, and the numerical results are presented below.

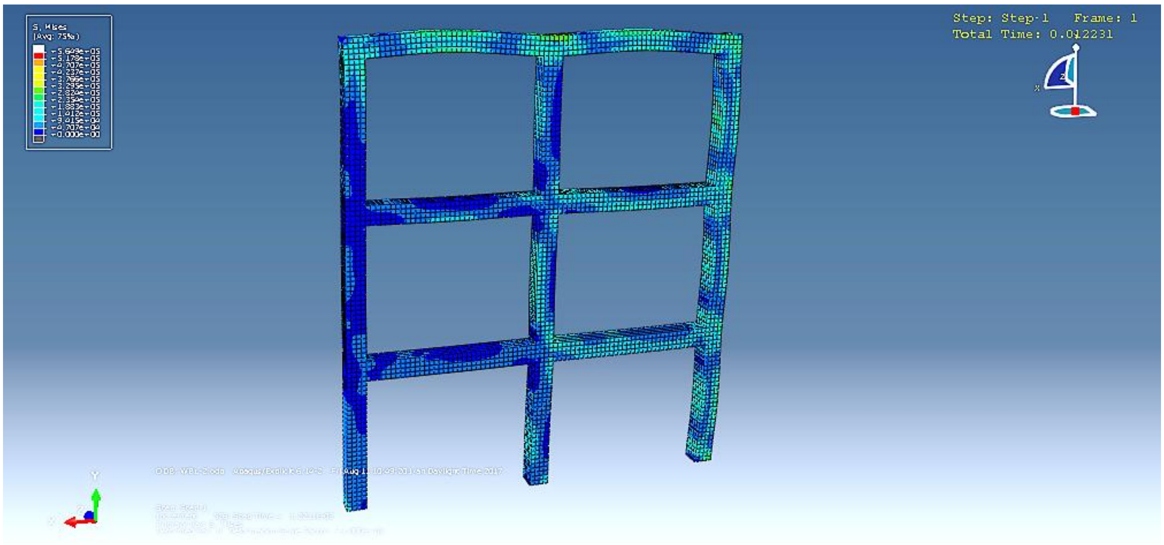

Figure 9. Tension contour in the modeled frame

In order To evaluate the retrofitting method with CFRP sheets, reinforced and non- reinforced concrete columns are evaluated. In this study, according to the UFC regulations the values of 1.2 for concrete and steel yield stress and 1.05 for the final stresses of steel, the behavior of the columns under bending explosion loading was determined based on the dynamic increase frequency (DIF) [12].

Table 4. The three explosion rates considered in this research

Number of the explosion	TNT (kg)	Z (m/kgl/3)	Pr (Mpa)	t_0
1	15	1.7	2.1	4.88
2	30	1.2	3.5	6.4
3	65	1	6.9	7.1

The values of P_r and t_0 are the maximum reflectivity pressure of the explosion and its time length, which are adopted from UFC Code. Performing nonlinear dynamic analysis on non-reinforced and reinforced samples under these three loading rates, it is observed that the column without reinforcement of these three explosive loading rates in the explosion number 2 enters completely into the plastic zone, and it could not bear the explosion number 3. However, the reinforced pillar tolerated all three explosion rates and had acceptable forms. The maximum value of displacement (Xm) and maximum tensile stresses in the longitudinal and transverse grooves of the species are shown in (Table 5).

Table 5. Maximum values of displacement and maximum stresses of the steel

Number of the explosion	Maximum strain tension (MPa)		Xm
	Longitudinal steel	Traverse steel	
Not reinforced column			
1	167	247	27
2	495	370	177.2
3	-	-	-
Reinforced column			
1	60	15	2
2	67	51	4.92
3	315	294	15.94

The results above are derived from nonlinear dynamic analysis by the ABAQUS finite element software. The positive effect of retrofitting RC columns with CFRP sheets is clearly observable.

7. Conclusion

In this study, using finite element modeling, the behavior of the column and reinforcement with CFRP sheets under explosive loading were studied. Due to the lack of experimental results and the high cost of empirical work in the area of explosion, today, numerical modeling is a more favorable method that should be used more and more and it should be tried to increase the accuracy and realization of the model.

Reinforcement using CFRP sheets has had a significant effect on the reduction and displacement of the column and tension in steel bars. This value for the maximum displacement is about 30percetnt. By the increase of loading values, the effect of improving the performance of reinforced columns increases. It was observed that the maximum tension was in the longitudinal columns, where, after loading, the tension reduced by about 43percent.

Among the different levels of the column under the explosion, side of the structure facing the explosion is of particular importance and the back sides and left and right sides of the explosion are respectively of less importance. In the third sample, the weight of the explosive of 65 kg and the scale factor of 1, due to the proximity of explosive materials and its high weight, the frame without the fibers is completely destroyed, while in the equipped state, the frame has been able to maintain its function.

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