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Numerical study of progressive collapse in reinforced concrete frames with FRP under column removal

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Abstract. Progressive collapse is one of the factors which if not predicted at the time of structure plan; its occurrence will lead to catastrophic damages. Through having a glance over important structures chronicles in the world, we will notice that the reason of their collapse is a minor damage in structure caused by an accident like a terrorist attack, smashing a vehicle, fire, gas explosion, construction flaws and its expanding. Progressive collapse includes expanding rudimentary rupture from one part to another which leads to total collapse of a structure or a major part it. This study examines the progressive collapse of a 5-story concrete building with three column eliminating scenarios, including the removal of the corner, side and middle columns with the ABAQUS software. Then the beams and the bottom of the concrete slab were reinforced by (reinforcement of carbon fiber reinforced polymer) FRP and then the structure was re-analyzed. The results of the analysis show that the reinforcement of carbon fiber reinforced polymer sheets is one of the effective ways to rehabilitate and reduce the progressive collapse in concrete structures.

Keywords: progressive collapse; concrete frame; column elimination; reinforcement; FRP

1. Introduction

As defined by the American Society of Civil Engineers, progressive collapse is an expanding rudimentary rupture from one component to another which leads to total collapse of a structure or a major part of it ASCE7 (2002). Progressive collapse matter chronicles, as an engineering problem caused the collapse of Ronan Point building in 1968. This 22-story building was made of premade bearing walls screwed together. A gas explosion on the 18th floor only destructed one of the premade walls in that floor. This destruction collapsed upper roofs on the bottom floors till the ground level which made it a progressive collapse (NIST2007). Then, on 25 January 1971, two third of the 16-story Finance building in Boston which was under construction by King and Dellate collapsed and killed 4 people, (2004). In another incident in 1995, a car bomb exploded near Alfred Mora building which collapsed almost half of the roof due to progressive collapse effect (genecorely *et al*. 1998). The last incident caused by progressive collapse was the collapse of 101-story twin towers of New York on 11 September 2001. In this catastrophic incident, two passenger airplanes crashed into the towers and 2830 people were killed (Zdenek and Verdure 2007). There are lots of regulations to study progressive collapse. The regulations of general service administration of USA and department of defense offer solutions to increase indeterminacy in structures, transferring loads from detours and, increasing local resistance in structures (GSA2003, DoD 2010). In addition, most static analysis procedures do not model the impacts of failed members after the initial partial collapse (Kokot *et al.* 2012, Ruth *et al.* 2006, Wang and Li 2011). In order to use concrete structures safely, restoration and reinforcement is necessary. One economic method is to use FRP plates (Fam and Rikalla 2003). FRP materials had been used since the mid-1980s for reinforcing concrete structures (Meier *et al* 1993). FRP materials are composite materials with high resistance yarns having different heat expansion coefficient in two directions along with yarns and vertical to them that under heat loading act in an orthotropic way, so does not get damage under heat strains (Guideline for Design Specification of strengthening 2006).

There are many studies on progressive collapse in reinforced concrete structures which we will peruse some of them. Bao *et al*. (2008) offered a two-dimensional macro model consisted of 2 beams and 3 columns in order to simulate the non-linear behavior of beam-column connections in reinforced concrete structures. Comparing their results to experimental results, they found that using macro model is a proper approach to analyze progressive collapse (Bao *et al*. 2008). Tsai and Lin studied an 11-Story concrete building in Taiwan using seismic design and column failure at the bottom floor with 3 types of analyzes (static, nonlinear static and nonlinear dynamic). They found that seismic design is efficient in decreasing progressive collapse in concrete buildings (Tsai and Lin 2008). Gregorio and et.al focused on the analysis of a specific volcanic event constituted by the pyroclastic deposits, falling on the roofs due to gravity, the so-called air falls deposits (Gregorio *et al*. 2010). Ceroni studied concrete beams reinforced with FRP and derived that the load resistance of concrete beams reinforced with FRP increase

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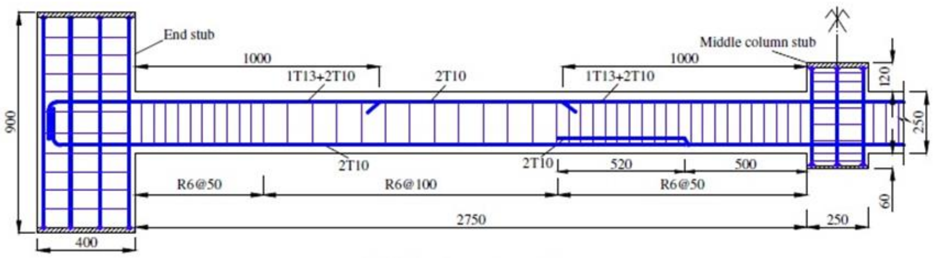

(a) Seismic specimen S1

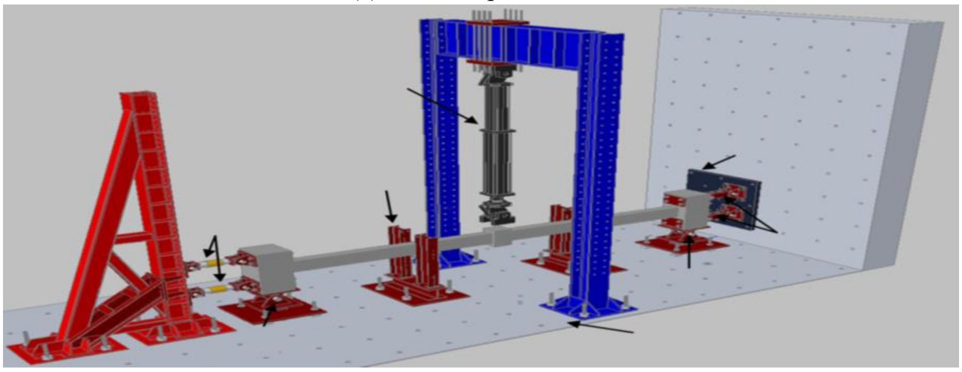

Fig. 1 Details of reinforcement and loading of the experimental model (Yu and Tan 2011)

from 26% up to 50% but this quantity for steel beams is less than 1% (Ceroni 2012). Hoda Helmy and et. al in a study, analyzed progressive collapse in a reinforced concrete structure with shear walls. They investigated eliminating side and corner columns and concluded that, not considering the slab effect will lead to incorrect behavior of structure and uneconomical plan (Helmy *et al.* 2012). In order to improve the reliability of the modeling procedure, researchers also employed methods such as robustness evaluation indeterminacy concept and vulnerability assessment of the structural system (Formisano *et al*. 2015). Ren *et al.* studied the resistance against progressive collapse in concrete slabs. In the study two concrete frames, one with and one without the slab had been analyzed and the middle column eliminated. The model was loaded with a 200-ton jack. The effects of two conditions with and without concrete slab were investigated. Based on the results obtained, considering the effect of Concrete slab increased resistance by 45.40% compared with not considering the concrete slab against progressive collapse. (Ren *et al.* 2014). Formisano *et al.* studied a research activity concerning the seismic behaviour of framed structures after damages deriving from application of an exceptional load Based on the results of a pushover analysis, a theoretical formulation to evaluate a simplified force-displacement curve for seismic appraisement of a structure damaged from an extreme event is reported (Formisano *et al*. 2016).

Progressive collapse is an overall structural response which involves both material and geometrical nonlinearity of structural members. Due to the complexity, it is necessary to decompose overall structures into multi-story, single-story and beam-column connection levels to obtain an in-depth understanding of their load-transfer mechanisms, load and deformation capacities. Reinforced concrete (RC) framed structures are one of the widely used structural systems. Over the last decade, a great many efforts have been dedicated to investigating the progress collapse performance of single-story RC beam-column substructures (Yu and Tan 2017).

In nature, progressive collapse is a dynamic response. However, the dynamic tests of RC beam-column substructures due to middle column removal by contact detonation and by free-fall have indicated that the failure patterns in the dynamic tests are identical to those in quasi-static tests, and thus the quasi-static results are capable of representing progressive collapse performance of RC substructures (Pham and Tan 2017). Ferraioli and et.al studied a design procedure that combines both progressive collapse design under column removal scenario and capacity design to produce the hierarchy of design strengths. The proposed procedure was applied to two typical steel framed building using linear static, nonlinear static and nonlinear dynamic analysis. The results showed that it is unsafe to assume that a structure designed for seismic loads can withstand accidental or abnormal load conditions (Ferraioli *et al*. 2018).

In this study, we pursue the effect of using CFRP on reinforcing the structure against progressive collapse. For this purpose, a 5-story building is modeled using finite element software, ABAQUS. Comprehensive research was conducted on three positions elimination including: corner, side and middle in each floor using nonlinear dynamic analysis. Then, the beams and the underside of the concrete slab were reinforced using CFRP sheets with a total thickness of 5mm. The effect of CFRP reinforcement on displacement and bearing capacity was investigated.

2. Development and validation of the models used

To verify the results obtained from ABAQUS/CAE, a

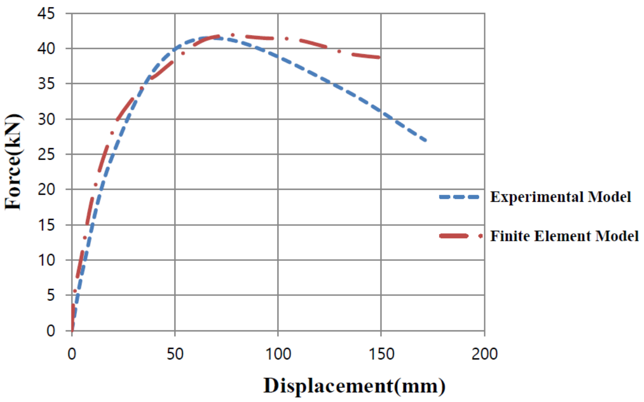

Fig. 2 Details of reinforcement and loading of the experimental model (Yu and Tan 2011)

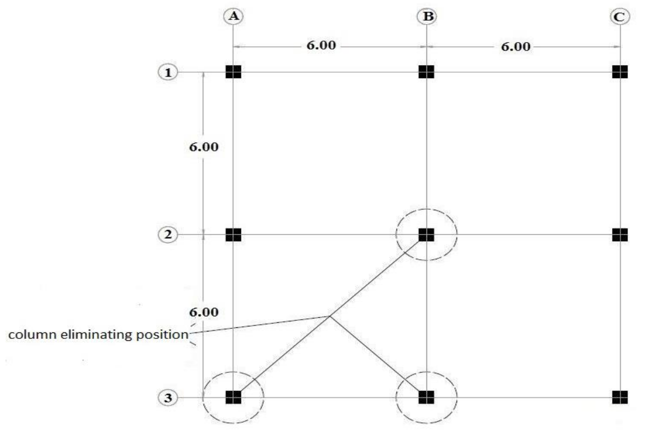

Fig. 3 column placement and column eliminating position plan

Frame studied by Yu and Tan (2011) was selected**.** The test model includes two samples with seismic design and without seismic design. Modeling software is modeled with seismic design. For this purpose, concrete with compressive strength of 31.2 MPa was used with rebar with a yield stress of 310-511 MPa**.** Fig. 1 shows details of reinforcement and loading of the experimental model**.** Fig. 2 shows the results of experimental and numerical modeling of the Progressive collapse in the form of displacement-force chart. As shown in the figure, there is a good agreement between the numerical and experimental modeling. The ultimate loads in the analytical and experimental models were 41.94 and 41.6 kN, respectively.

3. Modeling

In this study, A 5-story residential building in Sanandaj city was selected as the base model. The residential building with five floors is constructed with an area of 167 m^2 in each floor. The story height was 3200 mm. The building was designed with a concrete structure with an average ductility according to ACI-08 Regulation using ETABS. The building consisted of 6000 mm longitudinal and lateral outfall with the position of eliminating columns, as shown in Fig. 3.

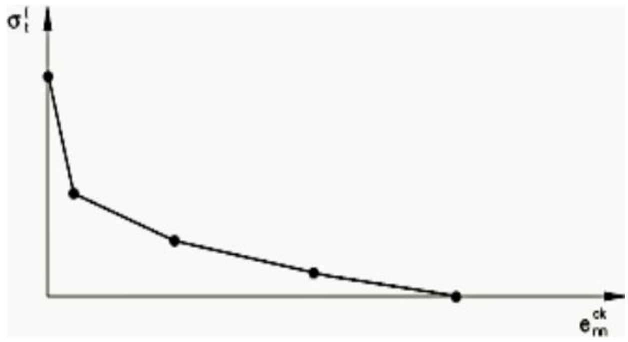

Fig. 4 Post failure stress-strain curve (Abaqus analysis user's manual 6.10)

Table 1 Properties of the materials used

Property	Concrete	CFRP	Epoxy	Steel
Density kN/m^3	24	16	-	78.5
Yield Strength, f_y (MPa)	-	-	-	400
Modulus of elasticity (GPa)	23.39	120	7	210
Tensile Strength, f_t (MPa)	3	3800	25	570
Compressive Strength, f_c (MPa)	25	-	70	-
Poisson's ratio	0.2	0.3	0.3	0.3

Table 2 Section specifications and beam reinforcement (mm)

Section Floor	Size Section		Top rebar	Bottom rebar	stirrups
	Width	Depth			
1	500	300	5ϕ20	3ϕ20	ϕ10
2	500	300	5ϕ20	3ϕ20	ϕ10
3	400	300	5ϕ20	3ϕ20	ϕ10
4	400	300	5ϕ20	3ϕ20	ϕ10
5	400	300	5ϕ20	3ϕ20	ϕ10

In this study, nonlinear dynamics finite element analyses were performed using ABAQUS. Concrete compressive strength is 25 MPa with modulus of elasticity of 23.39 GPa and steel ultimate strength of 570 GPa. The properties of the materials are described in Table1. Also, concrete slab thickness is considered 100 mm. In this study, Brittle Cracking of concrete is used for modeling concrete behavior. In reinforced concrete the specification of post failure behavior generally means giving the post failure stress as a function of strain across the crack Fig. 4. Where σ_t^I is remaining direct stress after cracking, e_{nn}^{ck} is direct cracking strain. In the model, it is assumed that compressive behavior of concrete is always linear and also the elastic behavior that presents the material behavior before cracking must be defined. However, it is defined for reinforced concrete; it can also be defined for not reinforced concrete. There is possibility of deleting element based on breaking damage criterion. For failure criteria at any time in any direction strain amount reaches 0.001 concrete elements of the model will be deleted. In the study, outfall beams which their columns are eliminated get wrapped completely.

Reinforcement details and beam section dimensions are shown in Table 2. Reinforcement details and column section dimensions and specifications are shown in Table 3. The stirrups distance is considered to be 100 mm. The 3D model

Table 3 Reinforcement and column section dimensions and specifications (mm)

Section Floor	Size Section		Rebar	stirrups
	Width	Depth		
1	450	450	3ϕ20	ϕ10
2	450	450	3ϕ20	ϕ10
3	450	450	3ϕ20	ϕ10
4	450	450	3ϕ20	ϕ10
5	450	450	3ϕ20	ϕ10

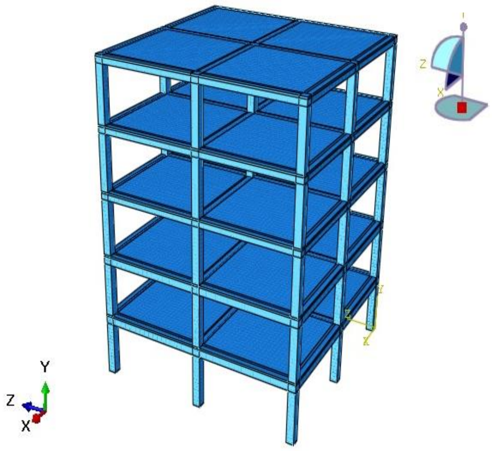

Fig. 5 3D model of the structure in ABAQUS

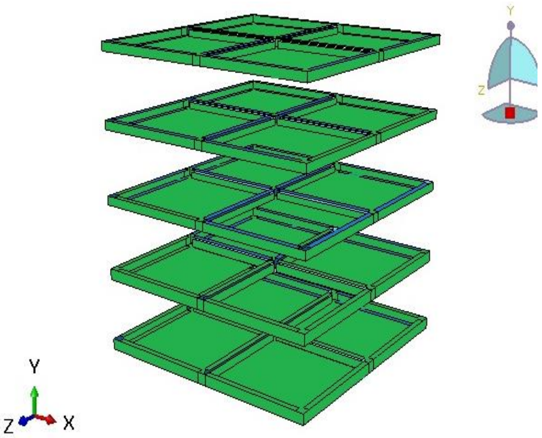

Fig. 6 Reinforcement pattern of specimens

of the structure in ABAQUS software is shown in Fig. 5.

For the purpose of wrapping of all beams, 5 CFRP layers with total 5 mm thickness are used. The CFRP sheets used in this study have bidirectional fibers with wrapping angles of 0° and 90°. The specimens with a 5770×5770 mm, For the underside of concrete slabs and 5500×500 mm, and 5500×400 mm, 5500×300 mm, for beams from the first floor to the fifth floor. Fig. 6 shows Reinforcement pattern of specimens.

A uniform dead load of 2.0 kN/m is used for non-structural exterior components applied on the perimeter frames. The live load is 2.5 kN/m^2, and the total dead load including self-weight is 7.1 kN/m^2.

In the phenomenon of progressive collapse, a member of the main carrier of the structure is disrupted by the load it

Fig. 7 3D mesh model of the structure in ABAQUS

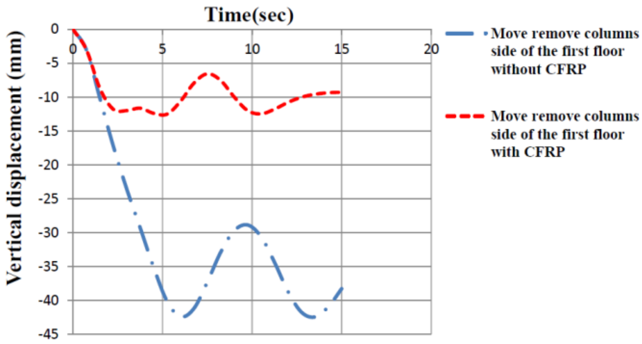

Fig. 8 Displacement-time graph for 1st floor corner column elimination

enters, and after the load is brought to adjacent members due to the low capacity of the members of the stable as well as the dynamic effects of the load, they are going. With the continuation of this rupture, the amount and intensity of the load are added and eventually, the entire structure or a significant part of it is destroyed. One of the things that can lead to the onset of collapse is the destruction of columns and instability in the structure.

In this study, the 30 kN/m^2 is applied to the column removed. The approximate location of the opposite loads applied to the column is almost at 1/6 of the story height. In addition, the structure is also subjected to its weight.

Embedded region interaction is implemented to define the contact between the concrete and reinforcement. The Tie constraint was used for contact between concrete and CFRP sheets. The 3D mesh model of the structure in ABAQUS software is shown in Fig. 7. The C3D8R is used to model concrete materials. This element is three-dimensional and has eight nodes, each node having three degrees of freedom (the node's displacement in the x, y, z directions). T3D2 is used to model steel bars. This element of the rod has two nodes at its two ends, each node having three degrees of transition freedom in the x, y, z directions. The S4R element is used to model CFRP sheets. This element is defined by eight nodes, each node having three degrees of freedom. In the free space, the nodes are transmitted in directions x, y, z. The mesh size is considered to be 100 millimeters.

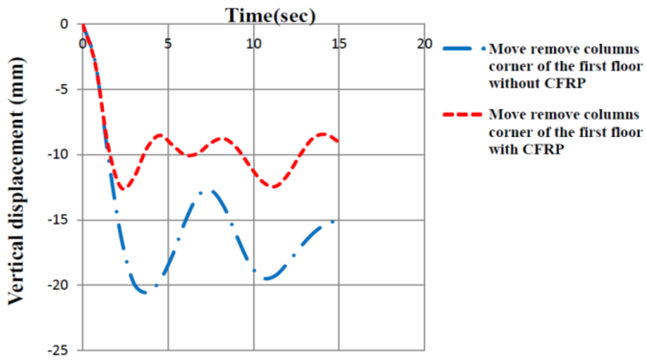

Fig. 9 Displacement-time graph for 1st floor side column elimination

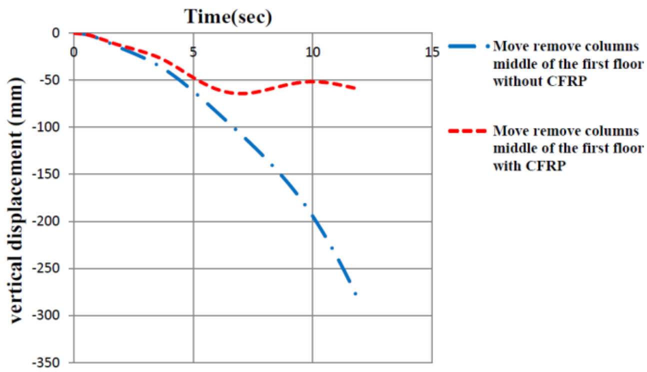

Fig. 10 Displacement-time graph for 1st floor middle column elimination

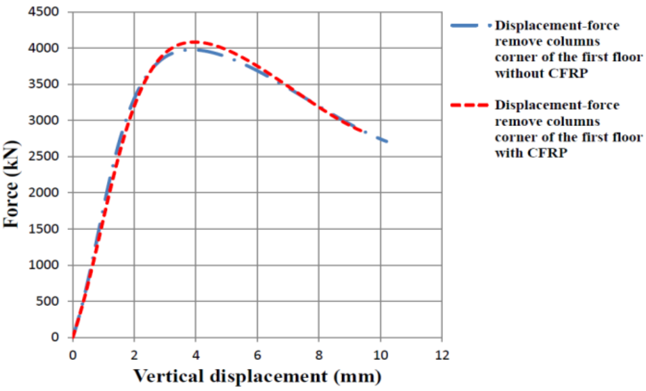

Fig. 11 Displacement-force graph for 1st floor corner column elimination

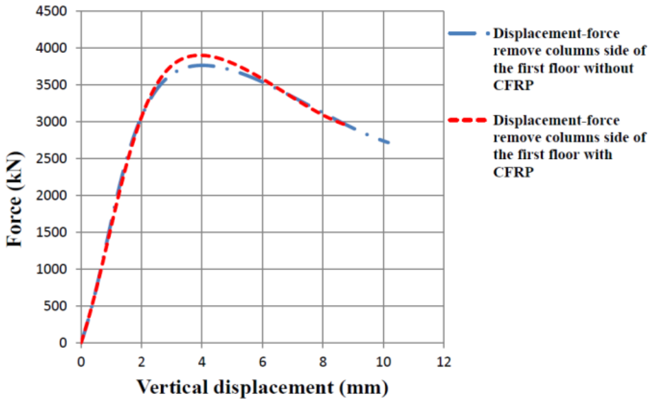

Fig. 12 Displacement-force graph for 1st floor side column elimination

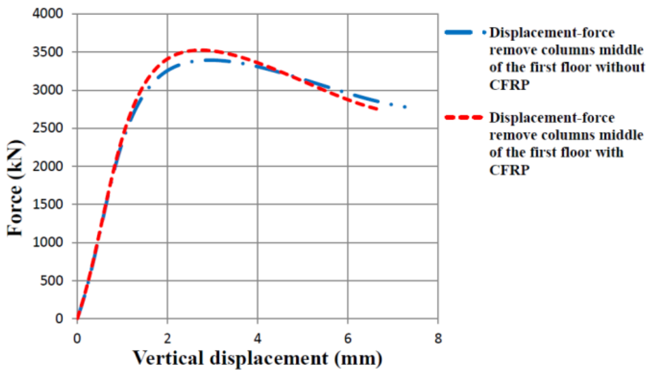

Fig. 13 Displacement-force graph for 1st floor middle column elimination

Table 4 Displacement and force quantities in 1st floor

Position remove columns	Floor	Displacement without CFRP (mm)	Displacement with CFRP (mm)	Force without CFRP (kN)	Force with CFRP (kN)
Corner	First	20	12	3879.59	3976.82
Side	First	42.4	12.4	3656.58	3770.85
Middle	First	280	60	3247.15	3395.72

4. Results

The final analyze results of eliminating 3 column position is defined as eliminating side, middle and corner columns. Displacement-time graph of eliminating column at 1st floor is shown in Figs. 8, 9, and 10 for instance.

Eliminating column force-displacement graph for the 1st floor, both in reinforced and no reinforced mood, are shown in Figs. 11, 12 and 13.

To calculate the amount of displacement in each mode, the displacement of the upper node of the removed column is considered. As presented in Fig. 10, the maximum displacement at non CFRP is in eliminating middle column of the 1st floor which is 280 mm and the minimum is 20 mm for eliminating corner column. For the CFRP mode these numbers decrease 60 and 12 mm for eliminating middle and corner columns, respectively. In the case of non-reinforcing mid-column removal with CFRP, due to a significant increase in displacement, the structure will be destroyed. However, in CFRP-reinforced mode, the displacement rate will be significantly reduced and the structural stability will be maintained. To calculate the force values, the number of response columns is considered to be eliminated. For non CFRP Force-Displacement graph, eliminating corner column has the maximum force of 3879.59 kN and the minimum force is 3247.15 kN for eliminating middle column, these quantities for CFRP mode increase 3976.82 and 3395.72 kN, respectively. Displacement and force quantities in 1st floor are shown in Table 4.

Displacement and force quantities of 2nd floor are shown in Table 5.

As presented in Table 5, the minimum displacement is for eliminating corner column and the maximum is for

Table 5 Displacement and force quantities in 2nd floor

Position remove columns	Floor	Displacement without CFRP (mm)	Displacement with CFRP (mm)	Force without CFRP (kN)	Force with CFRP (kN)
Corner	Second	23	13	4006.22	4029.26
Side	Second	49.9	15.1	2717.31	2962.90
Middle	Second	110.7	72.4	2888.81	2968.04

Table 6 Displacement and force quantities in 3rd floor

Position remove columns	Floor	Displacement without CFRP (mm)	Displacement with CFRP (mm)	Force without CFRP (kN)	Force with CFRP (kN)
Corner	Third	32.9	16.3	3999.57	4033.20
Side	Third	67.7	20	3785.40	3967.16
Middle	Third	133.5	98.1	3853.86	3942.30

Table 7 Displacement and force quantities in 4th floor

Position remove columns	Floor	Displacement without CFRP (mm)	Displacement with CFRP (mm)	Force without CFRP (kN)	Force with CFRP (kN)
Corner	Fourth	31.7	17.6	3935.10	3980.65
Side	Fourth	67	21.8	3942.41	3966.77
Middle	Fourth	119	93	3955.23	4045.49

middle one. Also, corner column elimination has the maximum force and the minimum is for middle column elimination at non CFRP mode. In CFRP mode, the minimum displacement is for corner elimination and the maximum belongs to middle one. Also, the maximum force is for corner column elimination and the minimum force belongs to side one. Force-displacement quantities in 3rd floor are shown in Table 6.

As presented in Table 6, the minimum displacement belongs to corner column elimination and the maximum is for the middle one. Also the maximum force belongs to corner column elimination and the minimum is for middle one, in non CFRP mode. In CFRP mode, the minimum displacement belongs to corner column elimination and the maximum is for the middle one. Also the maximum force belongs to corner column elimination and the minimum is for side one. Force-displacement quantities in 4rd floor are shown in Table 7.

As presented in table 7, the minimum displacement is for eliminating corner column and the maximum is for middle one. Also, middle column elimination has the maximum force and the minimum is for corner column elimination at non CFRP mode. In CFRP mode, the minimum displacement is for corner elimination and the maximum belongs to middle one. Also, the maximum force is for corner column elimination and the minimum force belongs to side one. Displacement and force quantities of 5th floor are shown in Table 8.

As presented in table 8, the minimum displacement is for eliminating corner column and the maximum is for middle one. As it can be seen in table 8, there is no considerable difference between reinforced and no

Table 8 Displacement and force quantities in 5th floor

Position remove columns	Floor	Displacement without CFRP (mm)	Displacement with CFRP (mm)	Force without CFRP (kN)	Force with CFRP (kN)
Corner	Fifth	22.9	14.9	4131.67	4153.13
Side	Fifth	69.7	29.8	4110.68	4206.38
Middle	Fifth	135.7	128.5	4171.04	4171.67

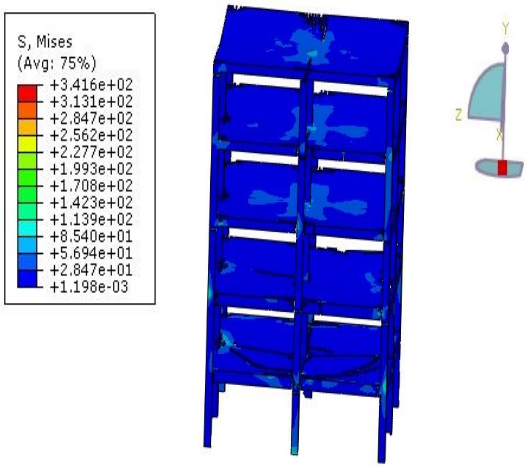

Fig. 14 Stress graph for 1st floor middle column elimination without CFRP

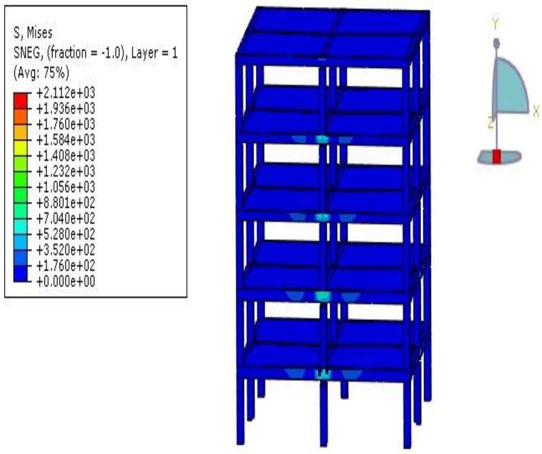

Fig. 15 Stress graph for 1st floor middle column elimination with CFRP

reinforced with CFRP for considering 5 mm thickness and also for the extend of destruction rate between quantities of reinforced and non-reinforced force. In this mode, the maximum force at reinforced mode belongs to side column elimination.

In this section, the results of stress and displacement for the most critical mode, namely, the removal of the middle column of the first floor in non-reinforced and reinforced state. In Fig. 14 stress graph for 1st floor middle column elimination without CFRP it has been shown. As shown in the figure, in the non-strengthen form, with the sheet of the CFRP, the roof of the floors is damaged and cracked. Removing the middle column on the first floor has led to an

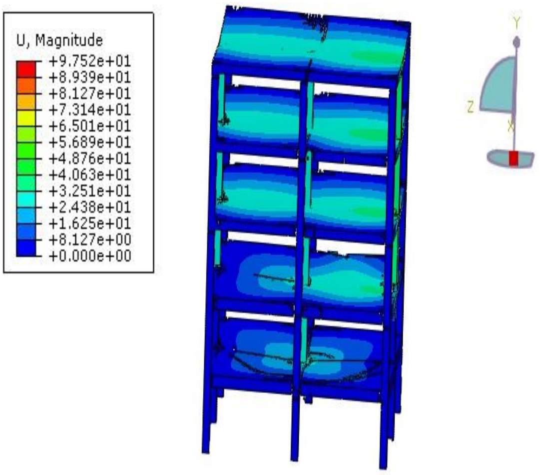

Fig. 16 Displacement graph for 1st floor middle column elimination without CFRP

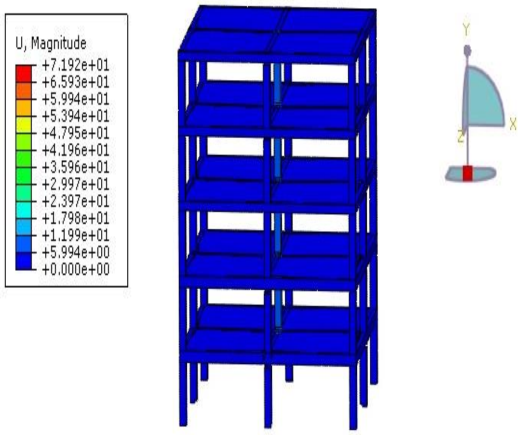

Fig. 17 Displacement graph for 1st floor middle column elimination with CFRP

increase in tension and failure in the column removal area.

In Fig. 15 Stress graph for 1st floor middle column elimination without CFRP it has been shown. As shown in the figure, in the strengthen form, with the sheet of the CFRP, the roofs of the floors of the damage and cracking floors has decreased and the roof remains healthy. In this case, the stress is tolerated by the sheets of CFRP, which leads to a reduction in the stresses on the structure.

In Fig. 16 Displacement graph for 1st floor middle column elimination without CFRP has been shown. As shown in the figure without strengthen, removing the column in the middle of the ceiling leads to an increase in the displacement in the floors, and the deformation causes cracking of the roof. As shown in Fig. 16, in the case of no reinforcement, elimination of the middle column on the first floor increases the displacement of the ceiling of the upper floors. With increasing displacement, the roof of the first floor and other floors have been cracked. Also in the joints, a beam to the column and the connection of the column to the cracking roof has occurred. As the displacement increase continues due to the removal of the middle column, the entire structure will collapse.

In Fig. 17 Displacement graph for 1st floor middle column elimination without CFRP has been shown. As shown in the figure shown in the strengthen mode, with removing the column in the middle of the roof, the level of displacement in the floors is reduced to the previous position and leads to a reduction in the cracking of the roof. As shown in Fig. 17, when reinforced with CFRP, the removal of the middle column on the first floor reduces the displacement of the ceiling of the upper floors. With a decrease in displacement resulting from the roof of the first floor and other classes, it is not damaged. Also observed, it remains stable with decreasing displacement of other structural regions and the stability of the structure is preserved. However, nowadays a general theory regarding the study of robustness and progressive (or disproportionate) collapse topics does not exist. In fact, if qualitative study approaches of considered phenomena are very diffused, no general quantitative recommendations to evaluate structural robustness have been yet implemented. In general, there are three alternative approaches to disproportionate collapse resistant design: improved interconnection or continuity, notional element removal and key element design. Nevertheless, no general criteria to quantify these structural evaluation approaches under extreme or unforeseen events have been implemented (Formisano and. Mazzolani 2012).

Therefore, the present paper attempts to consider an innovative method for the resistance of the structure to progressive collapse.

5. Conclusions

In the present paper, a 5 story concrete building were studied by 3 different positions of eliminating columns in each floor and, in the following, reinforcing of outfall beams which their columns are eliminated, with CFRP sheets. According to the results, it can be concluded that:

- In the position of column elimination, middle column elimination of 1st floor has a critical position and the maximum displacement.
- And, corner column elimination has the least critical position for displacement.
- According to the analyses, 1st, 3rd and 5th floors have more critical positions compare to 2nd and 4th against progressing collapse.
- Also, it can be derived that using CFRP sheet decreases displacement and, with respect to column elimination position, has the greatest impact on first and second floors and the least on the 5th floor.
- Dimensions of beams and columns have great impact on studying progressing collapse in a way that, decreasing their dimensions in third to fifth floor provides context for progressing collapse.
- In the case of removal of the column in the middle of the first floor, the concrete roof in elastic area has the highest stresses and cracking. By reducing the strength of the beams with the CFRP sheet, the amount of cracking and Stress significantly decreases.

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