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The Effectiveness Investigation of New Retrofitting Techniques for RC Frame against Progressive Collapse

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Abstract

Progressive collapse in a building has caused local and subsequent damage throughout the system to spread and large-scale causes the collapse of the entire building. Progressive collapse is usually due to fire, gas explosion, terrorist attack, vehicle collisions, misplaced design and construction. Therefore, it is necessary to study the iMPact of this phenomenon and rebuild the building against it. Based on this, in this research, we will examine and evaluate practical solutions for reinforcing reinforced concrete frames against progressive collapse. The proposed solutions in this study were the use of reinforcing bars at the top and bottom of the beam, the effect of the layout of the cross section reinforcement for the participation in the chain performance, the use of Carbon Fiber Reinforced Polymer (CFRP) sheet at the bottom and three sides of the beam and the effect of the additional layer of CFRP sheet in the section performance of the beam against progressive collapse. In this study, a 2-story frame is modeled using OpenSees software and retrofitted with the above techniques, and the effectiveness of each of these techniques is evaluated in the final performance. The results show that the best approach to reinforcing the beam is by rebar and CFRP, which has resulted in improved chain performance and the greatest reduction of vertical displacement in the beam.

Keywords: Progressive Collapse; RC Frame; Chain Performance; Retrofitting Frame; OpenSees.

1. Introduction

The progressive collapse is basically a small, localized structural failure that results in the collapse of a part of the structure or even the entire structure. One of the structural failure mechanisms that has received considerable attention in recent decades is the progressive collapse. In this phenomenon, one or more structural members deteriorate suddenly due to the explosion, and each re-distribution of load disrupts other structural elements and the building is progressively destroyed. The progressive collapse in the code is referred to as a state of destruction, in which the local fracture of the main structural member leads to the destruction of adjacent members one after another and ultimately causes additional damage [1]. Since the failure of the Forefront, improvements in the integrity and flexibility of structures to resist progressive collapse are included in various regulations. [2-4]. After the terrorist attacks, especially in the Twin Towers of the World Trade Organization, the issue of evaluating and evaluating the potential for progressive collapse in critical structures has become one of the research axes. This phenomenon can also create problems for structures constructed according to the current regulations, during severe earthquakes, and even lead to the destruction of the entire structure.

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Among the studies that can be mentioned in this regard are: Empirical studies [5-7] show that the progressive collapse is continuously increasing on a monotonically increasing vertical displacement on the column-to-column connection whose column is exposed. Cockot et al. [8] have studied the reinforced concrete frame in the structure. The behavior of metal and concrete structures under the column elimination scenario has been studied by Sedik et al. [9] and Sagirogouli and Sassani [10]. Kahan and Lee [11] investigated the effect of the interframe wall on performance resistance in the progressive collapse. Kim et al. [12] evaluated the folding frame capacity against a progressive collapse.

By studying nonlinear static and dynamic analyzes on a flexural structure, Sai and Lane [13] concluded that when nonlinear static analysis of load factor 2 is used, the results are coMPared with the results of nonlinear dynamic analysis be very conservative. Ren et al. [14] have evaluated the progressive collapse in two high concrete buildings with a shear wall system and examined the performance of the flexural frame and shear wall in progressive collapse for high structures. The results of this research show that the frame A of the shaft wall is weaker and the frame is stronger, more uncertain than the progressive collapse. The results of the research indicate that the frame A of the shear wall is weaker and the frame is stronger than the progressive collapse [15]. But in building B, it has a stronger shear wall and a weaker frame due to the hardening of a single point (shear wall) of the structure and the weakness of the remaining parts, as well as due to the appropriate stress distribution in all members and the high flexibility due to the framing frame system, has a decent redesign ability [16]. In another studies [17-18], which is aimed at retrofitting the RC frame using pre-tensioned tendons, a 6-story frame and a 20-story frame has been evaluated using a cross-linked and parallel tendon that shows that the use of a hard tendon has had the best performance, but generally prevents the use of tendons from vertical movement [19]. In another study by Kahan and Lee [20], the slab reinforcement using the CFRP was vertically and diagonally, which shows that with the CFRP slab reinforcement, the energy loss capacity, vertical displacement and horizontal response force are better. Yu and Tan, using special techniques to resist the structure against progressive deterioration, show that changing the location of the plastic joint and the use of steel sheaths can improve the chain performance and increase the strength of the structure. Development of a numerical model for the behavior of concrete is a challenging task. Concrete is a brittle material in tension and has different behavior in compression and tension. OPENSEES software demonstrated the reliable numerical results and the result of the concrete modeling has been verified [21]. The performance of OPENSEES software has been validated in several numerical and experimental studies [22-24]. The results demonstrate that the OPENSEES software can be used to simulate the retrofitting of RC frame against progressive collapse with the right precision [25-27].

2. Research Method and Simulation Assumptions

In the present study, the 2-floor reinforced concrete frame, which has undergone a progressive breakdown, will be investigated. In this structure the beam is reinforced using the reinforcement of the reinforcement at the top, bottom and middle of the cross section and the hinges using CFRP once at the bottom of the cross section and once on the three sides of the cross section. The following outputs have been used to coMPare the different reinforcement angles: 1. Maximum vertical displacement 2. Longitudinal displacement in the middle of the beam 3. Maximum and lasting moment at the beginning and middle of the beam 4. Maximum and lasting middle of the beam. The RC frame studied in this study, is modeled in OPENSEES software in two-dimensional format. Figure 1 shows the frame and Figure 2 shows the section detail of the beam.

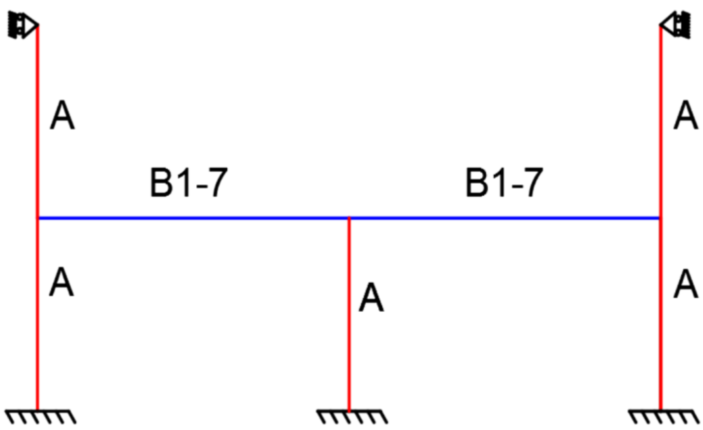

Figure 1. Retrofitting frame

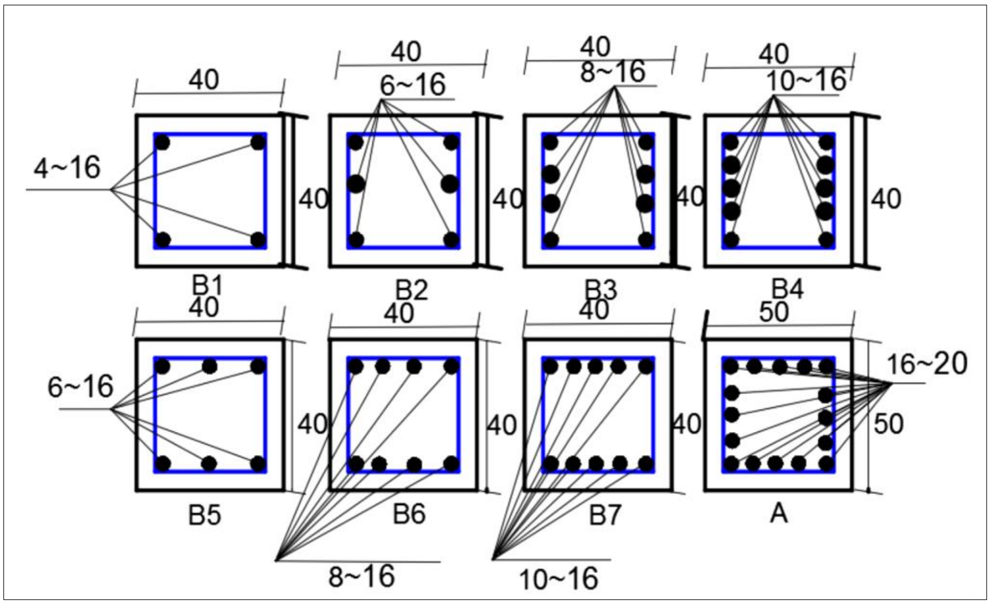

Figure 2. Details of the sections of the beam

In the frame, the height of the column is 3 meters and the length of the beam is 5 meters. Dead load is 6 kN/m^2 and the live load is 2.9 kN/m^2. Specifications of materials in Table 1 and sectional view of the beam are specified in Table 2. The framed column pillars are 50 cm in 50 centimeters with 16 longitudinal reinforcements with a diameter of 20 mm.

Table 1. Material Properties

Material	F'c (MPa)	E (MPa)	Fy (MPa)	Fu (MPa)	Ft (MPa)
Concrete (confined)	22	-	-	-	0.1×F'c
Concrete (unconfined)	21	-	-	-	0.1×F'c
Steel	-	199000	235	-	-
CFRP	-	210000	-	3200	-

Table 2. Reinforcement Detail of Beams

Number	Reinforcement percentage	Dimensions(mm)	longitudinal			
			Top	Left	Bottom	Right
1	ρ_{Total}=0.0057	400×400	2ϕ16	-	2ϕ16	-
2	ρ_{Total}=0.0086	400×400	2ϕ16	1ϕ16	2ϕ16	1ϕ16
3	ρ_{Total}=0.0115	400×400	2ϕ16	2ϕ16	2ϕ16	2ϕ16
4	ρ_{Total}=0.0144	400×400	2ϕ16	3ϕ16	2ϕ16	3ϕ16
5	ρ_{Total}=0.0086	400×400	3ϕ16	-	3ϕ16	-
6	ρ_{Total}=0.0115	400×400	4ϕ16	-	4ϕ16	-
7	ρ_{Total}=0.0144	400×400	5ϕ16	-	5ϕ16	-

2.1. The Process of Column Elimination in Dynamic Progressive Collapse

In analyzing nonlinear time histories, considering the nature of analysis, dynamic effects and nonlinear behaviors are well considered. Therefore, this analysis has been highly accurate to the static analysis and its results are more reliable. The process of removing the column in the structure is then initially loaded to the structure for 5 seconds, and then held constant for 2 seconds, so that the structure is stable, and then the middle column is removed. In Figure 3, the gravity load and column elimination are shown. The damping of the structure is considered constant.

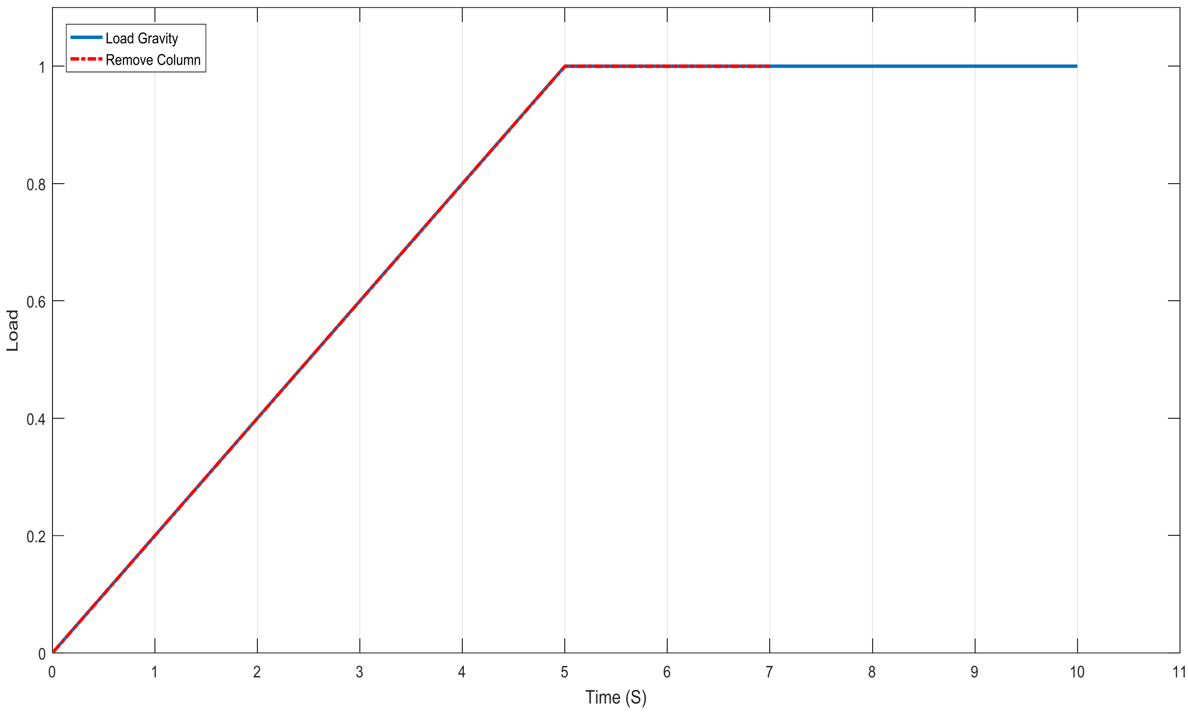

Figure 3. The gravity load and column elimination in time of progressive collapse

3. Numerical Results

Base on mentioned assumptions, five different retrofitting methods were considered to illustrate the effectiveness of the different approaches. The main differences between retrofiring approaches are the seven level of rebar percentage increments, the location of adding CFRP layers and the number of them in practical rehabilitation ways.

3.1. The Effect of Increasing the Reinforcement Percentage in Progressive Collapse

The effects of reinforcement percentage in progressive collapse in comprehensively studied in this study. Figure 4a shows the vertical displacement for the percentage of reinforcements. As shown in the figure, the displacement of the armature is reduced by increasing the percentage of the armature, and with increasing the reinforcement percentage, more than 1.15%, there is no significant effect on vertical displacement. The arrangement of reinforcement has a great effect on vertical displacement. Layout of reinforcement in top and bottom sections has the best performance. Figure 4b illustrates the maximum moment value of the beginning of the beam. In non-reinforcing beam mode, the maximum moment is equal to 77591 N, which is the smallest moment relative to the rest of the cross-sectional states. With an increase in the diameter of the armature, the moment of the beginning of the beam increased, and the increase in the reinforcement percentage from 15.1% up did not affect the initial moment of the beam. Figure 4c shows the amount of moment in the middle of the beam. The average moment in the middle of the beam is positive at first, but after the sudden removal of the column, its moment value is negated. The most negative moment is in the non-reinforcing beam, and with the increase in the reinforcement percentage to 1.15%, the negative moment value decreases. From this aspect, the increase in the percentage of the armature does not have an effect on its moment. Figure 4d shows the shear force diagram of beam. The summary of these graphs is shown in Table 4.

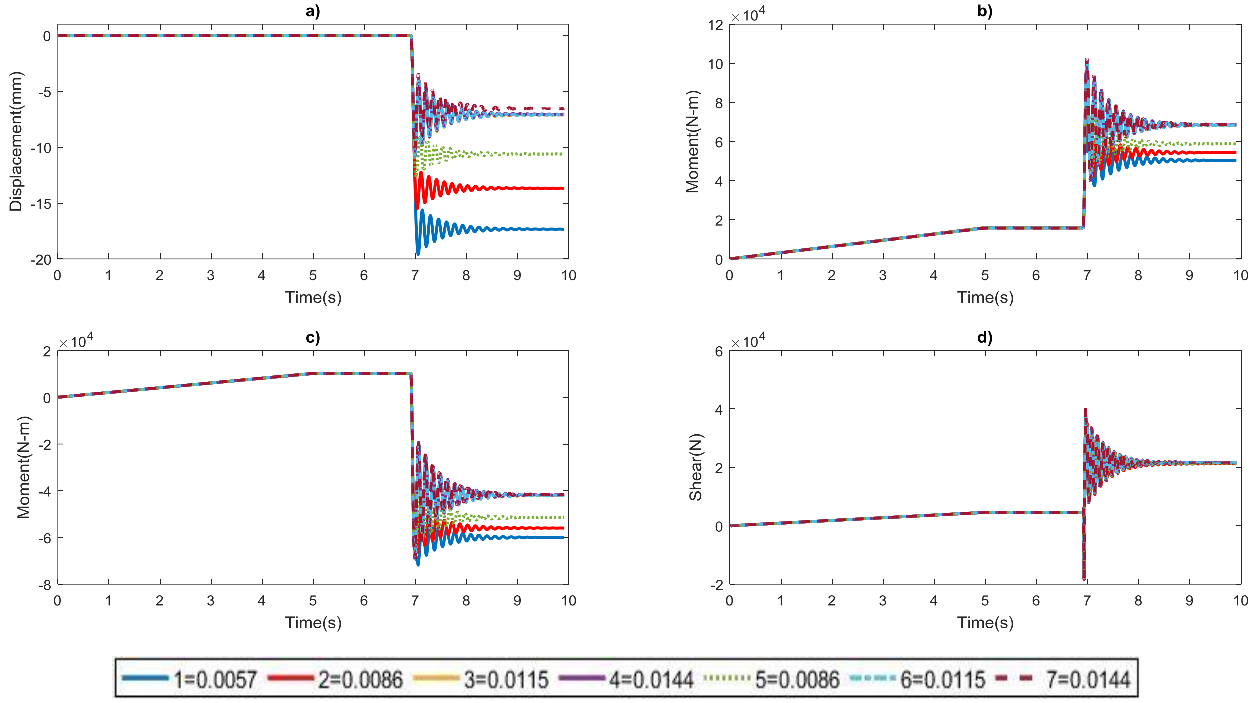

Figure 4. The effect of increasing the reinforcement percentage in progressive collapse, a) Vertical displacement in the middle of the beam; b) The moment of beam in end supports; c) The moment in the middle of the beam; d) The shear of beam in the end supports

Table 4. Result Strengthened by increasing the percentage of reinforcement

Strengthened by increasing the percentage of reinforcement			Vertical Displacement (mm)		Moment First (N-m)		Middle moment (N-m)		Shear (N)	
			Max	constant	max	constant	max	constant	max	Constant
1	ρ_{Total}	0.0057	-19.6	-17.35	77591.4	50400.1	-71832.6	-60012.3	52397	35788
2	ρ_{Total}	0.0086	-15.53	-13.68	78659.2	54404.2	-66639.8	-55993.1	44510	31342.5
3	ρ_{Total}	0.0115	-10.85	-7.11	100171	68311.1	-68070.7	-41905.6	46832.7	28588.2
4	ρ_{Total}	0.0144	-10.81	-7.05	100760	68476.1	-68524.2	-41757.4	46641.7	28525.5
5	ρ_{Total}	0.0086	-12.69	-10.61	90078.1	58832.5	-66809.8	-51452.5	46015.6	30855.2
6	ρ_{Total}	0.0115	-10.58	-7.11	100171	68311.1	-68070.7	-41905.6	46832.7	28588.2
7	ρ_{Total}	0.0144	-10.15	-6.53	102564	68720.7	-69222.6	-41562	46750.7	28224.2

3.2. The Simultaneous Effect of a CFRP Layer at the Bottom of the Section and Increment in the Reinforcement Percentage of the Beam

In Figure 5a, the vertical displacement diagram is shown with a CFRP layer at the bottom of the cross section. As seen in the Figure 5, the maximum vertical displacement corresponds to the lowest percentage of the reinforcement, which decreases the vertical displacement by increasing the reinforcement percentage. Increasing the reinforcement percentage, more than 15.1%, will not have much iMPact on vertical displacement. Figure 5b demonstrates the initial moment diagram with a CFRP layer at the bottom of the cross section. The minimum moment value for a non-reinforcing beam is. As the reinforcement percentage increases, the maximum moment increases, and the reinforcement percentage of the reinforcement, more than 1.15%, has no effect on its moment. In Figure 5c, a moment diagram shows the middle of the beam with a CFRP layer at the bottom of the beam, which after the column is removed in progressive collapse, the moment value is negated. The non-reinforced mode shows the maximum moment value. As the reinforcement percentage increases, the maximum moment decreases, and the reinforcement percentage does not affect more than 1.15% at its moment. Figure 5d demonstrates the shear force diagram of beam. Summary of results is shown in Table 5.

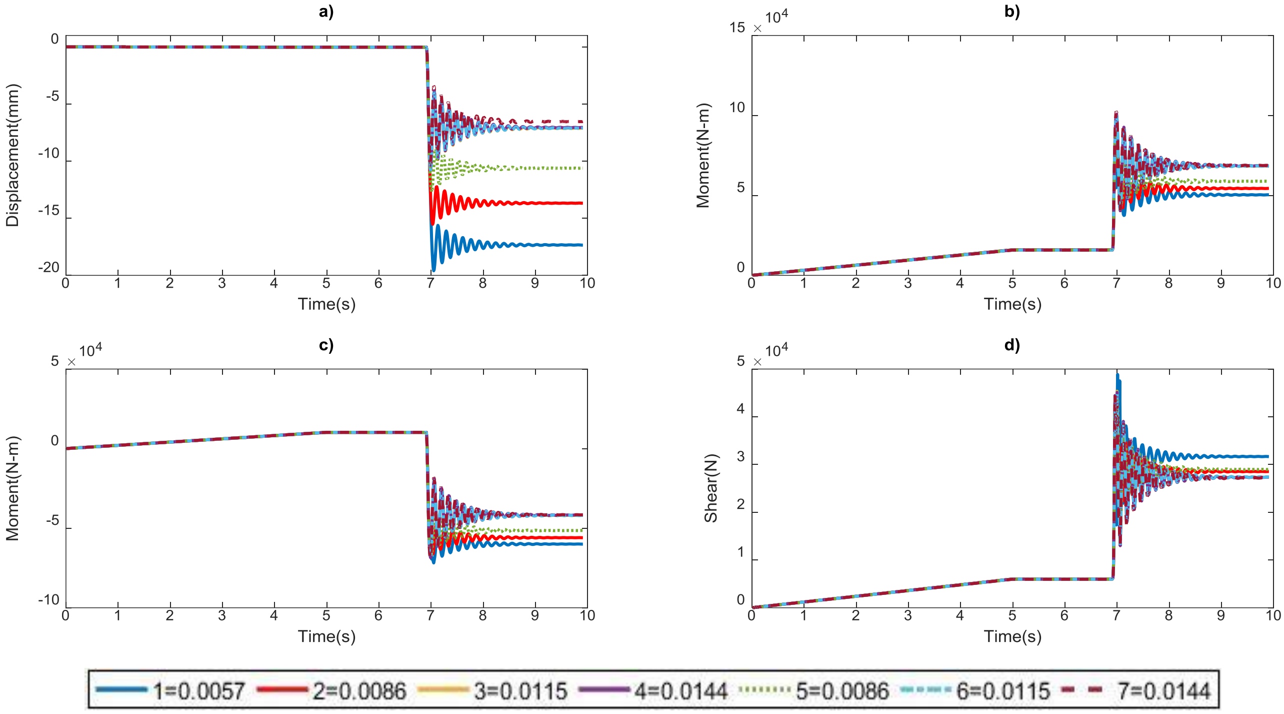

Figure 5. The effect of simultaneous increment of the reinforcement percentage and adding a bottom layer of CFRP in progressive collapse. a) **Vertical displacement in the middle of the beam; b) The moment of beam in end supports; c) The moment in the middle of the beam; d) The shear of beam in the end supports**

Table 5. The Summary results of Strengthening by simultaneous increment of the reinforcement percentage and adding a bottom layer of CFRP

strengthen a bottom layer CFRP			Vertical Displacement (mm)		Moment First (N-m)		Middle moment (N-m)		Shear (N)	
			max	constant	max	constant	max	constant	max	constant
1	ρ_{Total}	0.0057	-16.77	-14.72	77667.6	46083.7	-78079	-64197.3	48857.6	31658.1
2	ρ_{Total}	0.0086	-13.83	-11.91	78718.9	52140	-72146.5	-58248.4	43187.1	28544.7
3	ρ_{Total}	0.0115	-10.29	-6.66	98867.9	66625.6	-72429.7	43728.6	45355.2	27364.9
4	ρ_{Total}	0.0144	-10.25	-6.61	99460.6	66765	-72281.8	-43544.2	45117.9	27324.6
5	ρ_{Total}	0.0086	-12.2	-9.86	82373.3	56535.9	-72091.2	-53841.4	43746.2	28984.5
6	ρ_{Total}	0.0115	-10.29	-6.66	98867.9	66625.5	-72429.7	-43728.6	45354.2	27364.9
7	ρ_{Total}	0.0144	-9.72	-6.12	101990	67188.5	-72572.6	-43220.9	44727.2	27202.2

3.3. The Simultaneous Effect of a CFRP Layer on Three Sides and Increment in the Reinforcement Percentage of the Beam

Figure 6a demonstrates the vertical displacement graph in the case of a CFRP layer on the three sides of the cross section. In the case of CFRP at three sides, CFRP has a significant effect on vertical displacement relative to that of a CFRP cross-section. In non-reinforced beam mode, the maximum vertical displacement is observed, while with increasing the reinforcement percentage the vertical displacement decreases and with increasing the reinforcement percentage, more than 15.1%, no significant effect is observed. Also, the layout of the reinforcement in the top and bottom of the beam is better than other layout modes. In Figure 6b, the moment diagram of the beam is shown in the case where a CFRP layer is located on three sides of the cross section. The minimum amount of moment in the non-reinforced beam mode has been created and increasing the percentage of the armature increases its moment value. With an increase in the reinforcement percentage, more than 1.15%, there is no effect on the moment value. Also, the arrangement of the reinforcement does not have much effect on the moment of the beam. In Figure 6c, a moment diagram is shown in the middle of the beam, in which a CFRP layer is located on three sides of the cross section. The amount of moment becomes negative after the column is deleted. The maximum moment is observed in the case of the lowest percentage of the armature and with increasing the reinforcement percentage the moment value decreases, while with an increase in the reinforcement percentage, more than 1.15%, no effect is observed on the moment. The layout does not affect the moment. In Figure 6d, the shear cut pattern is shown in the case where a CFRP layer is located on three sides of the cross section. The presence of a CFRP layer on the three sides of the cross section has a great effect on the cutting. The increase in the diameter of the armature does not affect the amount of section cut and in the absence of reinforcement, there is no change in the diagram. Summary of results is shown in Table 6.

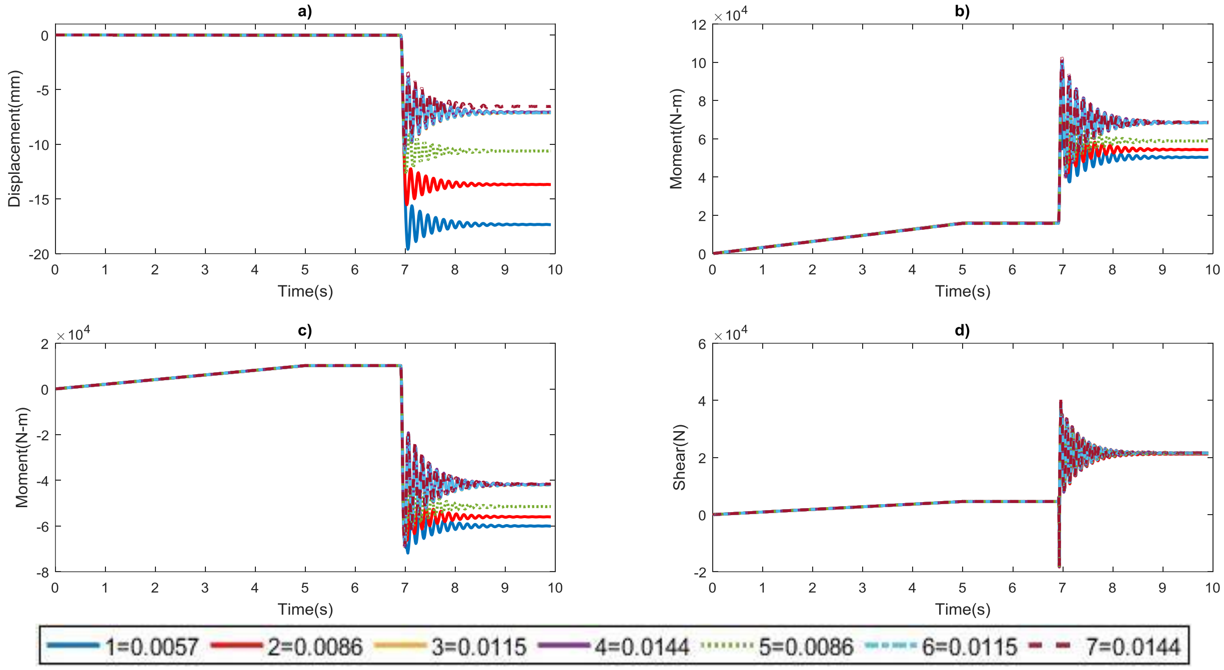

Figure 6. The effect of simultaneous increment of the reinforcement percentage and adding CFRP layer on three sides of beam in progressive collapse. a) Vertical displacement in the middle of the beam; b) The moment of beam in end supports; c) The moment in the middle of the beam; d) The shear of beam in the end supports

Table 6. The Summary results of Strengthening by simultaneous increment of the reinforcement percentage and adding CFRP layer on three sides of beam

strengthen three-side layer CFRP			Vertical Displacement (mm)		Moment First (N-m)		Middle moment (N-m)		Shear (N)	
			max	constant	max	constant	Max	constant	max	constant
1	ρ_{Total}	0.0057	-7.55	-4.46	104764	63599.6	-87132.6	-46754.8	37088.8	21249.4
2	ρ_{Total}	0.0086	-7.52	-4.43	104683	63495.6	-87355.6	-46849.1	37271.4	21257.2
3	ρ_{Total}	0.0115	-7.17	-4.19	105648	63674.2	-87672.4	-46664	39391.9	21594.5
4	ρ_{Total}	0.0144	-7.14	-4.17	105523	63585.4	-87855.7	-46762.1	39352.1	21584.8
5	ρ_{Total}	0.0086	-7.36	-4.31	105269	63620.1	-87422.3	-46680.5	38160.3	21414.6
6	ρ_{Total}	0.0115	-7.17	-4.19	105648	63674.2	-87672.4	-46664	39391.9	21594.5
7	ρ_{Total}	0.0144	-6.99	-4.07	105928	63702.2	-87875.6	-46665.6	40161.9	21741.5

3.4. The Simultaneous Effect of two CFRP Layer at the Bottom of the Section and Increment in the Reinforcement Percentage of the Beam

Figure 7a demonstrates the vertical displacement diagram in the case where the two layers of CFRP are located at the bottom of the cross section. In non-reinforcement mode, the maximum displacement is seen, while with increasing reinforcement the vertical displacement decreases. Also, the arrangement of reinforcement in the case of reinforcement at the top and bottom of the section, performs better than that in which the reinforcement is performed in the middle of the beam. Figure 7b exhibits the initial moment diagram in the case of two CFRP layers at the bottom of the cross section. The minimum moment value is in the case of no reinforcement of the armature, while the moment value increases as the reinforcement percentage increases. The increase in the reinforcement percentage, more than 15.1%, does not affect the initial moment of the beam. Also, the arrangement of armatures does not have much effect on the initial moment of the beam. Figure 7c shows the moment diagram in the middle of the beam in the case of two CFRP layers at the bottom of the cross section. The maximum moment value has been established in the non-reinforced form of reinforcement, and with increasing the reinforcement percentage, the moment value in the middle of the beam decreases. Also, the layout of the reinforcement is not very impressive on the moment. Figure 7d shows the middle section of the beam in the case of two CFRP layers at the bottom of the cross section. The greatest amount of cutting is in the case without reinforcement of the reinforcement, and with increasing the reinforcement percentage and its arrangement, there is no significant effect on the cutting value. Summary of results is shown in Table 7.

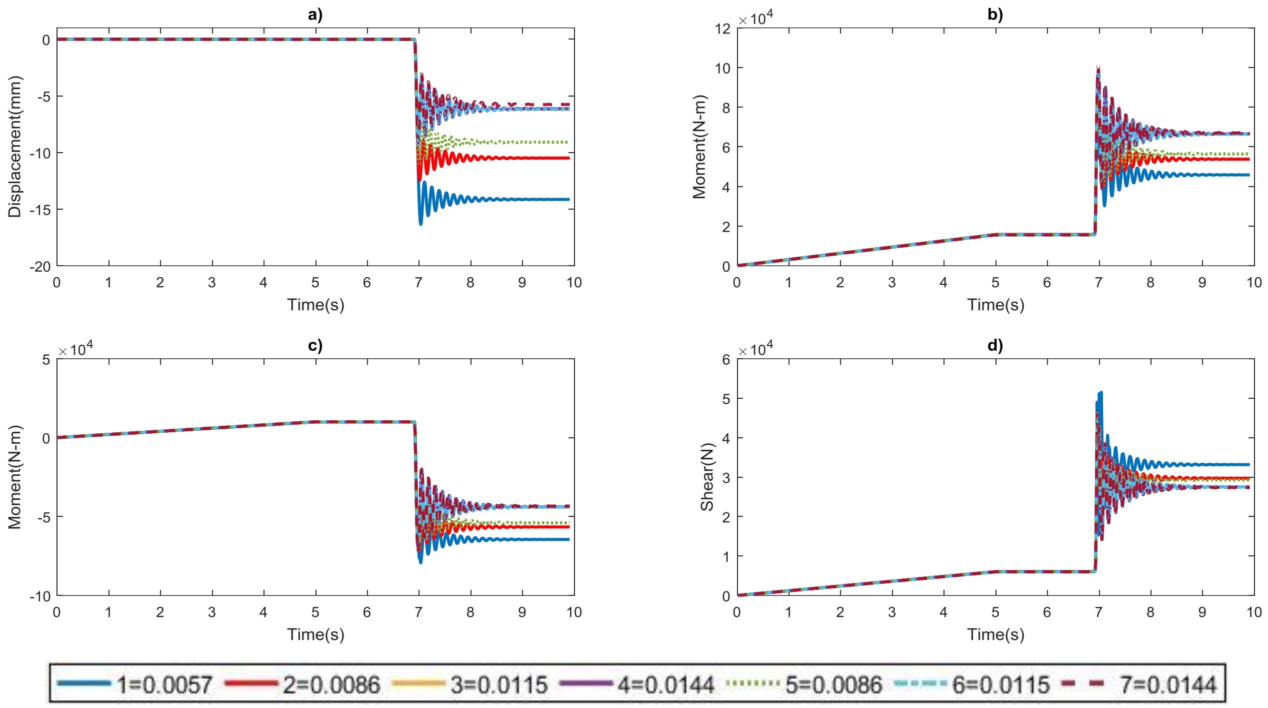

Figure 7. The effect of simultaneous increment of the reinforcement percentage and adding two bottom layers of CFRP in progressive collapse. a) Vertical displacement in the middle of the beam; b) The moment of beam in end supports; c) The moment in the middle of the beam; d) The shear of beam in the end supports

Table 7. The Summary results of Strengthening by simultaneous increment of the reinforcement percentage and adding two bottom layers of CFRP

strengthen two-bottom layer CFRP			Vertical Displacement (mm)		Moment First (N-m)		Middle moment (N-m)		Shear (N)	
			max	constant	max	constant	max	constant	max	Constant
1	ρ_{Total}	0.0057	-15.19	-13.21	77595.3	44123.3	-80807.2	-66236.1	46234.2	28748.3
2	ρ_{Total}	0.0086	-12.73	-10.43	78609.7	52302.3	-75858.9	-58003.8	42111.3	27421.9
3	ρ_{Total}	0.0115	-9.84	-6.33	98341.3	65210.3	-75018.8	-45125.8	43492.3	26409.3
4	ρ_{Total}	0.0144	-9.83	-6.3	98928.2	65406.5	-75042.1	-44963.1	43357.7	26413
5	ρ_{Total}	0.0086	-11.54	-9.25	82354.1	54732.6	-75384.5	-55544.9	43180.3	27461.9
6	ρ_{Total}	0.0115	-9.84	-6.33	98341.3	65210.3	-75018.8	-45125.8	43492.3	26409.3
7	ρ_{Total}	0.0144	-9.42	-5.92	101275	65871.2	-75754.3	-44388.9	43908.4	26348.8

3.5. The Simultaneous effect of two CFRP layer on three side of the section and increment in the reinforcement percentage of the Beam

Figure 8a exhibits the vertical displacement graph in the case of two CFRP layers in three sides of the section. The amount of reinforcement reinforcements, as well as their arrangement, does not have much effect on vertical displacement. Figure 8b illustrates the initial moment diagram in the case of two CFRP layers in three sides of the cross section. The amount of reinforcement reinforcements, as well as how they are arranged, have no effect on the moment of the beam. Figure 8c displays a moment diagram in the middle of the beam in the case of two CFRP layers in three sides of the cross section. The amount of reinforcement reinforcements, as well as their arrangement, does not affect the moment in the middle of the beam. Figure 8d demonstrates the shear cut pattern in the case of two CFRP layers in three sides of the cross section. The amount of reinforcement reinforcements, as well as how they are arranged, have no effect on the cutting of the beam. (Or we can say that in the case of two CFRP layers on three sides, the increase in the number of section reinforcements as well as their layout does not affect any of the vertical displacement values, the moment of the beginning of the beam, the middle moment of the beam, and the cross section. It can be said that increasing the reinforcement percentage and changing the arrangement of the reinforcement to reinforce the beam is not necessary. Furthermore, the summary of the results is shown in Table 8.

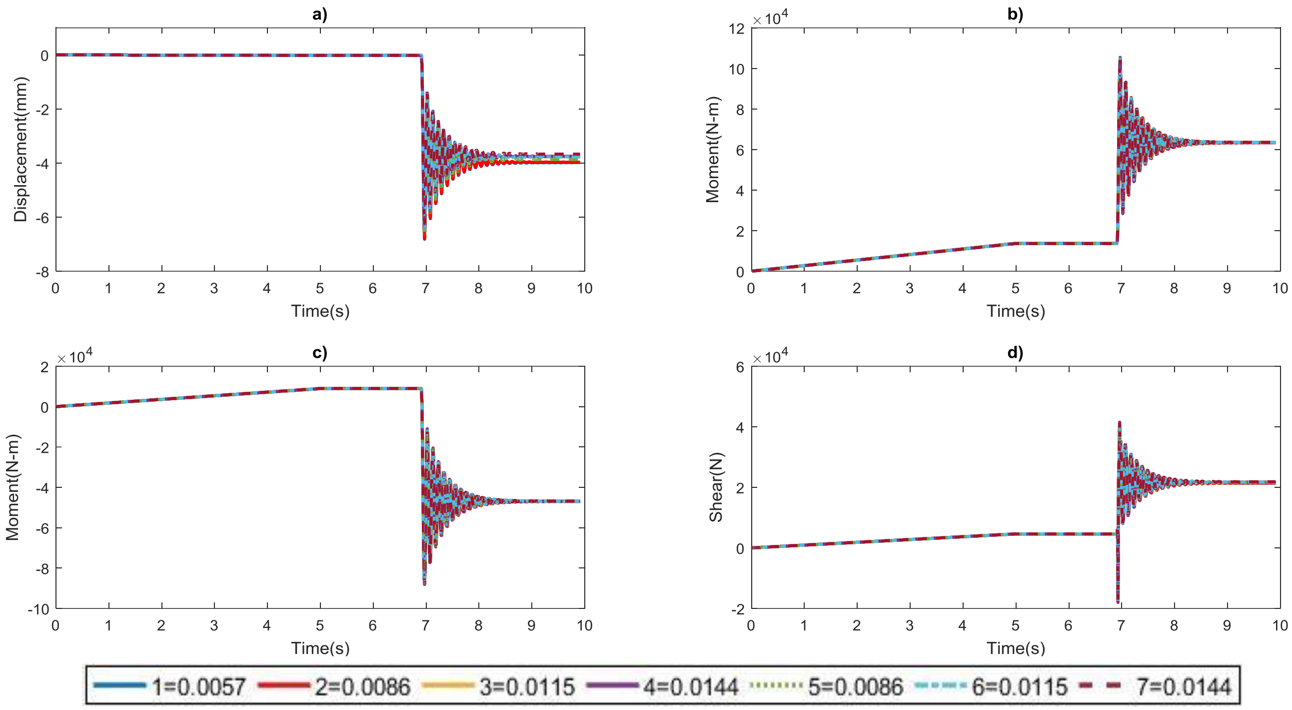

Figure 8. The effect of simultaneous increment of the reinforcement percentage and adding two CFRP layer on three side of the beam in progressive collapse. a) Vertical displacement in the middle of the beam; b) The moment of beam in end supports; c) The moment in the middle of the beam; d) The shear of beam in the end supports

Table 8. The Summary results of Strengthening by simultaneous increment of the reinforcement percentage and adding two CFRP layer on three side of the beam

strengthen three-side two-layer CFRP			Vertical Displacement (mm)		Moment First (N-m)		Middle moment (N-m)		Shear (N)	
			max	constant	Max	constant	max	constant	max	Constant
1	ρ_{Total}	0.0057	-7.49	-4.41	104688	63455.2	-87487.9	-46479.1	37349.2	21192.5
2	ρ_{Total}	0.0086	-7.46	-4.39	104595	63351.6	-87711.1	-46971.3	37538	21200.4
3	ρ_{Total}	0.0115	-7.12	-4.15	105494	63547.8	-88004.5	-46805.3	39452.4	21531.7
4	ρ_{Total}	0.0144	-7.08	-4.13	105405	63458.1	-88159.3	-46898.5	39579.2	21539.7
5	ρ_{Total}	0.0086	-7.3	-4.28	105151	63487.8	-87785.1	-46816	38436.9	21361.7
6	ρ_{Total}	0.0115	-7.12	-4.15	105494	63547.8	-88004.5	-46805.3	39452.4	21531.7
7	ρ_{Total}	0.0144	-6.94	-4.03	105754	63562	-88156.6	-46771.8	40371.3	21672.7

In general, it can been seen that the rebar addition is a good way against progressive collapse. However, in all of the retrofit cases, increasing the additional rebars cannot be effective more than 15% against progressive collapse. Moreover, the layout of the reinforcement in the upper and lower sections is better than other layouts in the beam studied in this research. Furthermore, simulation results demonstrate that the addition of CFRP layers are more effective than additional rebars in progressive collapse of structural beams. No significant improvement was observed with increasing number of CFRP layers against progressive collapse.

4. Conclusions

In the present study, the performance of structural system against the progressive collapse was studied in a variety of ways, such as the arrangement of reinforcement, the location and the number of CFRP layers. Numerical models of concrete beams, in 5 different cases with 7 different the reinforcement percentages, were developed and evaluated in the software. Following points could be summarized for the analysis results:

- It is recommended to utilize additional reinforcement bars to strengthen the beam against progressive collapse. However, the increasing the amount of reinforcements does not affect more than 15.1% on the performance of the structural beam. In the beam studied in this research, the layout of the additional reinforcement in the upper and lower sections is better than other layouts.

- In general, it is recommended to employ a CFRP layer at the bottom of the beam. Synchronizing CFRP layers with the additional rebars are more effective. Increasing the amount of additional reinforcements more than 1.15% will not be beneficial. In the beam studied in this research, the arrangement of the additional reinforcement bars will have a very small effect on the cross-sectional performance.
- Utilizing a CFRP layer on the three sides of the beam will improve its shear performance. The performance is better in coMParison with a CFRP layer at the bottom of the beam. Furthermore, increasing the amount of additional reinforcement bars and its layout does not have significant effect.
- The use of additional reinforcement of the beam simultaneous with two layers of CFRP on the three sides of the cross-section was not significantly different with the case of using a CFRP layer on the three sides of the beam. There is also no increase in the amount of additional bars reinforcement and its layout.
- The use of a CFRP layer on the three sides of cross-section to strengthen the beam and the simultaneous effect of reducing or increasing the compressive strength of the concrete does not affect its performance against progressive collapse.
- In the case of two CFRP layers at the bottom of the beam, the amount of additional reinforcement bars and the arrangement of them in the upper and lower sections effect on the vertical displacement. however, no significant change is observed on the moment at the support, the middle moment and the shear forces. Furthermore, increasing the amount of additional reinforcement bars more than 1.15% is not effective in any of the parameters.
- Using a CFRP layer on the three sides of the section is much more effective than a CFRP layer at the bottom of the cross-section.
- In the case of two-layer CFRP on three sides of the cross section are used in this study, the increase in the percentage and layout of additional reinforcement does not affect the cross-sectional performance in progressive collapse.

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