Progressive Collapse Assessment of RC Structures under Instantaneous and Gradual Removal of Columns

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SUMMARY:
The subject of progressive collapse assessment in RC structures has been dealt with in various studies. In contrast, most of these studies have attended to a scenario in which an instantaneous removal of a column due to unexpected impact, explosion or earthquake has occurred. The present study addresses progressive collapse in RC structures resulting from both instantaneous and gradual removal of columns. The scenario for a gradual removal is the result of slow decreasing strength due to fire propagation in a specific zone of structure which is partially fire-proved. Vertical displacement in the upper node of the removed column, redistribution of forces after removing the column, plastic deformations in adjoining elements, and the stress imposed on the sections of the beams adjacent to the removed column in both instantaneous and gradual cases are studied.

Keywords: Progressive Collapse, RC Structure, Instantaneous and Gradual Removal of Column

1. INTRODUCTION

Progressive collapse happens when local failure of a primary structural component leads to the failure of adjoining members and finally to the failure of partial or whole structure system. Collapse of the Ronan Point Building in 1968 due to gas explosion followed by a bomb plant in 1995 which deteriorated the Alfred P. Murrah Building drew researchers' attention to setting new regulations in order to reduce the progressive collapse potential in structures. According to the Unified Facilities Criteria (UFC) and General Services Administration (GSA) guidelines, progressive collapse can be analyzed using linear static, linear dynamic, nonlinear static and nonlinear dynamic procedures. The nonlinear dynamic analysis is computationally complex and time-consuming compared to other methods but results of this analysis are more accurate compared to other methods. Hyun Jin Kim (2006) studied the progressive collapse of reinforced concrete structures with structural defects and poor ductility. Sasani and Jesse Kropelnicki (2007) studied the approach of instantaneous removal of load-bearing element (e.g. column) to evaluate progressive collapse in reinforced concrete structures. Marlon Luis Bazan (2008) used nonlinear dynamic analysis to examine the response of reinforced concrete elements and structures after removing load-bearing elements. Talaat and Khalid M. Mosalam (2009) employed direct removal of element to model progressive collapse of reinforced concrete structures in order to formulate a new analysis algorithm of element removal. Most of these studies have attended to a scenario in which an instantaneous removal of a column due to unexpected impact, earthquake and explosion has occurred. The present study attempts to model the gradual removal of the column. Decreasing strength in terms of stiffness is modeled as the gradual removal and the modeling concept considered for this phenomenon is a gradual reduction in stiffness of the reinforced concrete cross section affected by fire. To study the structural behavior, the nonlinear dynamic method was used. Opensees software was used for nonlinear analysis of structure. At the end of the paper results of instantaneous and gradual removal were compared.

2. STRUCTURAL PROPERTIES

A five-story reinforced concrete structure model with RC resisting moment frames at either side was designed using a high ductility level. Typical plans of each story are presented in Fig 2.1. The first floor is 2.7 m high while the height of the other typical stories is 3.3 m. The structure supports are assumed to be restrained. Compressive strength of concrete is f'_c=24 MPa, yielding strength of reinforcement is f_y=400 MPa, and the modulus of elasticity for concrete and steel are E_c=24,459 MPa and E_s=2×10^5 MPa, respectively. Gravity loads are presented in Table 2.1.

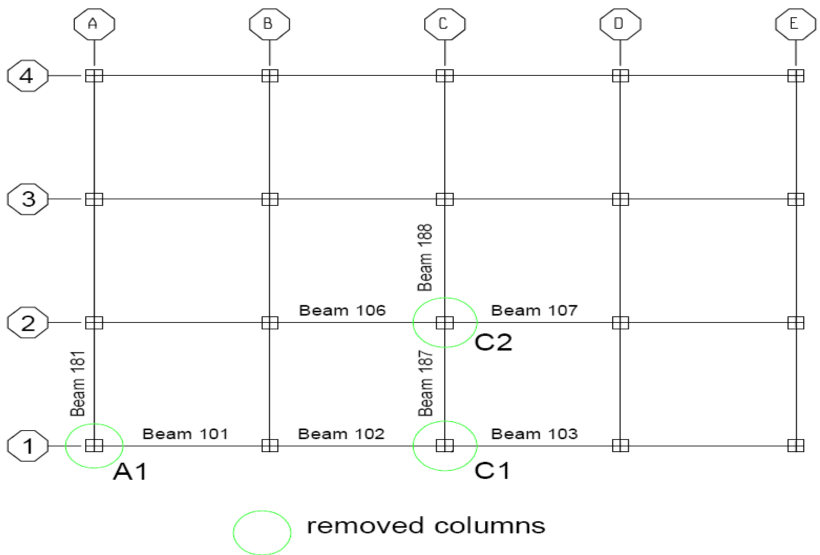

Figure 2.1. Typical plan of reinforced concrete structure

Table 2.1. Service Loads

	Typical Stories	Roof Story
Dead Load(kN/ m^2)	5.9	5.4
Live Load(kN/ m^2)	2	1.5
Perimeter Wall(kN/ m)	6.45	3.05

The beams' dimensions are 500×500 mm in the first 3 stories and 500×400 mm in the others. Depth of beams in the first three stories is 500 mm while the depth of the remaining beams is 400 mm. All beams consist of 2ø20 as continuous reinforcement on the top and bottom of their sections. Moreover, additional ø20 is used in the section of beams wherever needed. Column types, dimensions and reinforcement are shown in Tables 2.2 and 2.3.

Table 2.2. Reinforcement of Column Sections

Section	Dimension (mm×mm)	Reinforcement
Column 1	500×500	16ø20
Column 2	500×500	12ø20
Column 3	400×400	8ø20

Table 2.3. Column Types of Building

Position	Story1	Story2	Story3	Story4	Story5
Corner	Column 2	Column 2	Column 2	Column 3	Column 3
Others	Column 1	Column 2	Column 2	Column 3	Column 3

3. MODELING PROCEDURE FOR INSTANTANEOUS AND GRADUAL REMOVAL OF COLUMN

3.1. Instantaneous Removal

In this section, the procedure of nonlinear dynamic analysis for modeling the instantaneous removal of columns in a structure is described. First, static analysis is performed under gravity loads and then internal forces in the column to be removed through progressive collapse are determined. In the next step, the column is removed from the model and replaced by the reaction force at the top of the column. Once again, static analysis is performed under gravity loads. It has been verified that the results of this analysis are the same as the results of the previous analysis (prior to removing the column). Instantaneous removal is modeled by dynamic analysis in a case where forces equal to the reaction of the removed column are instantaneously exerted on the model in the opposite direction as an impulse.

3.2. Gradual Removal

In this part of the research, the modeling procedure for progressive collapse is caused by gradual reduction in stiffness of the column, or in other words, gradual removal of the column is examined. Progressive collapse has been studied based on strength reduction of columns affected by fire. Fig 3.1 shows the concrete strength reduction factor which is defined as the ratio of compressive strength of concrete at a certain temperature of fire to its basic compressive strength. The bars at the reinforced concrete section suffer from reduction in strength due to fire. Fig 3.1 depicts the bar strength reduction factor versus temperature of fire for ribbed bar. The reduction factor for bar strength is defined as yielding strength of reinforcement at a certain fire temperature to its base yielding strength.

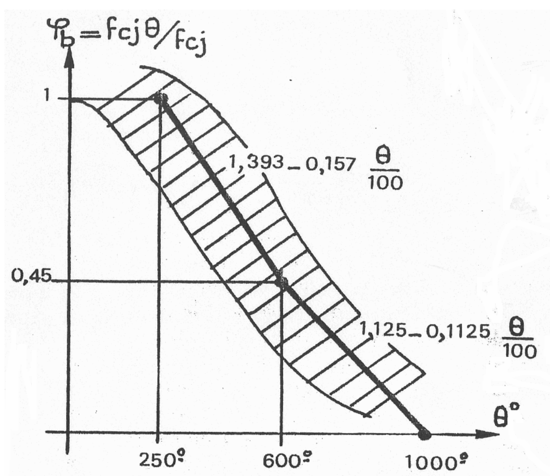

Figure 3.1. Concrete strength reduction factor versus temperature (°C) of fire

Fig 3.2 shows temperature variations for different dimensions of the sections. The dimensions are in centimeters and the time is shown in hours. To model the gradual removal of the column, first the column is replaced with several parallel secondary columns with equivalent total axial and flexural stiffness. The coordinates of nodes at either end of the secondary columns are the same as that of the main column. Removal of a secondary column at a certain time represents reduction in stiffness of the reinforced concrete section due to fire up to the same time. The secondary columns are arranged in a way that removal of the last secondary column means total failure of concrete section in fire under vertical load. Therefore, the characteristics of the secondary columns are defined based on strength reduction functions of concrete sections due to fire (Fig 3.1 and Fig 3.2) and the temperature-time curve for the reinforced concrete section (Fig 3.3). Discretizing the time, the temperature caused by fire is read using Fig 3.3 and dimensions of the section. In the next step, using the temperature obtained in the previous step and the abovementioned functions (Fig 3.1 and Fig 3.2), strength reduction factors for concrete and bars are determined.

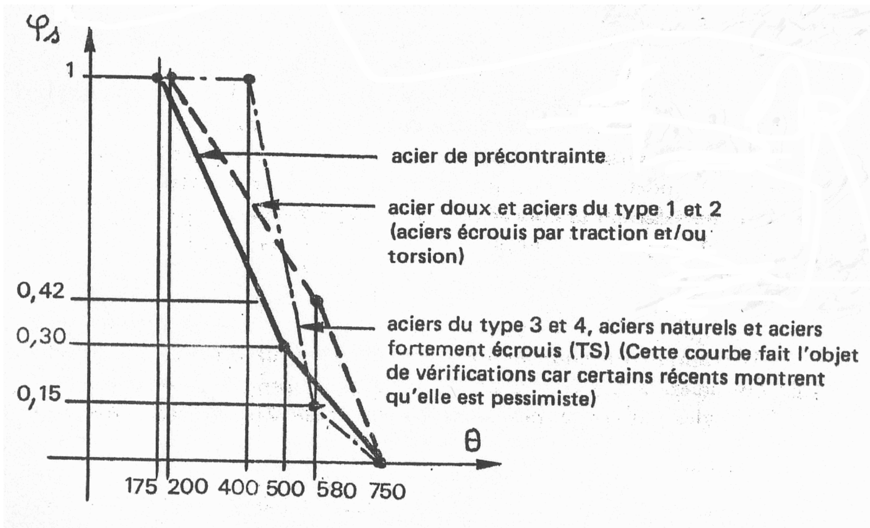

Figure 3.2. Bar strength reduction factor versus temperature (°C) of fire

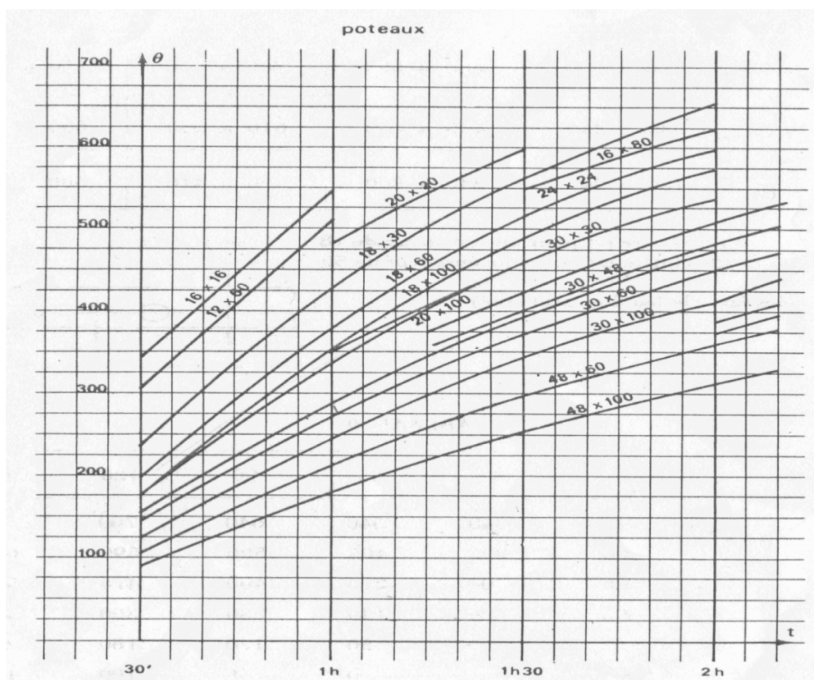

Figure 3.3. Temperature (°C) of reinforced concrete section versus time (h) during fire

Given the code formula for calculating concrete modulus of elasticity, it is concluded that the modulus of elasticity is directly related to the square root of compressive strength of concrete and keeping in mind that axial (EA) and flexural stiffness (EI) are reduced when the structure is on fire, the decrease in modulus of elasticity during fire is represented by gradual change in cross section and moment of inertia. As a result omitting the right number of secondary columns at right time would be resembling the gradual deterioration of column axial and flexural stiffness. In this way, time characteristics of secondary columns (A_t, I_t) representing cross section and moment of inertia are obtained, respectively. Given the description provided above, the ratio of secondary column stiffness to that of the main column (stiffness ratio) is presented in Table 3.1. Secondary columns are removed in the same manner as instantaneous removal. First, stiffness ratios are used to calculate the internal force of each secondary column, and then the forces are removed at predetermined points in time (forces equal reaction of each secondary column exerted in opposite directions).

Table 3.1. Stiffness Ratio of Secondary Columns to the Main Column

Time (Hour)	**Temperature (℃)**	**Concrete strength reduction factor**	**Bar strength reduction factor**	**Stiffness ratio of secondary column to main column**
0.5	105	1	1	0
1	225	1	1	0
1.5	325	0.88	1	6.05
2	350	0.84	1	2.11
3	400	0.77	1	4.38
3.5	450	0.67	0.76	4.61
4	500	0.61	0.53	4.88
4.5	550	0.53	0.29	5.21
5	600	0.45	0.13	5.61
5.5	650	0.39	0.09	4.41
6	700	0.34	0.05	4.65
6.5	750	0.28	0	5.06
7	800	0.23	0	5.60
7.5	850	0.17	0	6.36
8	900	0.11	0	7.54
8.5	950	0.06	0	9.82
9	975	0.03	0	6.95
9.5	1000	0	0	16.76

4. MODELING ASSUMPTIONS IN OPENSEES SOFTWARE

The analytical 3D model of the reinforced concrete structure was developed using OpenSees software. The beams and columns are modeled using force based nonlinear beam-column elements with distributed plasticity along het element. Each nonlinear beam-column element is modeled using five integrating points. The mass of each element of the structure is presented as mass of unit length. Given the nature of progressive collapse and resisting mechanisms in the structure once the column is removed, interactions between axial force and bending moment should be taken into account for precise modeling. The element “fiber” denotes this interaction and provides a more realistic model of behavior. Thus, cross sections of beams and bars are modeled using fibers. Each fiber section is divided into two parts: concrete cover and concrete core. The area of steel bars for each section is added to the model as steel fibers. Kent & Park’s modified model was used for presenting nonlinear stress-strain relation in core fiber (confined) and cover fiber (non-confined). To avoid non-convergence in nonlinear dynamic analysis and to reduce computation time, tensile strength of core and cover concretes were considered as zero. Concrete01 and Steel01 in OpenSees were used to model concrete and steel, respectively. Table 4.1 shows the parameters used for cover and core concretes. The strain hardening factor for Steel01 was set at b=0.01. All nonlinear beam-columns have elastic torsional stiffness which is aggregated to fiber sections. Torsional stiffness for each section is equal to G*J where G is the concrete modulus of torsion and J is the torsional moment of inertia calculated based on dimensions of the sections.

Table 4.1. Parameters of concrete material

	Peak stress (MPa)	Peak Strain	Ultimate stress (MPa)	Ultimate strain
Unconfined	-24	-.002255	-5.41	-.005
Confined	-27	-.002255	-5.41	-.013

Service loads for progressive collapse analysis of structures are calculated based on GSA guideline. Load factors of 1 and 0.25 are used for dead load and live load, respectively. These loads are applied to each node of the structure according to the node tributary area. Column and beam weights are applied to each node of the structure according to the tributary lengths. Obviously, progressive collapse is caused by removal of column results in major rotations and deformations in the structure, and particularly in the elements adjacent to the removed columns. For precise modeling of structural behavior, large deformations in elements were analyzed using the co-rotational coordinate system. The system geometrically transforms the stiffness of beams and resisting forces from the basic system to the global coordinate system. In this approach, rigid deformation is subtracted from total deformation. It is assumed that remaining deformations lead to strains in the updated local axis system of elements which, in turn, results in plastic deformation in the elements. Therefore, in addition to nonlinear behavior which was included in the model based on the definition of nonlinear stress-strain relationships for concrete and steel fibers, geometric nonlinearity is also applied to the model using co-rotational coordinate system.

5. RESULTS OF NONLINEAR DYNAMIC ANALYSIS

The damping ratio of 5% was used in dynamic analysis. The time steps were 0.01 sec and 1 sec for dynamic analysis of instantaneous and gradual removal, respectively. Total analysis time for the two cases was 4 seconds and 34,200 seconds, respectively. According to GSA, the time for removing the column should not be less than one tenth of a period for the structure. Since the structure period is 0.8 sec, the removal time is set at 0.08 sec. Therefore, loads used to simulate instantaneous removal are applied through linear increment from zero at t=0 sec to its ultimate value at t=0.08 sec. Thus, columns reactions were eliminated at t=0.08 sec. As seen in Table 3.1, 16 secondary columns were used to model gradual removal. Stiffness ratio and secondary column properties (cross-section and moment of inertia) were determined as explained earlier. In the developed model, the secondary columns were modeled as elasticBeamColumn elements. Fig 2.1 shows the position of removed columns based on the UFC guideline (column A1, C1 and C2 in the first story). To summarize the results of the analysis, only results of case C1 are explained in this part.

5.1. Instantaneous Removal

Nonlinear dynamic analysis was performed for 4 sec once column C1 was removed from the first floor. Fig 5.1 shows the time history for vertical displacement of Node 23 which is the top node of column C1. Maximum vertical displacement is 1.411 m occurring at t=1.19 sec.

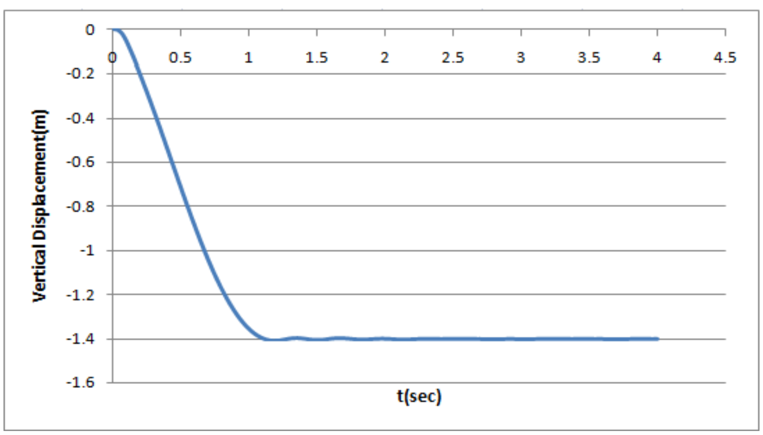

Figure 5.1. Time history for vertical displacement of upper node of Column C1 after instantaneous removal

Once this column is removed, the load bore by this column is transferred to the adjacent columns B1, C2 and D1. Fig 5.2 depicts the time history of axial force at columns B1, C2 and D1. Table 5.1 shows the values of axial forces at these columns under gravity loads prior to removing C1, maximum axial force, and the axial force at equilibrium after the removal of the column. The increased force exerted on B1, C2 and D1 after the removal of the column exceeds the axial force exerted on C1 prior to the removal by 281.28 kN. This can be the result of reduction in axial load or reloading on adjacent columns when column C1 is removed. Maximum axial force at B1, C2 and D1 during the nonlinear dynamic analysis occurs at t=1.19 sec. Table 5.1 shows the percentage of increase in axial forces at equilibrium compared to the same value prior to removal of the column, which reflects the contribution of each column in redistribution of forces bore by the removed column.

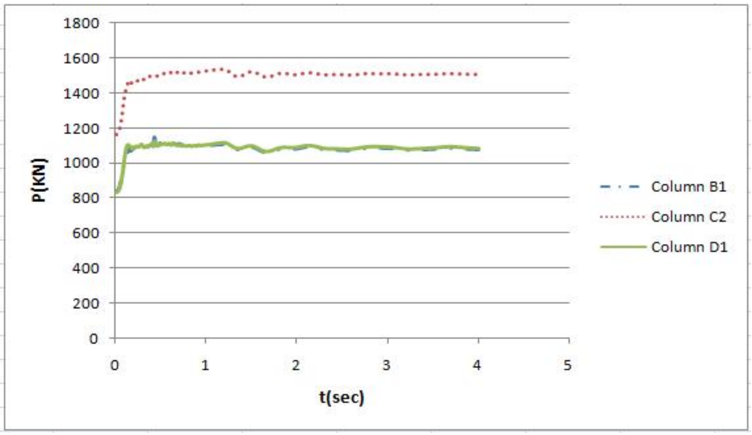

Figure 5.2. Time history for axial load of Columns B1, C2 and D1 after instantaneous removal

Table 5.1. Axial Load of Columns B1, C2 and D2 after Instantaneous Removal

Column	Axial load before column removal (kN)	Maximum axial load (kN)	Axial load in equilibrium state (kN)	percentage of increase in axial force
B1	753.65	1145.99	1076.37	42.82
C2	1046.35	1535.86	1506.11	43.94
D1	752.28	1129.44	1087.92	44.62

As mentioned earlier, removal of the column creates large deformation in adjacent components. Maximum plastic deformations in columns B1, C2 and D1 are 4.31e-4, 6.55e-5 and 4.04e-4 rad, respectively and in beams 102, 103 and 187 maximum plastic deformations are 0.256, 0.256 and 0.276 rad, respectively. Fig 5.3 depicts the time history of plastic deformation in beams 102, 103 and 187.

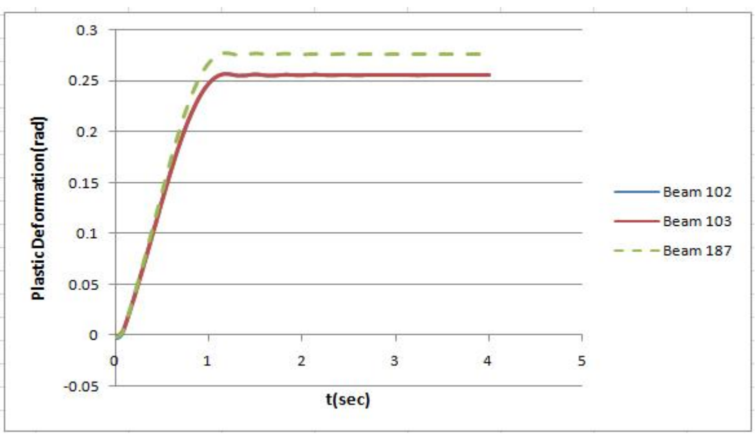

Figure 5.3. Time history of plastic deformation in beams 102, 103 and 187 after instantaneous removal

5.2. Gradual Removal

Nonlinear dynamic analysis was performed for 34200 sec once column C1 was removed from the first floor. Fig 5.4 shows the time history for vertical displacement of Node 23 which is the top node of column C1. Maximum vertical displacement is 1.03 m occurring at the end of the analysis.

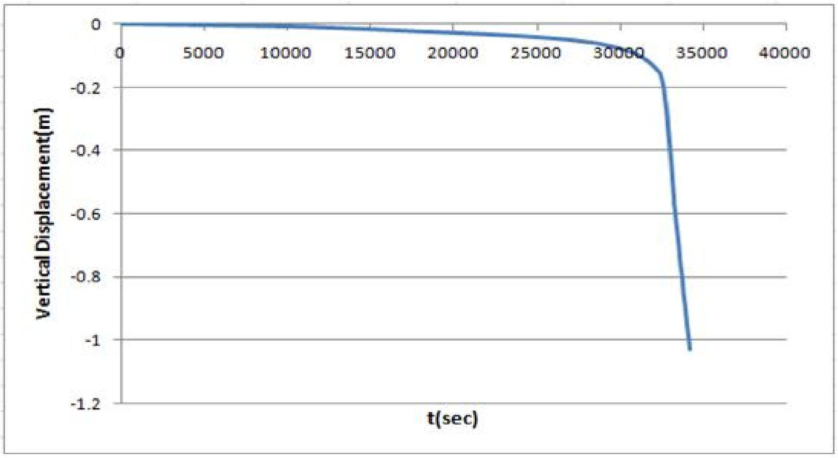

Figure 5.4. Time history for vertical displacement of upper node of Column C1 after gradual removal

Once this column is removed, the load bore by this column is transferred to the adjacent columns B1, C2 and D1. Fig 5.5 depicts the time history of axial force at columns B1, C2 and D1. Table 5.2 shows the values of axial forces at these columns under gravity loads prior to removing C1 and maximum axial force after the removal of the column. The increased force exerted on B1, C2 and D1 after the removal of the column exceeds the axial force exerted on C1 prior to the removal by 12.77 kN. This can be the result of reduction in axial load or reloading on adjacent columns when column C1 is removed. Maximum axial force at B1, C2 and D1 during the nonlinear dynamic analysis occurs at the end of the analysis. Table 5.2 shows the percentage of increase in axial forces at the end of the analysis compared to the same value prior to removal of the column, which reflects the contribution of each column in redistribution of forces bore by the removed column.

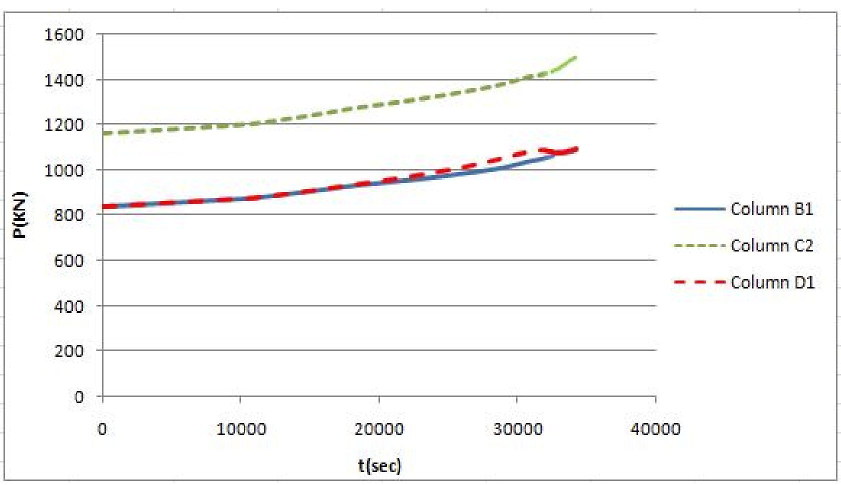

Figure 5.5. Time history for axial load of Columns B1, C2 and D1 after gradual removal

Table 5.2. Axial Load of Columns B1, C2 and D2 after Gradual Removal

Column	Axial load before column removal (kN)	Maximum axial load (kN)	percentage of increase in axial force
B1	752.56	1090.19	44.86
C2	1044.78	1501.20	43.68
D1	836.32	1096.15	48.44

As mentioned earlier, removal of the column creates large deformation in adjacent components. Maximum plastic deformations in columns B1, C2 and D1 are 4.26e-4, 5.38e-5 and 4.06e-4 rad, respectively and in beams 102, 103 and 187 maximum plastic deformations are 0.188, 0.188 and 0.201 rad, respectively. Fig 5.6 depicts the time history of plastic deformation in beams 102, 103 and 187.

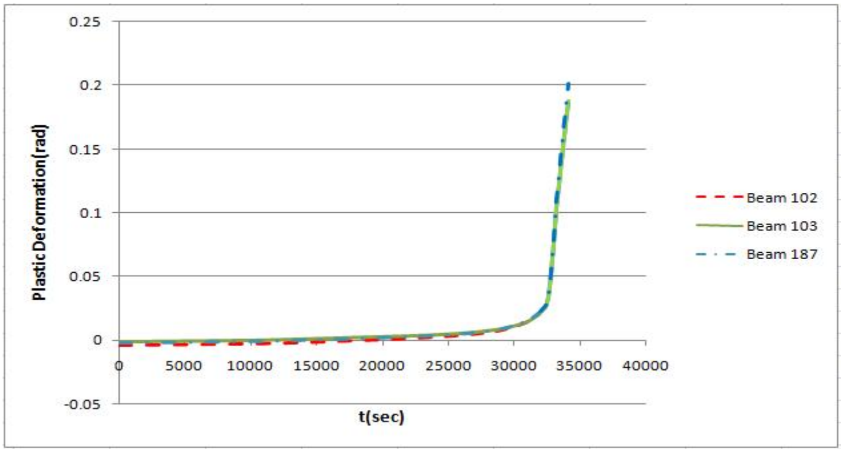

Figure 5.6. Time history of plastic deformation in beams 102, 103 and 187 after gradual removal

6. Conclusions

Results of dynamic analysis for different cases (columns A1, C1 and C2) show that:

-Methods of reducing the rate of fire lead to demand (stress and deformation) reduction in structure particularly in adjacent elements of the zone of fire.
-Dynamic amplification effects caused by instantaneous removal of the column lead to higher demand of stress and deformation in the structure compared to gradual removal of the column.
-Vertical displacement of the upper node of columns after gradual removal is 70 to78 percent of the maximum vertical displacement after instantaneous removal.
-In the instantaneous scenario, maximum axial forces at adjacent columns of the removed column are two to five percent greater than the forces exerted in the gradual scenario, while at the equilibrium, the axial load on adjacent columns of the removed column in instantaneous cases are the same as respective values in gradual cases with 1 percent error.
-The increased force exerted on adjacent columns after the removal of the column exceeds the axial force exerted on this column prior to the removal. This can be the result of reduction in axial load or reloading on adjacent columns when the column is removed.
-In both scenarios, the percentage of increase in axial forces of adjacent columns of the removed column at the end of the analysis (equilibrium state) compared to the same value prior to removal of the column, which reflects the contribution of each column in redistribution of forces bore by the removed column is equal to 1 percent error.
-Plastic deformation in the adjacent beams of the removed column in gradual removal is 70 to 73 percent of the plastic deformation in the instantaneous removal.

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