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Research Paper

Influence of Debris Impact on Progressive Collapse of a Steel Structure Building

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ABSTRACT

Progressive collapse is defined as the expansion of local failure which damages the entire structure or a big part of it. The failure created is very widespread compared with the initial event. The effect of debris, which is normally produced during a progressive collapse, has not been studied yet sufficiently. Despite, it is very important in the progressive collapse, based on experimental accidents. In this paper, the response of a building structure is investigated to consider the influence of separation of debris from one story and falling on the bottom floor. Nonlinear dynamic analyses have been performed on a four-story, four-span steel frame. A sensitivity analysis on the debris amount and its detachment time is carried out by OpenSEES. The obtained results indicate that the greater amount of debris leads to more intensive progressive collapse. In the case of detachment time, the most damaging effect occurs if debris is separated at the same moment when the top point of the removed column experiences its most vertical displacement. Debris amplifies the maximum and residual displacement of the top point of the deleted column up to 3.65 and 4 times, respectively. This shows that debris has a considerable effect and cannot be ignored in progressive collapse analyses.

Keywords:
Progressive collapse;
Debris; Collision;
Moment-resisting frame

1. Introduction

The probability of the occurrence of the progressive collapse has been increased over the past few decades, such as NY world trade center and P. Murrah building in Oklahoma, due to the construction of high-rise buildings, high density of buildings in cities and the risk of explosion inside the building and demolition of its part thereof [1]. Progressive collapse of some high-rise buildings in the 1970s, has drawn the attention of scientists and engineers for the first time [2]. Many articles and research studies have been focused on this phenomenon to counteract or prevent its occurrence [3].

Progressive collapse is defined as the extension of initial local failure from a member to another that eventually leads to the failure of the entire structure or a big part of it [1]. Possible risks and abnormal loads which can cause progressive collapse include: plane crashes, design or construction error, fire, gas explosion, random overload, vehicle crashes, bomb explosion, etc. [4]. The effect of these factors is not considered in designing phase of conventional structures, for low likelihood of their risks [5-6]. Progressive collapse is also discussed in other structures such as lifelines. For example in a cable stayed bridge, sudden rupture of a cable should not lead to the structural instability, based on Post-

Tensioning Institute [7]. Such criteria tries to prevent the zipped failure of such bridges, observed in Tacoma Narrows Bridge in US; after the first hangers of the suspended bridge broke due to excessive vibrations caused by the wind on the beam bridge, the beam crushed and fell [8]. Similar failure can be observed in controlled retaining walls, where the progressive collapse possibly begins with failure of one or more containment [9]. Consider a beam under bending or rod under axial tension. When a part of the cross section is omitted, the internal forces, which transferred to the part, are distributed again in the remaining cross section [10]. A corresponding increase of tension in some places can cause loss of other portion of the cross section and leading the failure continues throughout the entire cross section in the same way [4]. While this type of failure is not often called progressive collapse (called rapid fracture), its inclusion as a progressive collapse can be useful in some issues [9]. The reason for structure instability is small disturbances such as defects, transverse loading, which leads to high deformation or failure [3]. Structures are designed in a way that there will not be usually instability. Despite the failure of instability, stabilizer member (brace) could destabilize the system due to a small event and lead to failure. This can be used for truss structures with beam that the bracing members are used to secure rods with components of cross section in pressure [11]. One of the main causes of failure extension is the collision of degraded and isolated members as debris to healthy members of the structure and demolition of them [12]. During this practice, structure members may be damaged depending on the material of debris and height of falling. In earlier studies conducted in the field of progressive collapse [13], the impact of debris and its impact on the progressive collapse have not been studied. In other words, the effect of debris, which occurred due to the damage of the structural members and caused impact and overload on the lower floors, has not been considered. Ignoring this effect leads to providing inaccurate model of progressive collapse. The study attempts to examine this effect and consider the impact of debris on the progressive collapse of buildings according to international regulations. A sensitivity analysis of the debris and its detachment point from the floor is also performed by OpenSEES [5-6]. In fact, there is usually debris falling during the progressive collapse of buildings; however, its effect has not been investigated sufficiently yet. Considering debris influence on progressive collapse is the main subject of this paper.

2. Numerical Modeling

Elimination of column may cause failure in the roof, leading to falling some debris. In this study, modeling of column elimination and debris collision has been conducted separately. Finally, the effect of collision debris is applied on the model having the removed column and final answer of the structure will be examined. In this study, GSA-2013 guideline is applied with the simulation of debris collision in a single degree of freedom structure [14].

2.1. Column Elimination Model

Given that increasing the number of floors and three-dimensionality model reduce the potential for progressive collapse [15], a three-dimensional structure with four floors and four spans is designed and its outer frame, shown in Figure (1) is used. The structure has been designed regularly based on the Iranian Steel Design Code (Standard no. 10 of national codes for structural design) and Iranian Standard No. 2800 (2014) using ETABS software (2017). Demand to capacity ratio of the considered frame is shown in Figure (1).

This frame has four spans and four floors. The length of each span is 5 m and the height of floors is 3 m. Profile of sections used in this frame is provided in Table (1). Uniform distributed load on the beam is 8875 N/m.

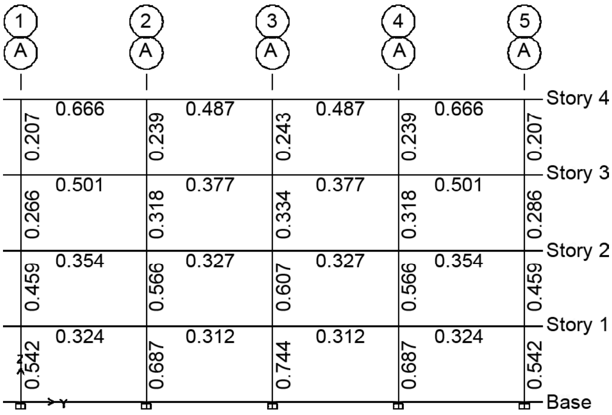

Figure 1. Demand to capacity ratio of the considered structure.

Table 1. Profile of steel sections used in the considered moment resisting frame.

Element	Story	Section
Column	1st	Box 240×240×17.5
	2nd & 3rd	Box 220×220×17.5
	4th	Box 180×180×12.5
Beam	1st and 2nd	IPE 300
	3rd	IPE 270
	4th	IPE 160

Given that in progressive collapse, the most critical state of the column elimination is related to the corner column elimination of the ground floor [16], right corner column on the ground floor, as the most critical mode, will be removed in this model.

In accordance with guideline of GSA-2013 in the model, instead of removing column abruptly, the internal forces obtained from static analysis are replaced in the top point of the removed column (Figure 2); and then dynamic analysis is performed by OpenSEES [5-6] by the following steps:

1. Forces have linearly increased for a period of 5 seconds to reach their final value.
2. These forces are constantly applied to the structure for 2 seconds to reach the system to a steady state.
3. In the seventh seconds, forces of removed members are suddenly eliminated so that the dynamic effects resulting from the column elimination can be obtained (Figure 3).

2.2. Collision Model

Collapse and collision of debris on a beam of the floor that one of its columns is removed, is taken into account for the collision. In this model, a percentage of the second floor debris in the span connecting to the removed column collides with the beam of the first floor (Figure 4).

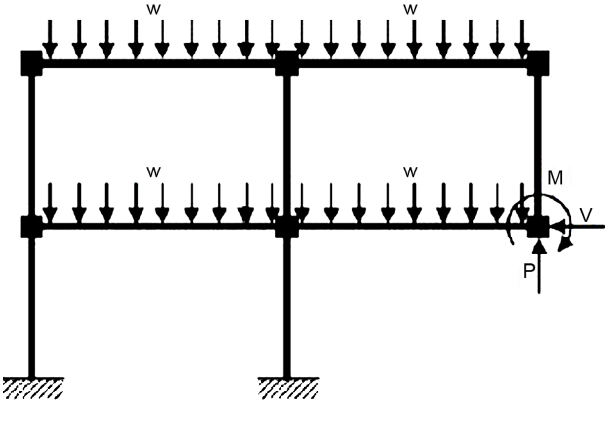

Figure 2. Internal forces of the removed column applied to the structure.

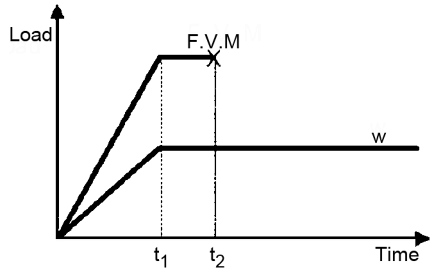

Figure 3. How to use and eliminate the internal forces.

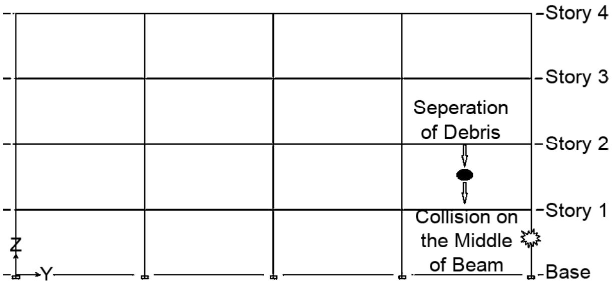

Figure 4. Separation of debris and its collision.

Given that debris just collides with one of the structural beams, its impact can be achieved separately on the beam and then response of this collision can be applied to the structure to determine its impact on the entire structure. For this purpose, response of a fixed beam with mass of m_1 is calculated under the impact caused by collision of debris with the mass of m_2.

This collision is assumed from type of fully plastic with zero resilient coefficient, i.e. m_2 mass is completely attached to the below beam after the collision and becomes as part of its mass (restitution factor is assumed as zero, which means that the debris is attached to the floor just after the collision).

According to velocity of debris and velocity of bottom beam before the collision, velocity of the system after the collision is calculated by Equation (1).

$$m_1 v_1 + m_2 v_2 = v_0 (m^*) \tag{1}$$

where m_1, m_2 and m^* are respectively the equivalent mass of bottom floor beam, the mass of debris and equivalent mass of system after the collision in Kilograms. V_1, V_2 and V_0 are respectively the velocity of bottom floor beam before the collision, velocity of debris before the collision and velocity of the system after the collision in meters per second.

The value of m1 is calculated by Equation (2) (based on Chopra [17]).

$$m_1 = \int_0^L m(x)\left(\Psi(x)\right)^2 dx \tag{2}$$

where L, $m(x)$ and $\Psi(x)$ are respectively the length of beam in meters, mass per unit length of the beam in Kilograms, and shape function of beam.

The total mass of the system after the collision (m^*) is also obtained from Equation (3) (based on Chopra [17]).

$$m^* = \int_0^L m(x)\left(\Psi(x)\right)^2 dx + \Psi_i^2 m_i \tag{3}$$

where m_i and Ψ_i are respectively the debris mass in Kilograms and shape function in the point of collision.

In this study, only the first mode of displacement is important considering that the debris collides on the middle of the beam. Therefore, a simple equation, discussed later, is considered.

As can be seen from Figure (5), the fixed beam system is modeled as a mass-spring system with which the debris with mass of m_2 and velocity of v_2 collides (m_1 is the mass of the beam).

Velocity of the debris at the moment of collision is calculated by the following equation:

$$v_2 = \sqrt{2gh} \tag{4}$$

where, h is story height and g is the acceleration of the gravity. Velocity of the beam at any time, caused by the removal of the column, can be obtained from nonlinear dynamic analysis.

With the insertion of Equations (2), (3) and (4) in Equation (1), the system velocity after the collision is calculated, and displacement caused by the collision of debris can be obtained by solving the motion equation of a beam on which the debris has fallen.

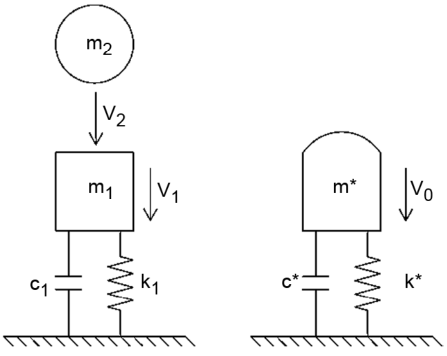

Figure 5. The mass-spring model of a fixed beam before and after the collision.

Differential equation of the mass-spring model after the collision is expressed as follows (based on Chopra [17]).

$$m^* \ddot{Z}(t) + c^* \dot{Z}(t) + k^* Z(t) = P^* \tag{5}$$

$$k^* = \int_0^L EI(x)\left(\Psi''(x)\right)^2 dx \tag{6}$$

$$c^* = \int_0^L c(x)\left(\Psi(x)\right)^2 dx \tag{7}$$

$$P^* = P_i \Psi_i \tag{8}$$

$$U(x,t) = \Psi(x) Z(t) \tag{9}$$

By inserting Equations (8) and (9) in Equation (5), Equation (10) can be obtained.

$$m^* \frac{\ddot{U}}{\Psi(x)} + c^* \frac{\dot{U}}{\Psi(x)} + k^* \frac{U}{\Psi(x)} = P_i \Psi_i \tag{10}$$

In this research, it is assumed that the debris falls on the middle of bottom beam. Given that the coordinates of the collision point and the examined point are the same, Equation (11) is achieved:

$$\frac{m^*}{\Psi_i^2}\ddot{U} + \frac{c^*}{\Psi_i^2}\dot{U} + \frac{k^*}{\Psi_i^2}U = P_i \tag{11}$$

The above equation could be rewritten as follows.

$$M^*\ddot{U} + C^*\dot{U} + K^*U = P_i \tag{12}$$

Given that the force of P_i in debris collision is unclear, the vibration caused by impact in the bottom floor beam cannot be achieved by solving the movement equation of the single degree of freedom system (Equation 12). As a result, the vibration caused by the impact can be obtained by solving Equation (13), in which the initial displacement is zero and initial velocity is calculated by Equation (1).

$$M^*\ddot{U} + C^*\dot{U} + K^*U = 0 \tag{13}$$

2.3. How to Apply the Effect of Debris Collision to the Structure

Separation of debris from a beam is modeled by the elimination of its mass and weight from the beam. The debris is connected to this beam through an impact. Modeling the impact itself in regular analysis software is very complicated; however, its effects can be modeled. The impact produces a deflection in the beam which can be produced by an equivalent load. The equivalent load produces the same maximum displacement in the beam caused by the debris. How to calculate the displacement is previously explained in section 2-2.

Displacement of the examined point in the structure due to the debris collision is calculated and shown in Figure (6). It can be shown that the middle of beam reaches its maximum displacement (y^*) after t^* seconds from the moment of collision.

The displacement of the beam midpoint is calculated under the progressive collapse, shown in Figure (7) (in this figure, the influence of column elimination is only considered); the moment of collision (t_1) is the detachment time (which may be different from the column elimination moment) added by the dropping time of the debris (from the top beam to the bottom). The corresponding displacement (y_1) can be obtained by Figure (7). Then the moment when the middle of the beam reaches the maximum displacement (t_2) can be calculated as:

$$t_2 = t_1 + t^* \tag{14}$$

Displacement of midpoint in this time (t_2) is equal to y_2, shown in Figure (7).

According to Figures (6) and (7), at the moment of t_2, the displacement of the midpoint of the beam under the losing column is y_2, and the displacement of the midpoint of the beam under debris impact is y^*, so the displacement of the midpoint of the beam under the combination effects of losing the column and debris impact is y', underestimated as:

$$y' = y_2 + y^* \tag{15}$$

The influence of column elimination is automatically considered in the model by the software. However, to model the influence of the debris, a linear vertical force from the moment of collision (t_1) until the moment of t_2 is applied to the structure, shown in Figure (8). The force value is determined by try and error to produce the same maximum displacement (y') at the middle of the beam.

As observed in most cases, the beam is not separated, but some parts of the connected slab are separated and fall. To model this phenomenon, the upper beam is not eliminated from the model but its load is decreased and after the falling time (t^*) is added to the bottom beam. Based on the above-mentioned procedure, the displacement of the middle of bottom beam under progressive collapse and collision of debris is obtained as shown in Figure (9).

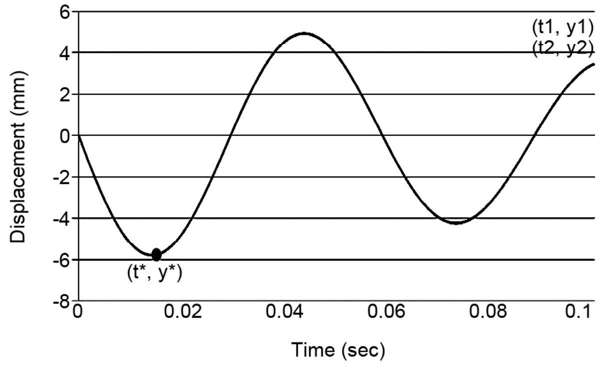

Figure 6. Displacement of the midpoint of beam due to the collision of debris.

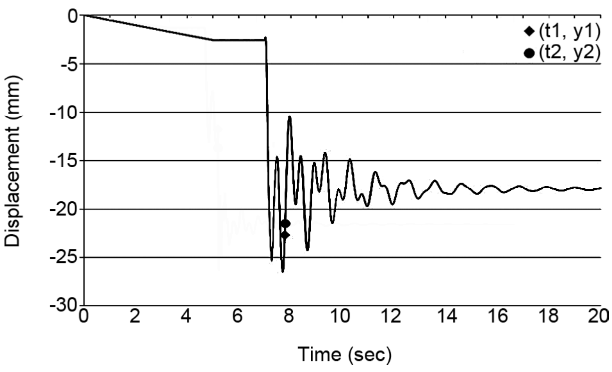

Figure 7. Displacement of the middle of the beam under the progressive collapse.

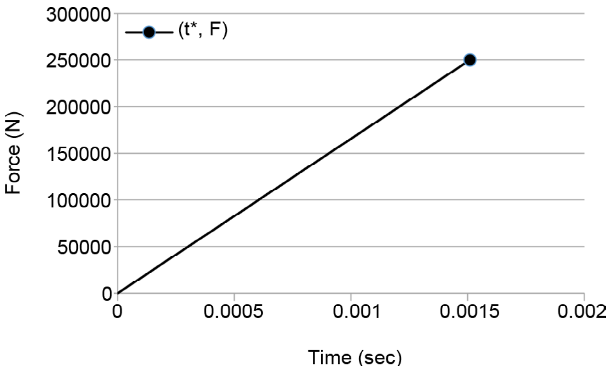

Figure 8. Equivalent force applied to the midpoint of the beam.

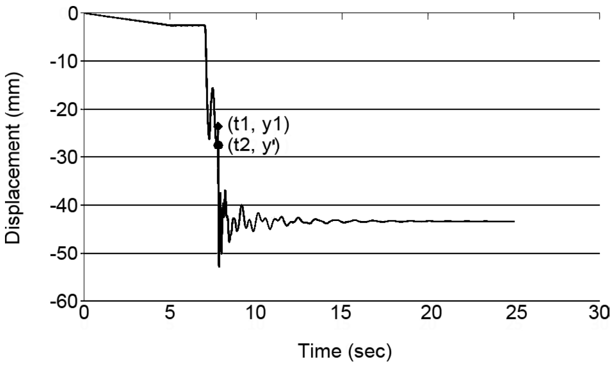

Figure 9. Displacement of the middle of beam under the progressive collapse and collision of debris.

3. A Sensitivity Analysis

A sensitivity analysis is carried out here on the debris mass and time of detachment. For the debris, mass of the above beam and its surcharge is calculated and its various percentages are assumed as debris.

For the location of debris collision, the middle of the bottom beam is considered as a point of the debris collision. Debris collides with the midpoint of the beam as a concentrated mass. To obtain the response, the beam under collision is assumed as a fixed beam, regarding that it is still connected to the upper column, and eventually is modeled as a spring. To estimate its equivalent mass, the following shape function is used with considering the most critical mode of the middle of beam and taking into account the beam length (based on Chopra [17]).

$$\Psi(x) = 1 - \cos\frac{2\pi x}{5} \tag{16}$$

Debris collision moment is measured as 0.78 seconds after separation, regarding that the floor height is 3 m. However, the separation time of debris is not specified precisely. In the sensitivity analyses, the separation time of debris has been considered variable in the study. Four different times are selected for debris separation:

1. Just after the removal of the column,
2. After 1 second,
3. After two seconds,
4. Exactly when the low beam reaches its maximum displacement.

Initial velocity of the system (beam + debris) can be measured using Equation (1) considering the velocity of bottom beam and velocity of debris before the collision. To use this equation, the velocity of debris could be measured from Equation (4) and the velocity of beam could be obtained from nonlinear dynamic analysis. Also, mass of debris could be measured in accordance with section 3 and equivalent mass of the beam before the collision will be calculated using Equation (2), the mass of the system after the collision will be measurable by Equation (3).

- According to the floor height, debris velocity before the collision would be:

$$v_2 = \sqrt{2gh} = \sqrt{2\times 9.81\times 3} = 7.67_{m/s}$$

- Velocity before the collision of low beam will be calculated by the dynamic analysis of structures according to the moment of collision.
- The mass of debris will be calculated according to the specific percentage of the collision mass.
- The mass of the low beam according to the shape function of Equation (16) and beam length of 5 m and mass of 804.69 kg/m would be:

$$m_1 = \int_0^L m(x)\left(\Psi(x)\right)^2 dx =$$
$$\int_0^5 804.69\left(1-\cos\frac{2\pi x}{5}\right)^2 dx = 6035.18_{kg}$$

- The mass of the system after the collision can be also measured according to Equation (3), by having shape function of Equation (16), equivalent beam mass of 804.69 kg/m, the collision point of the middle of beam, and debris percentage.

4. Structure Response Caused by Removing a Column

First, internal forces of the right corner column in the first floor are obtained using static analysis. The shear and axial forces are $V = 4215$ N and N = 84754 N, respectively and the bending moment is M = 8385 N.m. In accordance with GSA2013, structural dynamic analysis will be nonlinear and the response of nodes indicated in Figure (10) as number 10 and number 26 will be investigated. In the analysis, the mass on the upper beam is reduced regarding to the percentage of debris.

Because the maximum displacement belongs to

Figure 10. The point of debris collision (node 26) and the examined node (Node 10).

the node that the column below it is removed, displacement graph of this node is investigated as follows in the absence of debris collision.

Figure (11) shown displacement of Node 10 under the progressive collapse analysis (just caused by deleting the corner column); by increasing internal forces of column caused by the live and dead loads in 5 seconds, Node 10 reaches the maximum displacement under these forces. Then, forces are constantly applied for 2 seconds until the structure achieves complete stability. Now in seconds 7, loads related to internal forces of the column are suddenly removed in Node 10 and therefore the node will have a severe vibration due to this removal.

In the next sections, displacement of this node is investigated with taking into account the force caused by the collision with the strategy previously described in section 2-3. Due to the collision of debris with the middle of the bottom beam, a node has been considered at this point (node 26). Displacement graph of the node due to the removal of the column has been shown in Figure (12).

Figure (12) shows that the middle of beam reaches the maximum displacement by using the linear static forces over a period of 5 seconds. This displacement is greater than the displacement of Node 10 due to the greater deflection of the middle of beam. After two seconds and stabilizing structures, forces related to column in the Node 10 are suddenly removed. Due to the removal of corner column, node 26 experiences a severe vibration so that it reaches the maximum dynamic displacement in a short time that of course is less than the displacement of Node 10.

Also, the middle of beam reaches the stable and constant condition after about 25 seconds and remains at its maximum static displacement that is also less than the maximum static displacement of Node 10. This Graph is used to calculate the displacement taking into account the effect of debris.

To calculate the velocity of the system after the collision, the velocity of the middle of beam before the collision could be obtained through Figure (13).

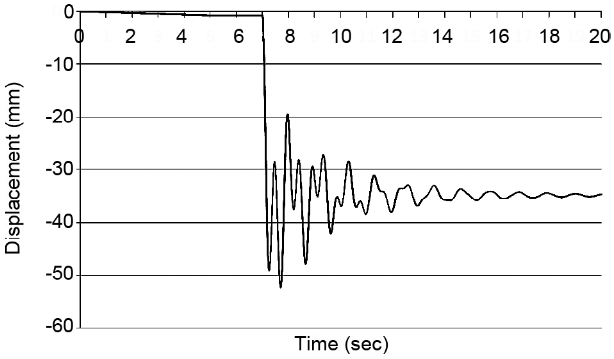

Figure 11. Displacement of Node 10 under the progressive collapse.

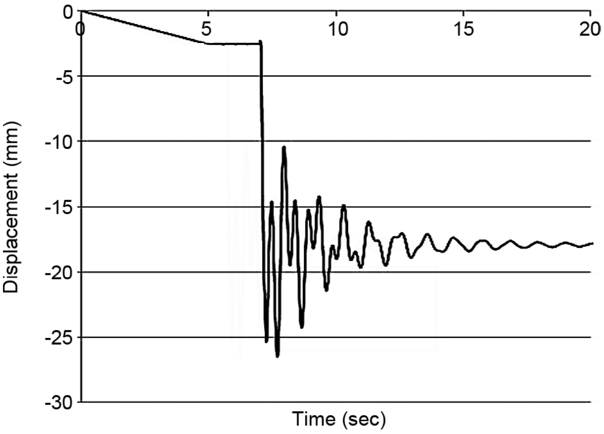

Figure 12. Displacement of node 26 (middle of bottom beam) under the progressive collapse.

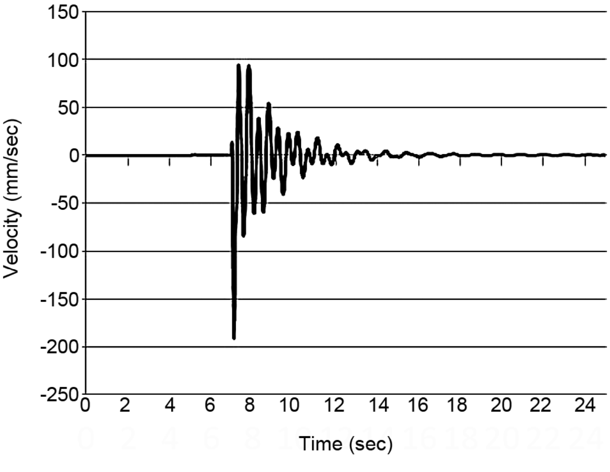

Figure 13. Velocity of node 26 under the progressive collapse.

According to this graph, the velocity of the middle of bottom beam has much volatility in the first moments of removing columns. This volatility becomes stable and comes to zero over time. Velocity of bottom beam at any desired moment is achieved using this graph and it can be used to calculate the velocity of beam after the collision of debris.

5. Separation of Debris at the Moment of Removing Column

In this section, it is assumed that debris is separated from the higher beam at the moment of column elimination. Thus, the debris collides the lower beam after 0.78 seconds with a velocity of 7.67 m/s. According to Figure (13), the velocity of middle point of the lower beam at the moment of collision is equal to 0.084 m/s.

Beam response in the case of collision of 10% debris on the midpoint is calculated as follows:

Equivalent mass of beam: $m_1 = 6035.17\ \text{kg}$

Debris mass: $m_2 = M_t \times 0.1 = 452.34\ \text{kg}$

Beam mode: $\Psi(2.5) = 1 - \cos\dfrac{2\times\pi\times 2.5}{5} = 2$

Mass of system: $m^* = \int_0^L m(x)\big(\Psi(x)\big)^2 dx + \Psi_i^2 m_i =$

$6035.175 + 2^2 \times 452.344 = 7844.55\ \text{kg}$

Debris mass and beam mass is calculated for other percentages of debris, summarized in Table (2).

Beam velocity before the collision: $v_1 = 0.09\ \text{m/s}$

Debris velocity before the collision: $v_2 = -7.67\ \text{m/s}$

System velocity after the collision:

$$m_1 v_1 + m_2 v_2 = v_0(m^*) \Rightarrow (6035.18 \times 0.089) +$$

$$\big(452.34 \times (-7.67)\big) = v_0(7844.55) \Rightarrow$$

$$v_0 = -0.38\ \text{m/s} \ \Rightarrow v_0 = -380\ \text{mm/s}$$

Stiffness of the beam after the collision:

$$k^* = \int_0^L EI(x)\big(\Psi''(x)\big)^2 dx = 109970.97\ \text{N/mm}$$

$$\omega_N = \sqrt{\frac{k^*}{m^*}} = 118.40\ 1/\text{s}$$

$$c_{cr} = \frac{2k^*}{\omega_N} = 1857604.43\ \text{kg/s}$$

$$c^* = \zeta \times c_{cr} = 92880.22\ \text{kg/s}$$

According to calculations made and Equation (13), differential equation of the mass-spring system movement is as follows:

$$M^*\ddot{U} + C^*\dot{U} + K^*U = 0$$

$$\frac{7844.55}{2^2}\ddot{U} + \frac{92880.22}{2^2}\dot{U} + \frac{109970.7}{2^2}U = 0$$

By solving the above differential equations, response equation and graph of the midpoint of beam will be as follows:

$$U(t) = e^{-5.92t}\left(-0.0032\sin 118.25t\right)$$

Figure (14) shows the vibration of the middle of the beam for the debris collision, calculated by the equivalent mass-spring model, explained in Figure (5). As Figure (14) specifies, the middle of beam reaches the maximum displacement after about 0.013 seconds from the debris collision. Since the

Table 2. Reaction of the top point of the removed column to progressive collapse due to the collision of debris.

Debris Percentage	Debris Mass (kg)	System Equivalent Mass (kg)	System Velocity After Collision (mm/sec)	Maximum Dynamic Displacement (mm)	Maximum Static (Residual) Displacement (mm)
%	0	6035.17	84	-52	-34.5
10%	452.34	7844.55	-378	-53.8	-37
20%	904.69	9653.93	-670	-53.9	-46
30%	1357.04	11463.32	-860	-75.2	-61.5
40%	1809.38	13272.7	-1010	-91.2	-74.7
50%	2261.73	15082.09	-1120	-106.1	-88.2
60%	2714.07	16891.47	-1200	-109.5	-91.4
70%	3166.42	18700.85	-1270	-120.2	-101.4
80%	3618.76	20510.23	-1330	-132	-112.4
90%	4071.11	22319.62	-1380	-140.5	-120.1
100%	4523.46	24129	-1420	-149.3	-127.7

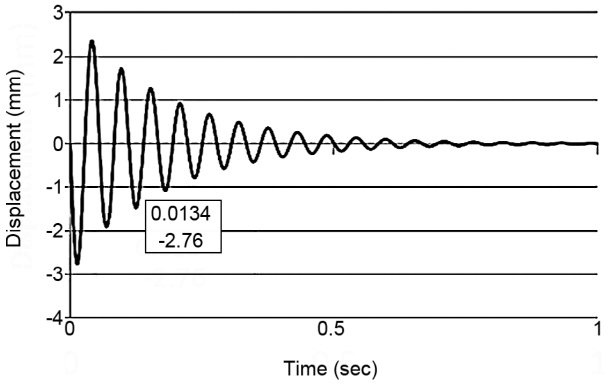

Figure 14. Displacement of the middle of beam due to the collision of debris.

collision occurs in 7.78 seconds, the midpoint of the beam due to the debris collision reaches the maximum displacement of 2.8 mm in 7.793 seconds.

Figure (15) shows the displacement of the middle of beam caused by column removal; it comes to 21.5 mm in 7.793 seconds.

According to Figure (14) and Figure (15), it is clear that the middle of beam as a result of progressive collapse and debris collision, experiences a vertical total displacement of 24.3 mm in 7.793 seconds.

Now, a linear equivalent force from 7.78 seconds to 7.80 seconds is applied to the middle of beam in the structure under the progressive collapse so that the middle of beam experiences the vertical displacement of 24.3 mm. The mass of the debris is also added to the existing mass on this beam. Finally, by eliminating the debris equivalent force, dynamic displacement graph of Node 10 will be as shown in Figure (16).

It is apparent in Figure (16) that the separation of debris from the higher beam is effective in raising the vibration amplitude of Node 10. Moreover, the residual displacement of Node 10 is greater for the case with debris than the other model in which just the column is removed, for the debris weight on the beam. For the case with 10% debris, the maximum dynamic and residual displacement of the top point of the removed column is determined as -53.8 mm and -37.0 mm, respectively. For greater percentages of debris, these displacements are calculated and summarized in Table (2), and also shown in Figure (17). Comparing the maximum dynamic and static (residual) displacements of Node 10 under different percentages of debris collision shows that when the percentage of debris is increased, maximum dynamic and static displacements of the top point of the removed column is also raised.

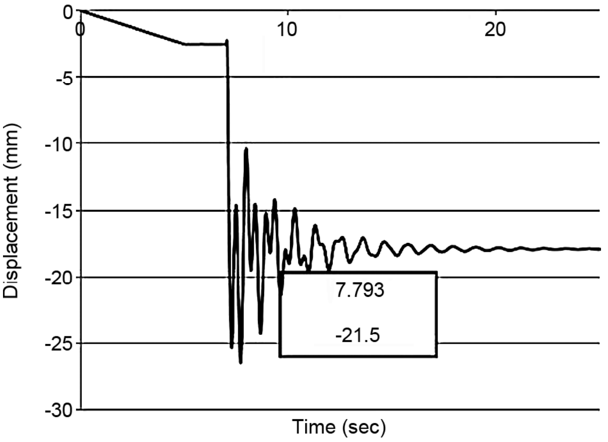

Figure 15. Displacement of the middle of beam caused by column removal.

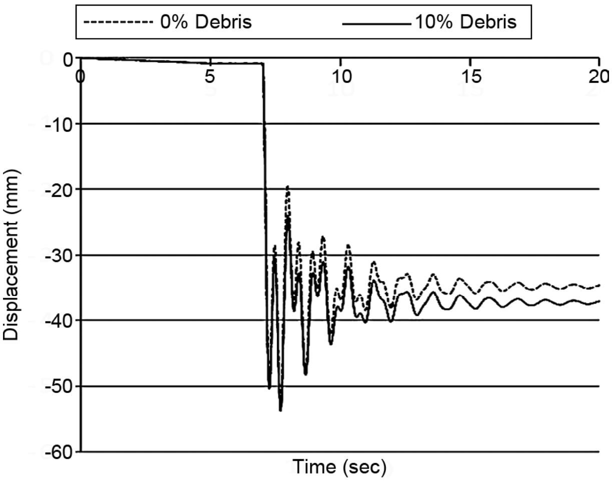

Figure 16. Comparing the response of Node 10, without the debris and 10% debris.

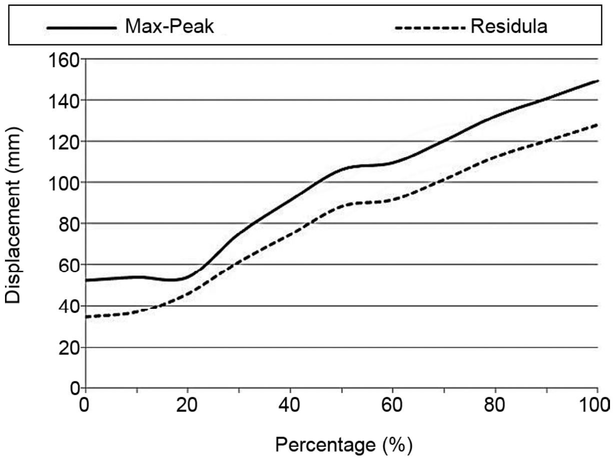

Figure 17. The maximum dynamic and residual displacements.

6. Separation of Debris, 1 Second After Removing the Column

In this section, it is assumed that debris is separated from the upper beam at 1 second after the removal of the column. Thus according to the moment of column removal, debris is separated from this beam after 8 seconds and collides with the below beam at 0.78 seconds after that with velocity of 7670 mm/s. According to Figure (13), the velocity of lower beam at the moment of collision is equal to 53.9 mm/s. The response of the structure to the collision of different percentages of debris is calculated and summarize in Table (3) and Figure (18). As shown in this figure, larger debris produces greater dynamic and residual displacements in the top point of the removed column and thus leads to more intensive progressive collapse

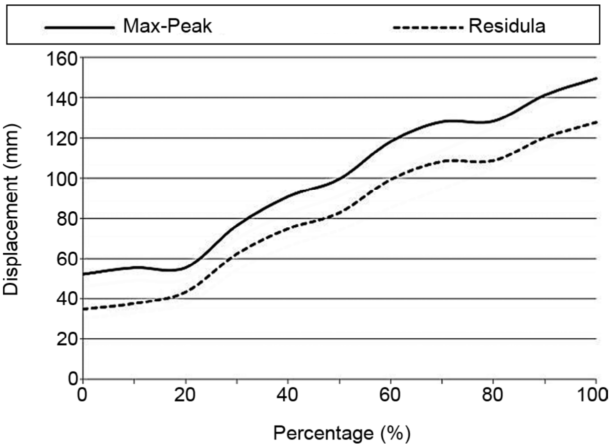

Figure 18. Maximum dynamic and residual displacements of Node 10, Debris separation is 1 sec after column elimination.

7. Separation of Debris, 2 Seconds After Removing the Column

In this section, it is assumed that debris is separated from the upper beam at 2 seconds after the removal of the column. Thus according to the moment of column removal, debris is separated from this beam after 9 seconds and collides with the below beam at 0.78 seconds after that with a velocity of 7670 mm/s. According to the Figure (13), the velocity of lower beam at the moment of collision is equal to 18 mm/s. Then, the response of the structure to the collision of different percentages of debris is calculated and summarized in Table (4) and Figure (19).

Table 3. Reaction of the top point of the removed column to progressive collapse due to collision of debris.

Debris Percentage	System Velocity After Collision (mm/sec)	Maximum Dynamic Displacement (mm)	Maximum Static (Residual) Displacement (mm)
0%	500	-52.2	-34.5
10%	-400	-55.5	-37.7
20%	-690	-55.5	-43.4
30%	-880	-76.6	-62.4
40%	-1020	-90.8	-75
50%	-1130	-99.7	-82.8
60%	-1210	-118.2	-99.4
70%	-1280	-128	-108.2
80%	-1340	-128.3	-108.6
90%	-1380	-141.3	-120.2
100%	-1420	-149.5	-127.7

Table 4. Reaction of the top point of the removed column to progressive collapse due to the collision of debris.

Debris Percentage	System Velocity After Collision (mm/sec)	Maximum Dynamic Displacement (mm)	Maximum Static (Residual) Displacement (mm)
0%	18	-52.2	-34.5
10%	-430	-55.5	-37.7
20%	-710	-56.5	-42.6
30%	-900	-78.9	-61.5
40%	-1040	-93	-74.7
50%	-1140	-102.7	-83.7
60%	-1230	-116.5	-96.2
70%	-1290	-128	-106.7
80%	-1350	-140.5	-118
90%	-1390	-154.1	-130.2
100%	-1430	-163	-138.3

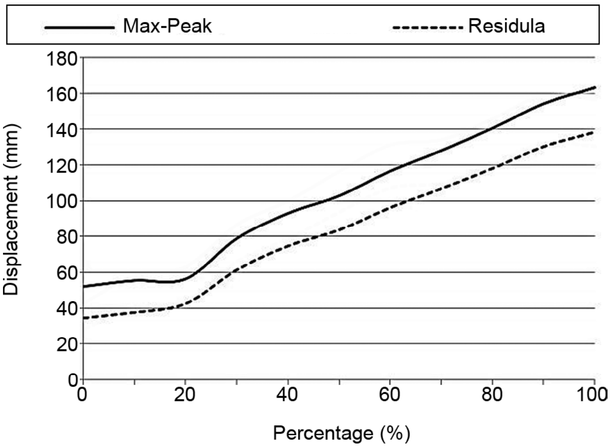

Figure 19. Maximum dynamic and residual displacements.

8. Separation of the Debris After Removing Column, Just When the Node 10 Reaches Its Maximum Displacement

In this section, it is assumed that debris is separated from the upper beam exactly at the moment when the node above the removed column (Node 10) reaches its maximum dynamic displacement after the column removal. This assumption is very close to reality, in which walls and slabs are sensitive to displacement or rotation of the structural elements. Thus, according to the moment of column removal and displacement graph of Node 10, debris is separated from this beam just after 7.696 seconds and collides with the lower beam at 0.78 seconds after that with a velocity of 7670 mm/s. Velocity of the lower beam at the moment of collision is 49 mm/s. Now, similar to the previous cases, the reaction of structure will be calculated which is summarized in Table (5) and shown in Figure (20).

By comparing the maximum dynamic displacement of Node 10 under the collision of different percentage values of the debris at different times, Figure (21) would be confronted; as it can be seen, the last case is the worst case with the greatest damage, in which the debris is detached from the upper floor just when the top point of the removed column experiences its maximum deflection.

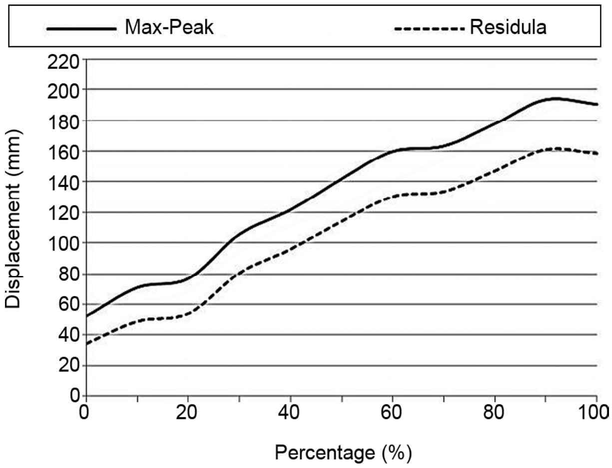

Figure 20. Maximum dynamic and residual displacements of Node 10, if debris is separated when the top point of the removed column reaches its max displacement.

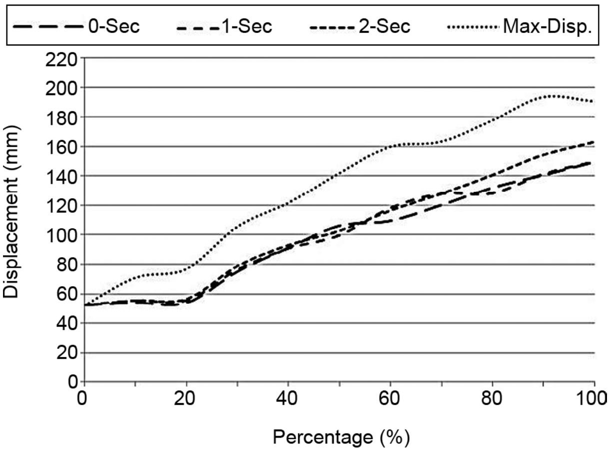

Figure 21. The maximum dynamic displacement of Node 10, for different debris percentage and for different debris separation time.

Table 5. Reaction of the top point of the removed column to progressive collapse due to the collision of debris.

Debris Percentage	System Velocity After Collision (mm/sec)	Maximum Dynamic Displacement (mm)	Maximum Static Displacement (mm)
0%	49	-52.2	-34.5
10%	-480	-71	-37.7
20%	-750	-77	-42.6
30%	-930	-105.6	-61.5
40%	-1070	-121.7	-74.7
50%	-1170	-141.8	-83.7
60%	-1250	-159.8	-96.2
70%	-1310	-163.2	-106.7
80%	-1370	-177.8	-118
90%	-1410	-193.4	-130.2
100%	-1450	-190.3	-138.3

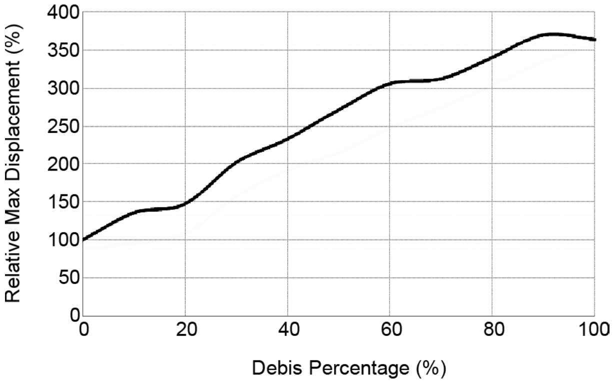

Figure 22. Relative maximum dynamic displacement of Node 10.

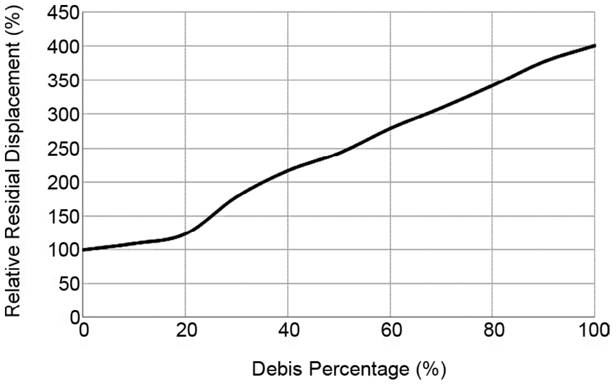

Figure 23. Relative residual displacement of Node 10.

Figure (22) shows the maximum displacement of Node 10 for different debris values, relative to the case with no debris. Figure (23) is similar to Figure (22) but for residual displacement of Node 10. Based on these two figures, the impact of debris has such a significant effect that the maximum and residual displacements of the top point of the deleted column can be even raised up to 365% and 401% those of the case with no debris, respectively. With regard to Figure (22), 90% and 100% debris values have almost the same effect on the maximum displacement. Figure (23) shows that debris values less than 20% have the same residual displacement as the case of no debris.

9. Conclusions

Based on experimental accidents, the effect of debris is very important in the progressive collapse on buildings, which is the main subject of the present study. A sensitivity analysis has been carried out here on the amount and detachment time of the debris for a considered moment resisting frame. It is assumed that the debris is separated from the mid-length of the upper beam and falls on the mid-point of the lower beam. The response during the collision of debris to the bottom floor is investigated by nonlinear dynamic analysis on a four-story, four-span steel frame. The most dangerous scenario, in which a corner column is removed, is considered for the analyses. The obtained results show that the larger amount of debris leads to more damaging progressive collapse. Furthermore, it is shown that the most damaging collapse scenario occurs if debris detachment time coincides with the maximum vertical displacement of the top point of the removed column. The debris amplifies the maximum and residual displacement of the top point of the deleted column, even up to 3.65 and 4 times, respectively. Generally, the maximum and residual displacements of the top point of the deleted column are raised accordingly by increasing the debris amount. However, the maximum and residual displacements remain constant for debris values greater than 90% and less than 20%, respectively. In summary, the results show that the debris has considerable effects on the progressive collapse, and cannot be ignored in progressive collapse analyses if it is probable.

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