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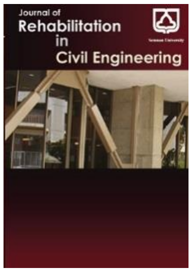

Macro Modeling of Column Removal in RC Frames with Consideration of Importance Factor and Infill Walls

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ABSTRACT

In this study, the effect of importance factor (IF) on RC frames with and without infill walls, in both with and without opening conditions, is evaluated against progressive collapse. For this purpose, RC building with the intermediate moment frame system for three levels of importance factor that these levels are intermediate, high, and very high IF is designed. OpenSees program is utilized for modeling RC frames. For this aim, the accuracy of modeling of column removal and infill walls are compared with experimental researches. In the present study, nonlinear dynamic analysis (NDA) and push-down analysis (PDA) were used for evaluating RC frames against progressive collapse in each column removal scenario. Analysis results showed that the effect of the importance factors in NDA and PDA are reduced to less than 24% and 13% when the infill walls are modeled in the frames. In the frame without infill walls, the influence of the importance factor is increased up to 36.1%. Also, in this study, it was found that the role of importance factors depends on the place of the removed column, which the effect of middle column removal is relatively twice than the corner column removal due to more redundancy. Other results about infill walls effects and opening in infill walls are presented in the paper. Finally, a proposed approach for column removal in NDA via OpenSees program is introduced, and its high accuracy is shown. This developed algorithm can remove any element of structure in different time intervals.

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1. Introduction

Progressive collapse or disproportionate collapse is one of the failures that can be a disaster. In general, progressive collapse is the creation of initial damage in a portion of the building, then spreading this collapse so that the whole building or most of it is collapsed. Among existing methods, the alternate path method (APM) is the best method for the assessment of the vulnerability of existing and new buildings against progressive collapse. General Service Administration (GSA) [1] and Department of Defense (DoD) [2] are the famous guidelines for APM of buildings against progressive collapse that have been used in this research.

In recent years, many studies are carried out about progressive collapse in RC buildings. Sasani [3] evaluated a six-story RC building with infill walls. In this study, he realized that infill walls could reduce the vertical displacement by 2.4 times compared to buildings without infill walls. Talaat and Mosalam [4] studied the modeling of column removal in the earthquake of RC frames in an open-source OpenSees program. They added some codes to OpenSees about element removal command. Also, they modeled infill walls through an equivalent compression strut method. Tsai and Huang [5] investigated three types of infill walls in RC structures in progressive collapse with linear and nonlinear static procedures. It was supposed that in each infill wall exists 60% opening and indicated that the presence of infill wall leads to reduction of bending moment in beams. Rahai et al. [6] studied the effects of wall removal in RC buildings. In this research, they found that the critical places of wall removal in the plan are in the corners and in elevations is in the places that wall section size was changed. Mosalam and Gunay [7] realized that infill walls might have negative and positive roles in a progressive collapse. They investigated the in-the-plane and out-of-plane action of the wall in disproportionate collapse. Li et al. [8] validated RC frames with and without infill walls condition against column removal condition. In this study, they found infill walls increase the capacity of the frames but reduce the ductility. Yu et al. [9] studied infill walls in RC frames with different heights of infill panel, location of the opening, and the number of stories. They realized that infill walls caused to increasing strength of RC frames, but the opening area of infill panel reduced considerably frame strength against column removal. In addition, impropriate location of the opening may reduce by 10% to 20% of RC frame strength. Eren et al. [10] concluded that infill walls increase the energy of RC frames due to column removal scenarios. In addition, macro modeling of infill walls via equivalent compression struts had high accuracy. Trapani et al. [11] investigated the RC frame with different shapes of infill walls against progressive collapse. In this research, it is found that infill walls redistribute loads to the neighbor beams and columns and lead to increasing of strength in RC frames. Besides, infill panels with square shapes have a better performance compared to rectangular shape panels. Wang et al. [12] studied the effect of concrete infill wall with and without opening on the column removal scenarios in precast RC frames. They found infill panels increase the capacity of precast of RC frames in flexural and catenary action stages. Besides, existing opening in infill panels leads to reduction of capacity in precast RC frames. Qian et al. [13] researched the influence of infill walls in RC frames due to column removal scenarios. In their study, they realized considering both slabs and infill walls are leads to increasing 70% and 169% of ultimate load and initial stiffness, respectively. In addition, when RC frames are modeled without considering of slab, infill walls are caused to increase 50% of ultimate load, but when the slabs are modeled, this effect is reduced to 32%. Bigonah et al. [14] investigated different types of infills in RC frames. They realized that using infill 3D panels is reduced vertical displacements and forces in neighbor elements. Aghayari et al. [15] investigated progressive collapse of RC buildings with the slab-wall system. They found that RC slab-wall systems are prone to collapse when increasing story numbers and length- to- height ratios.

In this study, the effect of importance factors (IF) on the RC frames with consideration of infill walls (with and without opening) are evaluated versus column removal scenarios. One of the most important issues about this research is that with increasing of IF levels, lateral forces are increased and it lead to dimensions and reinforcement increasing. Although increasing of dimensions and reinforcements are cause to better performance of RC concrete buildings against lateral loads but this effect is not investigated in the column removal scenarios. In this research, nonlinear dynamic analysis (NDA) and push down analysis (PDA) are used for evaluation of the exact behavior of frames after sudden column removal and ultimate capacity of RC frames, respectively. In the present study, three levels of importance factor (intermediate, high, and very high) are studied, and their effects are discussed. To consider infill walls, three levels of the infill wall are modeled. The first model is considered without infill wall, the second model is considered with infill wall but without opening, and finally, the third model includes the infill wall with 30% opening in the middle of infill panel. Comparison results of infill wall modeling in vertical displacement and ultimate capacity are very considerable. In addition, an algorithm is developed in the OpenSees program for column removal scenarios, which this algorithm can improve the run time and accuracy of the analysis.

2. Investigated Building

In this study, a six-story building with an intermediate moment frame system is chosen for progressive collapse. The reason for selecting a six-story RC building is that many RC buildings have stories between four to eight and have an intermediate moment frame system. In addition, when the number of stories increases, the strength of buildings against progressive collapse enhances due to redundancy increasing. Therefore, the probability of collapse in high-rise RC buildings is less than in mid-rise and low-rise ones. Plan and case frame of the building are illustrated in Figs. 1(a) and 1(b), respectively. The desired frame and different scenarios of column removal are depicted in Fig. 1(b). It is assumed that the building is regular in plan and elevation, and has not any type of irregularity.

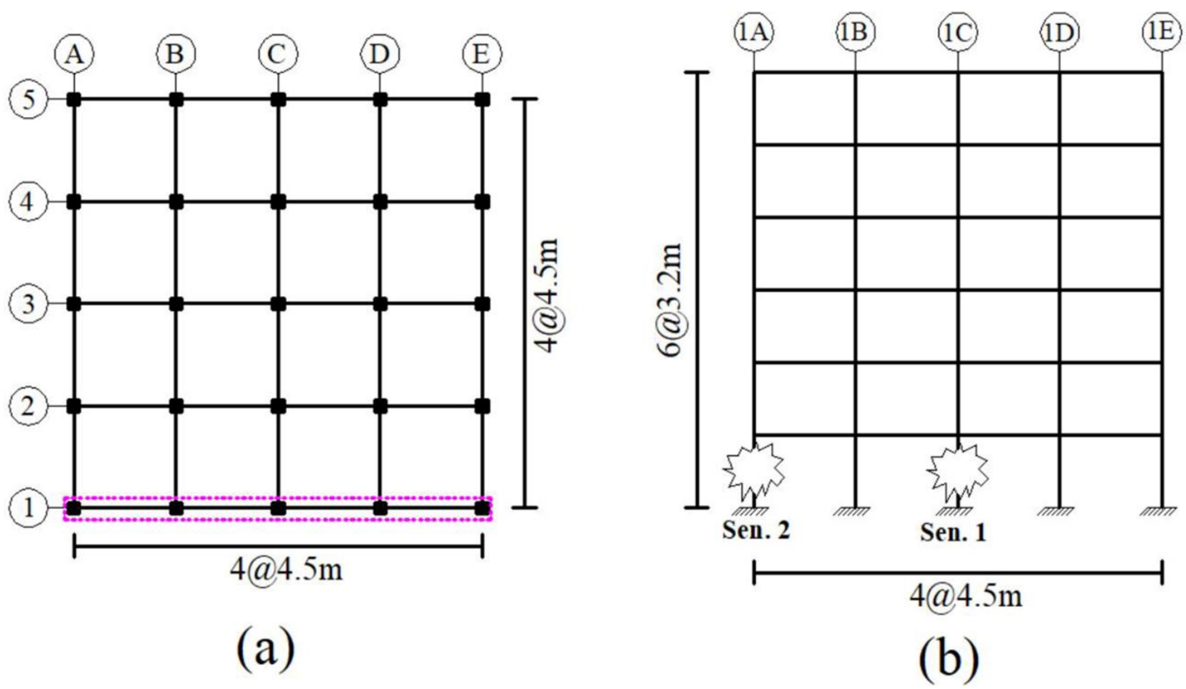


Fig 1. (a) Plan that been studied (b) external frame and considered scenarios for column removal.

Table 1. Sectional dimensions for building with intermediate importance factor (IF=1.0).

Stories	Beam size				Column size			
	Width (cm)	Height(cm)	Deformed bar size	Transverse Reinforcement*	width(cm)	height(cm)	Deformed bar size	Transverse Reinforcement**
1&2	40	40	Top 6ƒ18 Bot. 4ƒ18	ƒ8 @ 18 cm	45	45	16ƒ18	ƒ10 @ 20 cm
3&4	35	40	Top 5ƒ18 Bot. 4ƒ18	ƒ8 @ 18 cm	40	40	16ƒ16	ƒ10 @ 18 cm
5&6	30	40	Top 4ƒ18 Bot. 2ƒ18	ƒ8 @18 cm	35	35	12ƒ16	ƒ10 @ 15 cm

*The stirrup spaces were considered 90 mm for critical length of the beam
**The stirrup spaces were considered 100 mm for critical length of the column

Table 2. Sectional dimensions for building with high importance factor (IF=1.2).

Stories	Beam size				Column size			
	Width (cm)	Height(cm)	Deformed bar size	Transverse Reinforcement*	Width (cm)	Height(cm)	Deformed bar size	Transverse Reinforcement**
1&2	45	40	Top 6ƒ18 Bot. 4ƒ18	ƒ8 @ 18 cm	50	50	16ƒ16	ƒ10 @ 22 cm
3&4	40	40	Top 6ƒ18 Bot. 4ƒ18	ƒ8 @ 18 cm	45	45	16ƒ16	ƒ10 @ 20 cm
5&6	30	40	Top 5ƒ18 Bot. 3ƒ18	ƒ8 @ 18 cm	35	35	12ƒ16	ƒ10 @ 15 cm

*The stirrup spaces were considered 90 mm for critical length of the beam
** The stirrup spaces were considered 100 mm for critical length of the column

Table 3. Sectional dimensions for building with very high importance factor (IF=1.4).

Stories	Beam size				Column size			
	Width (cm)	Height(cm)	Deformed bar size	Transverse Reinforcement*	Width (cm)	Height(cm)	Deformed bar size	Transverse Reinforcement**
1&2	50	40	Top 8ƒ18 Bot. 6ƒ18	ƒ8 @ 18 cm	55	55	20ƒ20	ƒ10 @ 25 cm
3&4	45	40	Top 7ƒ18 Bot. 5ƒ18	ƒ8 @ 18 cm	50	50	16ƒ20	ƒ10 @ 22 cm
5&6	40	40	Top 4ƒ18 Bot. 3ƒ18	ƒ8 @ 18 cm	45	45	16ƒ18	ƒ10 @ 20 cm

*The stirrup spaces were considered 90 mm for critical length of the beam
** The stirrup spaces were considered 100 mm for critical length of the column

As shown in Fig. 1(b), two-column removal scenarios are considered. In the first scenario, the column is placed in the middle of the frame, and in the second scenario, the column is placed in the corner of the frame. Dead and live loads that applied to the floors are 560 kg/m^2 and 300 kg/m^2, respectively. These values of loads in the roof are 510 kg/m^2 and 250 kg/m^2. Dead loads for wall perimeters in floors and roof are considered 700 kg/m and 250 kg/m. In applied loading of buildings, according to the Iranian code for seismic resistance design of buildings, (Standard No.2800 [16]), the soil type is assumed type II, and the seismic zone is supposed in a high level of seismicity (A=0.30g). Tables 1 to 3 provide the sectional dimensions and number of rebars used in beams and columns in different levels of importance factors. It should be noted that Standard No.2800 in the distribution of lateral force with equivalent linear static is relatively similar to ASCE/SEI 7-16 [17].

In this research, the buildings are designed according to the high seismicity zone. For this purpose, ACI 318-19 [18] code was utilized for designing RC buildings with different levels of IF. Importance factors were considered 1.0, 1.2, and 1.4 for intermediate, high, and very high levels, respectively. It should be noted that for simplicity of beam modeling, rebar size of each beam was considered uniform in the whole length of each beam. In Tables 1 to 3, it was assumed that because of architectural restrictions, the depth of the beams was not exceeded 40cm, and for this reason, beam widths were increased.

3. Modeling

3.1. Overview of Modeling

OpenSees [19] is utilized for progressive collapse analysis of frames. OpenSees is a macro software that computationally efficient, and its accuracy compared with detailed FE softwares is reasonable [20,21]. For this purpose, the external frame of each building with intermediate, high, and very high IF is selected and modeled in OpenSees via 2D simulation. The effect of 3D and 2D simulation comes back to the transverse elements, which have a positive effect on the results due to redistribution of the loads. However, in this research, the effect of the transverse elements is not considered, and the results may be conservative. Fig. 2 shows the detail of each frame for consideration of the situation of infill. As illustrated in Fig. 2, three different situations of infill walls are considered. In the first situation, frame is considered without infill (bare frame in Fig. 2(a)), in the second situation frame is considered with infill wall (Fig. 2(b)), finally, in the third situation, the frame is included with 30% opening in infill wall (Fig. 2(c)).

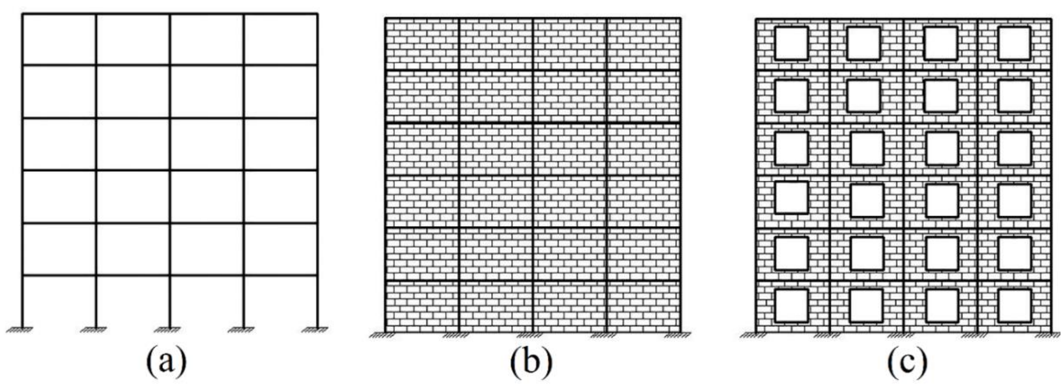


Fig 2. Different situation of infill walls in each frame (a) frame without infill wall (b) frame with infill wall without opening (c) frame with infill wall with 30% opening.

"Concrete01" and *"Reinforcing Steel"* materials were used for concrete and rebar, respectively. The specified strength of concrete was considered 28 MPa. For concrete material, two types of confined and unconfined concrete were used for the core and cover portions. In confined concrete material, the ultimate strain is more considerable than unconfined concrete [22]. Yield and ultimate strength of rebars are 400 MPa and 600 MPa, respectively. According to GSA2013, lower bound material strength should be converted to expected material strength. For this aim, the strength of concrete and steel materials should be multiple in 1.5 and 1.25, respectively [23]. Fiber section was used for beam and column elements. Fiber section was discretized to small fibers, each of these fibers behaves with regarding of their material properties.

Dimension of each fibers was considered 5cm. Fiber sections consider the interaction of axial force and bending moment (P-M). Interaction of P-M is vital for considering of real behavior of RC frame in progressive collapse [24]. Force-based element with distributed plasticity was used for beam and column elements. These elements have a good accuracy compared to other elements in progressive collapse simulation [25]. The *"Co-rotational"* transformation was considered. "*Co-rotational*" transformation has a significant role in the catenary action of the structure after column removal because this type of transformation has capable of transforming nonlinear resisting force and stiffening in local to the global coordinate system [26]. Beam-column joints are supposed to be rigid due to assuming proper detailing in the connection zone. In addition, end rigid zones in beam-column joints are ignored for avoiding extra stiffness in RC frames. Details of nonlinear modeling of each element have been shown in Fig 3.

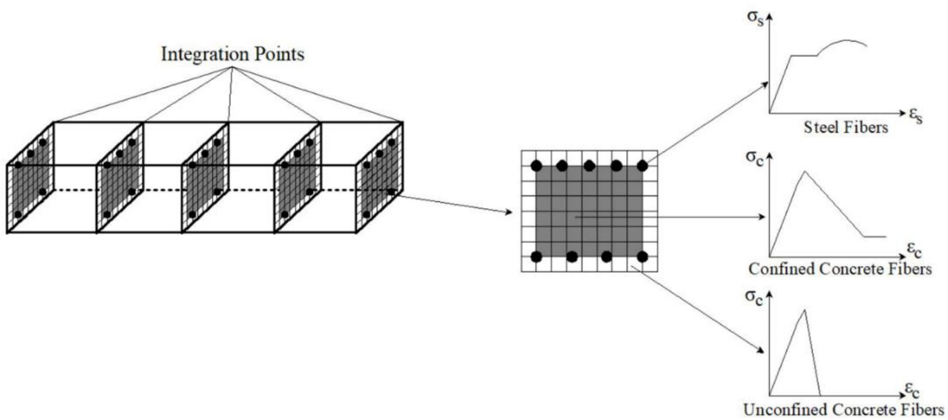


Fig 3. Overall considerations for each RC beam and column elements that are force based elements.

One of the key issues about RC beams is that such elements tend to longitudinal elongation after cracking and flowing of the tensile bars. While such a tendency to elongation is prevented by floor and columns. Such elongation tendency is so-called *"beam growth"* and since such phenomenon does not occur in reality due to confinement of the beams, so the reinforced concrete beams should certainly be confined to prevent their longitudinal growth. To avoiding of beam growth occurrence, all nodes in each story should be restrained [27].

3.2. Infill Wall Modeling

In this research, equivalent diagonal compression struts are used for modeling infill walls. According to previous researches that equivalent diagonal compression struts have good accuracy, it is assumed that these elements could be replaced with infill panels [3,4,10,11,14]. In modeling of infill wall by compression strut method, the thickness of strut and infill wall is equal to 17 cm (infill wall thickness). Compression strength of infill walls is assumed 3.68 MPa. The effective width of the compression strut is one of the most important parameters that must be determined. Since the nature of progressive collapse is in the vertical direction, so all parameters related to infill wall modeling against an earthquake that occurred in the horizontal direction must be changed [13,28]. The effective width of the compression strut is given in Equation (1) that is derived from the Equation mentioned in FEMA356 [29]. The differences of these Equations is depended on beam and column parameters that have been changed. All detailing of the infill wall is illustrated in

Figs. 4(a) and 4(b). For infill wall modeling of progressive collapse, direction of each infill should be placed in X-form [28,30]. It should be also noted that, progressive collapse is not cyclic load and it can simulate each infill in that direction that is subject to compression load only [31]. In OpenSees, *"concrete01"* material is utilized for masonry material. This material is proper for infill wall modeling because it works in compression only, and its strength in tension is zero (Fig. 4(b)) [32-35].

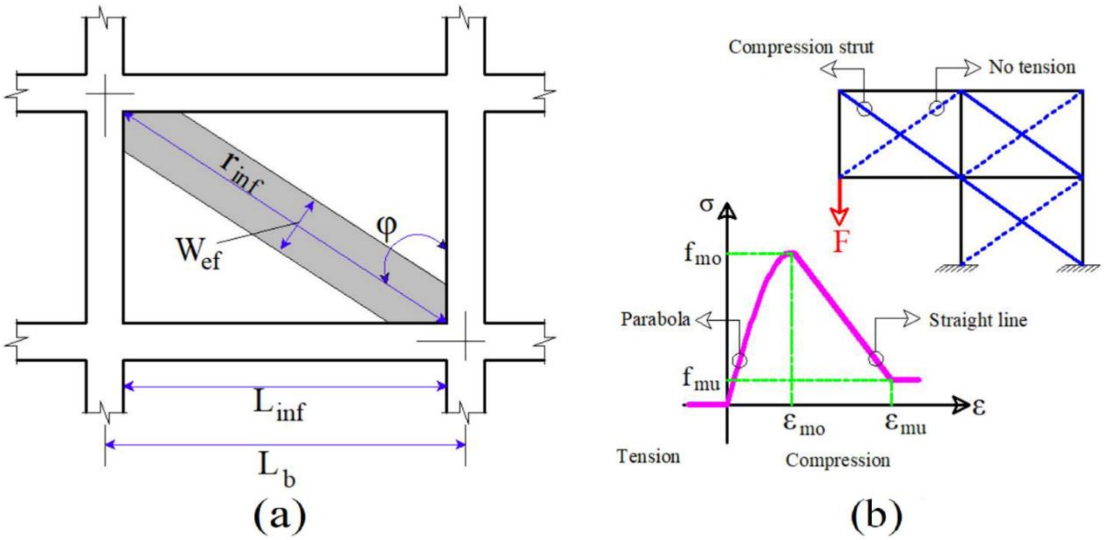


Fig 4. Detailing of equivalent strut compression for modeling of infill wall (a) Schematic of equivalent strut compression in an RC frame (b) Material that has been used in infill modeling.

$$\lambda_1 = \left(E_{me} \times t_{inf} \times \sin(2\emptyset) \Big/ 4 \times E_{fe} \times I_b \times L_{inf}\right)^{0.25} \tag{1}$$

$$W_{ef} = 0.175(\lambda_1 \times L_b)^{-0.4} \times r_{inf} \tag{2}$$

In Fig. 4(b), f_{mo} and f_{mu} are specified strengths of masonry material, which equals to 3.68 MPa and 0.74 MPa, and ε_{mo} and ε_{mu} are those values of strains that are equal to 0.0014 and 0.0028, respectively. Fiber section is assigned for compression struts, and *"coro-truss"* element is considered for diagonal elements.

In Equation (1), the effective width of compression strut is calculated. In Equations (1) and (2) parameters E_{me}, E_{fe}, L_b, L_{inf}, I_b , λ_1, r_{inf}, t_{inf} and φ respectively applied to expected modulus of elasticity of infill material (that equal to 750 f_{mo}), expected modulus of elasticity of frame material (that equal to $5000\sqrt{f_c}$), beam length between centerlines of columns, length of infill panel, moment of inertia of beam, coefficient used to determine equivalent width of infill strut, diagonal length of infill panel, thickness of infill panel and angle whose tangent is the infill length to length aspect ratio. Equation (3), is used for considering the opening in infill walls. Al-Chaar et al. [36] represent this Equation for openings that are placed in middle of infill panel.

$$R = 0.6\left(\frac{A_{opening}}{A_{panel}}\right)^2 - 1.6\left(\frac{A_{opening}}{A_{panel}}\right) + 1 \tag{3}$$

Where R, $A_{opening}$, and A_{panel}, respectively applied to the in-plane reduction factor, the area of the opening, and the area of infill panel. In-plane reduction factor (R) is multiplied by the width of the strut and results in a fairly accurate estimate of system strength and stiffness [37,38]. In Equation (4), the width of the strut with considering the opening is represented. In Equation (4), W_{eo} represents the width of the strut with opening. It should be noted that Equation (4) is the most accurate formula for considering the opening in the infill wall [37].

$$W_{eo} = R \times W_{ef} \tag{4}$$

The effective width (W_{ef}) for infill panels according to Equation (2) is equal to 51.4 cm and the effective width with consideration of opening (W_{eo}) for 30% of opening in each infill panel according to Equation (4) is equal to 29.5 cm.

According to ASCE 7-16, infill walls are considered as nonstructural elements, and these elements should be designed to the specified lateral force. It also should be noted that the lateral force for very high IF is twice than intermediate and high IFs.

3.3. Nonlinear Dynamic Analysis

Nonlinear dynamic analysis (NDA) is the best method for evaluating the response of structure after sudden column removal scenarios. By this type of analysis, it can determine the dynamic amplification factor and the structures natural behavior after sudden column removal [39,40]. In NDA, dead (DL) and live loads (LL) (gravity loads) should be applied to the frames according to the following [1,2]

$$W = 1.2D.L. + 0.5L.L. \tag{5}$$

For column removal modeling, the desired column should be removed suddenly. In the NDA, according to Equation (5), the gravity loads are linearly incremented at the duration of 5 sec to gain the final values, after that, gravity loads were remained constant for 2 sec to prevent dynamic effects. Once the gravity loads were completely applied for 7 sec, one column was removed suddenly [41]. It should be also noted that in frames with infill walls, concurrent with column removal, related infill walls should be removed suddenly from the frame. *"KrylovNewton"* algorithm is used for NDA since this algorithm helps the convergence of NDA [42,43]. Newmark integrator is used for integration of objects that beta and gamma are set to 0.5 and 0.25, respectively. Damping ratio of frames is considered 0.05, and the time step for analysis is used to 0.01 seconds. In this study, an implicit method for NDA is used. In many nonlinear analyses, an explicit method is required but in this study, the results of the two methods are almost close. Besides that, some of the progressive collapse analyses have been performed with an implicit approach [44–47]. The main differences between explicit and implicit methods are conditionally stable or unconditionally stable, time step size, coupled or uncoupled of equations, and matrix inversion. Generally, in NDA, the explicit approach is better than the implicit because it can be captured of strain rates. Explicit method for heavy and complicated structures is highly recommended, but in simple and regular structures, the results of the two methods are similar [48–50]. More information about implicit and explicit methods was given in some of the references [51,52]. In this study, for column and infill wall removal scenarios, the *"remove command"* in OpenSees has been used. In many recent studies for simulation of column removal in NDA by OpenSees, remove reactions method (RRM) has been used. In RRM, in the first step, the gravity loads (in Equation (5)) are statically applied to the structure, and the reactions of the desired column are specified. In the next step, the desired column is removed from the structure, and reactions that had been specified in the first step are replaced with desired column. In the final step, forces that are equal to reaction forces in the previous step should be applied in an opposite direction in a short time duration by NDA [27,44,53–59].

The Schematic of RRM is depicted in Fig. 5. As seen in Fig. 5, RRM is easy for one column removal, but in two or more column removal in sequential time, it is very time-consuming [60]. In addition, progressive collapse may lead to beams, braces, and infill walls failure that RRM is not a practical method for this purpose [61].

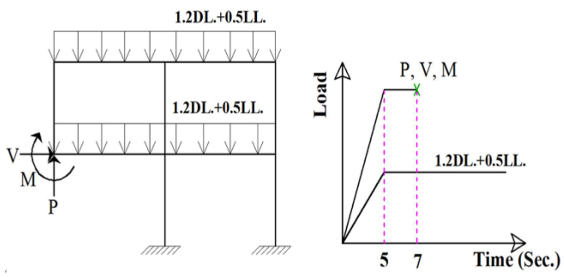


Fig 5. Overall illustration for RRM in previous studies [27, 44, 53-59].

In this study, using the developed algorithm and *"remove command"* in OpenSees, a new flowchart is suggested by authors that can remove any element of structure in each time interval. The overall flowchart is shown in Fig. 6, and a detailed flowchart for advanced element removal is shown in Fig. 7. This algorithm is very applicable for sequential column removals and other element removals such as beams, braces, and infill walls. In addition, this algorithm is useful for vertical nonlinear incremental dynamic analysis (VNIDA). By this algorithm, it can create a *"for loop"* for load increment, and then the column is automatically removed (by this developed algorithm) from the structure, this process is continued until the structure is collapsed. If RRM is used for performing VNIDA, it has a very considerable computational cost [62]. It should be noted that all steps in the flowchart in Fig. 7 are applied in a one-time step (i.e. those steps should be applied in a parallel manner).

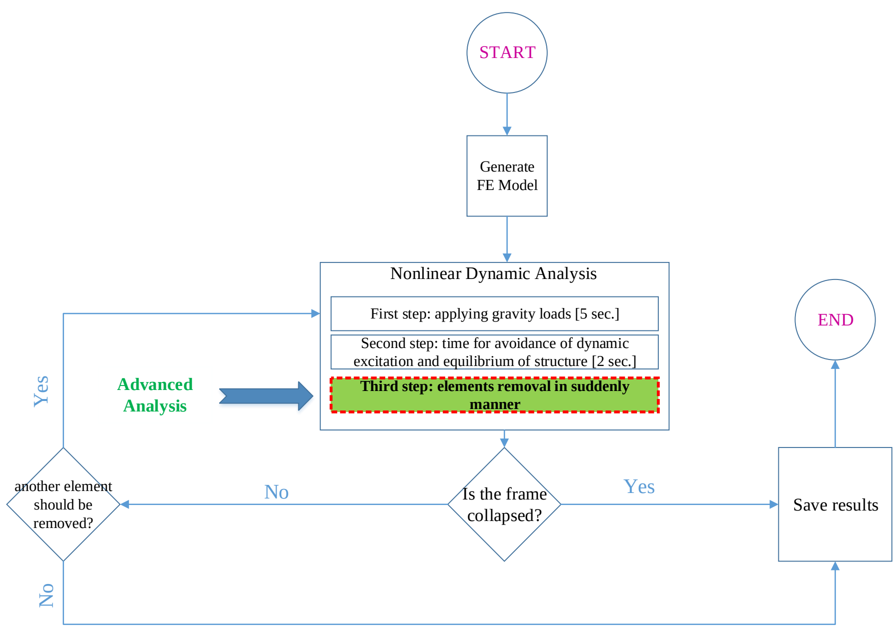


Fig 6. Overall flowchart of NDA in this study.

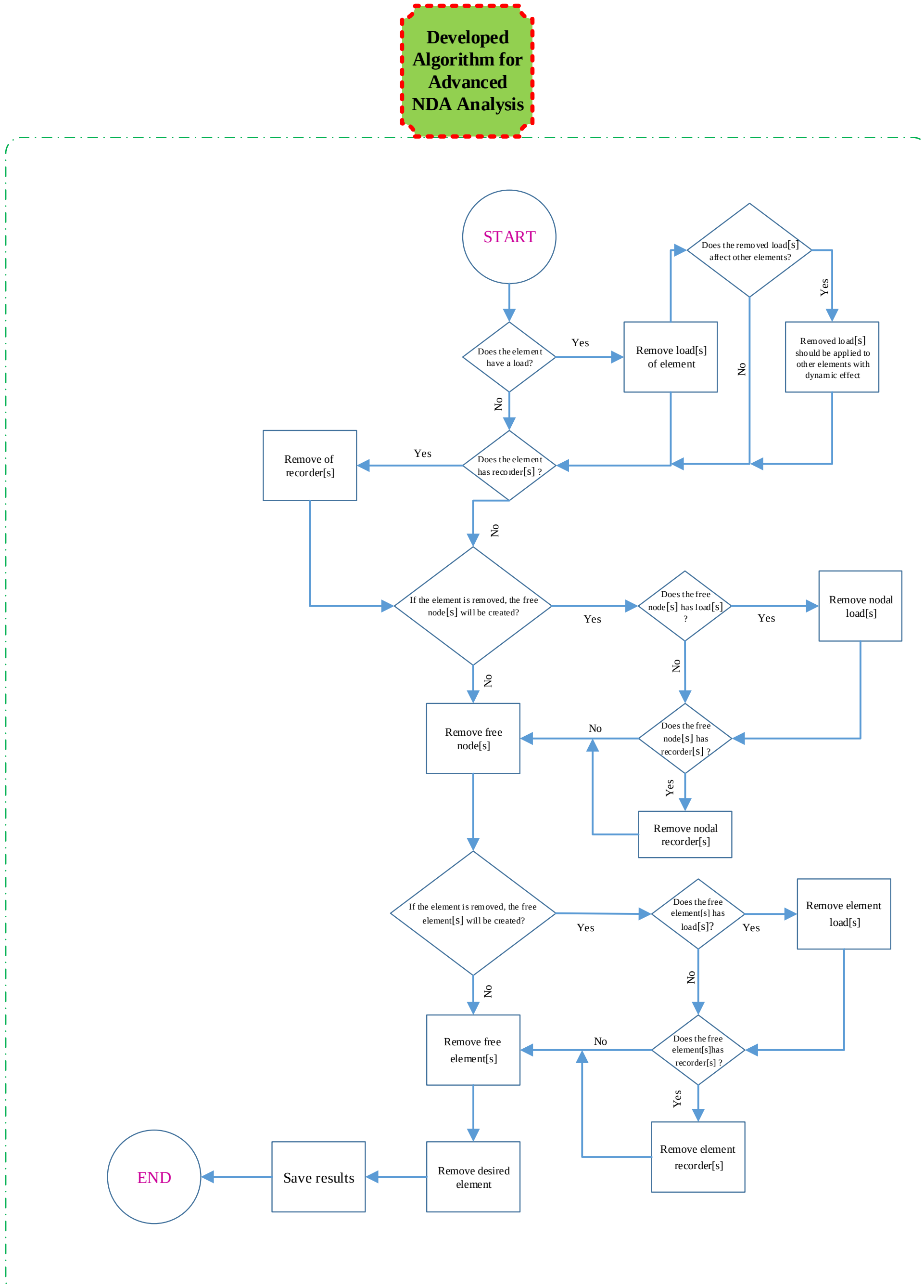


Fig 7. Detail of developed flowchart for element(s) removal in NDA.

For comparison of RRM and developed algorithm, the middle column (or first scenario) of the frame with intermediate importance factor is removed. Results of the two methods are shown in Fig. 8, which is the history of vertical displacement in the node above the removed column. In Fig. 8, vertical displacements of two methods have been shown, which the results of the two methods are very similar to each other at time 7.01 (when the column has been removed) until the end of the analysis. A portion of Fig. 8 is zoomed, and as seen, it can ignore of difference between RRM and the proposed method.

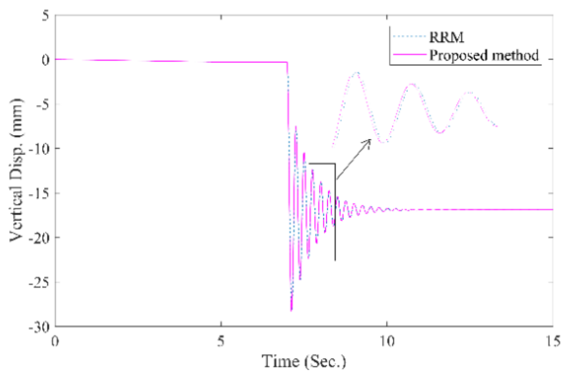


Fig 8. Vertical displacement of node above removed column in scenario 1 (without infill and IF=1.0).

For evaluation of two-column removal scenarios in different time intervals (successive removal of two-column) using the developed algorithm in the OpenSees program, Pachenari and Keramati's research [60] is presented for this aim. The overall framework for the two-column removal scenario (column *i* and *j*) in a successive manner in OpenSees is supplied by Pachenari and Keramati [60], which is depicted in Fig. 9. As seen in Fig. 9, for performing two-column removal scenarios in different time intervals, different steps are needed, which are specified in Fig. 9. In the first step, the forces of two columns (*i* and *j*) should be recorded under gravity loads via static analysis (Fig. 9a). In another step, the recorded forces of column *i* should be replaced with column *i* (Fig. 9b). Then, in short time duration, the forces equal but opposite to previous forces are exerted to the node *n* (the node above column *i*) for removing column *i* in a dynamical manner (Fig. 9c).

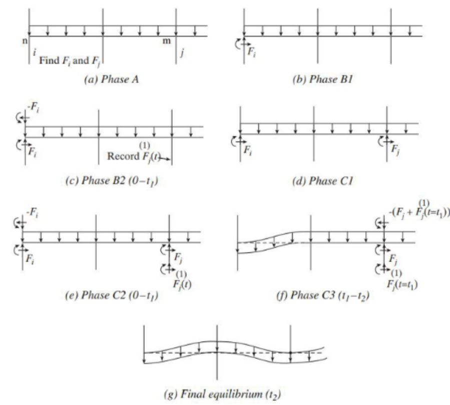


Fig 9. Proposed method for two-column removal in successive manner by Pachenari and Keramati [60].

Besides, the updated forces of column *j* (forces due to removal of column *i*) should be recorded (Fig. 9c). These updated forces are due to the dynamic forces in the *i* column removal scenario. In the next step, the forces of columns are replaced with columns (columns *i* and *j*) and after removing column *i*, updated forces of *j* column should be applied to the *m* node (Fig. 9d and 9e). Finally, in the desired time interval (t=t_1) the forces equal but in opposite direction are imposed to the *m* node (the node above column *j*), and it is supposed that the *j* column is removed from the RC frame (Fig. 9f). In this situation, it is assumed that two columns are removed suddenly from the RC structure in different time intervals.

For performing two-column removal via the developed algorithm, it needs to add "*if condition*" in the TCL code. It means that this developed algorithm can remove any element via "*for loop*" and "*if condition*" commands. For comparison of Pachenari and Keramati algorithm [60] and developed algorithm, two columns of RC frame with intermediate IF level are removed suddenly and the results of axial forces and vertical displacement are illustrated in Fig. 10.

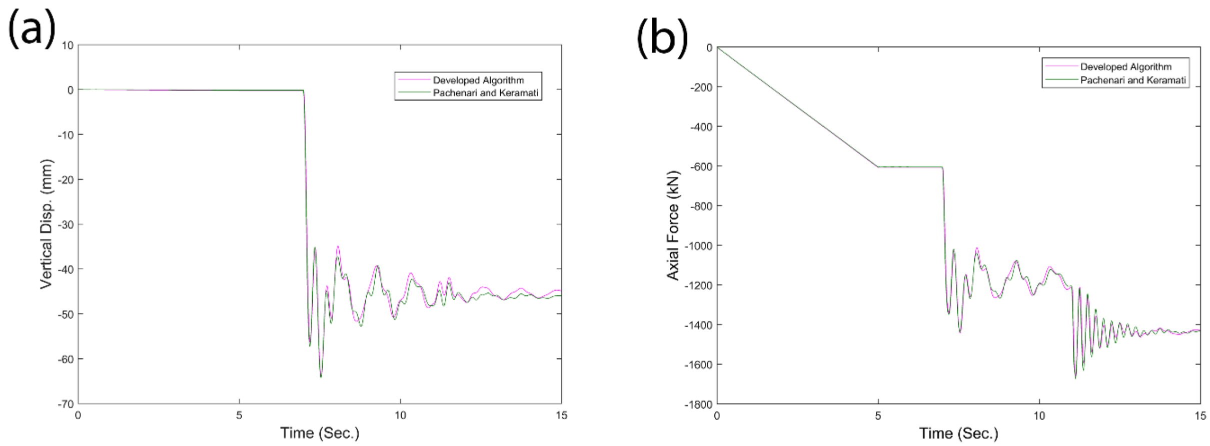


Fig 10 comparison of developed algorithm with proposed algorithm by Pachenari and Keramati (a) vertical displacements in node *n* (the node above column *i*) (b) axial force of column between columns *i* and *j*.

As seen in Figs. 10a and Fig. 10b, The results of the two methods are very close to each other. The tiny differences between the two methods in Fig. 10 are returns to this reality that in Pachenari and Keramati's research [60], only vertical forces (as a primary force) are considered, and other types of forces (like bending moment and shear force) were not exerted in the analysis.

3.4. Push-Down Analysis

In this study, push down analysis (PDA) is used to determine the capacity of frames after column removal [63]. In this type of analysis, in the first step, the desired column is removed from the structure, then the gravity loads in Equation (5) (1.2D.L. +0.5L.L.) incrementally applied to the structure with static analysis and normalized related to Equation (5). Capacity of the structure is determined before divergence of analysis (Fig. 11). Difference between pushover and pushdown analysis had been tabulated in Table 4.

The force-displacement diagram for pushdown analysis is captured from the node above removed column.

Table 4. Comparison of pushover and pushdown analysis.

Differences between pushover and pushdown analysis.		
Analysis	Pushover analysis	Pushdown analysis
Type of analysis	Nonlinear static (only displacement control)	Nonlinear static (displacement control or load control)
Direction of analysis	Lateral direction	Vertical direction
Ultimate value	Up to 1.5 times of target displacement	Divergence of analysis
prerequisite	None	Remove of desired column
Target of analysis	Lateral capacity	Vertical capacity

PDA is performed in two ways. In the first way, the gravity loads in Equation 5 are applied to bays that the column was removed but in a second way, the loads are applied to all bays uniformly [64]. The second way is better than the first way because the overall strength of the structure is measured [65]. In this study for PDA, loads are applied to all bays uniformly via the load control method that is depicted in Fig. 11.

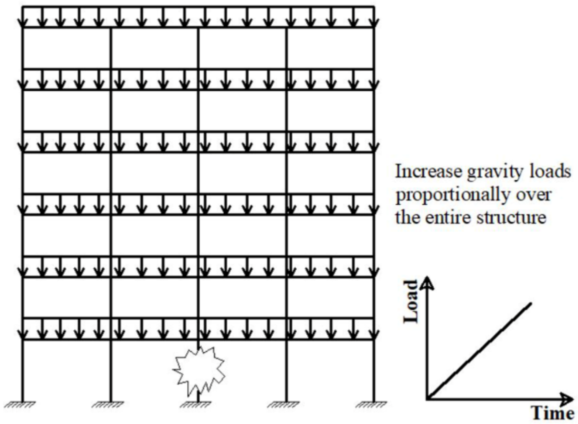


Fig 11. Overall schematic of PDA.

4. Validation

4.1. Validation of Column Removal

For verification of column removal is used an experimental work was performed by Shan et al. [66]. In this study, a two-dimensional RC frame was constructed and the effect of column removal in the middle of the frame was researched. Overall schematic and detailing of this experimental program are illustrated in Fig. 12. Concrete materials for the first and second stories were 41.3MPa and 31.8 MPa, respectively. Yield and ultimate strength for bea m and columns are 415MPa and 588 MPa, respectively.

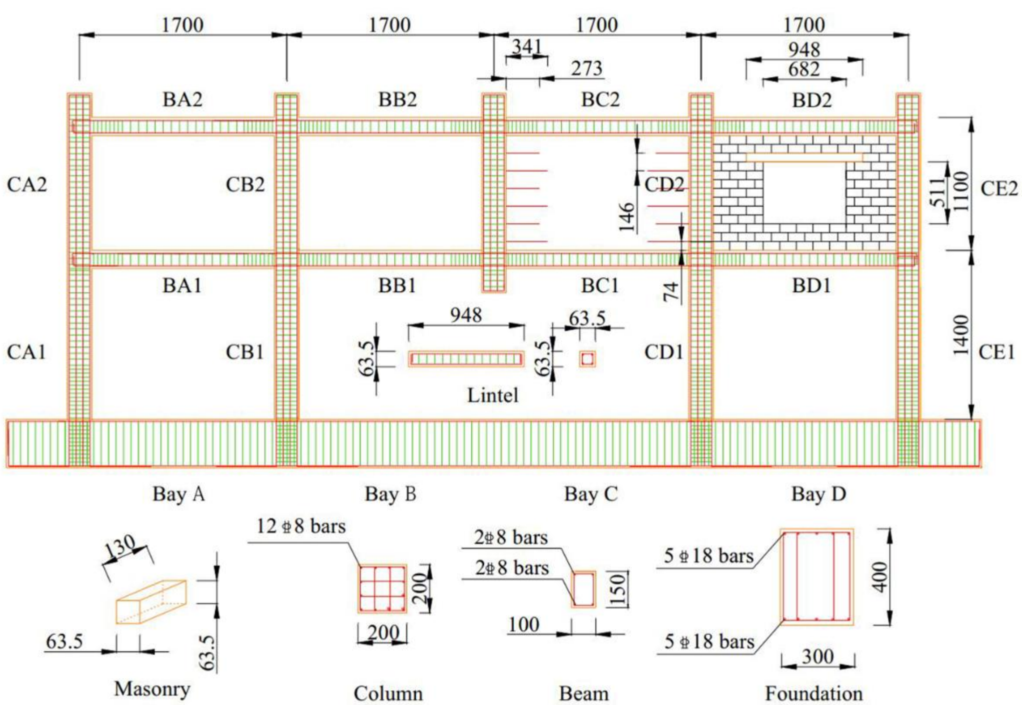


Fig 12 overall schematic and detailing of experimental research, which is conducted by Shan et al. [66].

The experimental study is contained in two parts. The first part is related to the effect of bare RC frame against middle column removal and the second part is related to the influence of RC frame with infill wall against middle column removal. In the first part, for middle column removal is used a cell load to push the middle column. This load cell pushed the RC frame until the frame is collapsed. For simulation of disproportionate collapse of RC frame is utilized OpenSees program. *"concrete01"* and *"steel02"* are used for concrete and rebar material, respectively. Yield strength and strain hardening for steel rebars are applied 415 MPa and 1.09%, respectively. In both concrete materials, unconfined and confined material properties for cover and core concrete are considered [22]. Fiber section is used for beam and column sections. Each fiber section should be divided into many fibers that in this study, the size of each fiber is considered about 5cm. For beam and column element is used force based element with distributed plasticity. This element type is proposed for modeling in a progressive collapse [27]. Co-rotational transformation is taken to considering geometric nonlinearity. Seven-point integration is assigned to each beam and column element. For PDA is used static analysis, which displacement control and Krylov-Newton are taken to integrator and algorithm respectively. Each step size of displacement increment is 0.1mm, and the total steps are 5000. For avoiding divergence, *"EnergyIncr"* with the tolerance of 0.01 and iteration of 500 is considered. Tolerance should not be smaller than 0.001, but in this study for overcoming to convergence problem this value is considered to 0.01. *"UmfPack"* is used for system, and Penalty method is taken to constraint parameter. It should be mentioned that in this simulation, the foundation is not modeled in OpenSees, and so columns are fixed. The FE model is shown in Fig. 13.

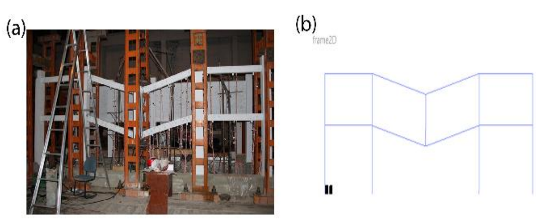


Fig 13. (a) Overall schematic of RC frame after column removal in experimental research [66] (b) FE modeling of RC frame that is simulated in OpenSees program.

Results of PDA in the experimental and numerical methods are given in Fig. 14. As seen, results of experimental and numerical methods are close together.

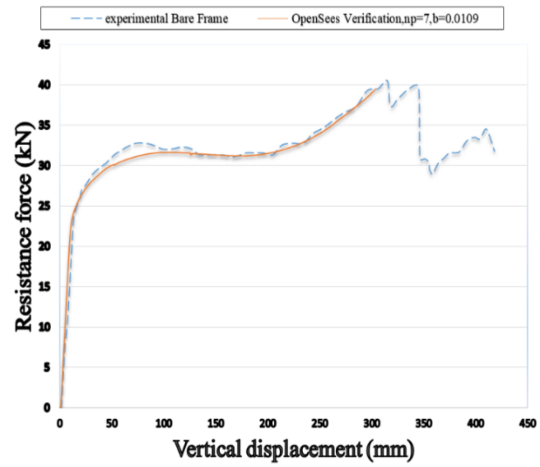


Fig 14 Comparison of numerical and experimental results of column removal in RC frame.

4.2. Validation of Infill Wall Modeling

In this study, The Essa et al.'s [67] experimental tests were used to validate the accuracy of infill wall models. The main purpose of this test was to study the effects of thickness and type of material filler on seismic parameters. Rebar detailing and geometric properties of this test are shown in Figs. 15(a) and 15(b) respectively. The size of rebar for transverse and longitudinal are 8 mm and 12 mm, respectively. The yield strength for transverse and longitudinal rebars are 240 MPa and 360 MPa, respectively. Average compression strength, according to cubic samples, has been achieved 60 MPa.

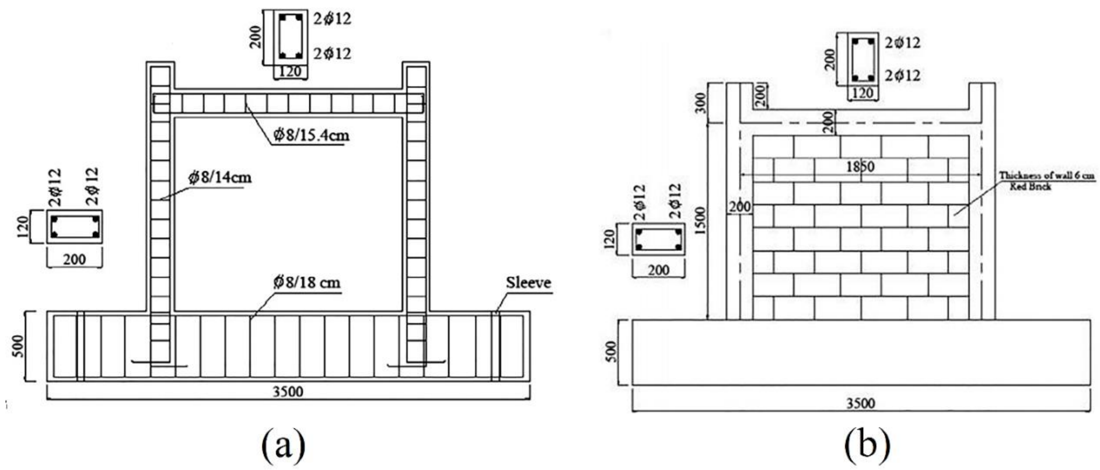


Fig 15. Detailing of experimental modeling (a) rebar detailing of frame (b) geometric and infill wall of frame [67].

RC frame with infill wall was under cyclic loads. For modeling of hysteretic analysis, is utilized static analysis with incremental 5 mm in each step. Each analysis considered positive and negative portions of the directions. The displacement is beginning from ±5 mm to ±200 mm. At the end, the force displacement diagram of analysis is captured. Boundary conditions of this experimental work have been shown in Fig.16. As seen in Fig. 16, cyclic loads are imposed via hydraulic jack with increasing lateral displacements. Simultaneously imposing displacements to the RC frame, the response of the structure is captured via different sensors.

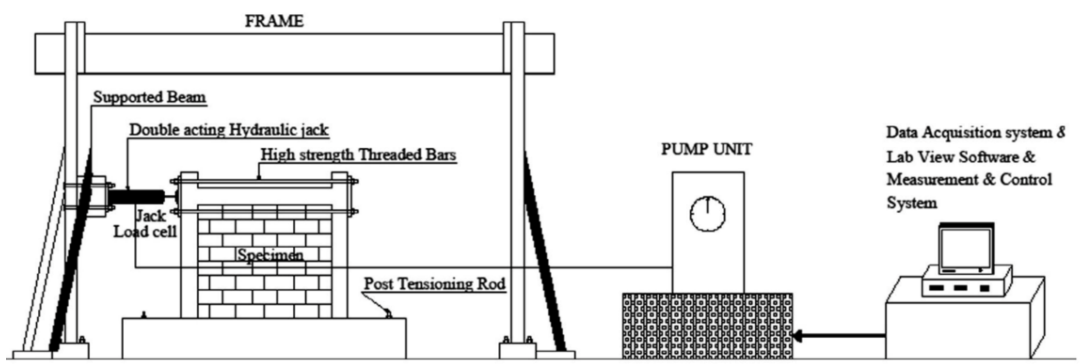


Fig 16. Boundary conditions and instrumentation system for the test [67].

The open program software OpenSees is used to provide the analytical model of the frame with an infill wall. For this purpose, the equivalent diagonal compression struts have been used. The thickness of the strut is equal to 12cm, which is equal to the thickness of the infill wall. Compression strength of the strut has been considered 3.45 MPa. The effective width of the compression strut at first was calculated according to FEMA356 [29], then it changed slightly to attain its correct value, which was assessed to 30cm. For modeling of concrete and reinforcing steel materials *"Concrete01"* and *"Reinforcing Steel"* materials in OpenSees were used, respectively. Fiber section was used for all beam and column frame elements. Force-based element with distributed plasticity is used for beam and column elements in the frame. The

"Concrete01" material is used for modeling material in infill wall. The *"corot-Truss"* element is used for modeling of compression strut. It should be noted that in progressive collapse analysis, the hysteretic curve is not necessary and so push curve of the hysteretic diagram is sufficient [1]. Push curves of experimental and analytical results are shown in Fig. 17.

As seen in Fig. 17, force- displacement diagram of experimental and numerical models similar to each other. The difference of two diagram is return to the masonry material selection in OpenSees. *"Concrete01"* is utilized for masonry modeling which is not considering pinching in the simulation. If pinching is considered, both diagrams are much similar to each other. As seen in Fig. 17, force-displacement diagrams of the two models are similar to each other where the maximum lateral load in the experimental is 10.2 tons, and this value for the numerical model is 10.5 tons. The displacements for analytical and numerical analysis are finished in ±60 mm. besides, the area of the two methods (that is identified as a structure's energy) is similar to each other. It should be noted that in infill modeling against progressive collapse, struts width calculations are some different than calculations in FEMA 356 which had been explained in section 3.2.

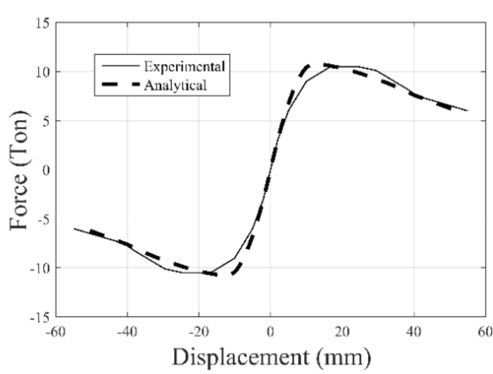


Fig 17. Comparison between push hysteretic in analytical and experimental results.

5. Results

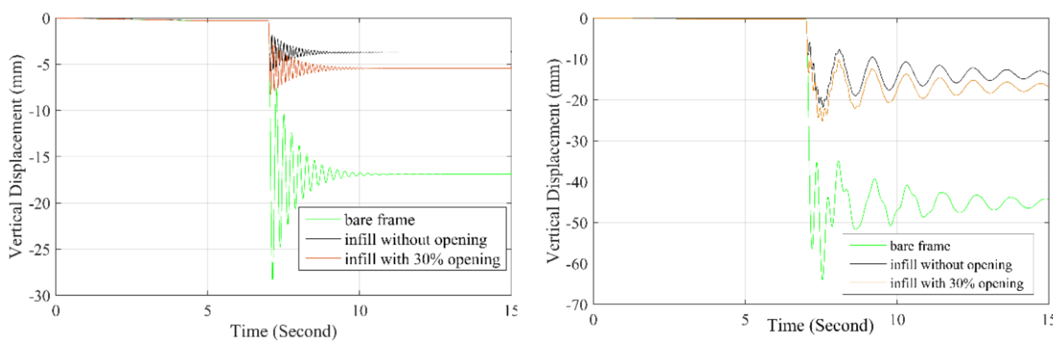
5.1. Results of NDA

NDA is utilized for the evaluation of the real behavior of frames after sudden column removal. Figs. 18, 19, and 20 express the vertical displacement of the node above-removed column in frames with based importance factor levels intermediate, high, and very high. Each of Figs. 18, 19, and 20 are divided into two Figs. (a) and (b) that representing scenarios 1 and 2, respectively.

Results of maximum and residual vertical displacement in all scenarios have been presented in Table 5. As shown in Figs. 18 to 20 and Table 5, the presence of infill lead to reduction of vertical displacement. The infill walls are caused 2 to 5 times reduction of vertical displacement. Values related to maximum vertical displacement, are given in Fig. 21. The most remarkable note is that presence of an opening in the infill wall has not a considerable effect on maximum and residual vertical displacement. According to Table 5 and Fig. 21, it can be said that in scenario 1 of the frame with intermediate IF, maximum vertical displacements in frames without infill wall, with infill wall without opening and, with infill wall with 30% opening are 28.3 mm, 5.73 mm, and 8.83 mm, respectively. These values for this frame in scenario 2 are 64 mm, 21 mm, and 25.2 mm. Therefore, the presence of the opening in infill walls in scenarios 1 and 2 increased vertical displacement by 54.1% and 20%, respectively, compared to the RC frame with infill walls without opening. However, frames without infill in scenarios 1 and 2 compared to this frame with infill and without opening increased vertical displacement 4.94 and 3.05 times, respectively.

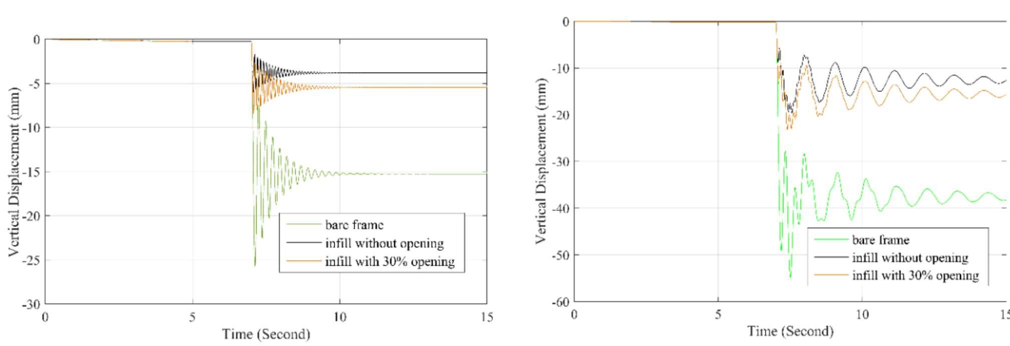
Table 5. Results of NDA for column removal scenarios.

Scenario	Type of importance factor	Infill situation	Maximum vertical displacement (mm)	Permanent vertical displacement (mm)
1	Intermediate	Without infill	28.3	16.9
		With infill without opening	5.73	3.73
		With infill with opening	8.83	5.44
	High	Without infill	25.8	15.2
		With infill without opening	5.99	3.8
		With infill with opening	8.42	5.41
	Very High	Without infill	22.6	13.2
		With infill without opening	5.45	3.5
		With infill with opening	7.89	5.08
2	Intermediate	Without infill	64	44.2
		With infill without opening	21	13.6
		With infill with opening	25.2	16.6
	High	Without infill	54.9	38.3
		With infill without opening	19.6	12.8
		With infill with opening	23.1	15.8
	Very High	Without infill	40.9	27.1
		With infill without opening	15.9	10
		With infill with opening	19.6	12.7



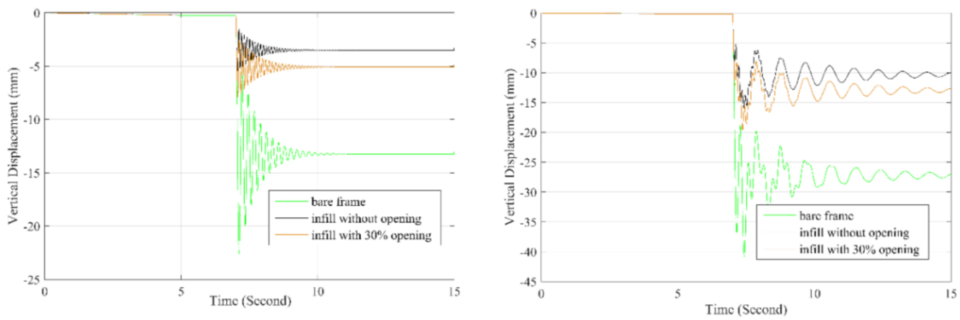
(a) (b)

Fig 18. Vertical displacements corresponding to frame with intermediate importance factor (a) scenario1 (b) scenario 2.



(a) (b)

Fig 19. Vertical displacements corresponding to frame with high importance factor (a) scenario1 (b) scenario 2.



(a) (b)

Fig 20. Vertical displacements corresponding to frame with very high importance factor (a) scenario1 (b) scenario 2.

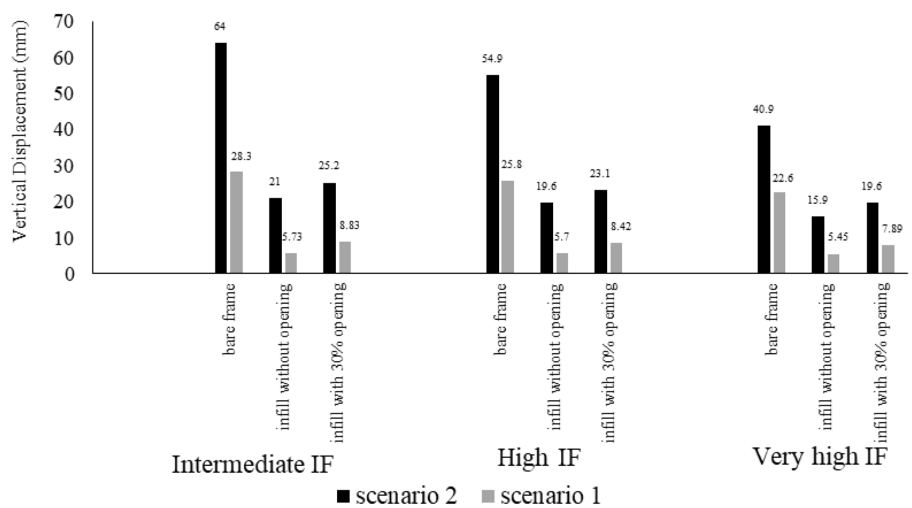


Fig 21. Chart of the vertical displacement in different stages of infill wall and importance factor levels.

According to Table 5, vertical displacement of frames with infill wall with 30% opening is considerably smaller than bare frames. In other scenarios in Table 5, the ratio remains unchanged. Therefore, the presence of an opening does not significantly increase the vertical displacement. Vertical displacement of different IF levels has been compared in Table 6. H/I is specified of High to Intermediate IF, similarly VH/I is indicated Very High to Intermediate IF, and finally, VH/H shows Very High to High IF.

Table 6. Comparison of maximum vertical displacement related to various IF levels in NDA.

Difference of NDA in various IF levels (%)				
Type	Situation of infill	H/I	VH/I	VH/H
Scenario 1	Bare frame	14.22	36.1	25.5
	Infill without opening	6.67	24.29	18.88
	Infill with opening	8.33	22.2	15.15
Scenario 2	Bare frame	8.83	20.14	12.4
	Infill without opening	0.5	3.32	2.81
	Infill with opening	4.64	10.65	6.3

According to Table 6, IF levels increment leads to vertical displacement reduction in bare frames. For example in scenario 1 values of H/I, VH/I and VH/H are 14.22%, 36.1%, and 25.5% respectively, these values for scenario 2 are 8.83%, 20.14%, and 12.4% respectively. In scenario 2, due to fewer element connections compared to scenario 1, IF levels had not a considerable effect on the reduction of vertical displacement.

Existing infill walls reduced the vertical displacement after sudden column removal intensively. Reduction of vertical displacement is due to an increase in frame stiffness. So existing infill walls in RC frames is caused less impact of IF levels in vertical displacement. For example, in frames with infill walls without opening in scenario 1, H/I, VH/I, and VH/H are 6.67%, 24.29%, and 18.88%, respectively, and these values for scenario 2 are 0.5%, 3.32%, and 2.81%, respectively. Therefore, in scenario 1, in frames with infill wall, various IF levels have not considerable effect, and in scenario 2, levels of IF are not important. According to Table 6, it can be said that the existing opening in the infill wall increased vertical displacement compared to the infill wall without opening. So stiffness of frame due to the opening in infill wall is reduced. In frame with infill with 30% opening, H/I, VH/I, and VH/H in scenario 1 are 8.33%, 22.2%, and 15.15%, respectively, and these values for scenario 2 are 4.64%, 10.65%, and 6.3%, respectively. Thus various levels of IF in the frame with infill wall with 30% opening have a more considerable effect in vertical displacement compared to the frame with infill wall without opening. According to Table 6, the VH level of IF has a considerable effect on vertical displacement compared to H and I levels.

5.2. Results of PDA

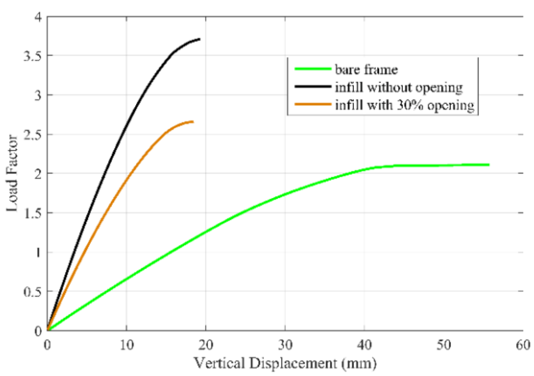
Pushdown analysis is used for the evaluation of frame capacity after column removal scenarios. Results of the pushdown analysis are shown in Figs. 22, 23, and 24 for scenarios 1 and 2. All of the results that were determined for the maximum load factor and corresponding vertical displacement are given in Table 7. Maximum load factor is the factor of gravity loads that can be applied on bays related to Equation (5). In meaning, load factors are normalized to Equation (5).

As seen in Table 7, the presence of infill walls has a significant role in the capacity of the frames. The existence of an opening in the infill wall has a considerable effect on the ultimate capacity of frames. For example, in scenario 1, in a frame with intermediate IF, the capacity of the frame without infill wall, with infill wall without opening, and with infill wall with an opening are 2.11, 3.71, and 2.66, respectively. The presence of an opening in the infill wall is caused a 28% resistances reduction compared to the frame without an opening. In other states, this relation is closed together. In PDA, the presence of infill walls leads to the increment of frame capacity. In all scenarios, the capacity of the frame with infill wall without opening in all states is less than 2 times of frame without infill wall. The presence of an opening in infill walls can reduce the capacity of the frame, these reductions are between frames with infill wall without opening and frame without infill.

As seen in Figs. 22, 23, and 24, although frames with infill walls can bearing of more load factors, its failure had been occurred in small vertical displacement. In other words, it can be said that frames with infill behave similar to truss frames, but frames without infill wall are the moment frame and can tolerate more vertical displacement, so the existence of infill walls can cause the brittle failure of the frame.

Table 7. Results related to push down analysis

Scenario	Type of importance factor	Infill situation	Maximum load factor	Vertical displacement related to maximum load factor (mm)
1	Intermediate	Without infill	2.11	55.77
		With infill without opening	3.71	19.26
		With infill with opening	2.66	18.47
	High	Without infill	2.29	42.75
		With infill without opening	3.71	19.53
		With infill with opening	2.69	18.53
	Very High	Without infill	2.49	43.71
		With infill without opening	3.75	17.7
		With infill with opening	2.74	17.05
2	Intermediate	Without infill	1.41	62.79
		With infill without opening	2.3	38.02
		With infill with opening	1.75	31.09
	High	Without infill	1.54	61.62
		With infill without opening	2.38	36.04
		With infill with opening	1.79	30.02
	Very High	Without infill	1.79	57.99
		With infill without opening	2.62	31.87
		With infill with opening	1.98	28.96



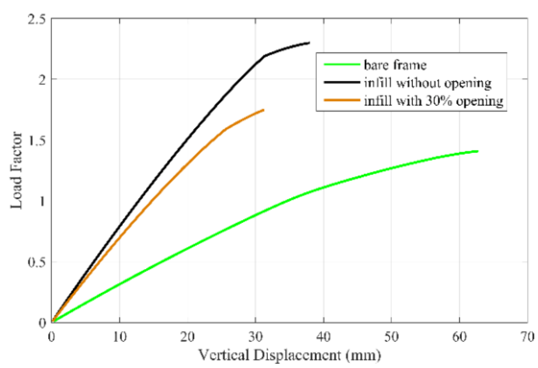
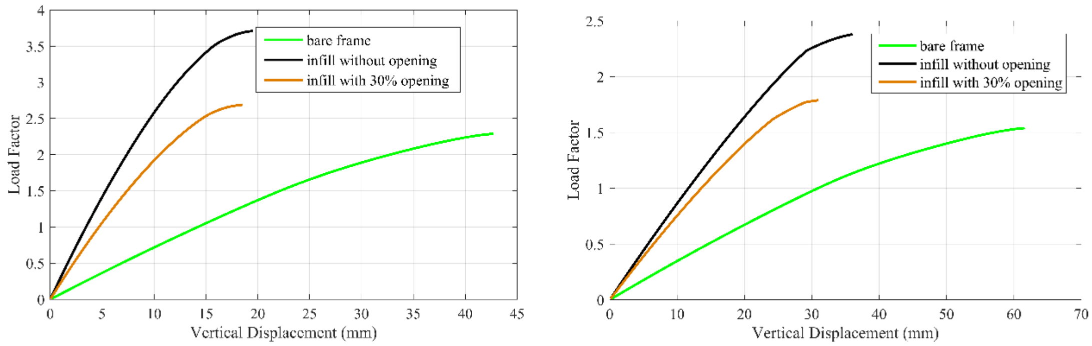
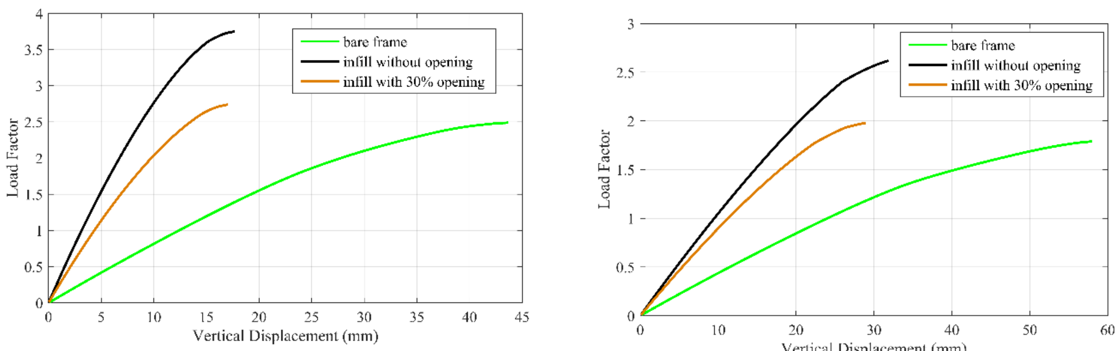


Fig 22. Vertical capacity of frame with intermediate importance factor (a) scenario 1 (b) scenario 2.



(a) (b)

Fig 23. Vertical capacity of frame with high importance factor (a) scenario 1 (b) scenario 2.



(a) (b)

Fig 24. Vertical capacity of frame with very high importance factor (a) scenario 1 (b) scenario 2.

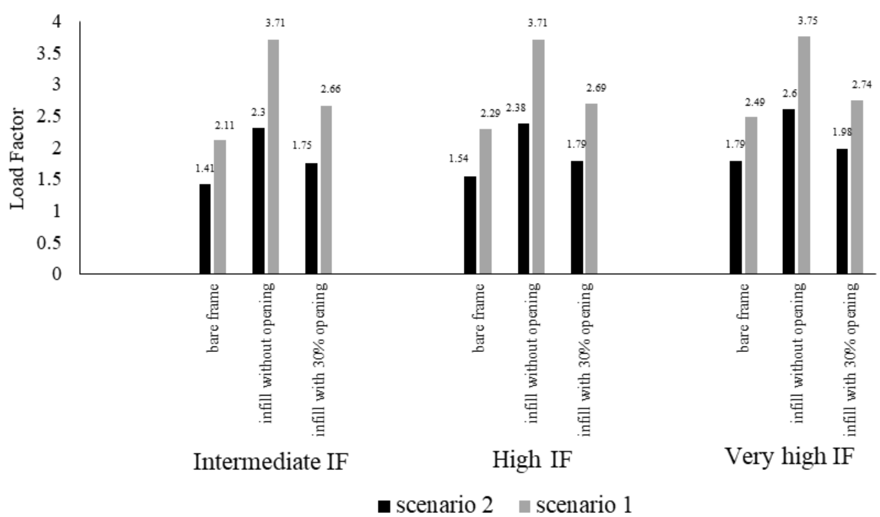


Fig 25. Chart of the maximum load factor in different stages of infill wall and importance factor levels.

Besides, according to Dabiri et al.'s researches [68,69], ductility is defined as follows:

$$\mu = \frac{\Delta_y}{\Delta_u} \tag{6}$$

Where Δ_y is the yielding point of pushdown analysis which can be measured with the balance of energy or general yielding. Δ_u is the ultimate displacement captured at the end of analysis. If the ratio of $\frac{\Delta_y}{\Delta_u}$ has a large quantity, the ductility of the structure has a considerable value. Besides, in Fig. 22 to 24, it can also be said that the ultimate displacement for RC frames with infill walls is less than bare RC frame. So, it can be concluded that RC frame with infill walls (with or without opening) has less ductility compared to bare RC frames.

As seen in Figs. 22 to 24, the existence of an opening in infill wall led to capacity reduction of the frames. Capacity reduction is almost near to the frames without infill wall. Values related to maximum load factors are given in Fig. 25.

The presence of IF levels in frames led to increasing in frames capacity. In scenario 1, in the frame without infill wall, the capacity for intermediate, high, and very high IF are 2.11, 2.29, and 2.49, respectively. So, increasing of ultimate capacity of high and very high level IF compared to intermediate level are 7.9% and 15.3%, respectively. Values of maximum load factor in scenario 2 of intermediate, high, and very high IF levels are 1.41, 1.54, and 1.79, respectively. These values show that frames with high and very high IF compared to intermediate IF are increased by 8.4% and 21.2%, respectively. Other ratios are represented in Table 8. According to Table 8, various IF levels lead to strength increment. In scenario 1 for RC bare frame values of H/I, VH/I and VH/H are 9.22%, 26.95%, and 16.23%, respectively. These values for scenario 2 are 8.53%, 18%, and 8.73%, respectively. Other values of H/I, VH/I, and VH/H for scenarios 1 and 2 in frame with infill (with and without opening) are given in Table 8. As seen in Table 8, as described in section 5.1, various IF levels in scenario 1 are more effective than scenario 2 because in scenario 1 more element are connected to the node above column removal phenomenon. According to Table 8, existence of the infill wall (with or without an opening) is reduced the influence of the different types of IF levels.

Table 8. Difference of ultimate load factors related to various IF levels in PDA.

Difference of PDA in various IF levels (%)				
Type	Situation of infill	H/I	VH/I	VH/H
Scenario 1	Bare frame	9.22	26.95	16.23
	Infill without opening	3.48	13.04	9.24
	Infill with opening	2.29	13.14	10.26
Scenario 2	Bare frame	8.53	18	8.73
	Infill without opening	0	1.35	1.35
	Infill with opening	1.13	3	1.86

6. Conclusion

In this study, a six-story RC building with intermediate moment frame system is considered. The building is designed according to different importance factors and infill wall situations. After the design of the building, the external frame of this building is selected and modeled in OpenSees. Progressive collapse is considered in two scenarios of column removal, so the middle and corner column in the first story are removed. In this study, NDA and PDA for actual behavior and vertical capacity of frames after column removal are used. In addition, the developed algorithm for column removal scenarios is presented, and its capability is illustrated for one and two-column removal scenarios. The most highlighted results are given below:

- The effect of IF levels in bare frames are more considerable than a frame with infill walls (with or without opening). The influence of IF levels in NDA is less than 36%, and for PDA, this influence is less than 24% in more cases. Besides, the effect of the importance factors in NDA and PDA are reduced to less than 24% and 13% when the infill walls are modeled in the frames.
- Very high IF level had more influence compared to high and intermediate IF levels. For example, in bare frames in scenario 1, the very high IF level increased 16.63% and 26.95% capacity frame compared to high and intermediate IF levels. Besides, a very high IF level reduces vertical displacement by 25.5% and 36.1% compared to high and intermediate IF levels.
- Place of column removal scenarios has an important role in the results. In scenario 1 (middle column removal), due to more connection to other elements, infill walls and IF levels have more influence on the results. It can be concluded that the effect of IF levels and infill walls are twice in middle column removal scenarios (scenario 1) compared to corner column removal scenarios (scenario 2).
- Existing infill walls in RC frames are caused to reduce 2 to 5 times of vertical displacements in NDA due to column removal scenarios. Besides, infill walls increased the capacity of RC frames, which is increased more than 50% for all cases (more detail are supplied in Table 8 and Fig. 25). It should be noted that frame with infill walls (with or without opening) failed in small displacement and behavior of frames were brittle. Therefore, the existence of infill wall is increased stiffness and strength but reduced the ductility of RC frames.
- Opening in infill walls caused to reduce 20% to 30% of the capacity frames.
- In this study, a new algorithm for column removals for NDA in APM is developed. In this algorithm, any type of element (such as columns, beams, braces, and infill) in different time intervals can be removed. The Main application of this algorithm is for the simulation of two or more elements in a different time of progressive collapse phenomena and VNIDA.

Appendix

Designing Procedure of the Buildings

According to Standard No. 2800, it can be used equivalent linear static analysis in regular buildings with shorter than 50 m. In this study, linear static analysis for designing all buildings is used. The base shear (V_u) is calculated according to Equation A1. It should be noted that distribution of V_u in all levels is accordance with ASCE/SEI 7-16.

$$V_u = C \times W_{eff} \quad \text{A.1}$$

In Equation A1, W_{eff} is the effective seismic weight of building that is calculated according to Equation A2. C is the coefficient of base shear that is calculated according to Equation A3.

$$W_{eff} = D.L. + 0.2L.L. \quad \text{A.2}$$

$$C = ABI/R_u \quad \text{A.3}$$

In Equation A3, A and R_u respectively applied to design acceleration of earthquake and response modification factor. Parameter A specified the seismic zone area that in this study, high seismic zone (A=0.3g/g) is considered for all buildings. Response modification factor according to the intermediate moment frame system is considered 5. IF for intermediate, high, and very high levels respectively applied to 1, 1.2, and 1.4. Parameter B is the reflection coefficient that is evaluated according to Equation A4.

$$B = B_1 \times N \qquad \text{A.4}$$

In Equation A4, B_1 and N are spectrum form factor and spectrum modified factor, respectively. B_1 and N for different values of T have been presented in Equations A.5 and A.6.

$$B_1 = S_0 + (S - S_0)\left(\frac{T}{T_0}\right) \leftrightarrow 0 < T < T_0$$

$$B_1 = (S + 1) \leftrightarrow T_0 < T < T_s$$

A.5 $$B_1 = (S + 1)\left(\frac{T_s}{T}\right) \leftrightarrow T > T_s$$

$$N = \frac{0.7}{4 - T_s}(T - T_s) + 1 \leftrightarrow T_s < T < 4$$

A.6

$$N = 1.7 \leftrightarrow T > 4$$

In Equation A5, T is the fundamental period that is determined according to Equation A.7. According to soil type (type of II) S_0, S, T_0, and T_s are considered 1, 1.5, 0.1, and 0.5, respectively. It should be noted that parameter T in the intermediate and high level of importance factor is the fundamental period, but in very high importance level, T is the analytical period that is determined by commercial software.

$$T = 0.05H^{0.9} \qquad \text{A.7}$$

In Equation A.7, H is the height of the building from base level to roof. Drift of the building should be controlled according to Equation A.8.

$$\Delta_M = 0.025h \qquad \text{Number of story} <= 5$$

$$\Delta_M = 0.02h \qquad \text{Number of story} > 5 \qquad \text{A.8}$$

In Equation A.8, Δ_M and h are real drift story and height of the story, respectively. As regards the building is more than 5 stories, allowable drift should be less than $0.02h$.

According to standard No.2800, for a very high importance factor level, drift shall be controlled by using a fundamental period. However, for intermediate and high importance factor levels, drift shall be controlled by using an analytical period. It should be noted that according to Iranian building codes if buildings are located in a very high seismicity zone and the importance factor is very high, so Special Moment Frame (SMF) should be used instead of Intermediate Moment Frame (IMF).

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