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Evaluating the effect of 3D sandwich infill panels on the progressive collapse potential of steel structures with extensive initial damage

Seyed Shaker Hashemi[1] · Saeid Javidi[2] · Mehrnaz Chubineh[1] · Mohammad Vaghefi[1]

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Abstract

Studying the potential of progressive collapse in structures is a new topic in the field of passive defense and has attracted the attention of many researchers, recently. This research investigates the behavior of steel structures with 3D sandwich infill panels after extensive damage. For this purpose, several moment resisting steel frames with different numbers of stories and span length to story height ratios are investigated. The steel frames have infill panels with 30, 50 and 100% of openings, and the initial widespread damage scenarios are consisted of removing 2 and 3 columns with their adjacent infill panels. The results show that the presence of the infill panel reduces the ductility of the structure by increasing the stiffness and prevents the extra rotation of the structural elements, significantly. On the other hand, infill panels can reduce the potential of progressive collapse by increasing the continuity and participating in transferring the extra load. According to the results, the frames without infill panels do not withstand the scenario of progressive collapse in extensive initial damage, however, infill panels help the 6 and 9-story studied structures survive regardless of their span length to story height ratios.

Keywords Progressive collapse · Extensive initial damage · Infill panels · Steel structures · Nonlinear analysis

1 Introduction

It is observed that the collapse of structures under non-conventional loadings such as explosion, impact and fire has led to severe financial damage and the death of a lot of people worldwide. Progressive collapse is one of the most crucial types of collapse mechanisms, in which the resulting damage distributes to the other members after the elimination of one or more structural members due to an unconventional loading. Therefore, the redistribution of loads causes secondary failure in the structural members. Consequently, the whole or a big part of the structure will collapse because of the initial damage (ASCE/SEI 41 – 13, 2013). Factors such as terroristic attacks, gas explosions, fire, car impacts, casual overloading on members or construction errors are the most common reasons for the initial damage. Although several important governmental, industrial and residential buildings have been attacked in terroristic operations so far, the collapse of Ronan point tower in 1968 attracted the attention of researchers and engineers to the progressive collapse phenomenon. In the aforementioned incident, the gas explosion on the 18th floor of this 22-story precast concrete tower led to the serial failure of the corners of several floors (Pearson & Delatte, 2005). The collapse of the Plasco 16-story building in Tehran is another example that happened in 2017 (Shakib et al., 2020). The structural members of the Plasco tower lost their bearing capacity because of the uncontrollable fire on the 11th floor, and the whole building collapsed unexpectedly. Fang et al., (2012) studied the behavior of a multi-story car park in terms of ductility and robustness under fire scenarios in the central area of the structure. They applied a temperature distribution model resulting from

✉ Seyed Shaker Hashemi
sh.hashemi@pgu.ac.ir

Saeid Javidi
saeid.javidi@mail.bcu.ac.uk

Mehrnaz Chubineh
mehrnaz.choubineh@gmail.com

Mohammad Vaghefi
vaghefi@pgu.ac.ir

1 Department of Civil Engineering, Persian Gulf University, Shahid Mahini Street, Bushehr, Iran

2 CEBE Faculty, Birmingham City University, Birmingham, UK

the vehicle fire scenario and its effect on the floor robustness after column buckling. Performing dynamic analysis showed the importance of the inelastic response of joints in triggering the progressive collapse. Fang et al., (2013), proposed a system failure criterion after performing a parametric study on the steel-composite fire-damaged structure. The results showed the effect of localized fire on the response of steel composite structures. The progressive collapse topic, which is of great importance in the field of passive defense, is professionally investigated in the GSA (2003) and UFC (2013) standards.

All structural elements and load-bearing members such as beams, columns, connections, floors and lateral load resisting systems involve in energy absorption. Lateral load resisting systems affect the ductility, base shear and energy dissipation of structures. Bazzaz et al., (2015a and b) investigated the performance of steel frames braced with a new off-center bracing system. The results showed that the off-center bracing system with optimized eccentricity have a better performance in terms of energy dissipation that the diagonal bracing system. The linear and non-linear analysis results on three steel frames with different eccentricities showed that the model with 0.3 eccentricity has the best seismic performance (Bazzaz et al., 2012; Andalib et al., 2018) used the steel rings made by two semi-rings as energy dissipative members in the bracing system to increase the structures' ductility. The numerical results in ANSYS software proved that the applied steel semi-rings improve the performance and increase the ductility of the structures. Experimental inspections showed that the rings absorb the energy and keep the bracing system members in the elastic zone (Andalib.et al., 2014).

Infill panels have a considerable impact on the response of structures to the vertical and lateral loads. Due to their high in-plane stiffness, they distribute the loads in damaged structures by forming compressive struts. Consequently, the progressive collapse can be controlled by infill panels, whereas they prevent force concentration. Tsai & Huang (2009) investigated the effect of interior brick-infill on the potential of progressive collapse in reinforced concrete buildings. They studied the axial force variation of the beams adjacent to the removed column and the variation of the demand-to-capacity ratio (DCR) of the beam-end moment using linear static analysis. The results indicated that the effect of infill strongly depends on the position of the removed column in the building's plan. Rahimi et al., (2013) proposed a model for simulating the effect of nonlinear interaction between reinforced concrete frames and brick infill on the progressive collapse potential after investigating the effect of infill panels on the response of reinforced concrete structures. Shan et al., (2016) tested three reinforced concrete frames with and without infill panels. They studied the patterns of strain change in structural members, local and global failure modes and crack distribution models to evaluate the potential of progressive collapse of the frames in the presence and absence of infill panels. The results showed that although the presence of infill decreases the ductility and changes the failure mode, the function of frames could be significantly affected by infill panels. The infill panels increase the resistance of structures by providing Load Alternative Paths (LAP). Rezazadeh et al., (2019) evaluated the progressive collapse potential of moment frames. They used weak and strong knee elements to control the position of plastic hinges in beam to column junction areas. The result showed that the structures occupied with strong knee elements have better function against progressive collapse, since strong knee elements increase the structure's stiffness and strength. Barmaki et al., (2020) used the finite element method to assess the nonlinear behavior of structures at the risk of progressive collapse, while the beams are connected to columns employing bolts.

Catenary action after the elimination of a structural member, specifically columns, is one of the most important factors for recovering the ability of the structure to find LAP. As a consequence, the structure can bear the resulting extra load and transfer it to the foundation without spreading initial damage. The results of a study on steel frame buildings demonstrated that the catenary action has been improved by increasing the number of stories, so the buildings with more stories are more resistant to progressive collapse than the buildings with lower number of stories (Kim & An, 2009).

Therefore, in most of the recent researches have been focused on the limited initial failure and less attention has been paid to the issue of widespread initial damage.

Fu (2009) studied two 20-story buildings in different column removal scenarios. The results showed that the structures should absorb more energy when two columns are removed in comparison with a one-column removal scenario, so the degree of vulnerability goes up as the number of removed columns increases. Furthermore, removing columns in high stories leads to more critical situation than in low stories since more elements participate in energy absorption in the latter case. Song & Sezen (2013) studied the redistribution of loads in a steel structure after removing four columns of the external frame in the first story. Then, they validated 2 and 3-dimensional numerical models to evaluate the efficiency of conventional design methods of progressive collapse. The numerical results indicated that the DCR exceeded the allowable limit in most of the members just after removing the second column, while the real examined model did not collapse even after removing the fourth column. Accordingly, they concluded that the real demands of members are not as high as the predicted amounts by linear static analysis. The 3-dimensional models have lower demands than 2-dimensional, and that is mostly because of the higher number of participating members in 3-dimensional models than 2-dimensional.

Although, a few researchers have addressed the extensive initial damage (Sasani, 2008), the effect of infill panels on the progressive collapse of the structures with widespread initial damage has not been specifically investigated. Infill panels affect the overall behavior of structures by increasing resistance, stiffness, and decreasing ductility, so ignoring them in modeling leads to misunderstanding the behavior of structures. Although universal standards have focused on removing one column scenario, the possibility of removing multiple columns cannot be denied.

2 Theory of research

There is an array of strategies to reduce the chance of structural failure due to progressive collapse, and in all of them adequate ductility should be provided, and the loads should be transferred to the supports through proper paths. So, required resistance and continuity will be supplied (UFC 2013). In this paper, the structures have been analyzed following the provisions of the UFC standard for studying their potential for progressive collapse. According to the UFC, inhabited buildings with less than 50 personnel are in occupancy category II and can be analyzed by LAP for specified column and wall removal locations. The LAP analysis method depends on the initial damage cause and focuses on the behavior of damaged structures. It also assess the structures' ability to absorb extra loads, resulting from removed elements, and the sufficiency in finding alternative paths to transfer them to the supports. The initial damage will expand in adjacent members if the structure could not properly absorb the energy and find an alternative path to satisfy the static principles.

Table 1 Beam and column designed sections for different models

Number of Stories	L/H	Floor number	Beams	Columns
3	1	1 and 2	IPE 270	BOX 140*140*20
		3	IPE 160	BOX 120*120*20
3	1.5	1 and 2	IPE 330	BOX 180*180*30
		3	IPE 220	BOX 180*180*20
3	2	1 and 2	IPE 400	BOX 220*220*35
		3	IPE 300	BOX 180*180*35
6	1	1 and 2	IPE 300	BOX 180*180*30
		3 and 4	IPE 300	BOX 160*160*30
		5 and 6	IPE 270	BOX 140*140*25
6	1.5	1 and 2	IPE 400	BOX 260*260*25
		3 and 4	IPE 360	BOX 240*240*20
		5 and 6	IPE 270	BOX 220*220*20
6	2	1 and 2	IPE 500	BOX 280*280*35
		3 and 4	IPE 450	BOX 260*260*28
		5 and 6	IPE 400	BOX 200*200*28
9	1	1, 2 and 3	IPE 400	BOX 180*180*30
		4, 5 and 6	IPE 400	BOX 160*160*30
		7, 8 and 9	IPE 270	BOX 140*140*30
9	1.5	1, 2 and 3	IPE 400	BOX 260*260*35
		4, 5 and 6	IPE 360	BOX 240*240*35
		7, 8 and 9	IPE 300	BOX 220*220*30
9	2	1, 2 and 3	IPE 500	BOX 300*300*40
		4, 5 and 6	IPE 450	BOX 280*280*40
		7, 8 and 9	IPE 360	BOX 260*260*25

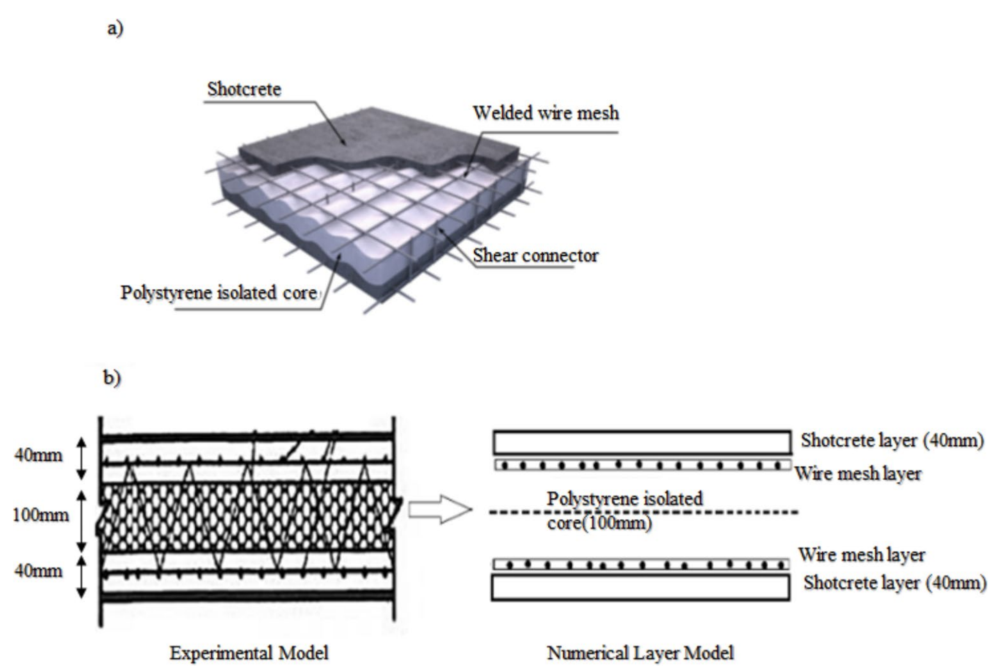


Fig. 1 (a) 3-dimensional picture of infill (Hashemi et al., 2018), (b) Simulated infill panel in SAP2000

2.1 Methodology of research

In the present research, SAP2000(v14.2.0) software (2014) has been used for modeling and analyzing the 3, 6 and 9-story moment resisting steel structures. All models have four spans along the x and y-axis. They also have the same height of story at all levels (3.2 m). The L/H (span length to story height) ratio varies from 1 to 2. Steel ST37 with the yield strength of 240 MPa and ultimate strengh of 370 MPa has been used for making columns and beams with Box and IPE sections respectively. The infill panels are installed in external frames, while the opening ratio varies from 30 to 100% of the infill surface in different models. The buildings have been loaded following Iranian national building code part 6 (2020) which has relatively similar criteria to ASCE7-16 (2016) and have been designed according to the AISC360-16, meanwhile, the nonlinear properties of the members have been defined by considering the UFC2013 provisions and fiber plastic hinges. Plastic hinges are modeled at both ends of the beam and column elements. The plastic hinge length is considered equal to half of the depth of frame sections. Table 1 represents the designed sections for beams and columns in different models.

Infill 3D sandwich panels are modeled using nonlinear layered shell elements in SAP2000 and designed according to Standard No. 385 (2013) (Fig. 1).The total thickness of the sandwich panel is 18 cm and its horizontal and vertical welded wires have 3.5 and 2.5 mm diameter, respectively. The spacing of the wire grids is 80 mm. In the layered shell element, the cross section of the shell element is divided into several steel and concrete layers and each layer follows the nonlinear behavior of its materials. The infill panels are divided into smaller element in such a way that the size of any element is less than 500 mm. The interaction between frame and infill is defined by the link element (Fig. 2). The behavior of the link element in pressure is considered as hard contact and in traction as very weak to model the interaction as realistic as possible. Infill 3D sandwich panel material properties are also given in Table 2.

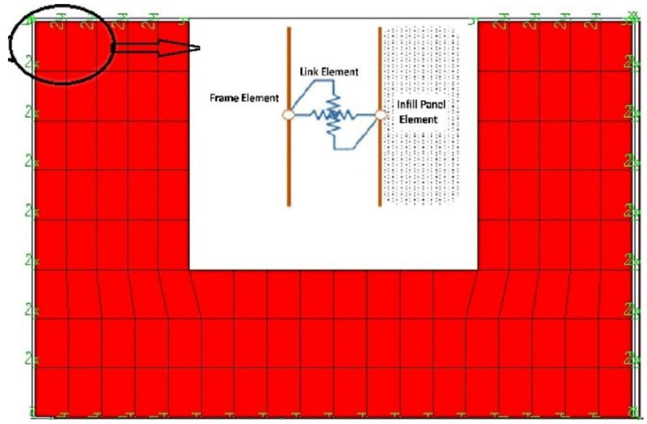


Fig. 2 Schematic view of the modeling of infill panels

Table 2 3D sandwich Infill panel's material properties

Properties	Value (MPa)
Concrete elastic modulus	23685.3
Concrete compressive strength	18
Yield stress of vertical bars	385
Yield stress of horizontal bars	450

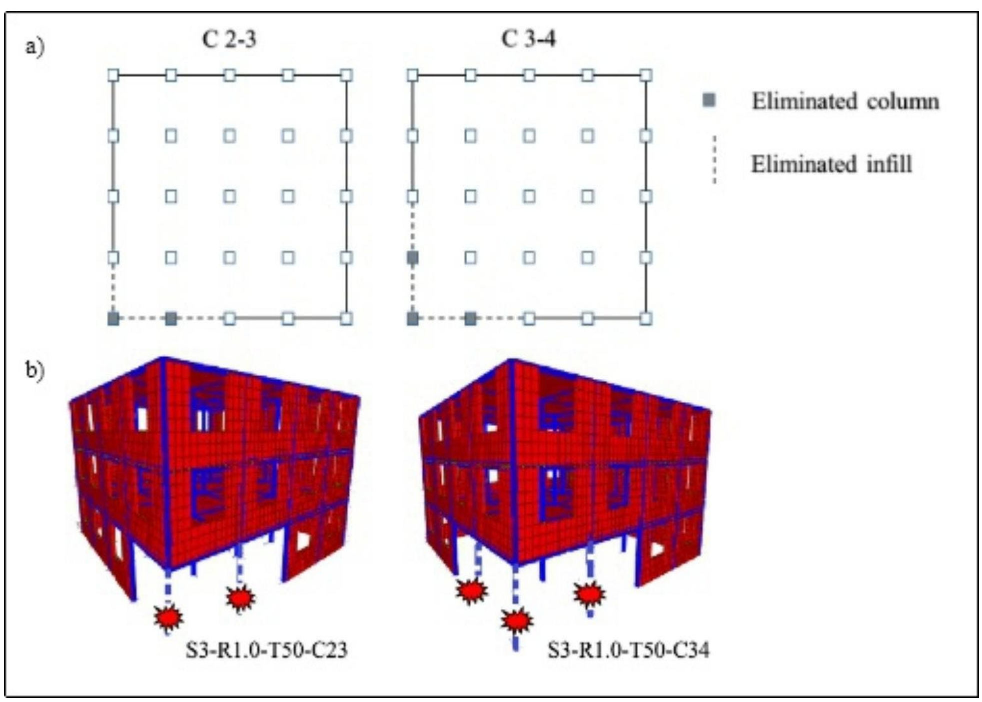


Fig. 3 (a) Removal scenarios in plan (b) 3-dimensional removal scenarios of three-story models

The LAP analysis method generally follows the LRFD (load and resistance factor design) method; however, some changes are applied to the load combination coefficients by changing the strength-reduction factors of the materials in LAP analysis. The progressive collapse analysis has been adapted to ASCE41 methods by applying a series of compatible changes. The effect of floor stiffness and its contributing role to the beam elements in structural behavior and resistance to progressive failure has not been considered from a conservative point of view.

In nonlinear dynamic analysis, gravity loads are exerted on the structures according to the recommended values of the UFC standard. Then, the column, which is supposed to be removed, is replaced by a force equal to its external force. The aforementioned force is eliminated in a short period, which is considered shorter than one-tenth of the structure's vertical vibration period. The damping coefficient is 5% for all models, and nonlinear dynamic analysis continues until reaching the maximum displacement or doing a completed vertical cycle at the location of the removed column.

2.2 Infill and column removal scenarios

Although most of the performed research in the progressive collapse field only considered the one-column removal scenario, the structures' potential for progressive collapse with extensive initial damage has been investigated in this research. Therefore, their ability to find alternative load paths after removing two or three columns and their adjacent infill panel have been studied.

A variety of models have been evaluated. Models have been named by Si-Rj-Tk, where i, j and k respectively represent the number of stories, L/H ratio and the opening percentage of infill panels. The removal scenarios are defined by Cxy, where x and y indicate the number of removed columns and adjacent infill panels, respectively (Fig. 3). It should be noted that all the removal scenarios happen at the first level of buildings. For example, S6-R1.0-T50-C23 presents the 6-story building with the L/H ratio of 1.0 and 50% opening. Furthermore, C23 stands for two columns and three adjacent infill panels removal scenario.

2.3 Research validation

Sadek et al., (2011) tested a steel intermediate moment frame (IMF) in the laboratory (Fig. 4), then they simulated the frame to study its behavior when the center column is removed. The steel frame had two spans and was made of steel with the yield strength of 345 MPa. It was designed according to the ANSI/AISC341-02, while the provisions of FEMA350 was applied for beam connection designing. The behavior of the frame was successfully simulated in their research. The nonlinear static behavior model of the

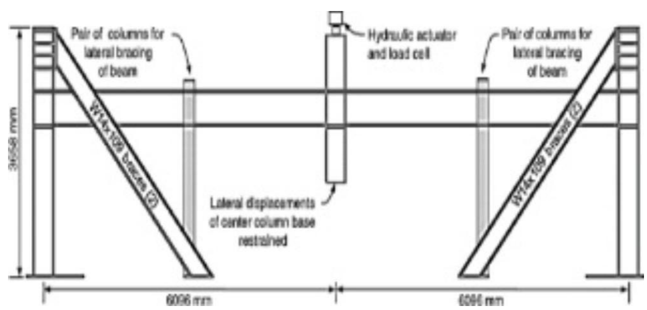


Fig. 4 2-dimensional side view of the frame tested by Sadek et al., (2011)

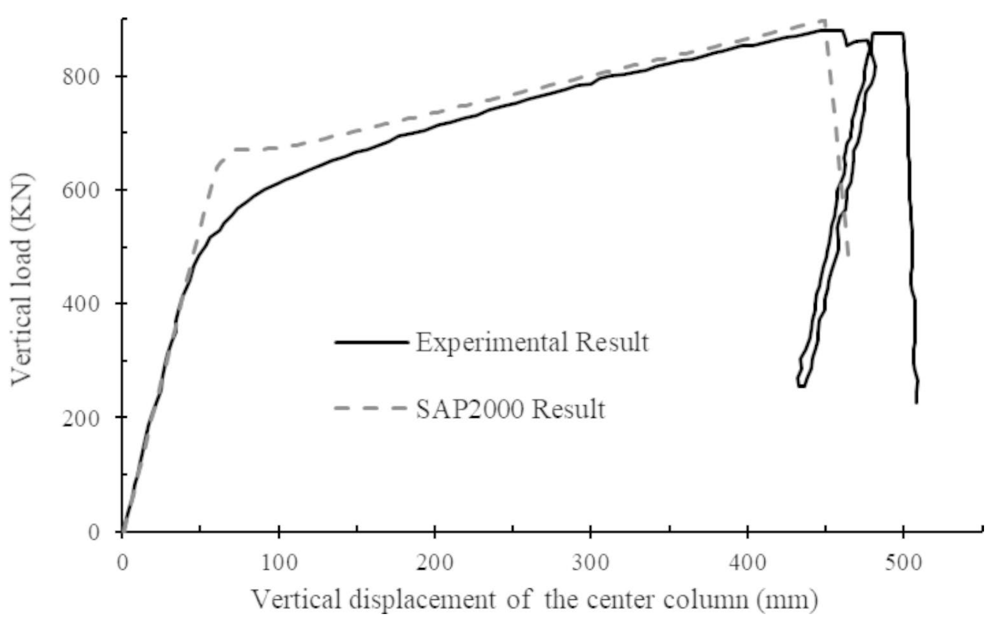


Fig. 5 Comparison of the frame's experimental behavior with the numerical result of SAP2000 (Sadek et al., 2011)

frame subjected to removal scenarios in the present research is validated through Sadek et al., (2011) test.

In SAP2000, fiber hinges with nonlinear behavior are assigned to two ends and the middle of the members. The length of the fiber hinges is considered half of the section depth.

The nonlinear static analysis method has been used to investigate the potential of progressive collapse. The numerical and experimental results are compared in Fig. 5, and details are presented in Table 3.

By comparing the experimental behavior of the aforementioned sample with the model's numerical response, resulting from applying fiber hinge theory in SAP2000, it can be seen that the frame's stiffness, deformation and member's capacity have been estimated with good accuracy. Therefore, the nonlinear modeling method can be trusted for modeling the various models of progressive collapse.

In this part, a 3D sandwich panel, which is tested by Qiao et al., (2019), is modeled in SAP2000 by using the nonlinear layer shell elements. The panel geometry and reinforcements are given in Figs. 6 and 7. More details about loading and material property can be found in Qiao et al., (2019).

Table 3 Comparison of the frame's experimental and analytical maximum displacements

Model	Max Displacement (mm)	Max Load (KN)	Max Displacement Difference %
Experimental test (Sadek et al.)	-445	885	0.67%
SAP2000 Numerical model	-448	890	

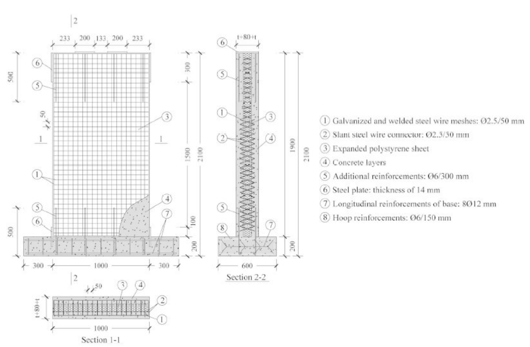


Fig. 6 Geometry of the 3D sandwich panel tested by Qiao et al., (2019)

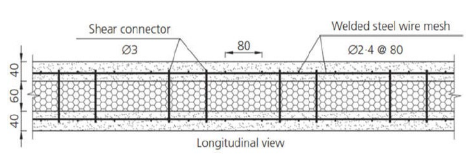


Fig. 7 Cross-section and reinforcements of the 3D sandwich panel tested by Qiao et al., (2019)

Figure 8 has illustrated the experimental and numerical responses of the 3D sandwich panel. It can be seen that the 3D sandwich panel behavior was accurately modeled by applying the nonlinear layer shell elements in SAP2000.

3 Evaluating the progressive collapse of models

3.1 Three-story models

Studying the function of plastic hinges in structural members is one of the crucial criteria for evaluating the performance of structures, which is why the most important parts of buildings' instructions and standards are dedicated to this issue, especially when it comes to evaluating the structure's progressive collapse potential. Table 4 has presented the maximum occurred rotation of the beams at the removed column location and their allowed rotation values for three-story models. For evaluating the progressive collapse according to the UFC2013, beams are permitted to rotate up to the life safety (LS) performance rotation; meanwhile, columns are just allowed to rotate up to immediate occupancy (IO) limitation, because of their importance.

Regarding the results, the beam rotation values are increased by the growth of the L/H ratio. The beams in S3-R1.5-T100-C23 and S3-R2-T50-C23 scenarios rotated more than the allowed limitation and have been damaged,

Fig. 8 Comparison of the 3D sandwich panel's experimental behavior with the numerical result (Qiao et al., 2019)

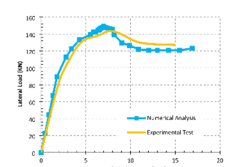


Table 4 Comparing the maximum rotation of critical beams with their allowed values for 3-story models

Models' names	Beam's allowed rotation (Radian)	Beam's rotation (Radian)
S3-R1-T100-C23	0.025676	0.018214
S3-R1-T50-C23	0.025676	0.0001
S3-R1-T30-C23	0.025676	0.000068
S3-R1-T100-C34	0.043832	0.026416
S3-R1-T50-C34	0.025676	0.000137
S3-R1-T30-C34	0.025676	0.000102
S3-R1.5-T100-C23	0.031476	0.055479
S3-R1.5-T50-C23	0.031476	0.000222
S3-R1.5-T30-C23	0.031476	0.000077
S3-R1.5-T50-C34	0.031476	0.000458
S3-R1.5-T30-C34	0.031476	0.000144
S3-R2-T50-C23	0.034716	Too much more than allowed rotation
S3-R2-T30-C23	0.034716	0.000216

while the rotation of all beams in models with L/H = 1 is less than their allowed rotation. It also can be observed that increasing the percentage of openings will lead to increasing the rotation values, and it makes the plastic hinges conditions more critical in beams.

Dynamic responses of S3-R1 and S3-R1.5 models are shown in Fig. 9. The figure shows the vertical vibration of the structure at the removal area after eliminating the columns and infill panels by changing the percentage of openings, in different scenarios. In the S3-R1 models without infill panels, maximum displacement in the final step of the analysis was 72.4 mm after removing two columns, then had a 140% growth and reached 174.1 by removing three columns, while the vertical displacement did not exceed 20 mm in all models with infill panels. Displacement and vibration values in models without infill panels had higher values in comparison with that in models with infills. Furthermore, the models with the lowest percentage of openings experienced the lowest displacements and vibrations, and they stabilized over a shorter period comparing other models. A similar interpretation can be given for the S3-R1.5 models.

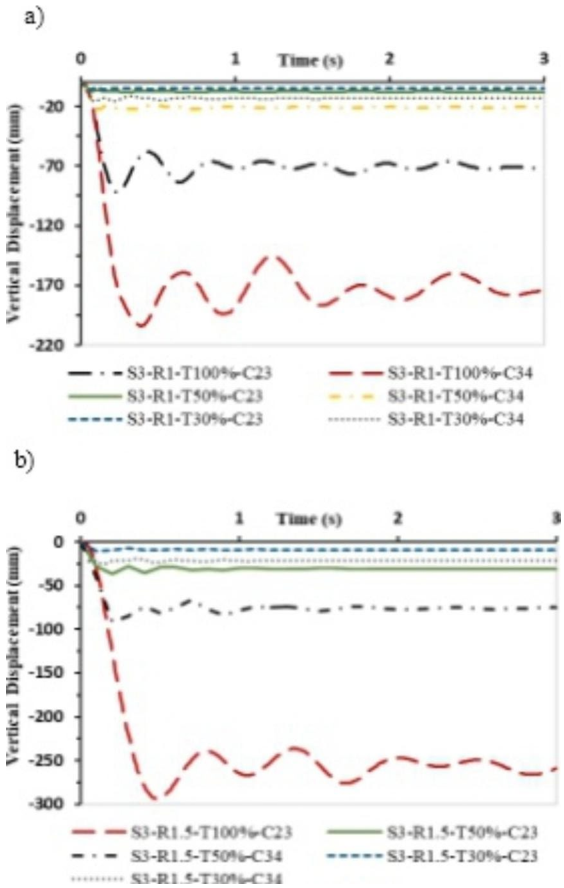


Fig. 9 Dynamic responses of 3-story models (a) L/H = 1 (b) L/H = 1.5

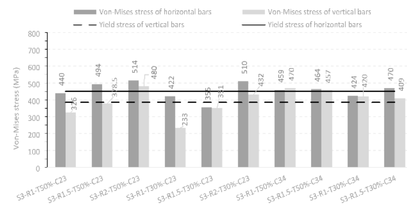
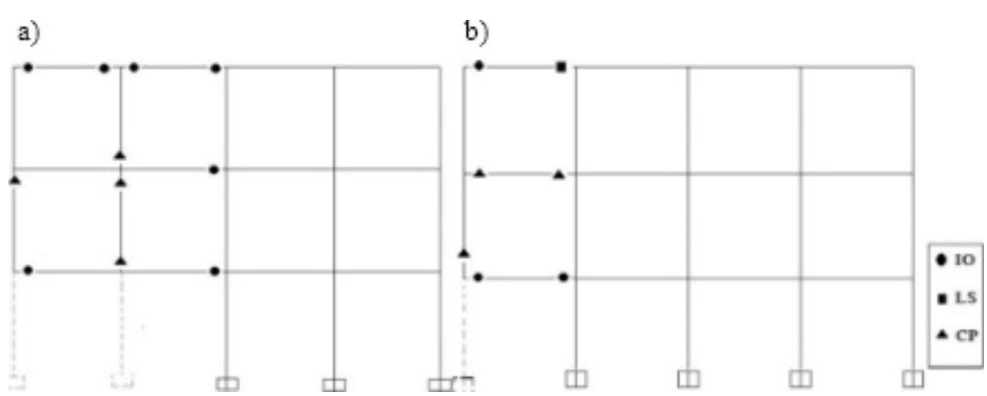


Fig. 11 Von-Mises stress of the vertical and horizontal bars in infill panels of the 3-story models

Figure 10 illustrates the hinge conditions for extensive initial damage in the exterior frame of three-story models without infill panels, where the L/H ratio is 1 and 1.5. The beams located above the removal area have rotated more than allowed values in the S3-R1.5-T100-C23 model, and the structure is damaged. Meanwhile, the beam's rotation stayed in the allowable range in the S3-R1-T100-C34 model, although the rotation of columns, which were located upon the removed columns, exceeded the collapse prevention performance (CP) level. The existing Von-Mises stress in the vertical and horizontal mesh of infill panels for three-story models is shown in Fig. 11. The results show that almost in all models the horizontal bars of infill panels had more critical conditions in comparison with vertical bars since they had more stress values. In C23 removal scenarios, S3-R2-T50 is the most critical model, since stresses in both vertical and horizontal bars have exceeded the yield limit by a large margin. Besides, the vertical bar situations are more critical than horizontal bars in all C34 removal scenarios as Von-Mises stress exceeded the yield limit in all vertical bars. The Von-Mises stress values have decreased

Fig. 10 Location of plastic hinges in (a) S3-R1-T100-C34 (b) S3-R1.5-T100-C23



by reducing the L/H ratio so that the S3-R1 model has witnessed the lowest stress values in both vertical and horizontal bars after removing four columns and three adjacent infill panels.

Figure 12 shows the stress contour of the bars in the last step of analysis for model S3-R1-T30-C34. The corners of openings located above the removed columns had the highest stress value with 424 MPa. The insignificant values of stress in other frames indicate their poor contribution in extra load transferring when the frames above the removal area and the opening parts have experienced the highest values of stress. Separation sections can be seen where the infill panels are connected to the structural frame, the reason is that infill panels are considered non-structural elements, and the link element creates a gap between frame and infill.

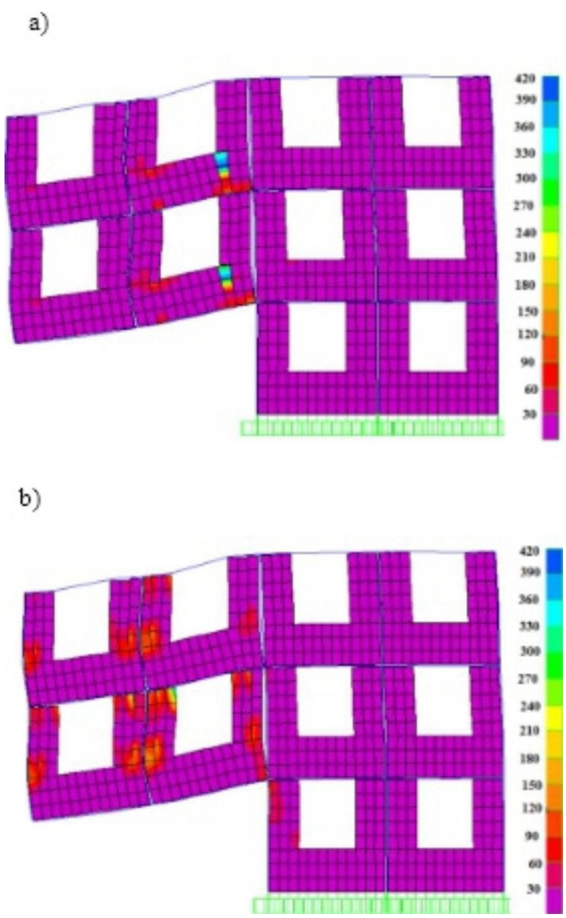


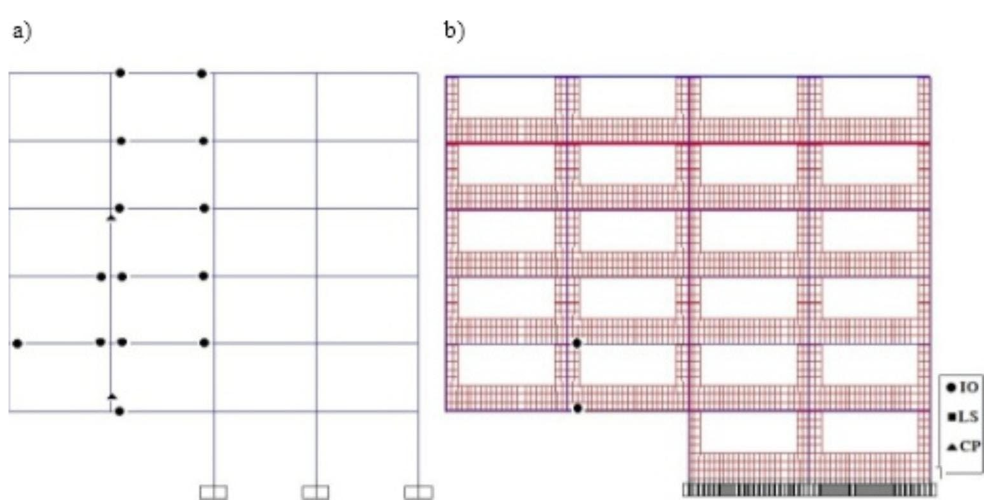
Fig. 12 Von-Mises stress contour of infill bars in S3-R1-T30-C34 model (a) horizontal bars (b) vertical bars

3.2 Six-story models

The rotation of beams of the all six-story models has satisfied the requirements of the allowed performance level with a safe margin to progressive collapse. Therefore, it can be concluded that the high cooperation of the elements in the upper stories has raised the chance of finding alternative paths to transfer the extra load. The beams of models without infill panels have much higher rotation values than that of models with infill panels. It can be noticed that the beams' rotation values decreased by increasing the number of stories for corresponding removal scenarios by comparing the three and six-story models. Therefore, comparing short and high structures, elements have experienced lower rotation values in high structures due to the participation of higher number of elements in energy absorption.

As an example, Fig. 13 presented the plastic hinges conditions in exterior frames of two six-story models subjected to extensive initial damage. The plastic hinges have occurred in beams and columns located upon the removal area. Although the beams' performance level did not exceed the IO performance level, some columns have the CP level in the model without infill panels. The performance level of columns of the S6-R2-T50-C34 model is in a desirable condition, and the plastic hinges did not occur even with the L/H = 2, which shows the elements' participation in dealing with the progressive collapse. There is a direct

Fig. 13 Location of plastic hinges in (a) S6-R1.5-T100-C34 (b) S6-R2-T50-C34



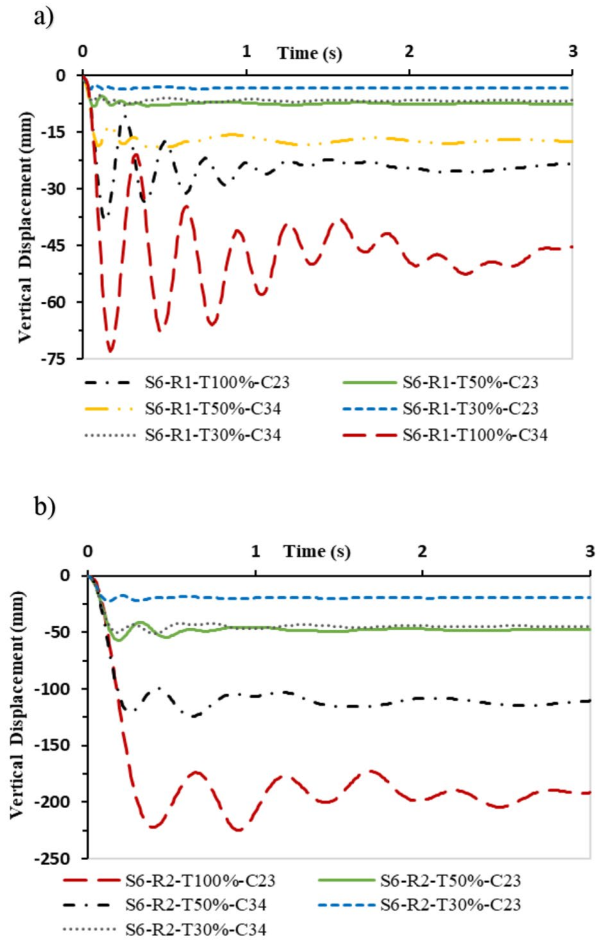


Fig. 14 Dynamic responses of the 6-story models (a) L/H = 1 (b) L/H = 2

relationship between the opening percentage and the number of occurred plastic hinges, as the S6-R2-T50-C34 and S6-R1.5-T100-C34 respectively have 12 and 56 plastic hinges in their beams and columns.

Investigating the dynamic responses of the six-story models revealed that the models without infill panels have the largest displacements, and that is mostly because of the gravity load concentration on the columns' removal area. Figure 14 showed that the displacements are decreased by the reduction of opening percentage. The vibration and displacement in S6-R1 models without infill panels are by far higher than that in their corresponding models with infills. So the displacement of the models with 50 and 30 opening percent has decreased by 61% and 85%, respectively, compared to the model without infill panel in the scenario of removing three columns and adjacent panels. A similar interpretation can be given for the S6-R2 models.

Vertical displacement of removal area in the six-story models, with and without infill panels, is illustrated in Fig. 15, and the effects of L/H ratio and opening percentage on the vertical displacement can be seen. The vertical displacement has increased by the growth of the L/H ratio and opening percentage in both C23 and C34 removal scenarios, although the displacement values in C34 scenarios are higher than that in C23 due to the extent of the initial damage. In S6-T100-C34 model with L/H ratio of 2, no displacement has been reported due to collapse and large displacements in the progressive failure analysis.

Figure 16 has shown the largest Von-Mises stress values for the vertical and horizontal infill bars of the six-story models. The results indicated that in the C23 scenario, the bars of the S6-R2-T50 model, which has the highest opening percentage and L/H ratio in comparison with other

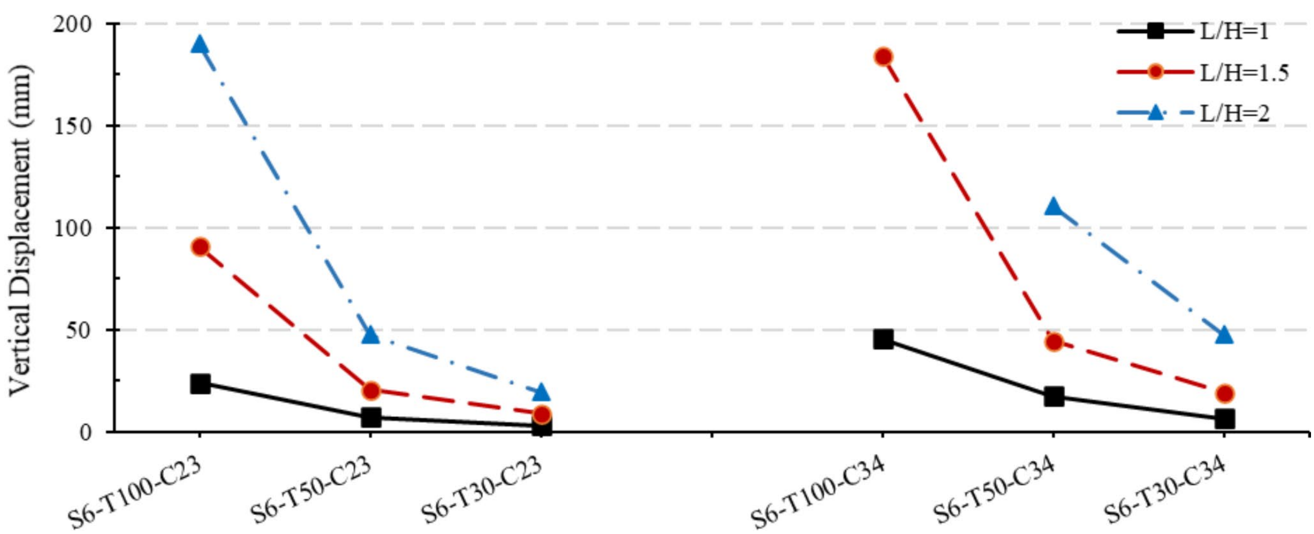


Fig. 15 Comparison of the maximum vertical displacement values in the 6-story models

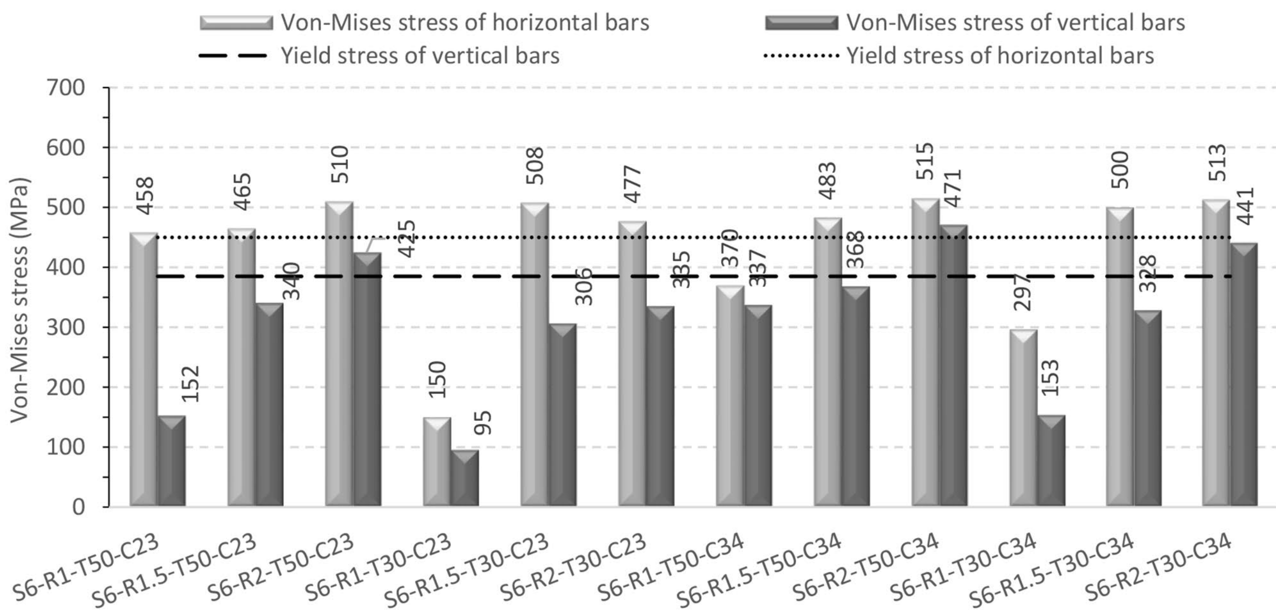
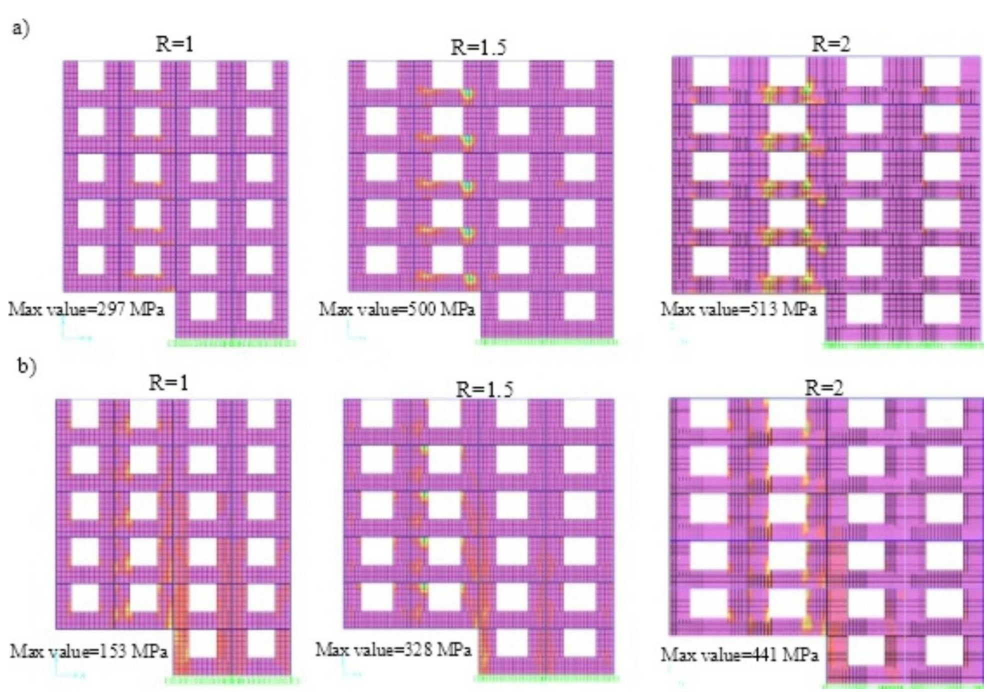


Fig. 16 Von-Mises stress of the vertical and horizontal bars in infill panels of the 6-story models

models, have experienced the largest stresses. Furthermore, the stress in horizontal and vertical bars has increased on average 1.6 and 2.6 times by increasing the L/H ratio from 1 to 1.5. In the C34 removal scenario, the largest stress values are related to the S6-R2-T50 model, which has the highest opening percentage and L/H ratio in comparison with other models. It has also been observed that in both C23 and C34 scenarios, the stress in the bars exceeded the yield limit in all models with L/H ratios of 1.5 and 2. Therefore, results show the infill panels have been damaged in these cases. While the models with L/H ratio of 1 have not been significantly damaged.

Figure 17 has shown the Von-Mises stress distribution in vertical and horizontal infill bars of the S6-T30 models with different L/H ratios subjected to C34 removal scenarios. The highest values of stress have been observed in the span of removed columns. Moreover, the surrounding infill panels have critical conditions due to the lack of columns

Fig. 17 Von-Mises stress contour of the bars in the S6-T30-C34 models (a) Vertical bars (b) Horizontal bars



and resistance reduction. The horizontal and vertical bars of models with L/H = 2 have the highest Von-Mises stress values by 513 and 441 MPa.

3.3 Nine-story models

Investigating the plastic hinges conditions of the nine-story models, with different opening percentages, expressed their high ability in dealing with the progressive collapse. All of the nine-story models satisfy the desirable progressive collapse performance level after removing columns and infill panels. The beams' rotation has increased by changing the opening percentages from 30 to 50, which shows the impact of infill on the progressive collapse potential of the models.

The vertical displacements of the last step of the nine-story models with different L/H ratios and infill opening percentages are compared in Fig. 18., No displacement has been reported for the S9-T100-C34 model with L/H ratio of 2, due to collapse and large displacements in the progressive failure analysis. The effect of the number of stories on the vertical displacement of the removal area can be seen in Figs. 15 and 18. The vertical displacement values are decreased by increasing the number of stories from 6 to 9 in corresponding removal scenarios.

Figure 19 has shown the Von-Mises stress condition in both vertical and horizontal infill bars of the nine-story models subjected to the extensive removal scenario. The results revealed that the stress has increased by raising the L/H

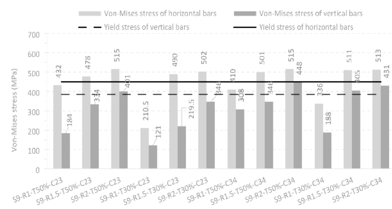


Fig. 19 Von-Mises stress of the vertical and horizontal bars in infill panels of the 9-story models

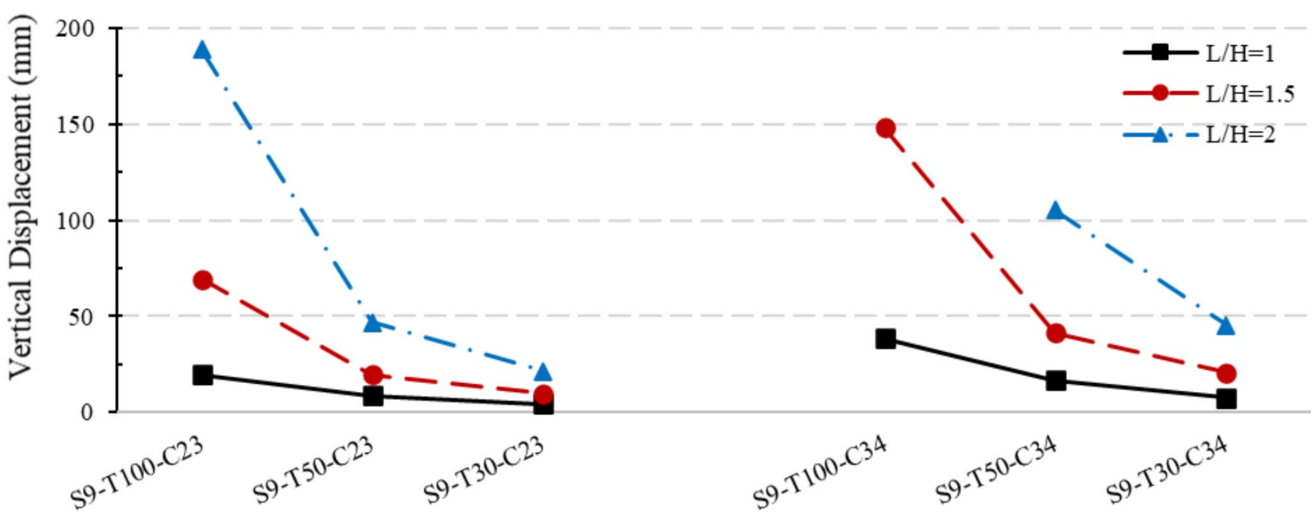
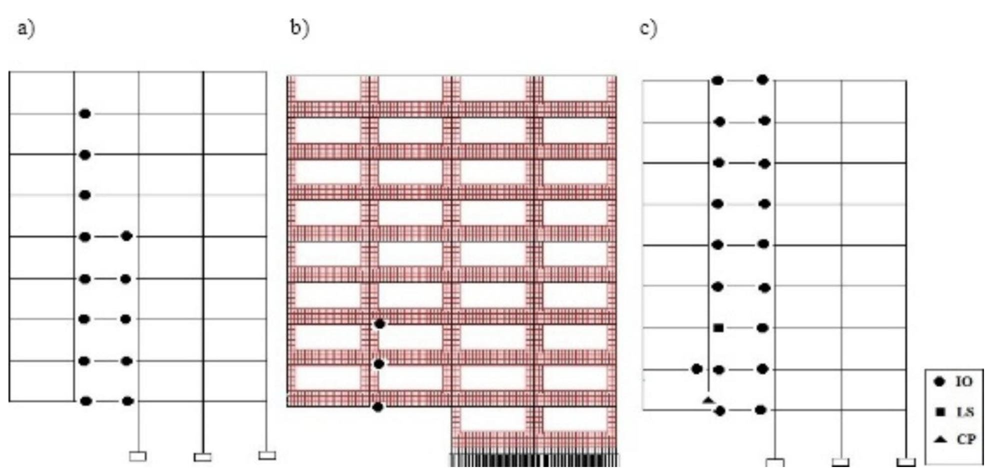


Fig. 18 Comparison of the maximum vertical displacement values in the 9-story models

Fig. 20 Location of plastic hinges in (a) S9-R1.5-T100-C23 (b) S9-R2-T50-C34 (c) S9-R1.5-T100-C34



ratio in all models, and the bars of the models with L/H = 2 have witnessed the highest stress values. Increasing the L/H ratio from 1 to 1.5 and from 1.5 to 2 have led to on average 50 and 12% of the growth in bars Von-Mises stress respectively, and the vertical bars have shown more sensitivity. It has also been observed that in both of the C23 and C34 scenarios, the stress in the bars exceeded the yield limit in all models with L/H ratio of 1.5 and 2, which means the infill panels have been damaged in these cases. While the models with L/H ratio of 1 have not been seriously damaged.

The plastic hinges conditions in exterior frames of several 9-story models are illustrated in Fig. 20, as an example. Studying all the nine-story models has indicated that the plastic hinges are initially concentrated in the beams located above the removal area, which plays an important role in threatening the overall stability of the structures. The rotation values of columns, located on the removal area, have exceeded the CP level in models without infill panels and L/H = 1.5. Although the structures remained stable and the beams above the removal area did not rotate more than their allowable performance level, some plastic hinges have been observed in some beams in the models with 50% infill openings in the C34 removal scenarios.

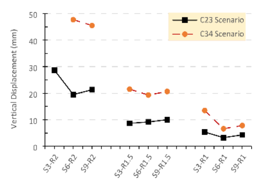


Fig. 21 Maximum of vertical displacement in different models due to progressive collapse scenarios with initial extensive damage

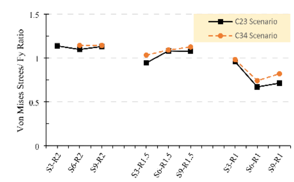


Fig. 22 Bar's maximum existed to allowed Von-Mises stress ratios in different models due to progressive collapse scenarios with initial extensive damage

Table 5 General evaluation of the investigated models due to progressive collapse with extensive initial damage

Number of Stories	L/H Ratio	Infill Panel Opening %	Progressive Collapse in C23 Scenario	Progressive Collapse in C34 Scenario	Status of Infill Panels in C23 Scenario	Status of Infill Panels in C34 Scenario
			Occur (O)/ Not Occur (NO)		Damaged (D)/ Not Damaged (ND)	
3	1	100	O	O	--	--
3	1	50	NO	NO	ND	D
3	1	30	NO	NO	ND	D
3	1.5	100	O	O	--	--
3	1.5	50	NO	NO	D	D
3	1.5	30	NO	NO	ND	ND
3	2	100	O	O	--	--
3	2	50	O	O	D	D
3	2	30	O	O	D	D
6	1	100	O	O	--	--
6	1	50	NO	NO	D	D
6	1	30	NO	NO	ND	ND
6	1.5	100	O	O	--	--
6	1.5	50	NO	NO	D	D
6	1.5	30	NO	NO	D	D
6	2	100	O	O	--	--
6	2	50	NO	NO	D	D
6	2	30	NO	NO	D	D
9	1	100	NO	O	--	--
9	1	50	NO	NO	D	D
9	1	30	NO	NO	ND	ND
9	1.5	100	NO	O	--	--
9	1.5	50	NO	NO	D	D
9	1.5	30	NO	NO	D	D
9	2	100	O	O	--	--
9	2	50	NO	NO	D	D
9	2	30	NO	NO	D	D

4 Models' general evaluation

The greatest vertical displacements of the last step of analyzing models with 30% infill openings are compared for both C23 and C34 removal scenarios in Fig. 21. Therefore, in addition to the studying L/H ratio and the effect of the number of stories, the infill presence and removal scenario impacts have been investigated. As expected, the C34 scenarios have higher values of vertical displacement in comparison with C23 scenarios in corresponding models. The S6-R2-C34 model has the highest vertical displacement value by 47.7 mm. The vertical displacement of the model decreased by about 50% as the removal scenario is changed from C34 to C23. In general, there are significant differences between the vertical displacement values of different scenarios in models with L/H = 2, as it increases with the growth of the L/H ratio and the number of removed columns. The C34 removal scenario has led to vertical displacement, which are on average 2.19 times bigger than that in the C23 scenario.

In the previous sections, it was concluded that the stress values in horizontal bars of the infill panels is more critical than vertical bars. Figure 22 presented the ratio of the Von-Misses stress to the allowed value for models 30 and 50 persent of openings. Based on the results, models with 30 and 50% of openings, no damage was detected in infill panels of the models with L/H = 1 since the bars had not yielded. Therefore, the initial extensive damage has not caused significant damage to the infill panels of these models.

Infill panel damage has been observed in the models with L/H = 1 and 2, as models with L/H = 2 had more significant damage than models with L/H = 1.

Comparing C34 to C23 removal scenarios, the panel bars witnessed higher values in the former scenario due to the more prominent role of the infill panel in bearing the forces and assistance to the frame structure. Therefore, the infill panel damage was more significant in the C34 scenario.

Table 5 summarizes the final status of the frame structures and infill panels in all of the studied models. The results show that the models without infill panels are not adequately stable in C23 and C34, so they collapse. Moreover, the stability and the resistance of the structures increase by increasing the L/H ratio and the number of stories. Overall, the structures without infill panels were not able to absorb the energy and find the proper alternative path for transferring the extra load, so they collapsed in the studied extensive damage scenarios.

Presence of infill panels helped the 3-story models with L/H = 1 and 2 to withstand in both scenarios of progressive collapse C23 and C34.It should be noted that, minor damages have been observed in infill panels in the panel-frame interaction locations in some cases.

The 3-story models with infil panels and L/H = 2 did not resist against both C23 and C34 initial damage scenarios, and their infill panels have been damaged.

The 6-story models with all L/H ratios and infills with 30 or 50% of openings successfully found alternative load paths in both C32 and C34 scenarios. However, some infill panels were slightly damaged in some cases due to panel-frame interaction. The 9-story models with infills are also resistant in both removal scenarios, although infills have been more damaged comparing the other models with the lumber of stories.

Briefly, the results show that models without infill panels do not withstand the scenario of progressive collapse with extensive initial damage. On the other hand in the presence of the sandwich infill panels, including 50% or less of opening and all L/H ratios, helps the 6-story or higher modelsto resistant against progressive collapse with extensive initial damage.

5 Conclusions

In the present paper, the progressive collapse potential of the 3, 6 and 9-story steel structures, with and without infill 3D sandwich panels in their peripheral sides, are studied to evaluate the effect of infill panels on the structures' performance when the first floor is extensively damaged. The investigated structures have different span length to story height (L/H) ratios (1, 1.5 and 2) and infill panels with different percentage of openings (30, 50 and 100). The behavior of the structural members, in critical parts around the removal area, are investigated after removing two and three columns and their adjacent infill panels by applying nonlinear dynamic analysis and considering the UFC provisions. In the nonlinear modeling process, fiber plastic hinge theory is used for the beam and column elements and nonlinear-layered shell theory is used for the infill sandwich panels. The uni-axial nonlinear behavior of the materials is adopted and the numerical modeling is done in the SAP2000 software. The effect of floor stiffness has not been considered in the progressive failure analysis. The interaction between frame and infill is defined by the link element and the behavior of the link element in pressure is considered as hard contact and in traction as very weak to model the interaction as realistic as possible. Two scenarios are defined by the names C23 and C34. The removal scenario C23 means that in this scenario 2 columns and 3 adjacent infill panels are removed and so on for the C34 scenario, 3 columns and 4 adjacent infill panels are removed. The results have indicated that the infill presence has increased the stiffness and reduced the structure's ductility by limiting the structural elements' rotation. Infill panels transfer a large proportion of the excessive force resulting from initial extensive damage, so that the infill's bars stress has exceeded the yield limit, which shows the crucial role of infill panels in finding an alternative load path. Furthermore, the infill panels reduced the collapse chance by providing continuity, especially when the initial damage is extensive. A summary of the other results is given below:

- The C34 vertical displacement values in the removal area have been on average 2.19 times bigger than that of C23.
- In the C34 removal scenario, the 3-story models have the most critical conditions, and the vertical displacement values were on average twice as big as that in their corresponding models subjected to C23.
- The time history analysis results have indicated that the models with infill panels have smaller vertical displacements, and the structures have stabilized in a shorter period in comparison with their corresponding models without infill panels.
- In models without infill panels, progressive collapse occurs under the effect of extensive initial damage scenarios C23 and C34, and the models lose their stability. Moreover, the stability and the resistance of the structures increase by increasing the L/H ratio and the number of stories. The 3-story model without infill panels and L/H = 2 lost its stability in both scenarios C23 and C34, while all other 3-story models with infill withstand in both removal scenarios.
- All 6- and 9-story models with infill panels remained stable after removal scenarios although some infill panels were slightly damaged in some cases. The amount of damage to the infill panels in 9-story models is greater compared to shorter structures.
- The results show that infill panels have a significant impact on progressive collapse prevention, especially in extensive initial damage. In 6-story and higher models with all L/H ratios, the presence of infill panels has made models resistant to progressive collapse.

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