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Seismic behavior of steel frames with lightweight-low strength industrialized infill walls

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Abstract. JK wall is a shear wall made of lightweight EPS mortar and reinforced with a 3-D galvanized steel mesh, called JK panel, and truss-like stiffeners, called JK stiffeners. Earlier studies have shown that low strength lightweight concrete has the potential to be used in structural elements. In this study, seismic contribution of the JK infill walls surrounded by steel frames is numerically investigated. Adopting a hybrid numerical model, behavior envelop of the wall is derived from the general purpose finite element software, Abaqus. Obtained backbone would be implemented in the professional analytical software, SAP2000, in which through calibrated hysteretic parameters, cyclic behavior of the JK infill can be simulated. Through comparison with earlier experimental results, it turned out that the proposed hybrid modeling can simulate monotonic and cyclic behavior of JK walls with good accuracy. JK infills have a panel-type configuration which their dominant failure mode would be ductile in flexure. Finally technical and economical advantages of the proposed JK infills are assessed for two representative multistory buildings. It is revealed that JK infills can reduce maximum inter-story drifts as well as residual drifts at the expense of minor increase in the developed base shear.

Keywords: infill walls; JK wall; EPS concrete; lightweight concrete; hysteretic behavior

1. Introduction

In most countries, regardless of their seismicity, Un-Reinforced Masonry (URM) is the dominant infill wall in framed structures. There is a clear consensus, however, that URM infill walls would behave in a brittle manner during a major or even moderate seismic event and are prone to in-plane and out-of-plane instabilities. Such stability problems have been reported in earlier experimental studies (Shalouf 2005, Hashemi and Mosalam 2007) as well as case histories (Haldar *et al*. 2013, Mostafaei and Kabeyasawa 2004). As discussed in earlier studies, behavior of a typical URM infill is highly pinched with pronounced strength degradation. Further details about hysteretic behavior of URMs can be found in FEMA 307 (1998). In addition to the brittle behavior, URM infills tend to interact with the surrounding frame and can impose excessive demand on columns and beam-column joints (FEMA 274 1997, Asteris 2003). Different micro and macro models have been proposed to simulate behavior of infilled frames (Asteris *et al*.

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2013, Asteris *et al.* 2011). Many researchers have also tried to improve seismic behavior of URM infills through many techniques, including pre-stressed cables (Shalouf 2005, Dawe and Aridru 1994), FRP strips (Shalouf 2005, Lunn and Rizkalla 2011), and steel strips (Tagdi 1998), among others.

URMs are not appealing in modern constructions which call for lightweight and fast techniques with minimal manpower. There are many industrialized partition and infill wall technologies currently in use and new ones are emerging. Some researchers have recently focused on seismic behavior of industrialized walls. Cyclic behaviors of wood frame studs with Gypsum drywall have been investigated by Memari and Solnosky (2014). Aref and Jung (2003) have proposed a new polymer matrix composite (PMC) infill panel by which lateral stiffness as well as damping of the whole system can be greatly improved. Kabir *et al*. (2006) have investigated contribution of 3D panel infills on steel moment resisting frames. In another study, a novel infill with frictional sliding fuses (FSF) were proposed and experimentally investigated by Mohammadi *et al.* (2010). They concluded that infills with FSF can have a pronounced ductility and strength capacity. Spatti *et al*. (2012) have experimentally and numerically evaluated seismic behavior of a new precast composite wooden-concrete wall, called ARIA. While considered ARIA panels were not surrounded by any frame, this new technology might be well suited to act as an infill panel as well.

The objective of this paper is to investigate seismic contribution of a new infill, called JK infill wall. The term "JK" stands for Joseph Kiefer who first proposed and constructed JK panels in 1982. JK wall is constructed by lightweight Expanded Polystyrene (EPS) mortar and reinforced by JK panel and JK stiffeners, as shown in Figs. 1(a)-(c). JK stiffeners pass through the JK panel in both vertical and horizontal directions. JK wall enjoys a fast constructional speed as it is a formless wall due to the sticky nature of the used EPS concrete. JK panels have a predefined dimension such that thickness of a typical JK wall is 0.12 m. Density and compressive strength of the used EPS mortar in JK wall are commonly in the range of 800 to 1000 kg/m^3 and 5 to 6 MPa, respectively. Further details about configuration and construction of JK walls can be found

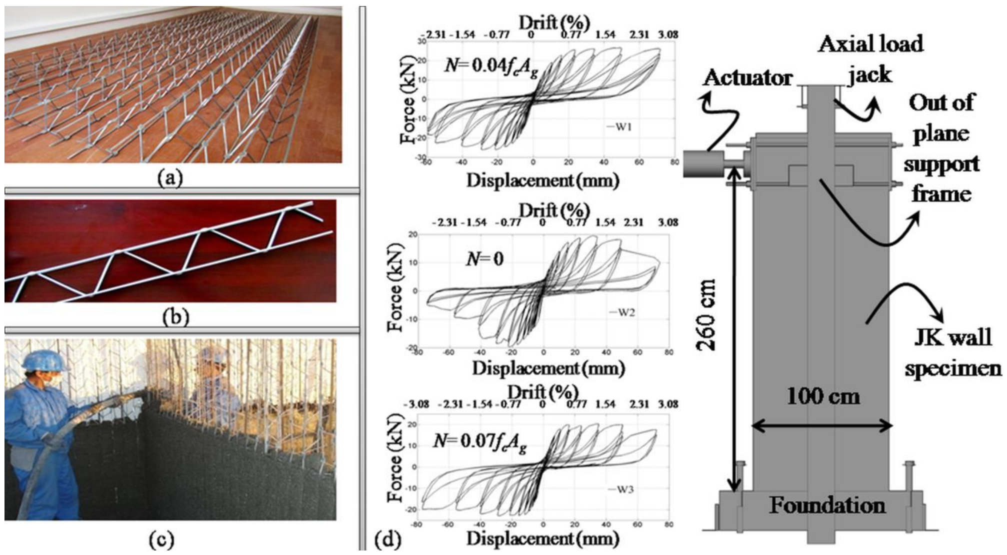

Fig. 1 (a) JK panel, (b) JK stiffeners, (c) injection of EPS concrete into the JK panel, and (d) hysteretic behaviors of JK walls with different gravity loads, after Mousavi *et al*. (2014)

elsewhere (Mousavi *et al*. 2014). Many codes of practice have defined a minimum value for compressive strength of structural concrete mainly due to durability concerns. However, recent technologies, such as EPS beads with fly ash (Babu *et al*. 2006) or polymer binders (ACI 548.3R, 2009), are able to increase durability of the concrete without affecting its compressive strength.

There are limited studies devoted to investigate structural behavior of low strength concretes. It turned out that the only difference between high and low strength concretes stems from their strength capacity. Meanwhile other parameters such as ultimate ductility, pattern of stiffness and strength degradation, and pinching are quite similar. For example Hiroaki *et al*. (2008) have experimentally shown that hysteretic behavior of a coupling beam with low strength (9 MPa) concrete can be even more ductile compared to the same coupling beam with higher strength (18 MPa) concrete. Bedirhanoglu *et al*. (2010) examined cyclic behavior of beam-column joints with low-strength (8 MPa) concrete. Again observed hysteretic behaviors of beam-column joints were similar to those from normal-strength concretes. Similar conclusion has been also made by Mousavi *et al*. (2014) for shear walls. Hysteretic behaviors of three slender full scale JK wall specimens are illustrated in Fig. 1(d). It can be seen that JK walls have a pronounced ductility which is comparable with that of current special reinforced concrete shear walls. Moreover, hysteretic behavior of JK wall is quite similar to other conventional concrete walls in terms of stiffness/strength degradation and pinching (Mousavi *et al*. 2014).

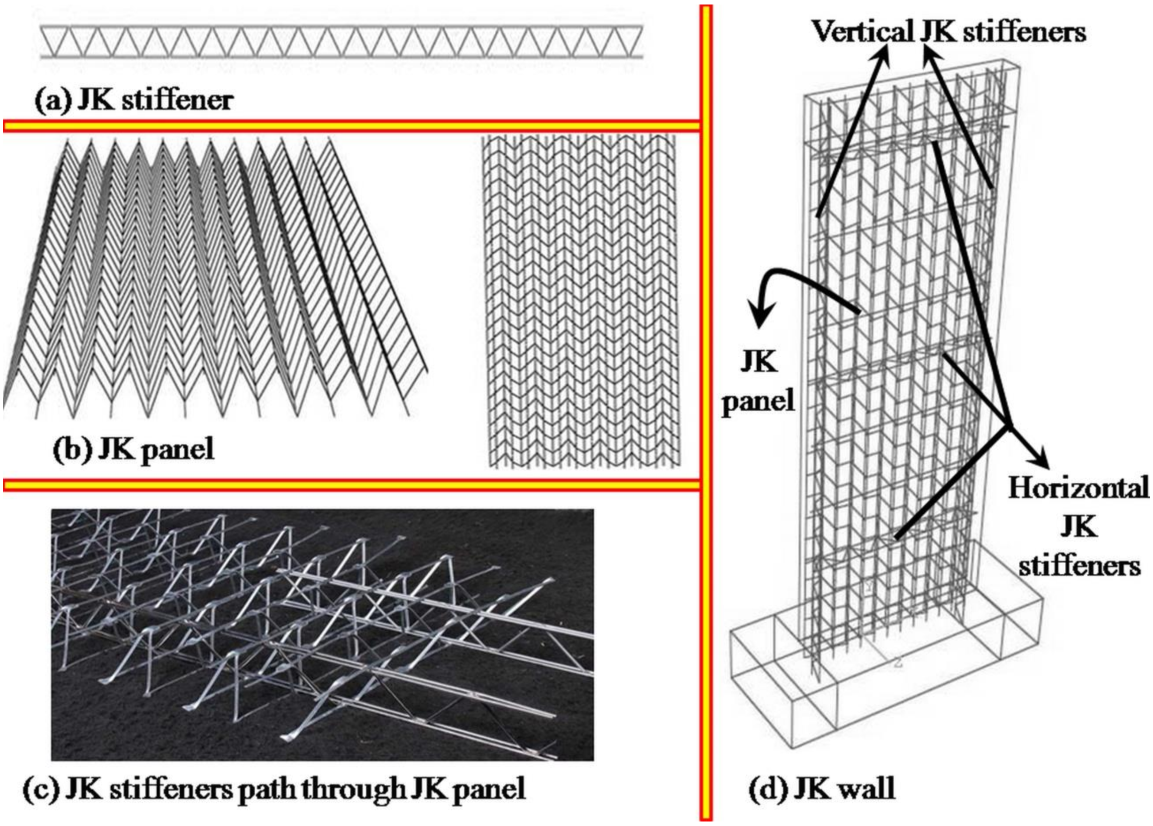

Fig. 2 (a) JK stiffener, (b) JK panel, (c) JK stiffeners inside the JK panel, and (d) a schematic illustration of JK wall reinforcement

While seismic behavior of JK shear wall has been investigated in some recent studies (Mousavi *et al*. 2014, Mousavi *et al*. 2013, Mousavi and Bahrami-Rad 2013), its contribution as an infill wall is not fully understood yet. As a result, this study is devoted to investigate contribution of JK infills on seismic behavior of steel moment resisting frames. Fig. 2 briefly illustrates the main components of the JK wall. Further details about JK wall have been provided by Mousavi *et al*. (2014). It should be noted that JK infills are well suited for modern mass constructions as they are lightweight, formless, and have superior fire resistance (EFECTIS france, 2009).

2. Hybrid modeling of JK infill walls

As suggested by Mousavi *et al*. (2014) monotonic and cyclic behavior of JK wall can be accurately simulated by the general purpose finite element software, Abaqus (2011), and IDARC 2D (Reinhorn *et al*. 2009), respectively. In this study, on the other hand, a hybrid modeling technique is proposed by which both monotonic and cyclic behavior of JK wall can be simulated with good accuracy. As schematically illustrated in Fig. 3, using the software Abaqus, envelope curve of the JK infill under monotonic load would be obtained first. The envelope would be assigned to a multi-linear plastic Link element in the software SAP2000 (2010) and required

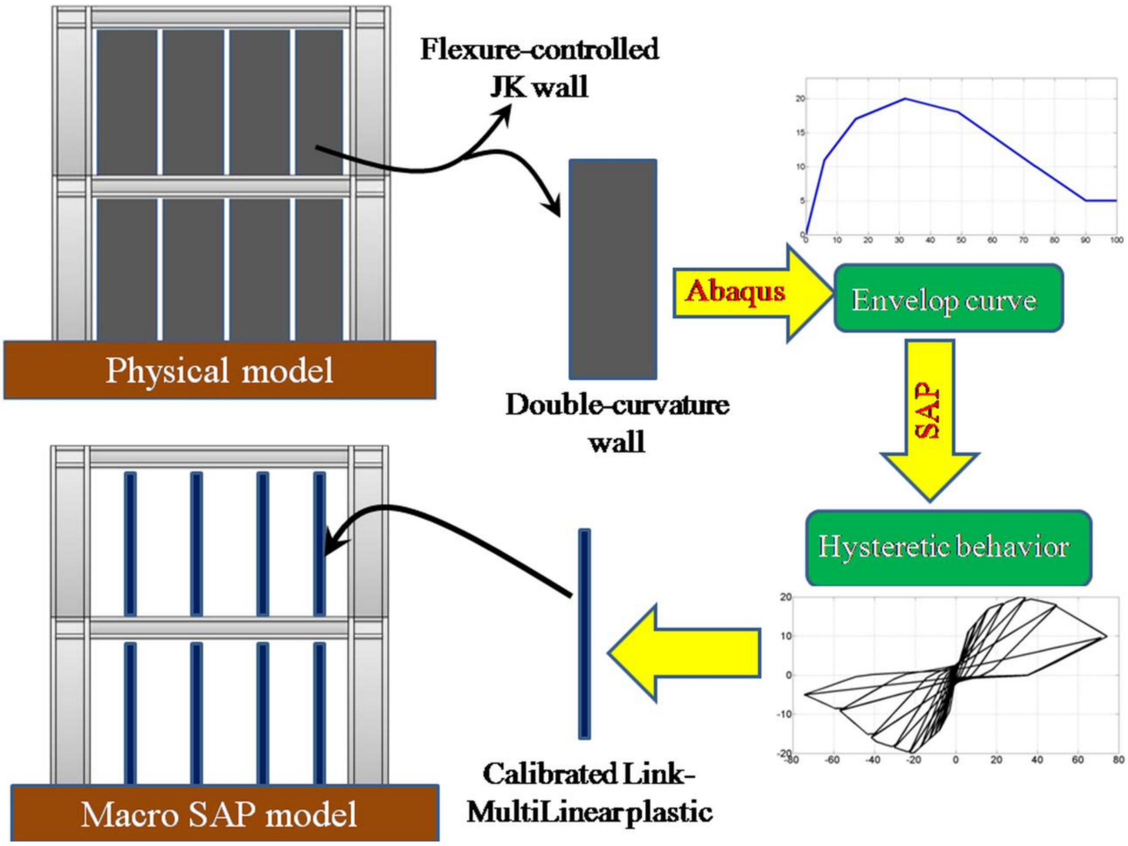

Fig. 3 Hybrid modeling of JK infill walls

hysteretic parameters, namely stiffness degradation and pinching, would be defined for the Link element. Note that, hysteretic parameters need to be calibrated through experimental results. In this way a simple yet efficient representative Link element would be defined in SAP2000 which can be added to the corresponding frame.

In other words, hybrid modeling technique merges experimental results with a rigorous finite element analyses to obtain a simple nonlinear spring with tunable hysteretic deterioration. Such nonlinear spring can be defined in most professional software. As a result, hysteretic behavior of the JK wall can be incorporated into the bare frame.

2.1 Envelope curve of the JK infill

Behavior of JK wall with height of 2.6 m, thickness of 0.12 m, and width of 1m under monotonic loading was simulated in Abaqus, as shown in Fig. 4. The concrete and reinforcement parts of the wall are modeled with solid, and wire (beam) elements, respectively. Adopted concrete model is damaged plasticity with elastic modulus of 600 MPa and compressive strength of 5.5 MPa. The compressive strength and elastic modulus of the EPS mortar have been obtained earlier by Mousavi *et al*. (2014). No gravity load was imposed on the wall and obtained envelope is compared with that of the experimental results. Note that obtained envelope belongs to a single curvature wall in which flexural plastic hinge was formed only on the base. This is because top of the wall has no rotational constraint and the wall has a single moment resisting connection at its base. Such boundary condition is similar to the adopted set-up by Mousavi *et al*. (2014). Depending on the infill-frame connection, JK infill can also behave in a double curvature manner in which plastic hinges would be formed at top and bottom of the wall. As shown in Fig. 4(c) obtained envelope should be increased (roughly by two times) in the case of JK infill with double curvature behavior. More details about single curvature and double curvature behaviors of RC elements can be found elsewhere (Caltrans 2006). In this study, it is assumed that the JK infill has a moment resisting connection to the upper and lower beams such that the assumption of strain compatibility is valid at the interface of the beam and the infill. Such connection can be achieved with closely spaced shear connectors along the interface of the beam and the JK infill. Considered JK infills in this study have double curvature behaviors due to the moment resisting connections to the upper and lower beams. Note that the JK infills have no connection with the surrounding columns.

2.2 Hysteretic behavior of the JK infill

Having the envelope curve of the JK infill (from experiment or rigorous finite element analysis), its hysteretic behavior can be simulated through the Multi-linear plastic Link element in SAP2000. Considering experimental envelope curve, accuracy of the proposed hybrid modeling technique is investigated in Fig. 5. The main hysteretic parameters in the Multi-linear plastic Link element are α and β which, respectively, account for stiffness degradation and pinching. Note that strength degradation have already been accounted in the envelope curve. As shown in Fig. 5(a) and (b) the calibrated hysteretic parameters for a flexure-controlled JK wall are α=1 and β=0.25. In order to signify effect of the hysteretic parameters, two additional hysteretic behaviors are also included in Fig. 5(a) in which their hysteretic parameters were intentionally not calibrated. Shape of the hysteretic behavior as well as energy dissipation of the JK wall can be accurately simulated through the proposed hybrid model. However, the calibrated hysteretic parameters are only

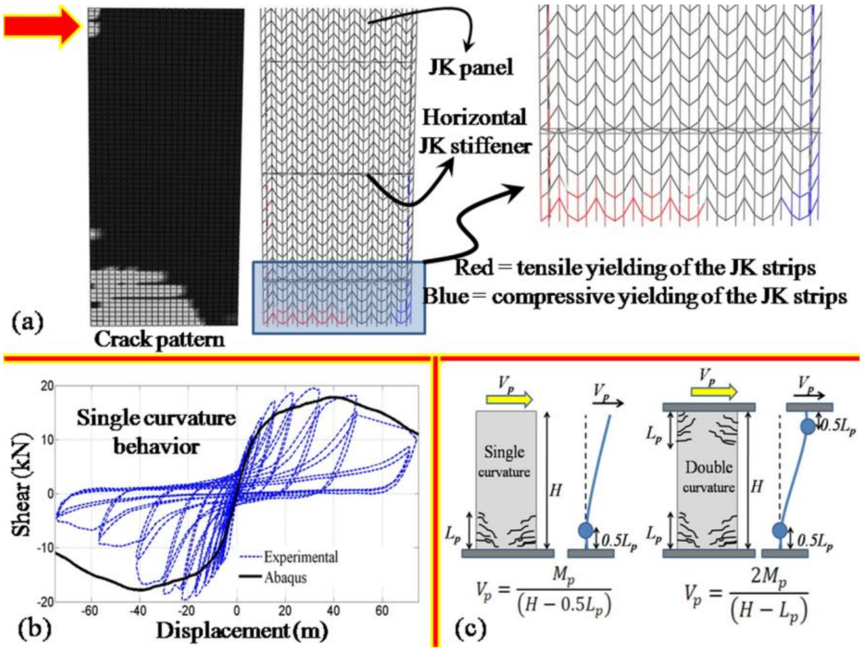

Fig. 4 (a) Crack and yielding patterns in the JK wall. (b) Envelope curve of the JK infill. (c) Shear capacity of the JK wall in single and double curvature behaviors (L_P=length of the plastic hinge, M_P=flexural capacity of the JK infill, V_p=required shear to develop M_p, and H=height of the JK infill)

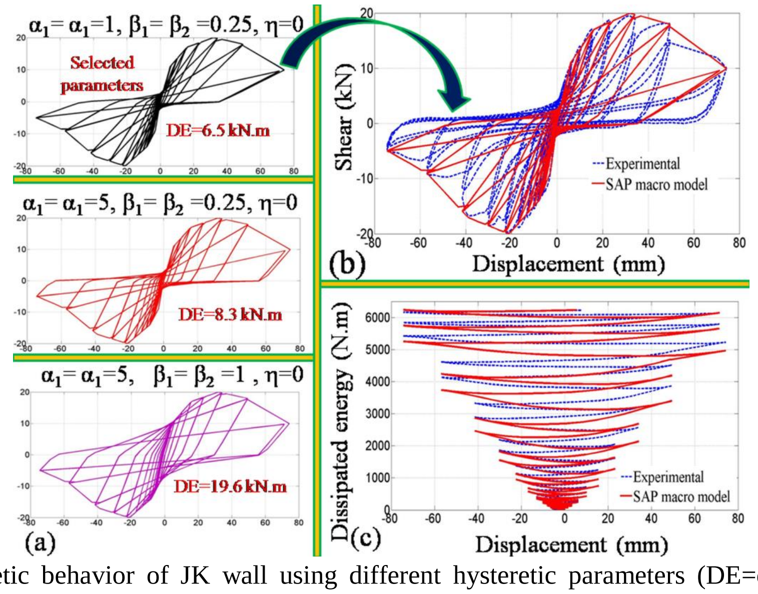

Fig. 5 (a) Hysteretic behavior of JK wall using different hysteretic parameters (DE=dissipated energy). Accuracy of the proposed hybrid modeling in terms of (b) hysteretic behavior and (c) cumulative energy dissipation

applicable for flexure-controlled JK walls. As there is no experimental data from squat JK walls, considered JK infill has a multi-panel configuration such that each infill panel would remain flexure-controlled. In addition, considered experimental behavior in Fig. 5(b) belongs to the JK wall specimen with no gravity load which is also the case in most infill walls. This is due to the fact that axial stiffness of the JK wall is very small compared to that of the steel frame.

3. Multi-panel JK infills

As suggested earlier, adopted configuration of JK infills is of multi-panel type. This is mainly because, currently available hysteretic behaviors of JK wall belong to slender specimens with flexural behavior. Another reason of adopting a multi-panel configuration is the fact that flexural-controlled behaviors are more ductile than shear-controlled ones. This claim is investigated in Fig. 6 in which a two-story steel frame with single-panel and multi-panel JK infills are subjected to a monotonic loading. Considered frames are modeled in Abaqus with bay of 5 m and story height of 3.2 m. In both cases the JK infills have no connection to the surrounding columns. In the multi-panel configuration there is 50 mm gap between the separate panels as a result the panels have no connection with each other. All infills are merged to the upper and lower beams. This technique

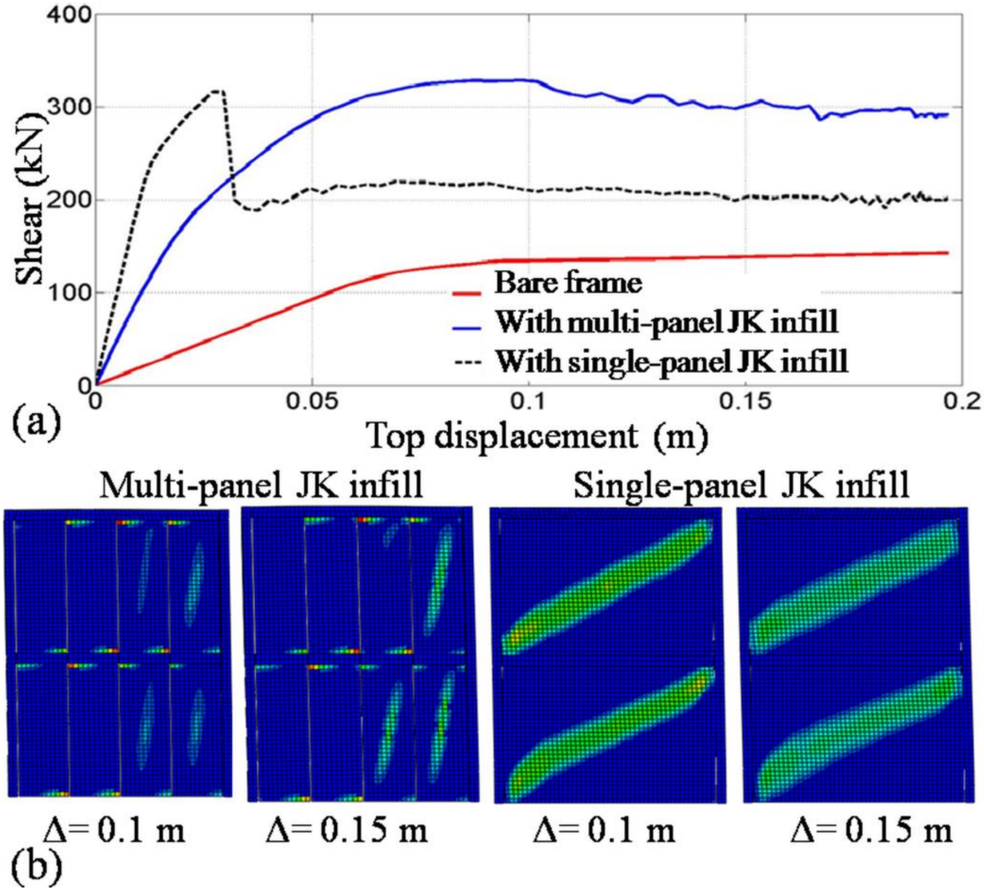

Fig. 6 Comparison between single-panel and multi-panel JK infills. (a) Capacity curves and (b) crack patterns of the JK infills

would simulate a moment resisting connection between the infills and the beams. It turned out that while initial stiffness of the single panel JK infill is higher than that of the multi-panel one, ductility of the multi-panel type JK infill is more than its single panel counterpart. Shear controlled behavior of the single panel infill is clear from the occurred diagonal crack. Behavior of double curvature multi-panel infill is flexure-controlled at the early displacement demands turning to shear-flexure at large displacement demands, as shown in Fig. 6(b). From Fig. 6(b) it can be seen that each panel in the multi-panel configuration behaved in a double curvature manner as flexural plastic hinges are formed in both top and bottom of the infill in each story.

Fig. 7 illustrates the analytical model for a single bay single story steel frame with multi-panel JK infill. The bay and height of the frame are 5 m and 3.2 m, respectively. From Fig. 7(b) it can be concluded that proposed hybrid modeling is in general agreement with a rigorous modeling approach in Abaqus and the minor deviation can be attributed to the frame behavior. Note that in Abaqus, behavior of the frame is simulated through the distributed plasticity while SAP2000 considers localized plasticity in some predefined plastic hinges. Figs. 7(c) and 7(d) indicate that JK infill can improve energy dissipation capability of the frame and also has a pronounced effect on post-yield stiffness of the whole system. As suggested by FEMA 307 (1998), residual displacements are highly sensitive to post-yield stiffness and hysteretic behaviors with positive post-yield stiffness tend to result in smaller residual displacements. Fig. 7 indicates that post-yield stiffness of the frame with JK infill is positive at moderate displacement demands but would be negative at larger displacement demands. Accordingly, self-centering capability of the JK infilled frame can be improved, if the displacement demands stay within the stiffening segment.

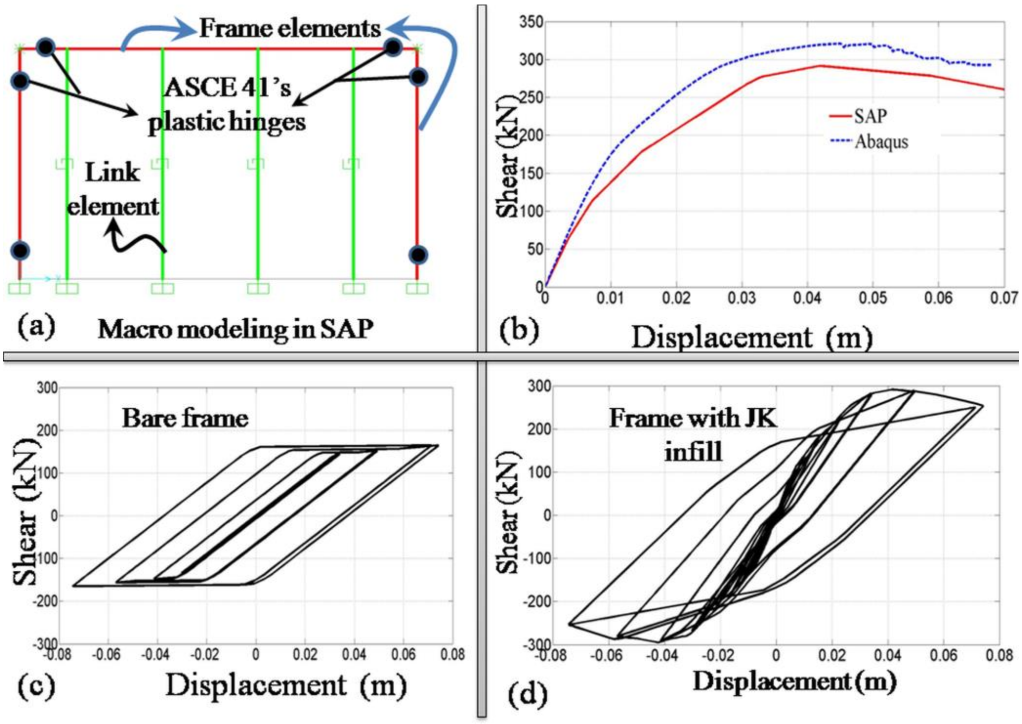

Fig. 7 (a) Macro model of the steel frame with multi-panel JK infill, (b) capacity curve of the frame with JK infill, (c) cyclic behavior of the bare frame, and (d) cyclic behavior of the frame with JK infill

4. Design consideration

A simplified double-phase design procedure is proposed in this section by which steel frame with multi-panel JK infills can be proportioned. Earlier experimental and analytical results indicated that hysteretic behavior of JK walls are very similar to special reinforced concrete shear walls (Mousavi *et al*. 2014). Therefore, during the preliminary design, it is assumed that lateral behavior of steel frame with JK infills is similar to steel frame in combination with special reinforced shear walls. Validity of such a simplified assumption would be checked within the second phase (final stage) of the design. Adopted codes of practice are ASCE 7 (2010) for loading, AISC 341 (2005) for seismic design of the steel frame, and ASCE 41 (2006) for the second phase in which performance of the frame and JK infills would be assessed through the so called nonlinear static procedure. Proposed design steps are summarized in the following subsections.

4.1 Phase I- Preliminary design

Step 1. Design the bare frame for gravity loads in combination with 25% of seismic lateral loads. Seismic loads can be obtained from ASCE 7 considering dual system of steel frame in combination with special reinforced concrete shear wall. Note that all seismic provisions of a typical steel moment resisting frame, as stipulated in AISC 341, should be considered at this step. These include related provisions with regard to compactness of the beam and column cross sections, prequalified beam-column connections, panel zones, lateral bracing of the beam elements, etc. Besides, the bare frame should be able to support all possible gravity load combinations in absence of the infill panels.

Step 2. Determine the placement and dimensions of the multi-panel JK infills such that behavior of each panel remains flexural-controlled. The recommended height to width ratio for each panel is 2.5 to 3.

Step 3. Determine envelope curve of each panel from available experimental results or carried out numerical results from Abaqus.

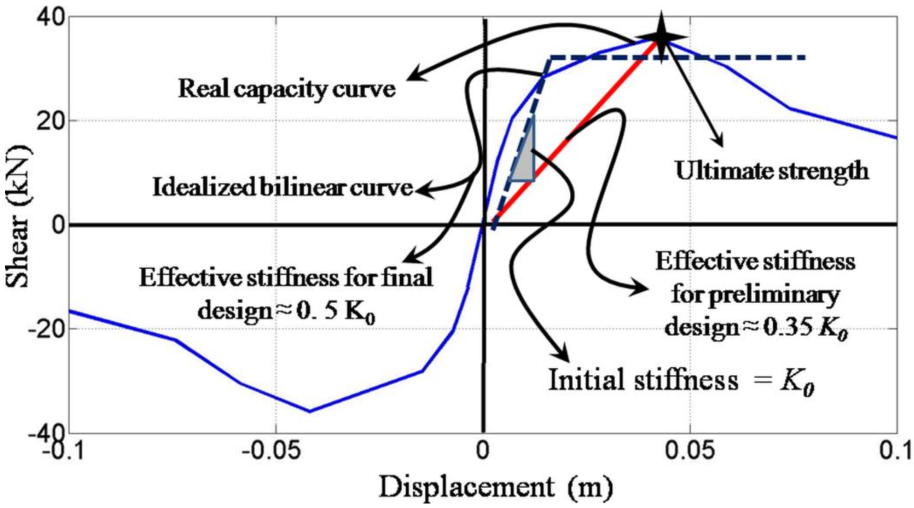

Fig. 8 Effective stiffness of the JK infill in different design phases

Step 4. Define related Link elements in SAP2000 and assign an effective stiffness of $0.35K_0$ (K_0 is the initial stiffness of the JK infill). Such effective stiffness roughly corresponds to ultimate capacity of the infill as depicted in Fig. 8.

Step 5. Reanalyze the whole structure (frame incorporated with JK infills) for gravity loads as well as full seismic lateral load. Beam and columns should be strengthened at this step, if required. Note that the analysis in this step would be elastic. At this stage the steel frame elements can be proportioned based on the so called capacity design technique. Again, the obtained frame should be in compliance with the seismic provisions of moment resisting frames per AISC 341.

4.2 Phase II- Final design

Step 6. Assign localized plastic hinges in beam and columns per ASCE 41. For those beams which are connected to the JK infills, it is recommended to assign shear and flexural plastic hinges between the Link elements (Link elements simulate the JK infills).

Step 7. Consider effective stiffness of $0.5K_0$ for JK infills (Link elements) and obtain fundamental period of the structure. As depicted in Fig. 8, such effective stiffness roughly corresponds to the yield strength of the infill.

Step 8. Obtain target displacement of the roof per ASCE 41 using the fundamental period of the previous step.

Step 9.Impose a lateral load pattern according to the fundamental mode shape of the structure as suggested in ASCE 41 and push the structure up to 150% of the target displacement.

Step 10. The whole structural elements should pass adopted acceptance criteria. Acceptance criteria of the frame components are based on the plastic hinge rotations as proposed by ASCE 41. However, acceptance criteria of JK infills is considered to be drift-based as follows,

Inter-story drift of 0.5% for immediate occupancy (IO), inter-story drift of 1.5% for life safety (LS), and inter-story drift of 2% for collapse prevention (CP) performances.

Above acceptance criteria are adopted based on the available experimental results of flexure-controlled JK walls (Mousavi *et al*. 2014). While Mousavi *et al*. (2014) have proposed strain-based acceptance criteria for JK walls, such criteria are not feasible for a macro model approach which is the case in this study. As a result, adopted acceptance criteria for JK infills are drift-based. Note that the proposed acceptance criteria are calculated based on the procedure proposed by ASCE 41 for novel structural elements. The proposed effective stiffness coefficients are based on the experimental results carried out by Mousavi *et al*. (2014) which are also in agreement with those proposed in ACI 318 (2008) and ASCE 41.

5. Numerical assessment

In order to investigate contribution of the proposed JK infills from technical and economical perspectives, two representative steel frames are considered in this section. Both frames are designed with and without JK infills. The frames with infiils are proportioned according to the proposed design procedure and the frames without infills are designed per AISC 341. Due to the length limitation of the paper, only some brief results are presented herein.

5.1 5-story plane frame

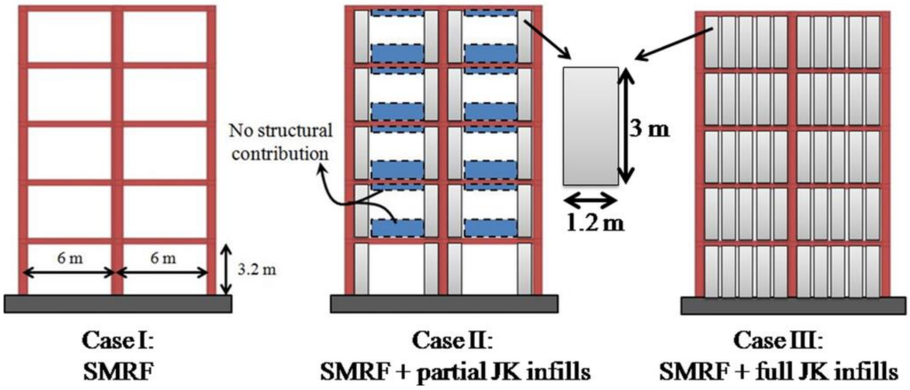

Fig. 9 Considered 5-story frames in different cases

Table 1 Main characteristics of the designed frame in all three cases

Case	Fundamental period	Maximum inter-story drift	Performance	Frame weight
I	1.44 s	2.27%	LS	78 kN
II	0.95 s	1.50%	LS	68 kN
III	0.88 s	1.46%	LS	65 kN

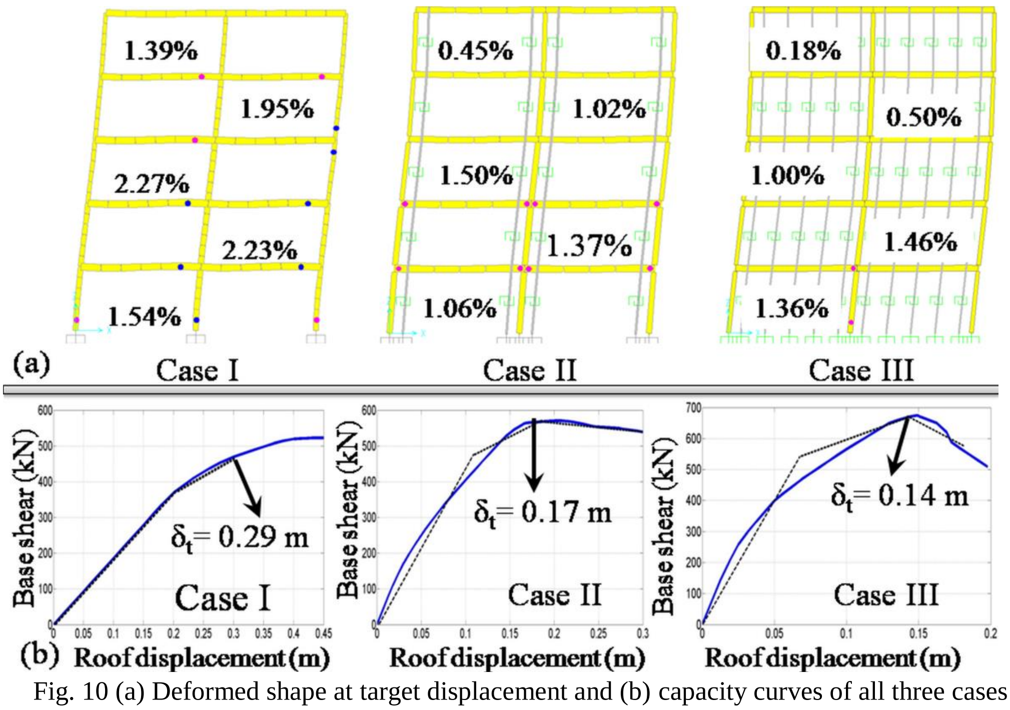

Fig. 10 (a) Deformed shape at target displacement and (b) capacity curves of all three cases

A 5-story residential plane frame is considered with three different configurations. Case I represents a conventional steel Special Moment Resisting Frame (SMRF) while cases II and III, respectively, account for presence of JK infills with and without opening. Considered cases are schematically illustrated in Fig. 9.

All infill panels have thickness of 0.12 m, width of 1.2 m, and height of 3 m. Dead and live loads of 25 kN/m and 10 kN/m were applied on the beams, respectively. Inherent damping ratio of the building is 5%. Considered seismic hazard was 10%-50 year (return period of 475 years) with S_{DS} and S_{D1} of 0.875 and 0.55, respectively. Per ASCE 7 S_{DS} and S_{D1} stand for design acceleration spectrum in periods of 0.2 s and 1s, respectively. The proposed double phase design procedure was adopted for the cases II and III while the case I was designed per AISC 341. Obtained results of the considered cases are presented in Table 1 and Fig. 10. It turned out that the JK infills have lead to a pronounced reduction in the maximum inter-story drifts.

From Table 1 it can be seen that JK infills reduce frame weight up to 17%. Note that in Table 1, “Frame weight” refers to steel weight which is required for the bare frame. As a result, from an economical perspective, frame weight should be as low as possible. Required steel weight deemed to be a reasonable economical index as construction costs of the JK infills are rather similar to those of conventional infills.

As presented in Table 2, in order to further investigate seismic contribution of the JK infills, seven ground motion records are considered and scaled based on the so called spectrum-compatible technique as adopted by ASCE 7. Fig. 11(a) shows the design spectrum, individual spectra of the scaled ground motions and the corresponding mean spectra. Both near-field and far-field ground motions are included in Table 2. Obtained hysteretic behaviors from one of the infill panels at the first story in the Case II are also depicted in Fig. 11(b) in which stiffness/strength degradation as well as pinching is reasonably simulated. Mean values of maximum base shear, maximum roof displacements, maximum inter-story drift, and maximum residual inter-story drift are also presented in Table 3. Comparison of the Case II with the Case I in Table 3 indicates that JK infills with opening lead to 44% and 29% decreases in roof displacement, and maximum inter-story drift, respectively. Meanwhile, base shear in Case II is increased by only 13% compared with Case I. These results indicate that, JK infills not only increase lateral stiffness of the frame, but also contribute to the energy dissipation capability of the whole system. Obtained results from the carried out nonlinear dynamic analyses are in general agreement with those from the nonlinear static procedure. For example, as shown in Fig. 10(b), according to the nonlinear static analyses, maximum roof displacements during the design level earthquake (return period of 475 years) are 0.29 m, 0.17 m, and 0.14 m, respectively, for cases I, II, an III. These displacements are very close to those of nonlinear dynamic analyses presented in Table 3. Table 3 also signifies self-centering capability of the JK infills. This latter future is also depicted in Fig. 12 for two sample earthquakes.

Table 2 Considered ground motions

No.	Earthquake	Station	Comp.	Mag.	Distance (km)
1	Kocaeli	Izmit	180	7.4	4.8 km
2	Kocaeli	Izmit	90	7.4	4.8 km
3	Northridge	24087 Alerta	90	6.7	9.2 km
4	Northridge	24087 Alerta	360	6.7	9.2 km
5	Northridge	90056 Newhall	WP1046	6.7	7.1 km
6	Northridge	90056 Newhall	WP1316	6.7	7.1 km
7	Landers	Yermo fire station	270	7.3	24.9 km

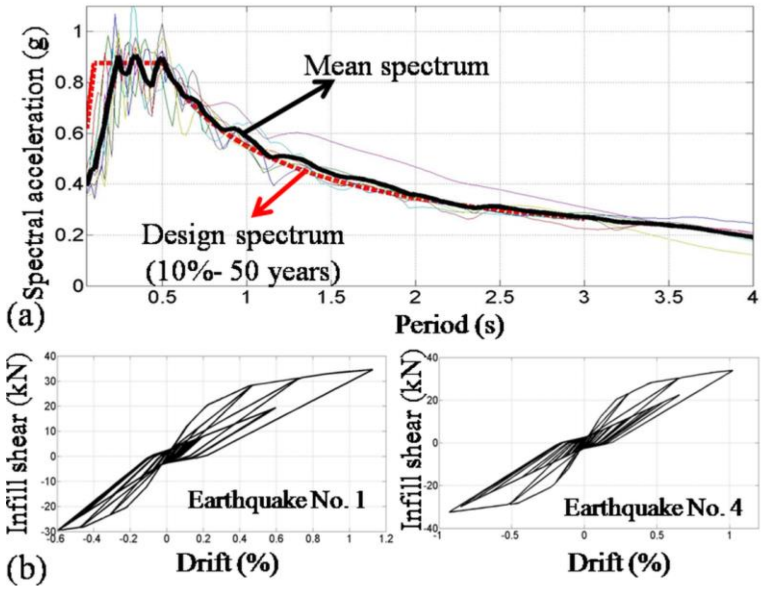

Fig. 11 (a) Scaled spectrum of the considered ground motions, and (b) sample hysteretic behaviors from one of the JK infills at the first story in Case II

Table 3 Mean results from the considered seven ground motions

Case	Maximum base shear	Maximum roof displacement	Maximum inter-story drift	Maximum residual inter-story drift
I	557 kN	0.32 m	2.23%	0.31%
II	628 kN	0.18 m	1.59%	0.09%
III	691 kN	0.13 m	1.29%	0.01%

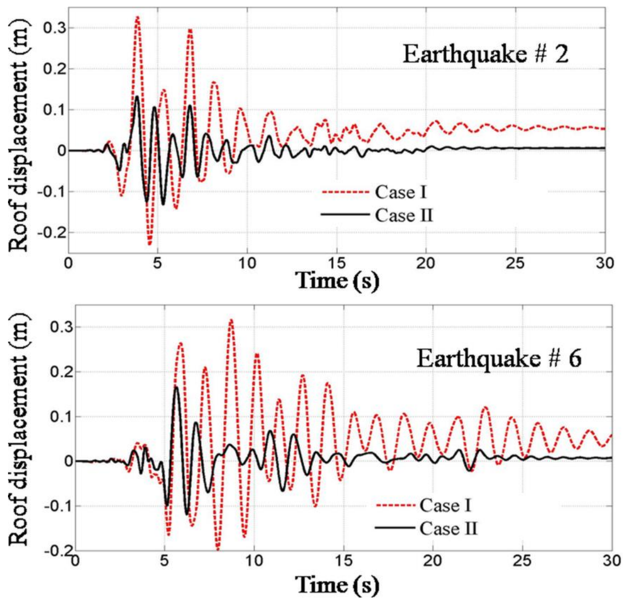

Fig. 12 Contribution of partial JK infill (Case II) on reducing maximum and residual displacements

5.2 10-story three dimensional frame

Fig. 13 shows the plan of a 10-story three dimensional residential steel frame in which contribution of the JK infills is evaluated. Again two cases are considered. Case A represents conventional SMRF along X direction and Special Concentrically Braced Frame (SCBF) along Y direction. Case B, on the other hand, reflects behavior of SMRF with multi-panel JK infills along both directions. Placement of the JK infills is also illustrated in Fig. 13. During the design procedure, JK infills with thickness of 0.24 m (with double reinforcement) were used along the Y direction while all infills along X direction are conventional JK walls with thickness of 0.12 m. In all cases inherent damping ratio of 5% was adopted for all modes of vibration.

Considered dead and live loads are 6 kN/m^2 and 2 kN/m^2, respectively, and an additional load of 15 kN/m is imposed on peripheral beams to represent dead loads from the exterior walls. Considered seismic hazard is similar to the previous example. Obtained results from the final design phase are presented in Table 4. Moreover, modeled structure in the Case B is illustrated in Fig. 14(a) and obtained capacity curves in both cases are shown in Fig. 14(b).

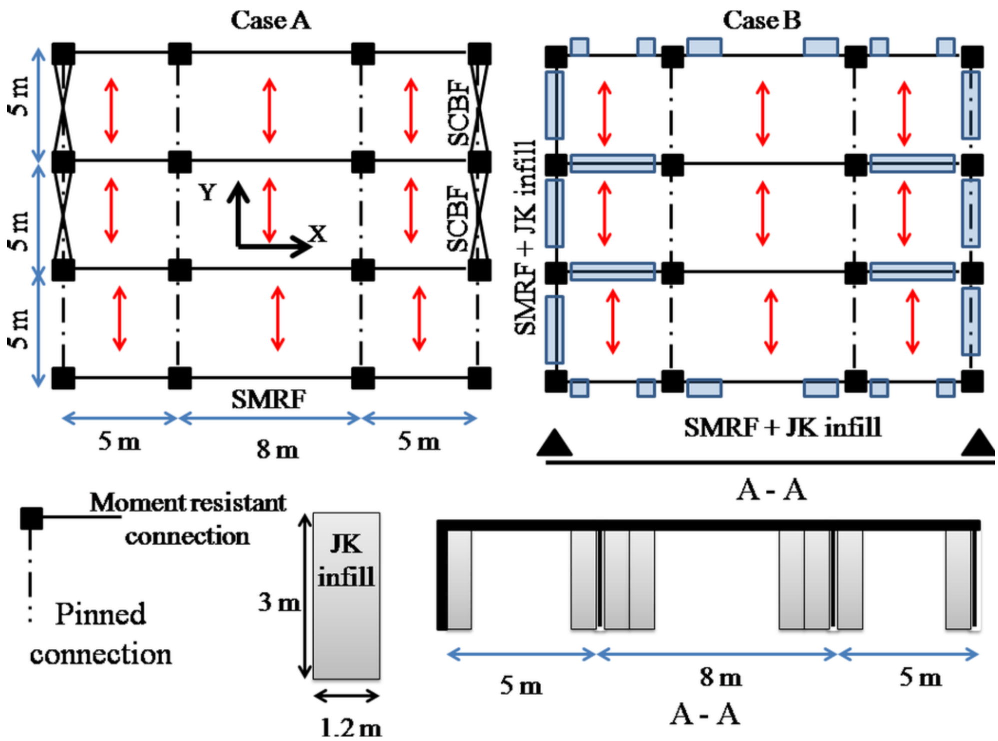

Fig. 13 Considered three dimensional 10-story frame

Table 4 Obtained results from final phase of the design

Case	Fundamental period along X	Fundamental period along Y	Maximum inter-story drift along X	Maximum inter-story drift along Y	Frame weight
A	2.22 s	0.89 s	2.64%	1.24%	1825 kN
B	1.53 s	1.65 s	1.53%	1.51%	1475 kN

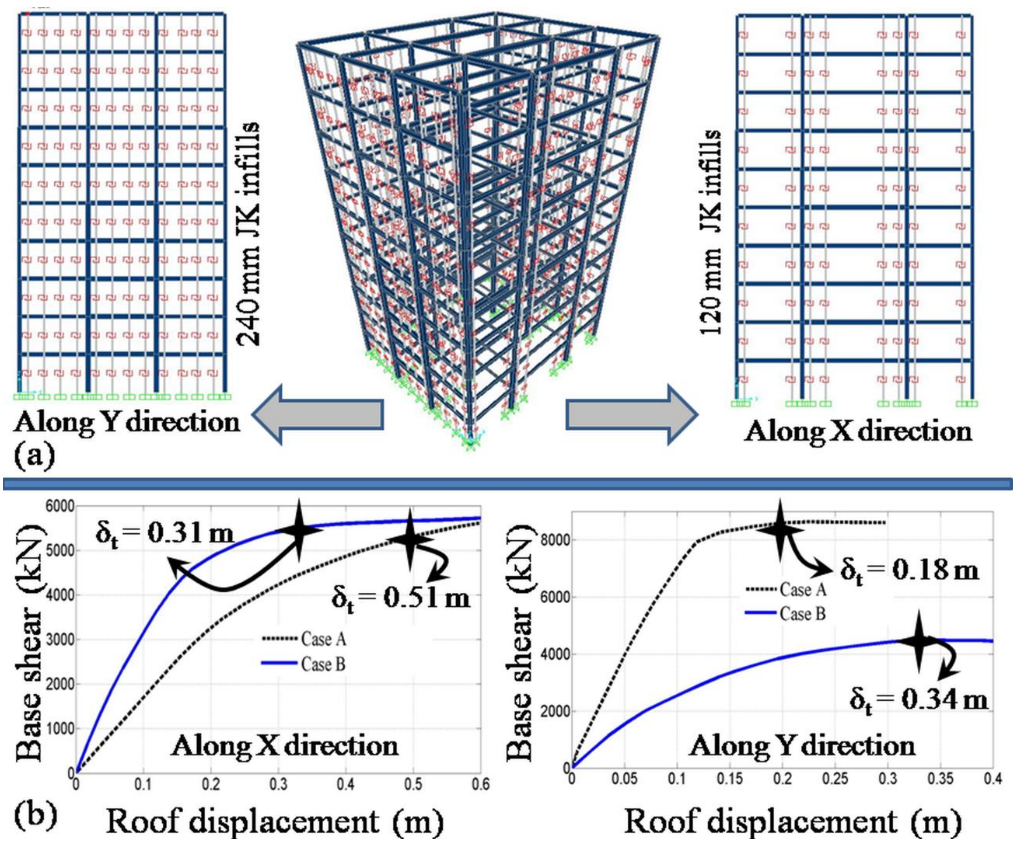

Fig. 14 (a) Adopted frame model in the Case B, and (b) obtained capacity curves at corresponding target displacements

Table 5 Maximum responses of the Case B from considered ground motion pairs

	Maximum inter-story drift -X	Maximum inter-story drift -Y	Maximum residual inter-story drift -X	Maximum residual inter-story drift -Y
Case B	1.21%	1.29%	0.14%	0.18%

Table 4 indicates that required steel weight in the Case B was reduced by of 20% compared with that of Case A. Designed 10-story building in Case B was subjected to three pairs of scaled ground motions (simultaneously in both directions) to further investigate effect of the placed JK infills. Table 5 reports maximum values of the maximum inter-story drift and the residual inter-story drift along both directions in Case B.

Table 5 indicates that performance of all JK infills is at least LS as the maximum inter-story drift is less than 1.5%. Deformed shapes of the frame at the moment of maximum roof displacement along both directions are depicted in Fig. 15(a). As shown in Fig. 15(a), all frame elements have also passed LS acceptance criteria. Moreover, two sample hysteretic behaviors taken from the 5th story are illustrated in Fig. 15(b). Note that double JK infill (with thickness of 0.24 m) has double capacity and stiffness compared to conventional JK infill (thickness of 0.12 m).

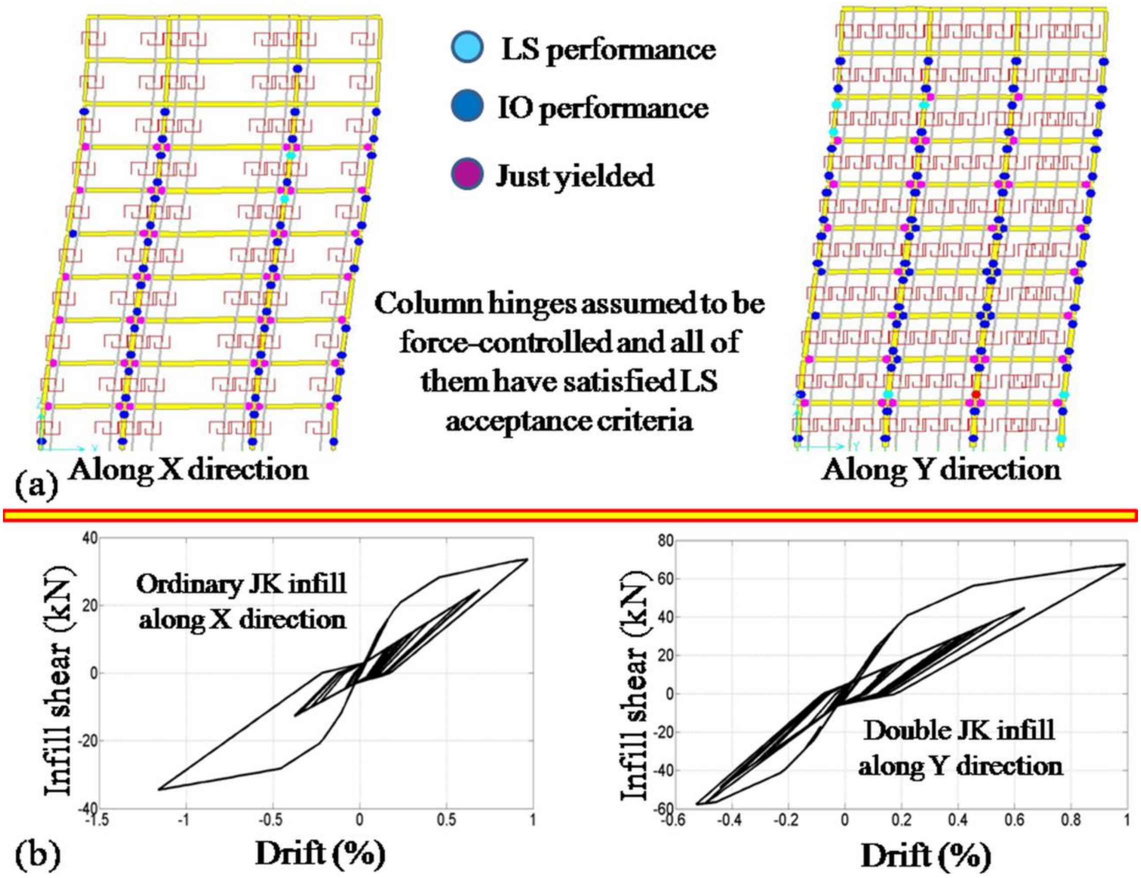

Fig. 15 (a) Deformed shape of the building at the maximum roof displacement, and (b) two sample hysteretic behaviors of the JK infills

6. Conclusions

A brief introduction about the super-lightweight EPS concrete shear wall, called JK wall, is presented. JK wall is made of lightweight low strength EPS concrete and reinforced with JK panel and JK stiffeners. Earlier experimental and numerical results suggested that hysteretic behavior of the JK wall is very similar to that of conventional special RC walls. As a result, in this study, seismic contribution of JK infill walls incorporated with steel moment resisting frames is numerically investigated. A calibrated hybrid model is proposed by which monotonic and cyclic behavior of the JK wall can be simulated with good accuracy in the professional software, SAP2000. It is also revealed that, compared with single panel JK infills, multi-panel JK infills lead to better lateral performance mainly because of their flexure-controlled behaviors.

A simple double phase design procedure is proposed for steel frames with JK infills and its applicability is investigated for a 5-story plane frame and another 10-story three dimensional frame. Using a linear procedure, a preliminary design would be carried out during the first phase. The final check of the structure is addressed in the second phase in which performance of the structure would be estimated through the nonlinear static procedure. Adopted acceptance criteria of the JK infill are assumed to be drift-based and were gained from earlier experimental results.

It turned out that JK infills would lead to significant reduction in terms of maximum inter-story drift and residual deformations. This was achieved at the expense of a minor increase in the developed base shear. Besides, JK infills can reduce, up to 20%, required steel weight of the frame. This latter feature is a significant promising from economical point of view. While obtained results of this study are based on a calibrated numerical model, experimental studies on JK infills are still required for a comprehensive understanding about their local and global behaviors.

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