The Effect of Infill Wall Collapse on the Deformation Estimations of Reinforced Concrete Frames

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***Abstract*- Infill walls are generally used as partition walls in structural systems. Their contributions to stiffness and strength during earthquakes are often neglected in the design of new buildings. 1999 Kocaeli, 2003 Bingol and 2011 Van earthquakes in Turkey revealed that the presence of infill walls may significantly affect the vulnerability of structures depending on failure of walls in first stories and formation of soft story mechanism. Since the building stock in Turkey is mostly composed of reinforced concrete frame buildings with masonry infill walls, simulation of building collapse under seismic loads becomes an important issue. In this paper, the failure mechanisms of the infill walls were numerically simulated by integrating an element removal algorithm to the traditional diagonal strut models. The possible unfavourable effects of infill walls on the reinforced concrete structures were investigated under the earthquake loads. For this purpose, a 4-story 3-bay deficient reinforced concrete frame with infill walls was examined and the results were compared with those of the bare frame. 7.4 magnitudes 1999 Duzce earthquake was used as the ground motion record in the nonlinear time history analyses. The analysis results indicated that including infill wall collapse in analyses resulted in large deformation demands, sudden stiffness degradations and formation of a soft story. These detrimental damage events were not observed when the presence of infill walls was neglected.**

***Keywords*- RC Frames; Infill Walls; Nonlinear Analyses; Soft-Story; Element Removing**

I. INTRODUCTION

In Turkey, reinforced concrete frame buildings with masonry infill walls are usually designed by neglecting the presence of infill walls. The major earthquake events showed that infill walls have significant influence on the seismic performance. In the 1999 Kocaeli earthquake, most buildings of this type were severely damaged or collapsed. Although the infill walls may have significant contribution to lateral load resistance, their sudden failure can also be dangerous resulting in sudden increase in deformations at a story. In Fig. 1, different degrees of the infill wall failures after the 1999 Kocaeli earthquake are illustrated [1]. In some of these cases, collapse was induced by a soft story mechanism, which was result of compression failure or out-of-plane failure of the infill walls. 2011 Van earthquake confirmed the significance of infill walls in deficient reinforcement concrete frame structures. A building with heavily damaged infill walls in its first story is illustrated in Fig. 2 after Van earthquake. It is observed that, sudden failure of infill walls may lead occurring of structural failure more quickly [2].

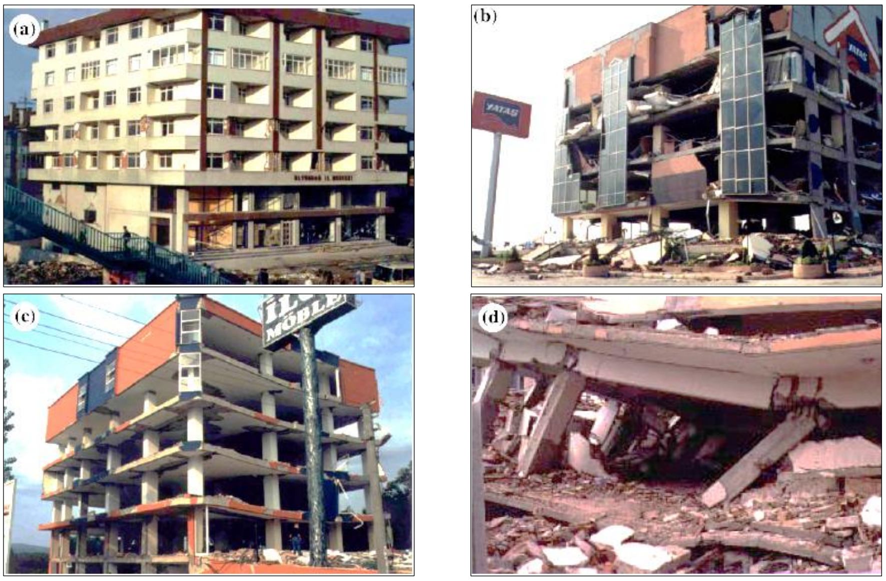


Fig. 1 Different levels of contribution of masonry infill walls to reinforced concrete frame responses: (*a*) limited masonry damage; (*b*) extensive damage to masonry, no apparent distress in frames; (*c*) total masonry damage with some distress in first-story columns; (*d*) total damage to masonry and structural collapse [1]

In the light of field observations, we understand that numerical simulations may play an important role to understand the behaviour of infill walls during seismic events. So the ability of accurately modelling infill wall behaviour is a major challenge. General approaches in infill wall analyses include the use of diagonal strut models (Fig. 3) and detailed finite element idealizations. The diagonal strut models with prescribed force-deformation rules can be considered as effective, but they may not necessarily provide a full picture of the collapse onset and events afterwards, unless advanced numerical techniques are incorporated. In [3], a numerical approach that implements the automated removal of collapsed elements during an on-going simulation was proposed. Researchers verified their simulations for one-story and five story structural systems that have deficient columns and infill walls. In this study a similar element removal algorithm was adapted for accurately modelling the behaviour and the failure of the infill walls. A case study is presented to demonstrate the expected effects of including infill walls and their failure.

Fig. 2 A building after 2011 Van earthquake with heavy damage on first story walls [2]

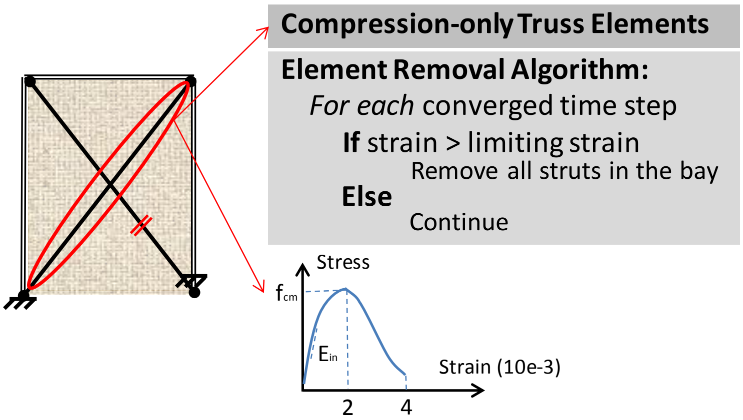


Fig. 3 Modelling of infill walls with element removal algorithm

II. MODELLING AND ELEMENT REMOVAL ALGORITHM

Infill walls are generally made of hollow clay bricks with a thin layer of plaster in Turkey. The method of construction and uncertainty in material properties of these members (as they are non-engineered in reinforced concrete frame systems) lead them to exhibit complex behaviour under seismic loadings. In the design of reinforced concrete frames with infill walls, the infill walls are usually neglected. In the seismic evaluation of existing buildings they may be modelled using equivalent diagonal struts but their sudden collapse and redistribution of forces are not modelled. In this study, nonlinear time history analyses were performed utilizing Opensees simulation platform version 2.1 [4] to shed some light in the post and pre collapse stages of infill walls and their influence on the deformation demands. Force based fiber frame elements were used to model beams and columns. The infill walls were modelled using compression only truss elements and connected to the diagonal nodes of the boundary frame. Calibration of the infill wall model was performed by using the results of a pseudo dynamic experimental study described in detail in [5].

The main motivation of the model calibration was the fact that when an infill diagonal strut failed in one direction in the numerical simulation, the strut in the opposite direction at the first story could still have significant capacity and stiffness. Hence the frame could not deform in the opposite direction upon failure of only one diagonal strut. However, the experimental results demonstrated that an infill damaged due to diagonal cracking in one direction was not capable of carrying any further load in the other direction as well. In order to overcome this modelling error, element removal algorithm as suggested by [3] was adopted and applied as shown in Fig. 3. When the failure strain of the diagonal strut is exceeded in one direction, the struts in both directions are removed from the simulation. In this way, complete failure of the infill wall was simulated and numerical results became in agreement with the test results. Further details on our modelling strategy and calibration of our models are presented in [6] and they are not presented herein for brevity.

III. ANALYSIS DETAILS AND CASE STUDY

In this chapter, the numerical model of the calibrated infill walls was applied to an actual building frame. The exterior frame of an existing 4-story 3-bay reinforced concrete structure was analysed with and without modified strut model. The frame's general layout is given in Fig. 4 where the complete details are available in [7]. The frame has 250x400 mm columns which are oriented in their strong axis for B-axis and their weak axis for A, C and D-axes. All the beam dimensions are 150x500 mm and their details are illustrated in Fig. 5. Uniaxial compressive strength of the concrete is 9 MPa and the yield strength of reinforcing steel is 220 MPa in tested structure. Tie spacing is 260 mm for beams and 280 mm for columns with a clear cover of 25 mm.

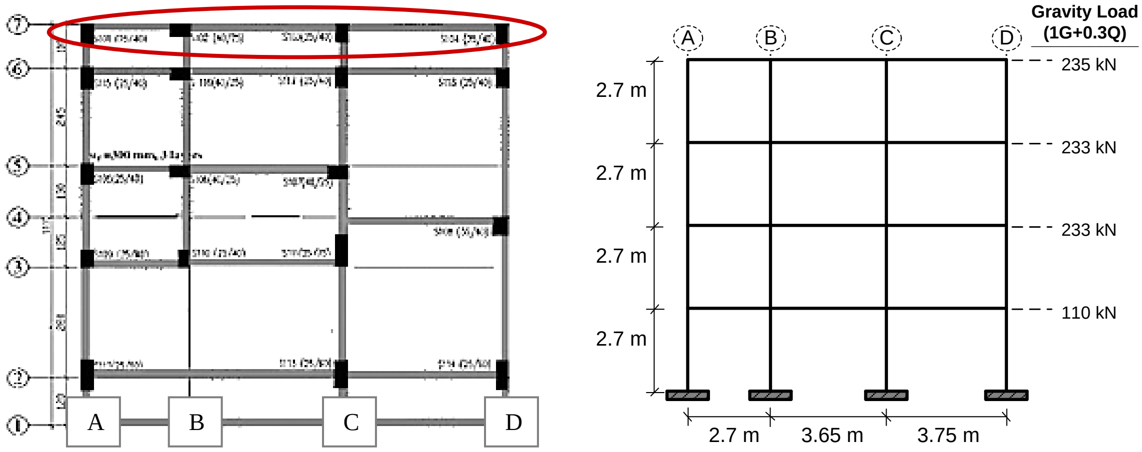
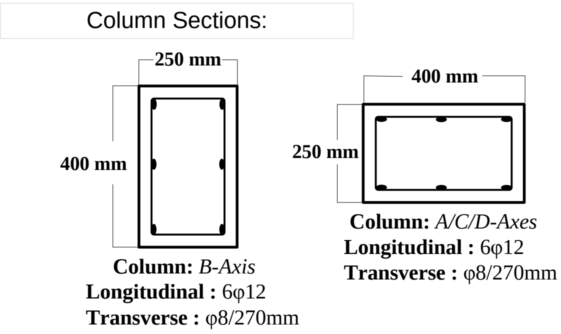
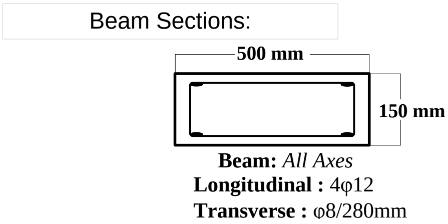


Fig. 4 Plan of the structure and tested frame





Material Type	Concrete	Reinforcement Steel	Confinement Steel
Material Strength (MPa)	9	220	220

Fig. 5 Beam and column sections

The effect of infill wall amounts was studied by considering three different infill wall schemes as shown in Fig. 6. Analysis was also conducted for the same frame by neglecting their presence. In order to follow common application in Turkey, it was assumed that infill wall has a width of 150 mm (110 mm brick, 40 mm mortar) which is same as width of the beams in analysed structure. Compressive strength of the brick and the mortar was selected as 12 MPa and 14 MPa, respectively.

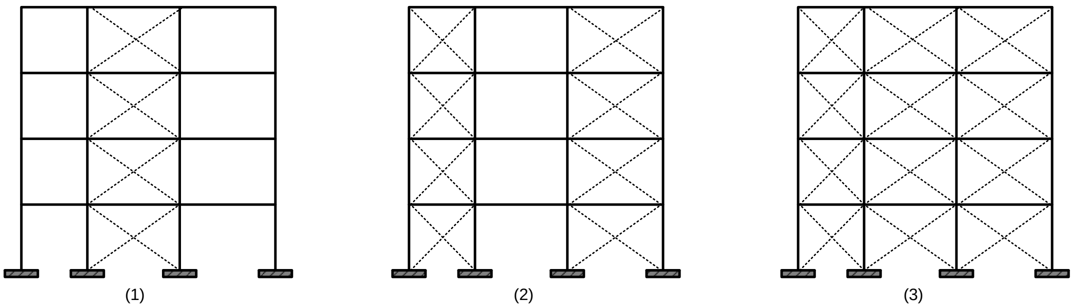


Fig. 6 Examined infill wall layouts

In the analyses, the material model used for concrete sections (*Concrete01*) follows the rules of the confined and unconfined concrete models proposed by [8] with plastic offset rules of [9]. Reinforcing steel was modelled using a bilinear elasto-plastic model (*Steel 02*) with a kinematic hardening slope of 1%.

For the material model of trust elements, it was decided to employ recommended material properties and relevant equations from [10]. Effective strut area for the infill walls was calculated using the following equations:

$$a = 0.175(\lambda_1 * h_{col})^{-0.4} r_{\inf} \tag{1}$$

$$\lambda_1 = \left[\frac{E_{ms}(t_{in} + t_p \sin 2\theta)}{4E_c I_c h_{in}} \right]^{\frac{1}{4}} \tag{2}$$

Above, h_{col} is the column height, r_{inf} is the diagonal length of infill wall, θ is the angle whose tangent is the infill height to length ratio, E_c and E_{ms} are the modulus of elasticity of concrete and the plaster-infill composite, I_c is moment of inertia of column and t_{in} and t_p are the thicknesses of brick units and the plaster.

The modulus of elasticity of the plaster-brick composite, E_{sm} was computed from [11] as 10000 MPa with the equation:

$$E_{ms} = \frac{E_{in}t_{in} + E_m t_p}{t_{in} + t_p} \tag{3}$$

where E_{in} and E_m are the modulus of elasticity of the infill wall and mortar/plaster, and t_{in} and t_p as described above. Accordingly, E_{in} was taken as 7700 MPa ($550F_m'$) based on recommendations in [10] and E_m was calculated as 16200 MPa ($4700\sqrt{Fc'}$) using equation in [12].

Consequently, compressive strength of the strut (F_{cm}) was computed from [10] assuming that bed-joint shear strength governs the strength of the diagonal strut either in the form of a diagonal crack or a single horizontal bed joint by using equations:

$$V_{ss} = f_{mv}L(t_{in} + t_p) \tag{4}$$

$$F_{cm} = V_{ss}/(a\cos\theta) \tag{5}$$

in which V_{ss} is the total shear resistance along the wall length, L is the length of the infill wall, f_{mv} is the shear strength of bed mortar/plaster mix which was taken from [10] as 0.25 MPa for masonry in good condition. Calculated effective strut areas and their compressive strengths are summarized in Table 1.

TABLE 1 PROPERTIES OF STRUT MEMBERS

BAY	Effective Strut Area (m^2)	Compressive Strength (MPa)
A-B	0.047	2.72
B-C	0.057	2.71
C-D	0.062	2.60

Mathematical model of [13] was employed for the compressive stress-strain behavior of the infill struts (*Concrete 04*) as suggested by [14]. The strain at peak compressive strength and diagonal strut failure was taken as 0.002 and 0.004. Lumped mass approach with a Rayleigh critical damping of 5% was utilized during the analyses by also incorporating the second order nonlinear geometric effects.

The north-south component of the 1999 Duzce earthquake was used for the time history analysis (Fig. 7). In this figure, the spectral acceleration vs. time plot of the Duzce earthquake, spectrum defined in [15] and the fundamental period the analyzed frames are also shown.

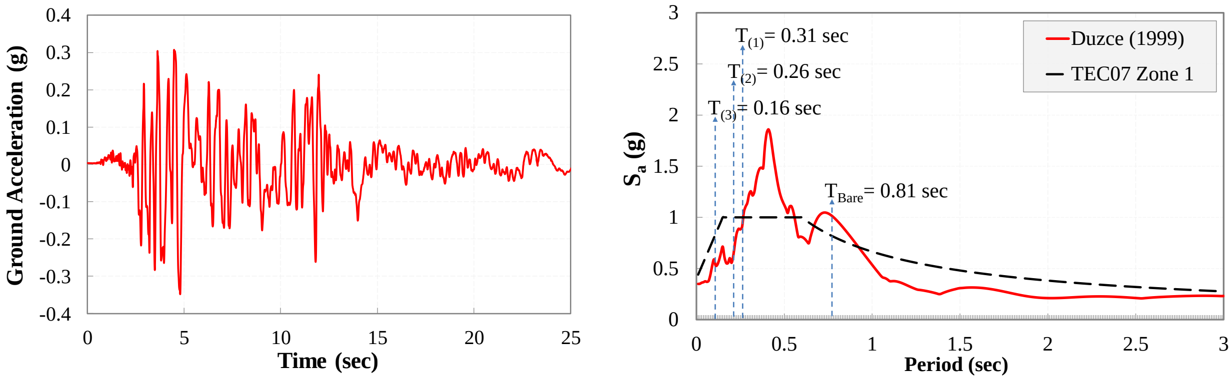


Fig. 7 Duzce ground motion and its spectrum

IV. ANALYSIS RESULTS

Analyses were conducted in three steps namely, Eigen value analysis, gravity analysis and time history analysis. The results of first-step, the identified periods of the tested frames are illustrated in Fig. 7. According to these results, including the infill walls increased the stiffness of the system significantly. Shifts in the fundamental periods ranged between the bare frame fundamental period and approximately half of the period of the bare frame for the three cases.

The nonlinear time history analyses results of the bare frame and infilled frames are presented in Fig. 8. To represent the common analysis approach all results were compared with the results of the bare frame. For the bare frame, peak first-story drift ratio was found to be 3.3%. However, the case study with infill wall scheme (1) experienced more than 8% drift ratio at its first story level. When the infill wall diagonal strut reached a compressive strain of 0.004 in any direction (corresponds to a first-story drift ratio of 1.4% for case 1), both of the diagonal struts were automatically removed from the system to simulate infill wall collapse. However, the infill walls of the upper stories did not experience any significant damages and survived until the end of analysis. For the infill wall scheme with case (2), a similar result was obtained. The first story infill walls were able to remain intact up until about 1.1% drift ratio. After that diagonal trust in A-B and C-D bays collapsed, which was simulated by the element removal. This caused a sudden change in the stiffness of the system. For case (3), continuity in the infill walls affected the response somewhat in a positive way. Failing of the infill walls occurred in two steps, (failure of the infill wall in bay C-D and failure of the infill walls A-B and B-C simultaneously) which prevented sudden amplification of first story deformations to a lesser extent.

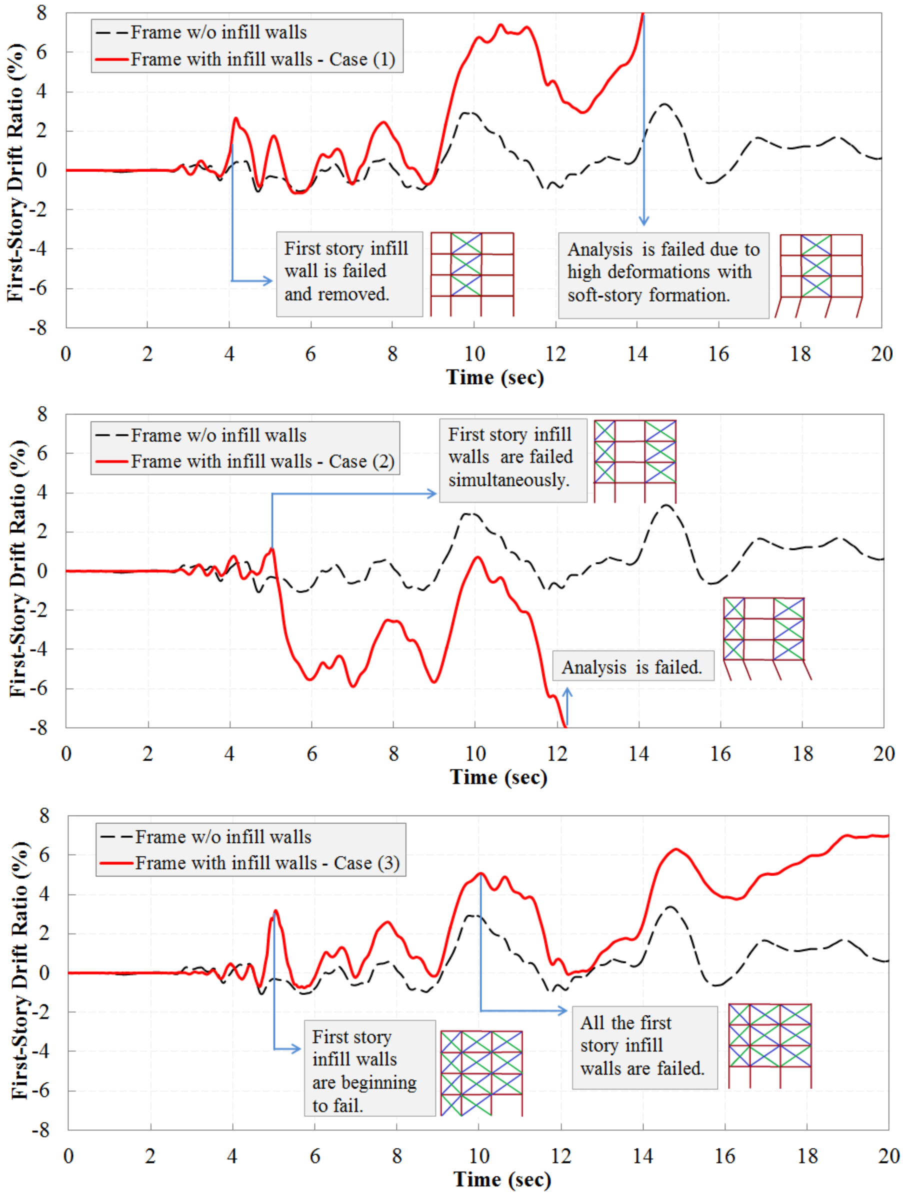


Fig. 8 Comparison of drift ratio results with and w/o infill walls

Base shear versus first story drift ratios are given in Fig. 9 for all cases. Results showed that incorporating infill walls to the system increased the initial stiffness significantly. In addition to that the lateral load capacities increased by about 100% and 260% for case (1) and case (2), respectively. However, after crushing of first story infill walls, this capacity dropped to the same value as the bare frame. A similar result was observed in the third case. Adding one more bay of infill walls to the system increased the lateral loading capacity about 100% with respect to case (2).

The formation of soft story mechanism could be seen more clearly in Fig. 10. To evaluate the response of frame from bottom to top, inter-story drift ratios for all stories are identified and compared with drift ratio limits given in [15]. According to results, frame without infill walls satisfied inter story drift ratio limits for the collapse limit state according to the [15] and managed to remain in the high damaged region. Furthermore, code estimation would suggest no collapse for this building. However, incorporating the infill collapse in all cases suggests that the building would collapse soon after the infill walls are completely damaged. Our analysis results should certainly be tested by conducting experiments for various infill wall configurations. However, they are important as they suggest that infill wall collapse needs to be simulated in detail and neglecting the infill walls may not always lead to safe deformation demand estimations.

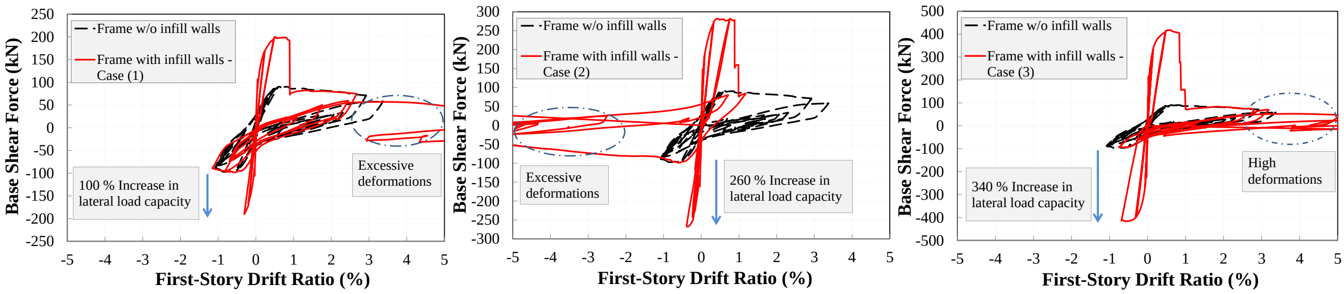


Fig. 9 Base shear versus top-story drift ratios with and w/o infill walls

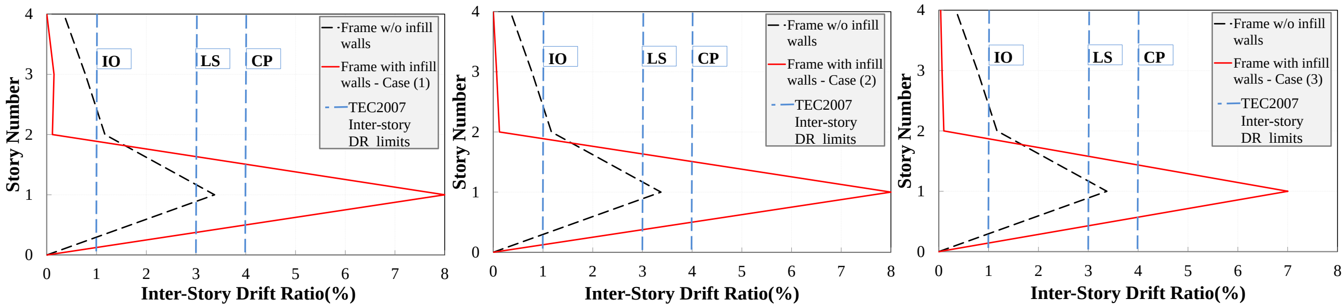


Fig. 10 Comparison of inter-story drift ratios with limit states

V. CONCLUSIONS

In the case of structural analysis, infill walls are generally accepted as non-structural members. However, the contribution and modelling of infill walls may be important to have a more accurate estimation of seismic performance. By considering these facts, the main results of the study had been summarized below:

- The contribution of infill walls should be carefully judged by considering the importance of them in changing dynamic response and collapse status of RC frame buildings.
- The failure of the first story infill walls during an earthquake may trigger a soft story mechanism leading to the collapse of the structural system.
- Simultaneous failure of infill walls (case 2) may lead sudden and significant rigidity differences between first story and upper stories. As a result, extreme deformations may be observed for the very early stages of the earthquake. Such results may not be observed in analyses that neglect the presence of infill walls.
- Modeling infill walls with diagonal struts may increase both stiffness and the lateral loading capacities of systems. However, such capacity enhancement may turn to be redundant when deformation limit states need to be checked.
- Distribution of walls on frame and characteristics of ground motion affects the simulation of collapse significantly. The more there are infill walls in different bays of a story the more possible redistribution with less deformation demands will be.
- Our results certainly need more experimental proof. However, they are extremely important for performance based seismic design requiring accurate collapse simulations.

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