Seismic Collapse Resistant Capacities of RC Special Moment Frames Considering Effects of Infilled Masonry Walls

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SUMMARY:
Collapse prevention capacity is one of the most important objectives of performance-based seismic design. Building structures should possess sufficient safety margin to avoid collapse when subjected to rare earthquakes. However, current design practice lacks an explicit design or a quantitative evaluation method for collapse resistant capacity. This paper investigates the collapse resistant capacities of RC special moment frames under extreme earthquake events considering the effects of infilled masonry walls. Although a great deal of research has been conducted regarding the seismic behavior of masonry infilled RC frames, very limited knowledge is available for practicing engineers to evaluate the collapse resistant capacities of masonry infilled RC special moment frames located in medium and high seismic regions. In this paper, the collapse resistant capacities of infilled RC special moment frames are quantitatively evaluated using the collapse fragility analysis based on the incremental dynamic analysis procedure. Several masonry infilled RC special moment frames are designed and modeled using the finite element analysis program SEISMOSTRUT. The equivalent diagonal strut model is introduced to simulate the behavior of the infilled masonry walls and the interaction between infilled walls and frame members. The IDA method is used to conduct the dynamic pushover analysis of the frames. Based on the analysis results, suggestions are made to improve the current design of RC special moment frames with infilled masonry walls in high seismic regions.

Keywords: seismic collapse; RC frame; infilled wall; masonry

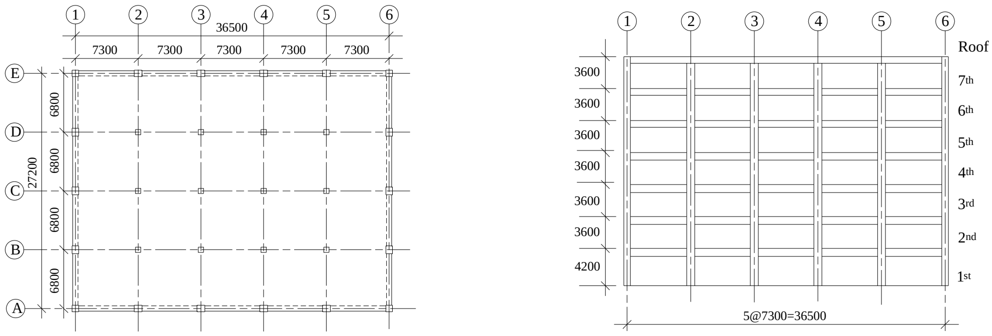
1. Introduction

The seismic safety of RC moment frames during medium and rare earthquakes is ultimately related to their collapse resistant capacities. However, current seismic codes don't explicitly provide provisions for seismic collapse safety design for RC structures. Many researchers carried out comprehensive research programs to investigate the effectiveness of the current seismic provisions in ensuring sufficient seismic collapse safety for RC moment frames located in medium and high seismic regions. Haselton et al designed a set of representative archetype RC moment frames based on ASCE 7-02and ACI 318-05 and used the incremental dynamic analysis (IDA) to evaluate the risk of collapse of the archetype structures.

Infilled masonry walls are very common in RC moment frame structures for the purpose of exterior enclosure. Previous research on seismic collapse safety of RC structures, however, ignored the effects of infilled masonry walls, which also contribute to the lateral force resistance and thus impact the structural response characteristics during ground excitation. On the other hand, available literature of research on infilled RC frames mainly focused on their seismic behavior instead of their collapse resistant capacities. Therefore, it is necessary to evaluate the seismic collapse resistant capacities of RC frames with the consideration of the influence of infilled walls. In this paper, the focus is put on the comparison on the behavior of bare frames and infilled frames under earthquake ground motions. Although the IDA based collapse vulnerability analysis is believed to be able to yield a complete knowledge about the collapse behavior of the structure, this method is cumbersome owing to the large amount of analysis work required. The incremental dynamic analysis is used to carry out dynamic pushover analysis to study the performance characteristics.

2. Archetype Structures

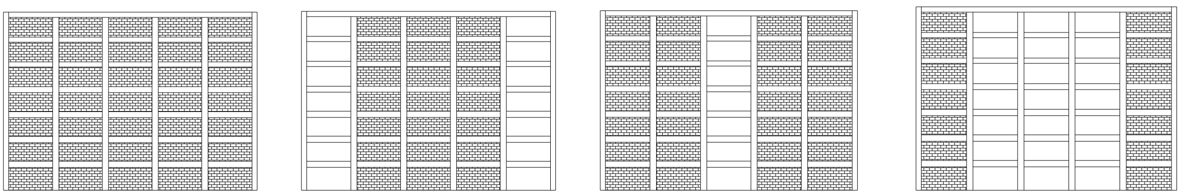
The archetype structure for the study is a 7-story RC office building located in high seismic region of Southern California, as shown in Fig. 1. The lateral force resisting system of the building consists of two multi-bay special moment frames on the perimeter in each direction. The typical floor plan is given in Fig. 1(a), having a plan area of 36.5m×27.2m. Elevation view of a typical 5-bay moment frame along line A is shown in Fig. 1(b). The story height is 4.2m for the first story and 3.6m for the other stories, resulting in a total building height of 25.8m. The archetype building is designed according to the provisions regarding the strength, stiffness, capacity design and detailing requirements from the International Building Code 2006, ASCE 7-05 and ACI 318-05. Seismic design is based on the mapped hazard for a Los Angeles site with S_s=1.5g and S_1=0.5g and soil site class *D*. 7.0kN/m^2 and 7.8kN/m^2 for roof and floor dead load are used respectively. Theee roof and floor live loads are 0.96kN/m^2 and 2.40 kN/m^2, respectively. The specified concrete strength f_c' is about 28MPa. The specified yielding strength of both the longitudinal rebars and stirrups is 420MPa.



(a) Typical floor plan　　　　(b) Typical frame elevation on line A

Fig. 1 Archetype office building

In order to study the seismic collapse resistant capacity of RC special moment frames considering the effects of infilled walls, four different schemes for the infilled wall arrangement were adopted, as shown in Fig. 2. The first scheme represents a bare frame (Fig. 2(a)). The second scheme is corresponding to a full arrangement of infilled walls (Fig. 2(b)). In the third and fourth schemes, infilled walls are set in the inside and outside two bays respectively (Fig. 2(c,d)).



(a)　　　　(b)　　　　(c)　　　　(d)

Fig. 2 Infilled wall schemes

3. Structural Model and Collapse Assessment methodology

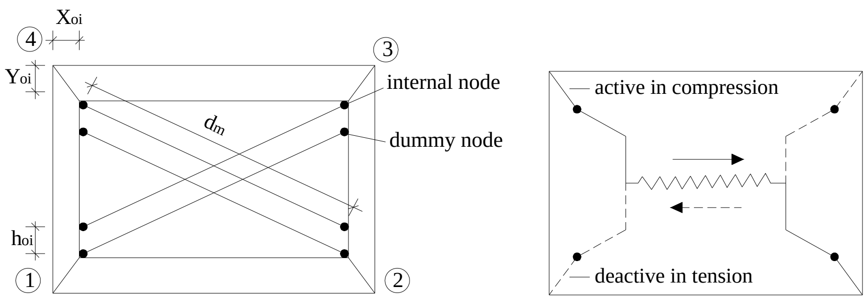
The finite element analysis software SEISMOSTRUT is used to carry out the analysis on the five-bay and seven-story two dimensional frame alone axis A in Fig 1(b). The influences of infilled walls are considered in terms of four schemes, as shown in Fig. 2. In order to simulate the post-elastic behavior of the model, elemnt types that can capture the critical characteristics to the collapse behavior of the frame are used.

3.1 Modeling of the Frame

The inelastic force based plastic hinge frame elements (infrmFBPH) are used to simulate the moment frame beams and columns. Although it is believed that the fiber model is more efficient in simulating the cracking and tension stiffening behavior of frame members under low to medium levels of ground motions, while the concentrated plastic hinge model more suitable to capture the deterioration characteristics at large deformation under rare earthquakes, the advantages of the fiber model compared with the lumped plastic hinge model are evident. The fiber model doesn't require a calibration of empirical response parameters against the actual of ideal frame elements. By selecting appropriate material constitutive relationship, the structural collapse behavior can be satisfactorily modeled. Compared with typical fiber models, the infrmFBPH model adopts the features of plastic hinge model by concentrating the inelasticity within a fixed length of the element. The Menegotto-Pinto steel model with Monti-Nuti post-elastic buckling is used to simulate the longitudinal rebars for frame members.

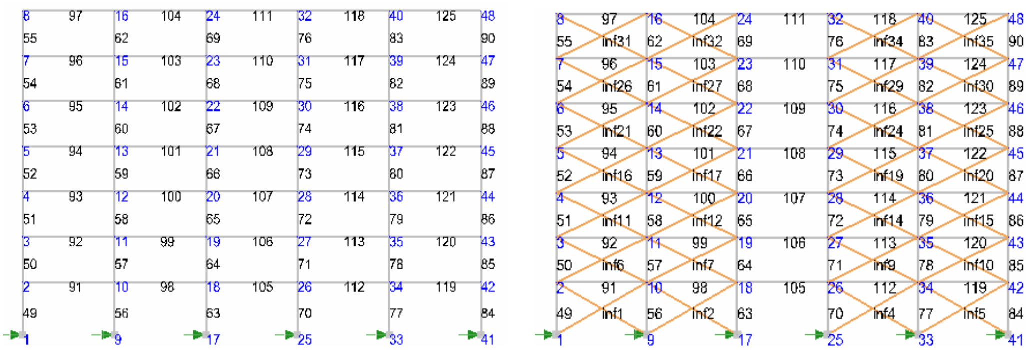
3.2 Modeling of the Infilled Walls

The infilled masonry wall panels are modeled using a four-node element developed by Crisafulli and implemented in Seismostrut. As shown in Fig. 3, two type of strut are included in the wall panel modeling, the compression strut and the shear strut. The compression strut can only resist compressive force while its tensile strength equals zero, resulting in a pair of such struts to account for the loading from both directions. For each diagonal strut, two corner nodes and two dummy nodes are used. The shear strut can only be activated in compression, as shown in Fig. 3(b).



(a) compression struts (b) shear struts

Fig. 3 Infilled masonry wall modeling



(a) bare frame (b) infilled frame

Fig. 4 Models for IDA analysis

3.3 Vulnerability Analysis vs. Dynamic Pushover Analysis

The seismic collapse vulnerability is the probability that the structure will collapse under earthquakes of different intensities. In recent years, the collapse vulnerability analysis based on the incremental dynamic analysis (IDA) has become a research field that attracts a great deal of attention. The main steps of carrying an IDA procedure include: (1) establish the mathematical model of the structure that can simulate the seismic behavior of the structure accurately enough; (2) select a set of earthquake ground motion records that match the seismic characteristics of the site where the structure is located. The number of the ground motion record set should be sufficient to reflect the statistical characteristics of the ground motion. The set of the records are then normalized based on an appropriate intensity measure (IM); (3) under certain intensity level, conduct inelastic dynamic analysis on the structure using all set of the ground motion records and obtain the number of the records that cause the collapse of the structure, N_{collapse}. The collapse probability of the structure corresponding to the intensity level is defined as the ratio of N_{collapse} and the total number of records N_{total}; and (4) monolithically increase the intensity level and repeat step three to get the collapse probabilities of the structure under different intensity levels. The fragility curve can then be developed.

In this paper, the scaling technique for the vulnerability analysis is adopted to determine the incremental steps for each selected ground motion record. Each horizontal ground motion is individually applied to the two-dimensional frame model using the IDA approach. The ground motions are increasingly increased until sideway collapse occurs. The sidesway collapse is caused by dynamic instability, which can be indicated by the lateral story drifts of the frame model increasing without bounds, or by the IDA curves become flat.

3.4 Selection of Ground Motion Records

In order to reflect the random characteristics of earthquake input, sufficient number of ground motion records is needed for the structural collapse vulnerability analysis. ATC-63 suggests the following rules for the selection of ground motion records:

1) earthquake magnitude $M \geq 6.5$;
2) hypocenters are strike-slip faults or thrust faults;
3) stiff soil or rock sites and vs≥180m/s;
4) fault distance for near fault earthquake $R \leq 10$km and fault distance for far-field earthquake $R \geq 10$km;
5) number of records from same earthquake event no more than two;
6) strong ground motions with PGA >0.2g and PGV>15cm/s;
7) instrumentation devices on free ground surface or ground level of low rise building;
8) effective frequency range of seismograph 4s.

Based on the above rules, ATC-63 recommends a database for the ground motion records, including 22 far-field records and 27 near-fault records. In this paper, 22 far-field earthquake ground motion records recommended by ATC-63 and an additional record from the El-Centro earthquake are used.

Table 1 Ground motion records

	Magnitude	Year	Location	Station	Component
1	6.7	1994	Northridge, USA	Beverly Hills-Mulhol	NORTHR/MUL279
2	6.7	1994	Northridge, USA	Canyon Country-WLC	NORTHR/LOS270
3	7.1	1999	Duzce, Turkey	Bolu	DUZCE/BOL090

4	7.1	1999	Hector Mine, USA	Hector	HECTOR/HEC090
5	6.5	1979	Imperial Valley, USA	Delta	IMPVALL/H-DLT352
6	6.5	1979	Imperial Valley, USA	El Centro Array #11	IMPVALL/H-E11230
7	6.9	1995	Kobe, Japan	Nishi-Akashi	KOBE/NIS090
8	6.9	1995	Kobe, Japan	Shin-Osaka	KOBE/SHI090
9	7.5	1999	Kocaeli, Turkey	Duzce	KOCAELI/DZC270
10	7.5	1999	Kocaeli, Turkey	Arcelik	KOCAELI/ARC090
11	7.3	1992	Landers, USA	Yermo Fire Station	LANDERS/YER360
12	7.3	1992	Landers, USA	Coolwater	LANDERS/CLW-TR
13	6.9	1989	Loma Prieta, USA	Capitola	LOMAP/CAP090
14	6.9	1989	Loma Prieta, USA	Gilroy Array #3	LOMAP/GO30090
15	7.4	1990	Manjil, Iran	Abbar	MANJIL/ABBAR-T
16	6.5	1987	Superstition Hills, USA	El Cetro Imp. Co	SUPERST/B-ICC090
17	6.5	1987	Superstition Hills, USA	Poe Road (temp)	SUPERST/B-POE360
18	7.0	1992	Cape Mendocino, USA	Rio Dell Overpass	CAPEMEND/RIO360
19	7.6	1999	Chi-Chi, Taiwan	CHY101	CHICHI/CHY101-N
20	7.6	1999	Chi-Chi-Taiwan	TCU045	CHICHI/TCU045-N
21	6.6	1971	San Fernando, USA	LA-Hollywood Stor	SRERNPEL180
22	6.5	1976	Friuli, Italy	Tolmezzo	FRIULI/A-TMZ270
23	7.0	1940	Imperial Valley, USA	El Centro Array #9	IMPVALL/I-ELC180

4. Main Analysis Results

4.1 Periods

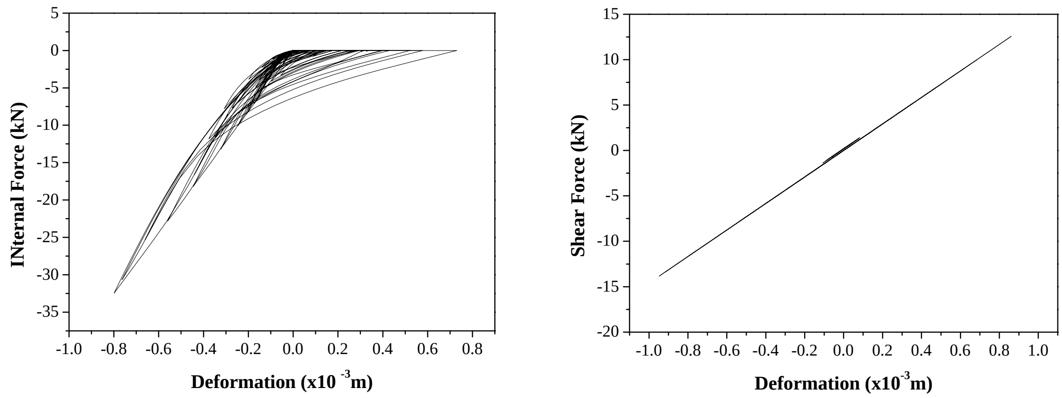
The periods of the first five mode shapes are given in Table 2. It can be seen very obviously that the infilled walls reduce the fundamental period. And the number of wall panels has a direct influence on the magnitude of the fundamental period.

Table 2 First five periods of archetype frames

	Case 1	Case 2	Case 3	Case 4	Case 5
1^{st} mode	0.715	0.387	0.445	0.414	0.497
2^{nd} mode	0.244	0.137	0.158	0.147	0.177
3^{rd} mode	0.129	0.083	0.094	0.088	0.102
4^{th} mode	0.089	0.080	0.079	0.076	0.076
5^{th} mode	0.074	0.076	0.075	0.078	0.074

4.3 Infilled Wall Panel Behavior

Fig. 5 depicts the typical infilled wall response during earthquake excitation. Since the infill panel is modeled suing the equivalent diagonal strut consisting of diagonal compression struts and shear strut, the response of such a panel can be characterized by the diagonal behavior and the horizontal behavior. As can be seen in Fig. 5(a) the diagonal strut only developed compression forces. The shear behavior is basically linear elastic



(a) diagonal strut (b) shear strut

Fig. 5 Infilled wall Panel Behavior

4.3 Dynamic Pushover Analysis Results

The incremental dynamic analysis is carried out for both the bare frame model and an infilled frame model. Although no obvious flat segments of the top displacement and base shear curves can be seen in Fig. 6, the difference between infilled frame and bare frame is very obvious. According to the definition of the sidesway collapse used in this study, the bare frame has a better collapse prevention capacity than the infilled frame.

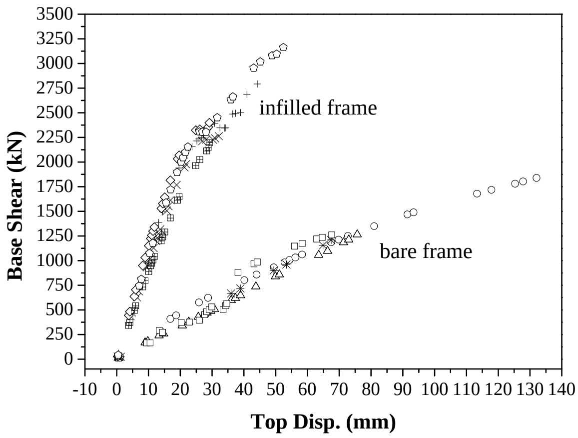


Fig. 6 Top displacement vs. base shear curves

5 Concluding Remarks

Efforts are made in this study to extend the research on the infilled RC moment frames from the conventionally concentrated topics to the sidesway collapse assessment. Although the current study is very preliminary, some concluding remarks can be made as follows:

(1) The seismic performance prior to the structural collapse is significantly related to the structural collapse behavior. Thus the infilled masonry walls have a significant impact on the collapse characteristics of the entire structure.

(2) The infilled wall can increase the lateral stiffness and shorten the fundamental period of frames, resulting in a higher lateral force demand. Judging from the trend of the dynamic pushover curves, the collapse of infilled frames are more probable to occur at low lateral drift ratio levels than bare frames.

(3) The equivalent diagonal strut model can capture the main characteristics of infill panels during earthquake excitation.

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