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Retrofit of RC Frame to Resistant Progressive and Seismic Collapses with Steel Braces

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ABSTRACT

Structural collapses may be due to man-made accidental loads or seismic excitations, which are commonly termed as progressive collapse and seismic collapse, respectively. To explore the progressive collapse and seismic collapse resistances of reinforced concrete (RC) frames, collapse performances of a code-designed frame is investigated by nonlinear dynamic analysis, and retrofit strategy by steel braces for the frame to resistant collapse are discussed. Analysis results indicate that the frame may suffer progressive collapse in the corner column removed scenario, but has enough seismic collapse resistance. For the frame with full layout steel brace retrofit strategy, the Λ-brace and V-brace are adopted both for improving progressive collapse and seismic collapse resistance of the structures, while the results shows that the V-brace is better. For the frame with partial layout steel brace retrofit strategy in the top story or in the second story, the V-brace located in the top story can be the better choice for improving the collapse resistance. After the retrofit for the progressive collapse, the retrofit also gives improved seismic performances for the frame.

1. INTRODUCTION

Progressive collapse is referred to the phenomenon of disproportionate collapse of structures in local column loss scenario induced by hazard loads. Seismic collapse of structures is mainly due to deficient lateral load resistance during earthquake. The differences between the two kinds of collapses worth to be distinguished, but the evaluation of collapse resistant capability of a single structure need to consider the two kinds of collapses in a unified way.

Over last a few years, a number of publications covering the subjects of

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progressive collapse and seismic collapse have appeared in the literature. Moreover, the researches increased explosively in the past decade, in which contains many aspects. Besides the researches on developing numerical methods to analysis the phenomenon of structural collapse (Izzuddin et al. 2008; Asgarian and Rezvani 2012) and design methods to resistant structural collapse (Griffith et al. 2002; Kim et al. 2009), the structural global and local performances during a collapse procedure are also the important topics. The structural performances are responses of residual structure after column loss in progressive collapse or responses at story or member levels under seismic collapse, which have been done by several researchers. In addition, the structural performance research also contains the studies on the effects such as joint, slab, and infill walls (e.g., Sadani 2008; Sadani and Sagiroglu 2008; Tsai and Huang 2011, 2013; Li et al. 2012, 2016; Shan et al. 2016).

An important issue is that one certain design of frame beams and columns may enhance one kind of collapse resistance, but may aggravate another kind of collapse during loading. Hence, there has been growing interest among researchers in studying relationship between progressive collapse and seismic collapse performances of a structure. Hayes et al. (2005) investigated the relationship between seismic details and progressive collapse resistance, which showed that strengthening the perimeter members will improve progressive collapse resistance. Bao et al. (2008) found that reinforced concrete frames designed for high seismic risk has high progressive collapse resistance than frames designed in low to moderate seismic zones. On the other hand, another issue is that the strengthening technology when the structure has high collapse potentials. Ellingwood et al. (2007) discussed several commonly used retrofit methods for RC frames. Kim and Shin (2012) presented a retrofit method for RC frames against progressive collapse using prestressing tendons. Some retrofit methods for steel structures are also presented (Galal and El-Sawy 2010; Ma et al., 2009; Chen et al. 2012). In the above studies, the performances of progressive collapse retrofitted structures under seismic excitation were not verified. This means that the potentially harmful effects of strengthening one kind of collapse on the response or damage mechanism of a structure to another kind of collapse are not considered.

This study focuses on analysis on progressive collapse performances of code-design RC frames, as well as the performances of the frame under seismic excitations. Retrofit methods to resistant collapse using braces are investigated. The different structural capabilities and damage mechanisms of the frame in progressive and seismic collapses are discussed.

2. ANALYTICAL MODELING

A 8-story RC bare frame is adopted in the analysis. The plan layout is shown in Fig. 1. The structures were designed according to the Chinese code for seismic design of buildings. The story height is 3.3m, and the spans are 6.0m, 3.0m and 6.0m.

ABAQUS software (2010) is used for the analysis procedure. Damping ratio is assumed to be 5% of the material damping for the general element model and Hilber-Hughes-Taylor method is used in the integration solution. Beam element B21 in is used to model beams and columns and fiber cross-section is adopted. In the analysis, bilinear model is used to simulate steel reinforcement. The elastic Young's modulus (E_s) is 2×10^5MPa and plastic modulus is set with $0.01E_s$. Concrete constitutive model in Ref. (GB 50010, 2002) is used to simulate concrete subjected to uniaxial compression and tension.

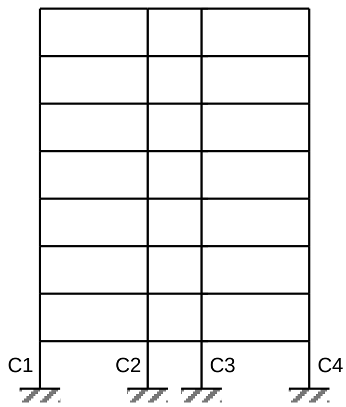


Fig. 1 Elevation of the frame

3. EVALUATION OF PROGRESSIVE COLLAPSE POTENTIALS

Fig. 2 shows the loading layout when column C1 or C2 is removed in incremental dynamic pushdown analysis (IDPA). As seen in Fig. 2, C1, C4 denotes first-story external columns and C2, C3 denotes first-story internal columns. Based on Alternate Path Method recommended in GSA2003 (2003), and according to analysis method introduced in researches (Kim et al. 2009; Khandelwal et al. 2011), the IDPA is applied to investigate progressive collapse resistance of the frame. The load α(DL+0.25LL) applied on bays directly above failure column is incrementally increased until frame collapse, while the load 1.0(DL+0.25LL) is applied on other bays, where DL represents dead load and LL represents live load and α represents load factor. The maximum strength less than 1.0 implies that the frames cannot resist the gravity load. Fig. 3 presents the loading layout when the nonlinear dynamic analysis is performed.

To simulate the phenomenon that the column is removed, the ABAQUS keyword command of *MODEL CHANGE is used. The command can be used to remove elements during analysis. Three analysis steps are existed in the analysis procedure. The first is a static analysis step dealing with gravity analysis, the second is a dynamic step with removal of the column in an appropriate time interval, and the third step is also a dynamic analysis up to the end of response. The appropriate removed time is validated by numerical analyses. The removed time interval is selected as 1/10 *T*, where *T* is structural vertical fundamental period. The analysis result shows that the displacement history of beam-column joint directly above failure column increases as removed time interval decreases, but as the removed time interval is shorter than 1/10 *T*, the displacement history changes little. Hence, 1/10 vertical fundamental period of structures can be used as column removed time interval in analysis to get stable results.

The loading method in ABAQUS automatically considering the dynamic effect of sudden removed columns from structure, in this way, the analysis is simplified comparing with most existing researches which manually apply the nodal resistant forces in the analysis.

The pushdown curves illustrated in Fig. 4(a) shows the load factor of the frame when the column C1 suddenly fails. As can be seen, the maximum load factor of the frame is lower than 1.0, which corresponds to load 1.0(DL+0.25LL) and it illustrates that the frame collapse in corner column removed case. The pushdown curve illustrated in Fig. 4(b) shows the load factor of the frame when the column C2 is suddenly removed. The frame can resistant the progressive collapse under normal gravity load. The dynamic analysis result in Fig. 5 also illustrates the same collapse situation.

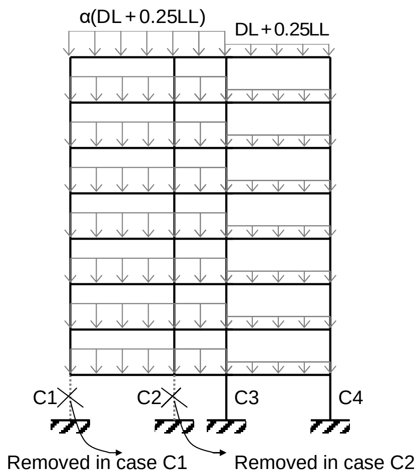


Fig. 2 Loading layout in incremental dynamic pushdown analysis

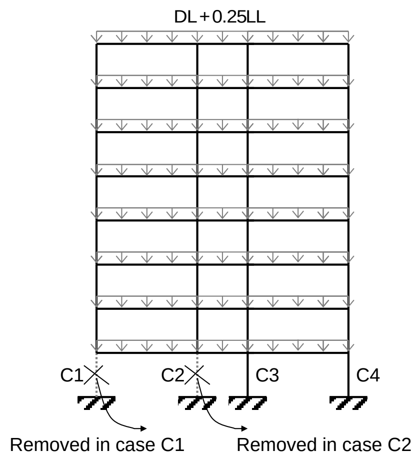
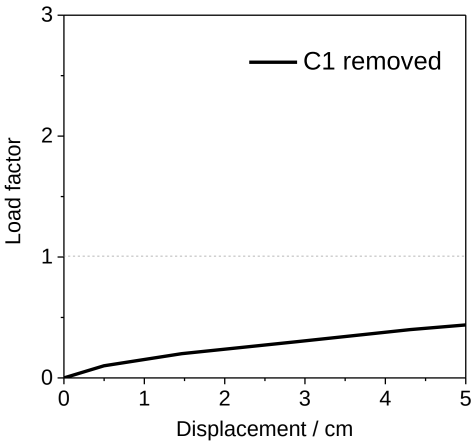
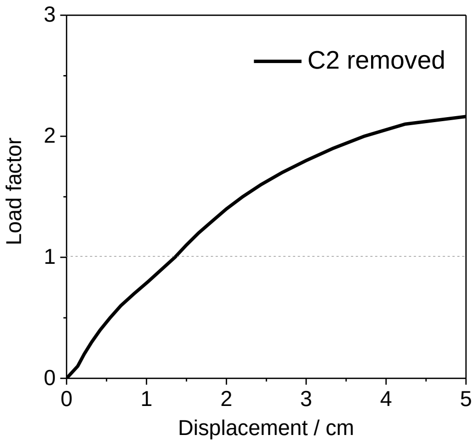


Fig. 3 Loading layout in nonlinear dynamic analysis



(a) case C1



(b) case C2

Fig. 4 IDPA curves of the frame

4. RETROFIT STRATEGY

The frame collapse in the corner column removed scenario. Hence, it needs a further study on how to improve progressive collapse resistance of structures in this scenario. In this section, retrofit strategies for the frame is studied. Considering the merit of simplicity and low costing, steel braces are chosen for retrofitting the frame.

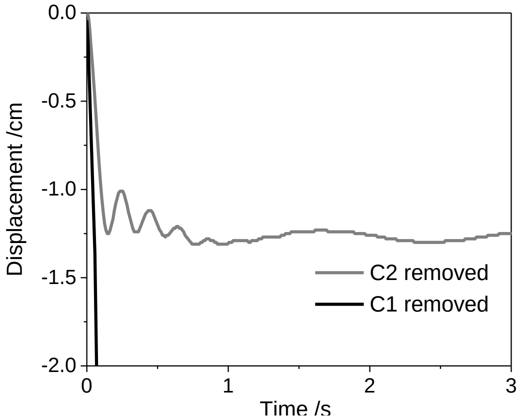


Fig. 5 Nonlinear dynamic displacement histories

4.1 Modeling of the braces

The braces are modeled by beam element B21 by ABAQUS. Hinge connections between braces and structural members are adopted in the model. Bilinear constitutive model is used to simulate the material of steel braces. The Young's modulus is 2×10^5MPa and yield strength is 235MPa.

Since the steel pipe has the higher compressive capacity and buckling resistance than other steel braces, pipe section is adopted in this study. The cross section is controlled by slenderness ratio, which is specified smaller than 120 and the thickness is 10mm for sections of all brace. From equation (1), cross section *A* is determined, then the radius of pipe section can be obtained

$$\lambda = \frac{l_0}{i}, \quad i = \frac{I}{A} \tag{1a,b}$$

where λ is slenderness ratio, l_0 is effective length of braces, i is radius of gyration for cross section, I is moment of inertia for braced cross section, and A is sectional area of braces.

4.2 Full layout steel braces retrofit on frame

Some old structures have low progressive and seismic performances, which need full layout steel braces retrofit strategies. Full layout is that the steel braces located in all structural bays and stories. Frames with two type full layout braces are investigated to study progressive collapse potential in corner column removed case, and to study seismic collapse potential under seismic excitation. Braces configurations are shown in

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