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Prediction of local seismic damage in steel moment resisting frames

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ABSTRACT

Steel moment resisting frames (SMRFs) are widely utilized as a lateral load resisting system. Their seismic performance is usually assessed by examining the maximum value of inter-storey drift (MID) of all floors. The accuracy of such assessment is debatable given the wide spread of values of MID at collapse that exist in the literature. In this study, a simplified method to define the failure inter-storey drift for each floor of a SMRF is proposed. The method was validated with the experimental and analytical studies by other researchers. Three- and ten-storey SMRFs were considered to further validate the proposed method. The effects of the vertical and/or horizontal seismic components of five different ground motions on the SMRFs were evaluated using incremental dynamic analysis. The proposed method accurately identified the severely damaged floors of SMRFs.

1. Introduction

Steel moment resisting frames (SMRFs) are widely used as the lateral load resistance system for mid- to high-rise buildings. After 1994 Northridge earthquake, significant research was conducted to improve their global seismic performance. While damage of individual elements (beams, columns, and connections) can be based on their rotations, damage to the full frame is usually related to the maximum inter-storey drift (MID). Reported MID values at collapse have large variations in the literature. While FEMA 356 [1] limited the MID for steel structures to 5%, FEMA 350 [2] defined collapse of SMRFs in midrise buildings (4–12 storeys) to occur at 10% inter-storey drift. The New Zealand standard [3] limited the MID to 2.5%. UBC 1997 [4] specified MID values of 2.5% and 2.0% for structures with short and long period of vibrations, respectively. The actual MID depends on many factors including design assumptions, characteristics of the ground motion, and effect of higher modes of vibrations.

The damage due to the vertical component of a seismic excitation was observed to be very significant by many researchers [5–7]. The interior columns and interior beams of moment-resisting frames are significantly affected [5,6]. The increase in the column axial forces caused by the vertical excitation of near-field and far-field earthquakes can reach 65% and 8%, respectively [7]. The fluctuation of column axial force can also increase the column's rotational ductility demand, and, thus cause significant structural damage [8]. Several building codes account for the vertical seismic component by assuming that the vertical design response spectra is 2/3 of the horizontal design spectra [1,4]. Eurocode 8 [9] and the National Earthquake Hazards Reduction Program [10] define the vertical spectrum independently from the horizontal spectrum.

The relationship between seismic damage and inter-storey drift (ID) was examined in this study to allow identification of the severely damaged storeys without the need for conducting nonlinear incremental dynamic analysis (IDA). The study proposes a simplified method that can identify the severely damaged floors of SMRFs when exposed to an earthquake while accounting for the vertical seismic component.

2. Proposed method

Youssef and Elfeki [11] proposed a simplified method to predict the ID at collapse for reinforced concrete frames. The method does not account for the *P*-Δ effect, which might be appropriate for concrete structures. In this study, the method is further extended to account for *P*-Δ effect.

2.1. Lateral drift (Δ_m) based on *P*-Δ effect

The increase of fixed-end moments and shear forces of columns due to the *P*-Δ effect are shown in Fig.1 and can be calculated using Eqs. (1) and (2).

$$M_f = \frac{6E_sI_c}{h_c^2}\Delta_m + \frac{P\Delta_m}{2} \tag{1}$$

$$V_f = \frac{12E_sI_c}{h_c^3}\Delta_m + \frac{P\Delta_m}{h_c} \tag{2}$$

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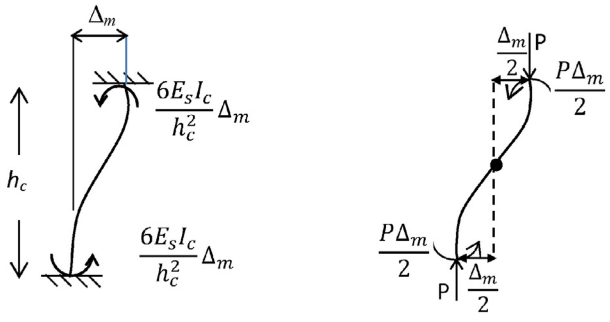


(a) Moment without axial force (b) P- Δ effect

Fig. 1. Fixed-end moments induced by lateral displacement Δ_m.

Fig. 2 shows an isolated column and the connecting beams. The figure assumes that: (1) joint rotations are equal for any two successive storeys, (2) the stiffness of each beam is equally utilized by the columns above and below a specific floor (beams are split into hypothetical halves, each half possesses 50% of the stiffness of the original beam), and (3) contra-flexure points are assumed to be at the mid-span of each beam and mid-height of each column [11–13]. The stiffness is presented in the figure by the ratio K where $K = I/L$.

If a relative lateral displacement Δ_m is applied between the column ends, the column fixed-end moment can be obtained using Eq. (1). As the flexural stiffness of the top beams and the column are $3E_sK_1$, $3E_sK_2$ and $6E_sK_c$, the moment distribution factor d_{ct} can be calculated using Eq. (3). Applying the principal of moment distribution, the final moment at the column top (M_{ct}) can be obtained using Eq. (4).

$$d_{ct} = \frac{6K_c}{3K_1 + 3K_2 + 6K_c} = \frac{2}{K_t + 2} \tag{3}$$

where $K_t = \frac{K_1+K_2}{K_c}$.

$$M_{ct} = \left(\frac{6E_sI_c}{h_c^2} + \frac{P}{2}\right)\Delta_m \frac{K_t}{K_t + 2} \tag{4}$$

Similarly, the moment at the bottom end of the column (M_{cb}) can be calculated using Eq. (5).

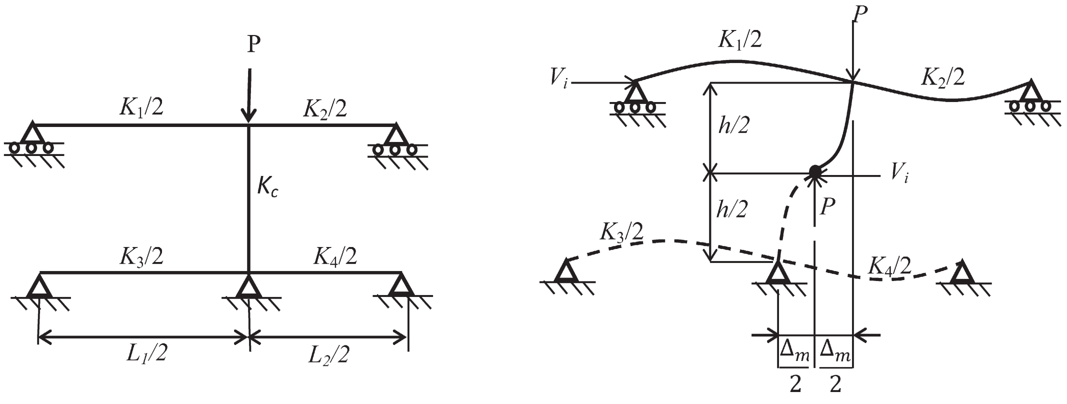
$$M_{cb} = \left(\frac{6E_sI_c}{h_c^2} + \frac{P}{2}\right)\Delta_m \frac{K_b}{K_b + 2} \tag{5}$$

where $K_b = \frac{K_3+K_4}{K_c}$.

The values of Δ_m that lead to instability failure for each of the floor columns can be estimated using Eqs. (4) and (5).

2.2. Lateral drift (Δ_m) based on storey-pushover analysis

The calculation for Δ_m in this section is based on pushover analysis, and, thus accounts for nonlinearity of the beams as well as the columns. For each storey, the columns are first assumed to be fixed at their lower ends, i.e. the lower storeys are removed. Gravity loads are then applied to the remaining storeys. Displacement-controlled pushover analysis is



(a) Subframe idealization (b) Distortion of subframe

Fig. 2. Isolated column and restraining beams.

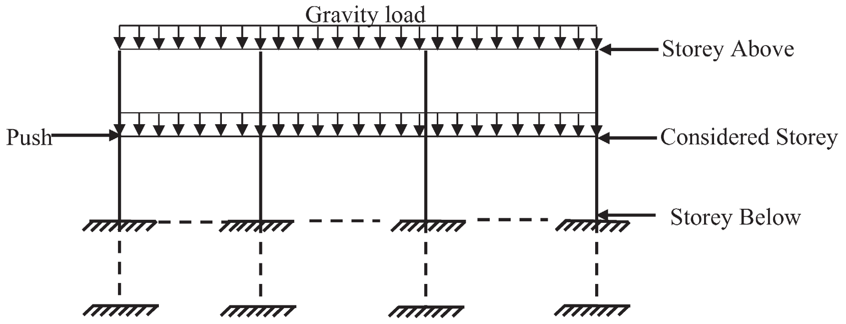


Fig. 3. Proposed method to estimate inter-storey drift limits for the second storey of a three storey building.