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Investigation on Deflection Amplification Factor for Special Moment Resisting Frames with Soft Story

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ABSTRACT: One of the most common irregularities in structures is the irregularity in height and lateral stiffness. Due to the commonness of the use of irregular structures and also the different seismic responses of this type of structures, in comparison with regular structures, investigating the seismic response of irregular structures has always been the subject of several research studies. The structures designed for the reduced base shear, under the design earthquake, have inelastic response. To calculate the real (inelastic) displacements of structures under the design earthquake, the displacements obtained from the reduced base shear, are amplified by the deflection amplification factor (C_d). Seismic codes have dedicated a C_d for each structural system. But different studies have shown that the dedicated C_d by the codes cannot accurately estimate the real displacements. The main purpose of this research is to propose the C_d values for more accurately estimating the maximum inter-story drift ratio (MIDR) and maximum roof drift ratio (MRDR) in steel special moment resisting frames (SMRFs) with the soft story. The number of stories and the location of the soft story are the variables considered in this research. The results show that the use of $C_d = 5.5$, recommended by the 2800 standard and ASCE 7-16 for steel SMRFs, underestimates the real MIDR and also MRDR, under the design earthquake. It is shown that by increasing the number of stories, the mean Cd obtained from the analyses increases. The reason for this issue is the P-Δ effects that increase by increasing the number of stories. In addition, it is shown that a specified trend cannot be found between the location of the soft story and the mean C_d values in the stories of the structures. Thus, for more accurately estimating MIDR in the considered structures, under the design earthquake, $C_d = 8.5$ is proposed. Furthermore, for more accurately estimating MRDR, $C_{d\ roof} = 8.0$ is proposed.

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1- Introduction

Typically, for seismic design of common building structures, the forced-based method, recommended in seismic codes, is applied. According to this method, the seismic forces, calculated from design earthquake, are reduced by a response modification coefficient (R) at the design step and the required stiffness and strength of structural elements are obtained based on these forces. Then, to satisfy the displacement control criteria and calculating inelastic displacements under the design earthquake, the elastic displacements obtained under reduced seismic forces are amplified by the deflection amplification factor (C_d) [1]. ASCE 7-16 [2] recommends $C_d = 5.5$ for steel special moment resisting frames (SMRFs).

Several researchers have evaluated C_d for different structural systems (e.g., [1, 3, 4]). Uang and Maarouf [1] investigated C_d to estimate inelastic maximum inter-story drift ratio (MIDR) and also the inelastic maximum roof drift ratio (MRDR) in different structural systems. They concluded that the ratio of C_d/R to estimate the MRDR varies between 0.7 to 0.9. But, the value of C_d/R to estimate the MIDR can be greater than 1.0. Yakhchalian et al. [3] investigated C_d for steel buckling restrained braced frames (BRBFs) to estimate inelastic MIDR and inelastic MRDR. They showed that applying $C_d = 5.0$, recommended by ASCE 7-16 [2], underestimates the MIDR in lower stories of the BRBFs. They proposed a new equation for C_d to precisely estimate the MIDR in the height of steel BRBFs. They also proposed a new equation to accurately estimate MRDR. In the present study, the variation of C_d in low- to mid-rise steel SMRFs with soft story is investigated.

2- Methodology

In this study, three steel SMRFs including 3-, 5- and 7-story structures were designed for a site with high seismicity in California. The design spectral response accelerations at short periods (SD_S) and at a period of 1.0 s (SD_1), were considered equal to 1.0g and 0.6g, respectively. 3-dimensional models of the structures were built in ETABS

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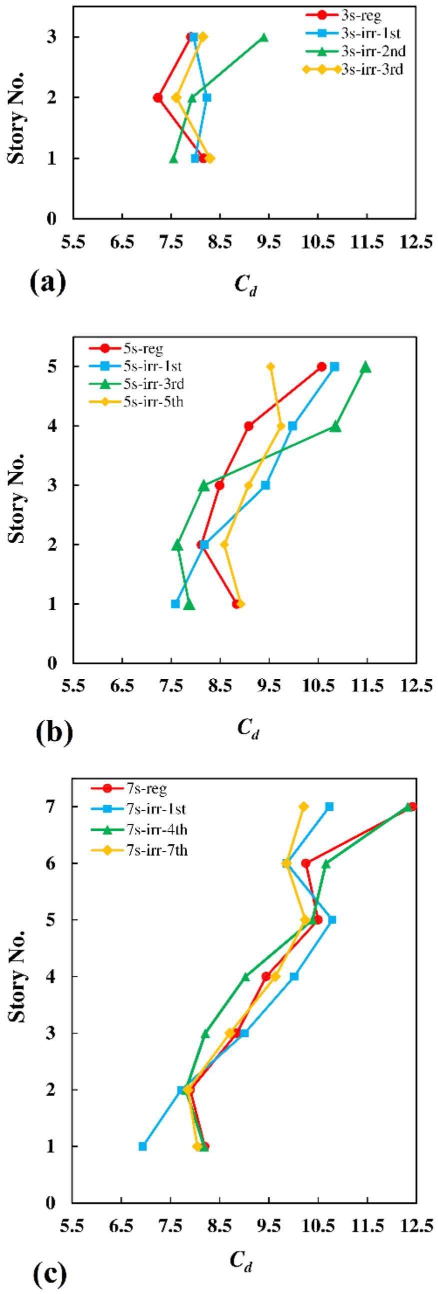
[5]. The typical story height was considered as 3.9 m. The elastic modulus and specified minimum yield stress of beams and columns were considered equal to 200 GPa and 345 MPa, respectively. Modal response spectrum analysis, according to ASCE 7-16 [2], was used to determine the seismic loads. The importance factor (I) and the response modification coefficient (R) were considered equal to 1.0 and 8.0, respectively. To generate irregular structures, i.e., structures that have a soft story, the story height of one of the bottom, middle, or top of the structures was increased to 1.5 times the typical story height. According to ASCE 7-16 [2], the design of structures with extreme weak stories were not permitted in sites with high seismicity. Therefore, in the design procedure of the structures, the member sizes were selected to prevent the generation of an extremely weak story in the structures. Totally, considering the regular and irregular structures, 12 structural models were designed and investigated. Because the plan of buildings is regular, for each structure, one of the perimeter moment resisting frames with four bays in X direction was modeled in OpenSess [6] as a 2-dimensional frame. The concentrated plasticity approach was applied to model the beams, and distributed plasticity approach was applied to model the nonlinear behavior of columns.

To conduct nonlinear dynamic analyses, a set containing 78 ground motion records used by Haselton and Deierlein [7] was applied. The ground motion records were scaled as recommended by ASCE 7-16 [2]. To compute C_d for each story of the structures considered, the inelastic MIDR values obtained from nonlinear dynamic analyses, underground motion records scaled with respect to the elastic design response spectrum, were divided by the design inter-story drift ratio of the story, obtained from linear modal response spectrum analysis, under reduced design seismic forces. It is noteworthy that Kuşyılmaz and Topkaya [8] and Yakhchalian et al. [4] applied a similar method for calculating C_d. To calculate the deflection amplification factor for estimating inelastic MRDR, $C_{d\,Roof}$, similar to the method of calculating C_d, the MRDR values obtained from nonlinear dynamic analyses were divided by the design roof drift ratio.

3- Results and Discussion

Figure 1 shows the mean C_d values obtained from the analyses for the structures considered. The structures considered in this research and presented in this figure are named in the following manner. The first part of the structure name indicates the number of stories, the second part shows the regularity (reg) or irregularity (irr) of the structure. In the case of irregular structures, the third part indicates the location of the soft story. For example, 5s-irr-3rd represents the irregular 5-story structure in which the soft story is located in the 3rd story. It can be seen that the use of C_d = 5.5, recommended by the 2800 standard [9] and ASCE 7-16 [2] for steel SMRFs, underestimates the inelastic MIDR in all the structures and stories. In other words, to have an accurate estimation of inelastic MIDR, the C_d value should be considerably greater than that recommended by ASCE 7-16 [2]. The results show that by increasing the number of stories, the mean C_d values tend to be increased. The reason for this issue is that by increasing the structural height, the P-Δ effects increase and therefore, the seismic demands increase and the nonlinear behavior becomes more severe.



(a)

(b)

(c)

Fig. 1. Obtained mean C_d values for the (a) 3-, (b) 5- and (c) 7-story structures

To determine a value for C_d that minimizes the error in the estimation of MIDR, an investigation on the total error, considering all the structures considered, for the estimation of MIDR, given different values of C_d, was performed. Thus, C_d = 8.5 was recommended to more accurately estimate MIIDR in steel SMRFs with the soft story. A similar method was applied to investigate $C_{d\,roof}$, and it was shown that C_d = 5.5 recommended by ASCE 7-16 [2] also considerably underestimate the MRDR. It was shown that the location of the soft story does not considerably affect the $C_{d\ roof}$ value and by increasing the number of stories it tends to be increased. Thus, $C_{d\ roof} = 8.0$ was recommended to more accurately estimate MRDR in steel SMRFs with the soft story.

4- Conclusions

In the present study, C_d and $C_{d\ Roof}$ were investigated to estimate inelastic MIDR and MRDR, respectively, in steel SMRFs with soft story under the design earthquake. The results showed that the recommended value of $C_d = 5.5$ by ASCE 7-16 for steel SMRFs, considerably underestimates inelastic MIDR and MRDR values under the design earthquake. It was shown that as the number of stories increases, the mean C_d values of the stories increase. In fact, by increasing the number of stories, the P-Δ effects increase and this increase leads to an increase in the seismic demands and the nonlinear behavior of the structures becomes more severe. To minimize the error in the estimation of inelastic MIDR in steel SMRFs with soft story, $C_d = 8.5$ was recommended. In the case of accurate estimation of inelastic MRDR in the structures considered $C_{d\ roof} = 8.0$ was determined.

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