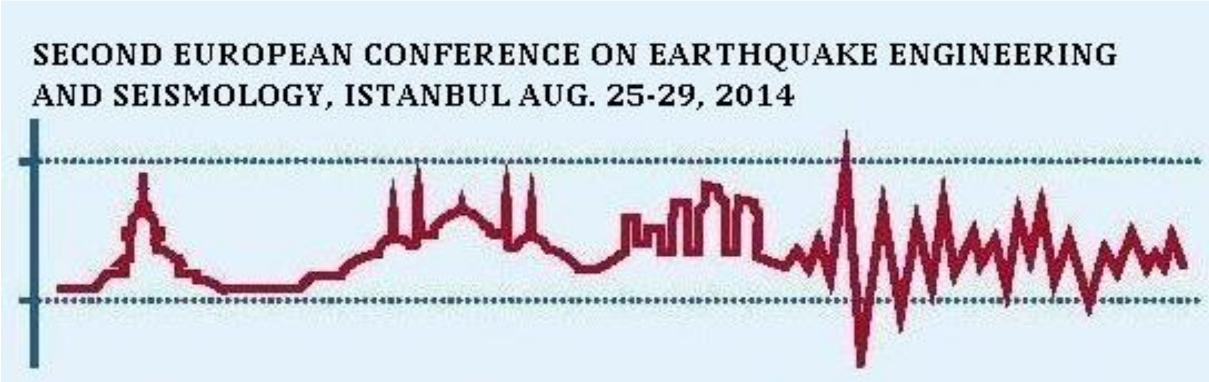

SEISMIC RESPONSE OF OUT-OF-PLUMB BUILDINGS

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ABSTRACT

Building out-of-plumb may result from construction tolerances or post-earthquake residual deformations. Recently, a number of techniques have been developed around the world to minimise the possibility of structural damage using replaceable links, friction connections, or special devices. As a result, a building may have almost no structural damage after an earthquake. However, there may be permanent displacements. If these displacements are small enough, the building can be immediately reused. However, if these permanent displacements are too large, then even if there is no structural damage, the building may need to be pulled down if it cannot be straightened. There is a need to quantify the effect of out-of-plumb on seismic response. In this research, simple models of out-of-plumb steel structures are analysed using inelastic dynamic time history analysis to quantify effects of building out-of-plumb under a suite of ground motion records. Structures considered were designed according to the AISC with different values of deflection amplification factor (C_d) and response modification factor (R).

INTRODUCTION

A perfectly regular plumb building has no horizontal offset of stories when it is at rest. However, no building is perfectly plumb, and the degrees of out-of-plumb (OOP) may affect the behaviour of the building under both non-seismic and seismic loads. Direct Analysis Method (DM) can be used to consider building OOP in the 2010 American Institute of Steel Construction (AISC) Specification (AISC 2010a). Direct Analysis provided by AISC Specification for Structural Steel Buildings requires Second-Order analysis, reduced stiffness and initial out-of-plumb. In the second-order analysis, initial out-of-plumb can be modelled with either using a notional load or alternatively by directly modelling. The AISC Code of Standard Practice (AISC 2000) specifies the tolerances on column out-of-plumb due to erection, shown in Figure 1 below. The maximum tolerance, without considering adjacent buildings increases linearly with a slope of 1/500 up to a value of 50 mm below the 20th floor. This limit increases linearly with storey height to 76 mm at the 36th floor. The maximum tolerance with considering the adjacent building is 25 mm at the 20th floor. This limit increases linearly up to the 36th floor with a limit of 50 mm.

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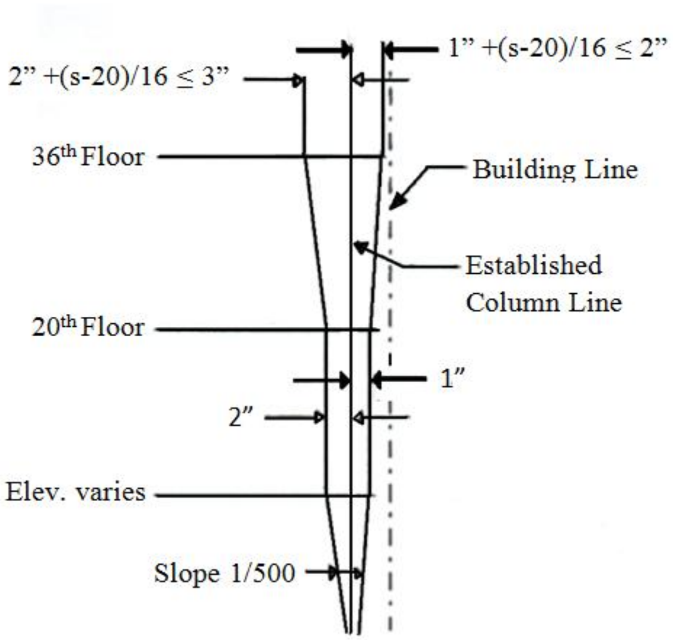


Figure 1: American Institute of Steel Construction specified tolerances on out-of-plumb (AISC 2000)

The commentary to the 2010 AISC Seismic Provisions for Structural Steel Buildings (AISC 2010b) states that the DM is not intended “to ensure stability under seismic loads where large inelastic deformations are expected.” This is as a result of not considering the seismic design in the development process of the DM. Previous researches (e.g. Surovek-Maleck and White 2004a and 2004b, White et al. 2006) have shown that geometric imperfections can have an appreciable impact on stability behavior in design scenarios that do not contain seismic loading.

Moreover, an extension of the direct analysis method which is termed “Extended Direct Analysis (or EDA)” (Lu, 2009) has recently been developed. It considers frame plasticity in addition to all the factors in the AISC direct analysis method. However, for seismic design the effects of frame out-of-straightness are not considered.

For structures in seismic regions, methods to evaluate the likely demands on structures have generally been developed based on the response of initial perfectly straight structures. Few studies have been conducted to systematically evaluate the effect of buildings out-of-straightness on its seismic response and the dynamic stability of structures (Masuno et al., 2011; Yeow et al. 2013). However, they did not study the effect of deflection amplification factor (C_d) and response modification factor R.

Since there is no such thing as a perfectly straight structure, it may be seen that there is a need to evaluate the effect of straightness on the seismic response. This study seeks to address this need by answer to the following question:

“How do deflection amplification (C_d) and response modification (R) factors influence the peak and residual displacements of out-of-plumb (OOP) buildings?”

RELATED STUDIES

Few studies have been conducted to evaluate the dynamic stability of structures. A study by MacRae and Kawashima (1993) and Yeow et al. (2013) looked at the behaviour of bridge columns subject to axial force and moment before earthquake shaking occurred. They showed that during earthquake shaking the moment tended to cause extra deformation in the direction in which the moment was applied.

Moreover, Masuno et al. (2011) studied the effect of OOP in shear structures. Two classes of the shear-type structure stiffness distribution were designed (i) the Constant Stiffness ratio (CS) and (ii) the Constant Inter-storey Drift Ratio (CISDR) as shown in Figure 2. Continuous columns were used with the shear-beam model to obtain realistic drifts as shown in Figure 3. A rigid link between shear beam and continuous column slaves the horizontal displacement of the joined nodes. The continuous column was pinned at the bottom. A continuous column stiffness ratio, α_{acci}, (MacRae et al. 2004) defines the continuous column stiffness relative to the shear beam stiffness at the ith floor. It is computed using Equation 1 where E is the material Elastic Modulus; H_i = storey height of the ith floor level; I_i = moment of inertia at the ith floor level; and K_{oi} = initial stiffness of the ith floor level.

$$\alpha_{cci} = \frac{E I_i}{H_i^3 K_{oi}} \quad (1)$$

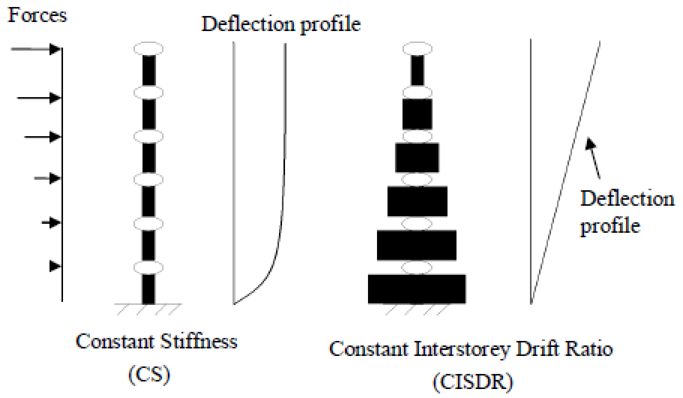


Figure 2: Two classes of stiffness distribution models

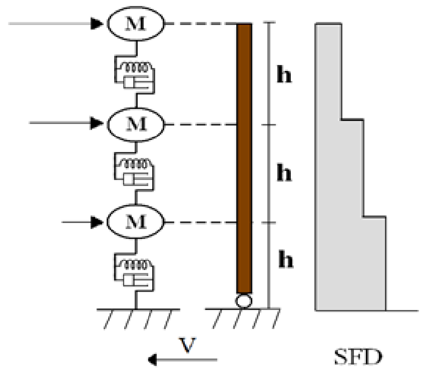


Figure 3: Shear beam with Continuous Column

Masuno et al. (2011) pointed out (i) greater initial out-of-plumb generally causes greater response increases relative to structures with no initial out-of-plumb, and (ii) structures with a greater number of storeys and those with greater design ductility also tend to have greater response.

In addition, Abdolahirad et al. (2014) studied the effect of target inter-story drifts design on the seismic response of structures with different levels of out-of-straightness. The authors found that greater target drift design generally causes greater response increases relative to structures with no initial out-of-straightness.

MODELING AND EVALUATION APPROCH

In this study, the shear type structure with continuous column is used (Masuno et al. 2011) as shown in Figure 3. The model is 8-stories shear structure. That is assumed to have a constant lumped mass, m, of 20,000 kg at each floor. The structure is also assumed to have story height, h, of 3m. Out-of-plumbs of 0.5%, 1% and 1.5% are considered in this study. These structures were entered into the programme in their deformed configuration before the seismic analysis started as shown in Figure 4.

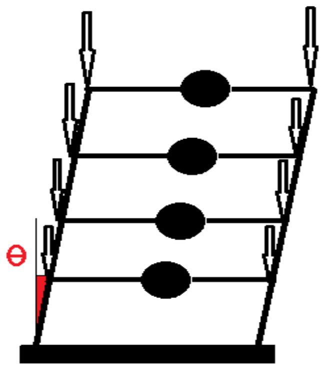


Figure 4: Out-of-plumb Building

The basic structure was designed as an ordinary building in Los Angeles on site class B. Structures were designed with target inter-story drift of 1.5%, with R factor of 6, 7, and 8 and with Cd/R ratios of 0.75, 0.8, and 0.85 according to the Equivalent Lateral Force Procedure in ASCE7-10 (2010). The structure stiffness distribution is designed with the CISDR. The iteration steps to obtain design of the structure are shown in the Figure 5 flow chart.

Bi-linear hysteresis loop with bi-linear factor of 1% was used for shear beams of the model and continuous column was assumed to be elastic during an earthquake. Critical damping of 5% is assumed for all modes and P-delta effects were considered by using an additional elastic column which is pinned at the bottom.

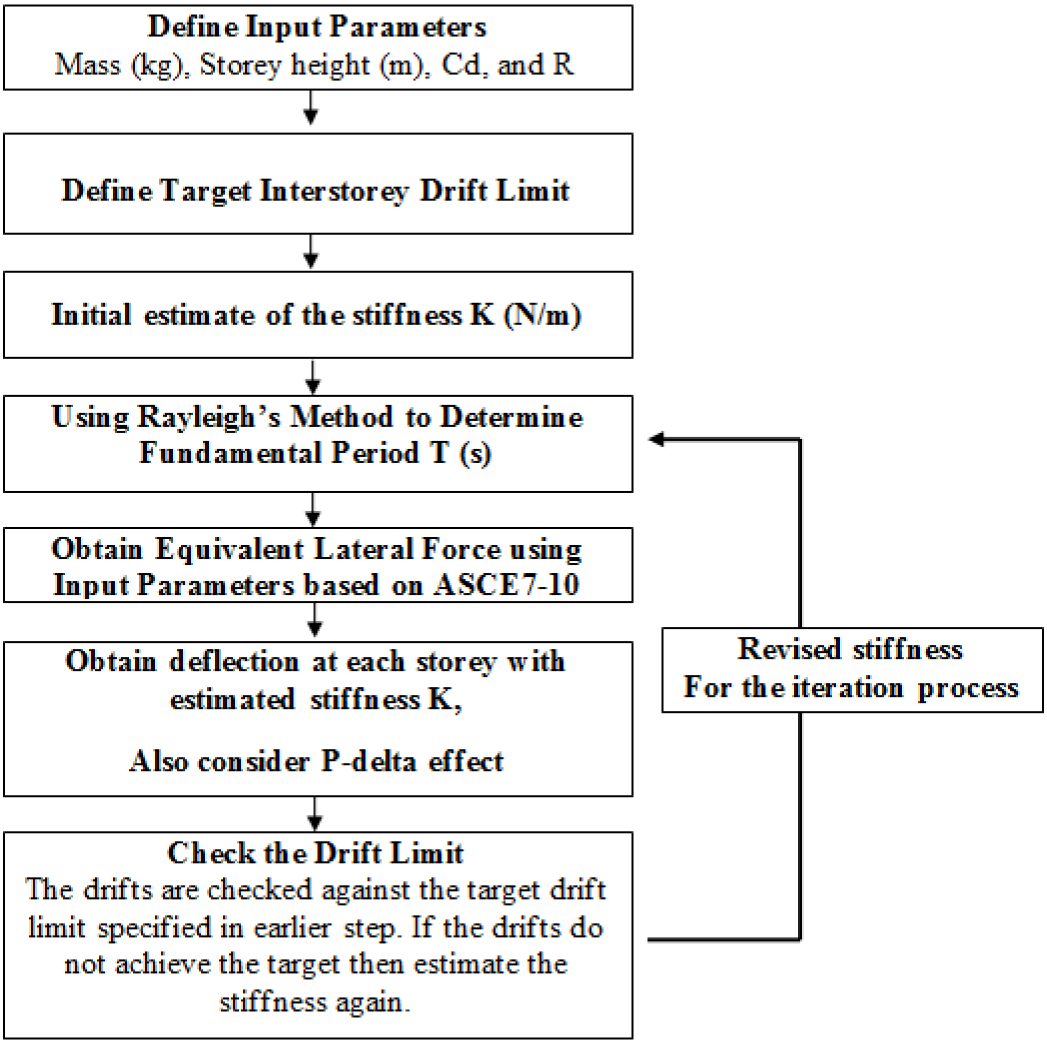


Figure 5-Flow Chart for Stiffness Determination

The twenty SAC (SEAOC-ATC-CUREE 2000) earthquake ground motion records for Los Angeles with probability of exceedance of 10% in 50 years were used as provided. To eliminate the directional trends in displacement from ground motion records, they were run from both directions.

The dynamic inelastic time history computer programme RUAUMOKO (Carr 2004) was used in this project to run the analysis. Input files for RUAUMOKO are generated using MATLAB (The MathWork Inc 2008). The two programmes are automated to run analysis and the desired output values are extracted in the process the analysis.

By assuming that the distributions of the residual and peak displacements are lognormal (Cornell et al. 2002), the median is found using Equation 2.

$$\hat{x} = e^{\left(\frac{1}{n}\sum_{i=1}^{n}\ln(x_i)\right)} \tag{2}$$

where x_i = Residual or peak displacements of structures due to i^{th} record
n = Total number of earthquake records considered.

In order to compare the response, the absolute maximum median peak displacement (MMPD) response and the maximum median residual displacement (MMRD) response is normalized with the MMPD or MMRD from initially perfectly straight models. Normalization was found using Equations 3 and 4:

$$NMMPD = \frac{MMPD\ (out-of-plumb)}{MMPD\ (perfectly\ straight)} \tag{3}$$

$$NMMRD = \frac{MMRD\ (out-of-plumb)}{MMRD\ (perfectly\ straight)} \tag{4}$$

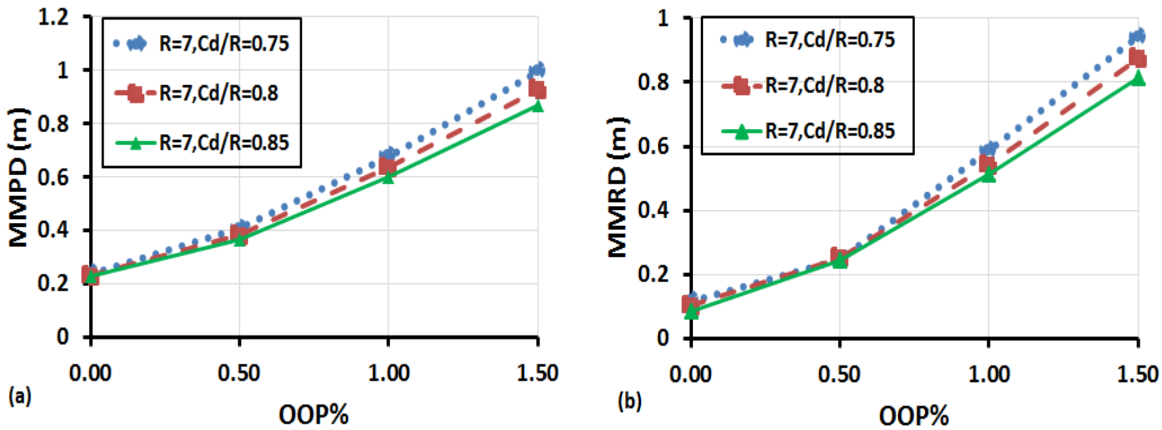
This absolute peak/residual displacement was computed for every record individually at each level. Then the median for each level was obtained for all records. Finally, the maximum median peak/residual displacement was found as the maximum value over the height. This maximum value occurred at roof level.

These normalized values were plotted against the degree of OOP. This plot allows user to estimate the effect of out-of-plumb relative to the perfectly straight responses.

RESPONSES AND COMPARISON

Effect of deflection amplification factor:

Figure 6 shows that the residual and peak displacements of the buildings increase with increasing of out-of-plumb and decrease with increasing of C_d/R ratio. Here the designed building with a high ratio of C_d/R will have less peak and residual displacements during an earthquake. This is expected because the structure was designed for a target interstorey drift ratio. By estimating greater displacement designs (i.e. C_d), the structures become stiffer and has lower displacements. The values given are the outputs from the computer programme. To obtain the total peak or residual displacements, the out-of-plumb values need to be added.

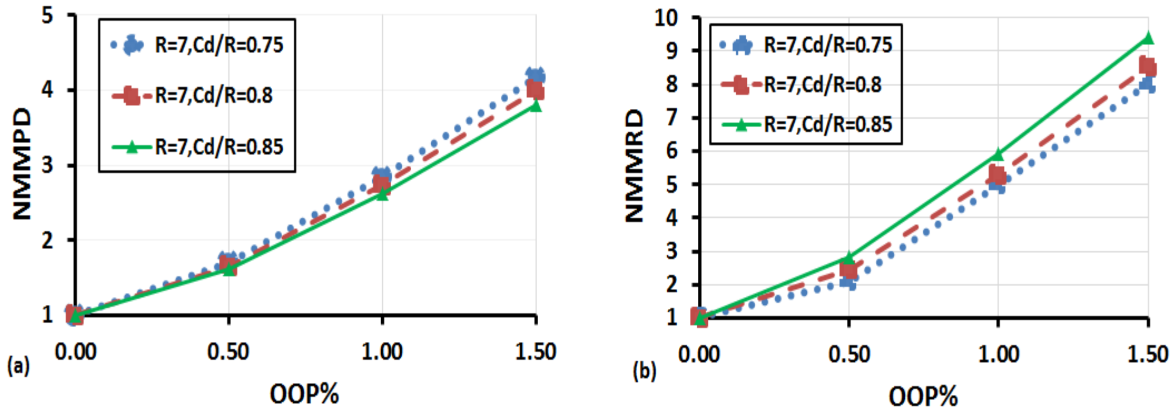


(a) Peak displacements (b) Residual displacements

Fig. 6: Comparison of maximum median displacements of out-of-plumb building with different C_d/R

Also, Figure 7 shows normalized values against the out-of-plumb. It indicates that maximum residual displacements of building grow at a faster rate for high C_d/R ratio as the OOP degrees increases. This is because the peak residual displacement is related to the ductility (and here C_d). However, maximum peak displacements grow at a faster rate for lower C_d/R ratio because the response of the structure with low C_d increases at a faster rate than that with high C_d for all OOP.

Moreover, the comparison between the normalized residual and peak response shows that residual response is more sensitive to change of C_d/R ratio and OOP than peak response. Compared to the peak response, NMMRD is very high.



(a) Peak displacements (b) Residual displacements

Fig. 7: Comparison of normalized maximum median displacements of out-of-plumb building with different C_d/R

Furthermore, to compare the residual and peak displacement with increasing of OOP, it is convenient to normalize the residual displacement with peak displacement which is mathematically expressed as follows:

$$RPR=RD/PD \tag{5}$$

Figure 8 shows that by increasing OOP, residual peak ratio, (*RPR*), increases from about 0.5 to 1. It indicates that by increaing OOP, residual and peak deformation is going to close to each other and and building could not come back to its initial position. This trend seems to be independent of C_d/R over the range considered.

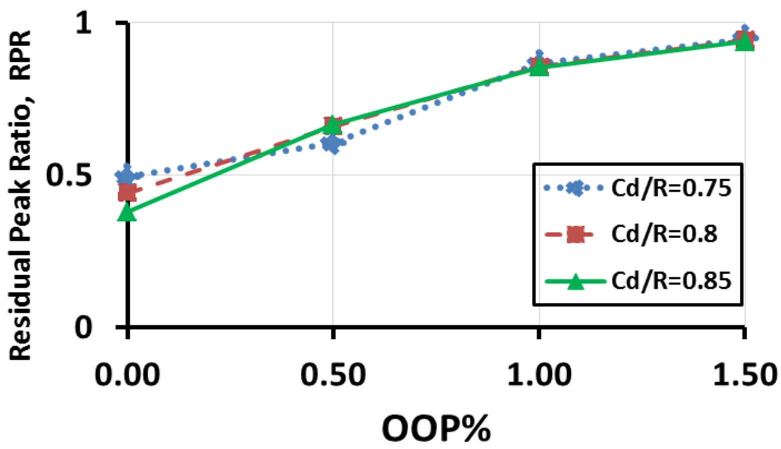
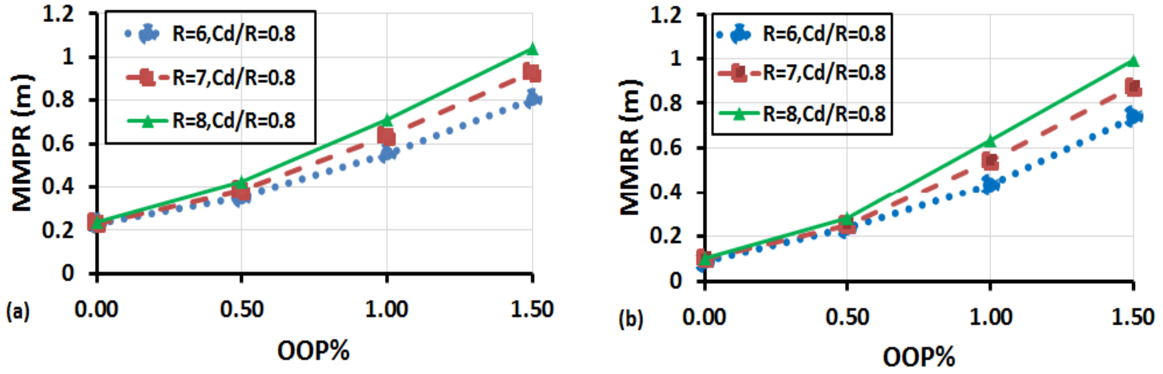


Fig. 8: Residual to peak displacements versus OOP for building with *R*=7.

Effect of response modification factor:

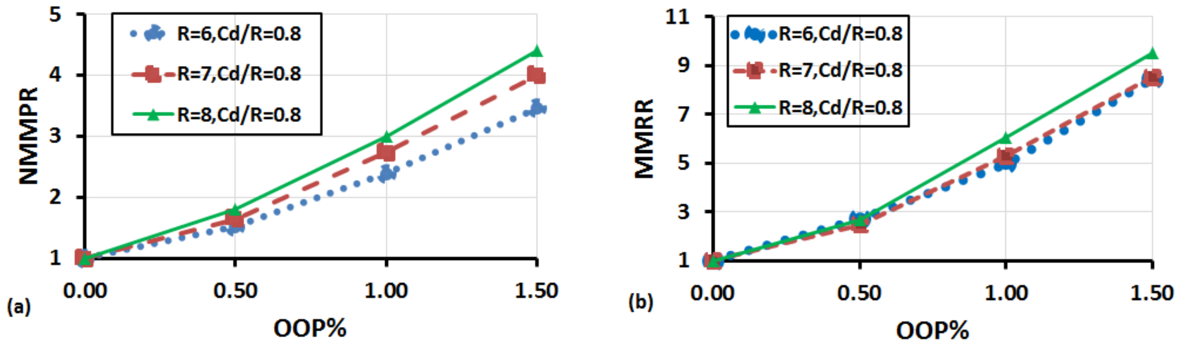
The effect of the response modification factor, (*R*), is illustrated in Figures 9 and 10. Figure 9 shows that the maximum peak and residual displacements of the building increase with increasing of *R* and OOP. This is because by increasing *R*, the building is designed for lower strength; therefore, it has higher displacements during earthquake ground motions.



(a) Peak displacements (b) Residual displacements

Fig. 9: Comparison of maximum median displacements of out-of-plumb building with different *R*

Moreover, Figure 10 compare the normalized maximum median peak and residual response of building designed with different *R*. This comparison suggests that although residual response is more sensitive to change of OOP than peak response, peak response is more sensitive to change of *R* than residual response.



(a) Peak displacements (b) Residual displacements

Fig. 10: Comparison of normalized maximum median displacements of out-of-plumb building with different *R*

DESIGN APPLICATION

A residual displacement prediction procedure may be developed here for structures with out-of-plumb. For example, if the 8 story building with story height of 3 m was designed with C_d/R ratio of 0.8 and *R* factor of 7, what is the likely residual displacement of the roof for structure with OOP of 0.5%?

Step1: Estimate peak displacement of plumb structure (Figure 6a), which is about 0.2 m;
Step2: Estimate NMMPD (Figure 7a), which is 1.7;
Step3: Compute relative peak displacements of OOP building: 1.7*0.2 = 0.34 m;
Step4: Compute total peak displacements of OOP building: 0.34+0.005*24= 0.46 m
Step5: Estimate *RPR* (Figure 8), which is about 0.6;
Step6: Compute total residual displacement: 0.6*0.34 +0.005*24=0.324 m

CONCLUSIONS

A number of analyses were conducted on an 8 story shear type structure with continuous columns to evaluate displacements for some typical deflection amplification factors (C_d) and response modification factors (R) under seismic loads considering out-of-plumb. Relationships showing increasing displacements with increasing OOP were obtained. Those with high OOP had median residual displacements close to the median peak displacements. An example shows how this information can be used to estimate peak and residual displacements.

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