Seismic evaluation of buildings with out-of-straightness

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ABSTRACT: Building out-of-straightness result from construction tolerances or post-earthquake residual deformations. In addition to peak displacement responses, residual displacements may detrimentally affect structure performance in subsequent seismic events. Therefore, it is desirable to know how an undamaged building with a specified out-of-straightness is likely to behave in an earthquake and how one which is damaged and out-of-straight due to an earthquake may perform in an aftershock. In this research, simple models of steel structures with different levels of out-of-straightness are analysed using inelastic dynamic time history analysis to quantify effects of out-of-straightness under a suite of ground motion records. Structures considered were designed with different target inter-storey drifts.

1 INTRODUCTION

In the 2010 American Institute of Steel Construction (AISC) *Specification for Structural Steel Buildings (AISC 2010a)*, the Direct Analysis Method (DM) is the standard stability analysis and design method. Compared to older methods, such as the Effective Length Method (ELM), the DM accounts for the critical factors that affect stability of steel buildings in a more transparent manner. Accounting for these factors, which include geometric nonlinearity, initial geometric imperfections, and inelastic behavior due to residual stresses, allows the effective length factor, K, to be set equal to 1 in column strength calculations. Research conducted over the course of nearly twenty years (e.g. Liew et al. 1994, White and Hajjar 1997 and 2000, Surovek-Maleck and White 2004a and 2004b, White et al. 2006) has shown that these two effects can have an appreciable impact on stability behaviour in design scenarios that do not contain seismic loading.

While the DM could potentially be applied to seismic design, the interface between the DM, steel seismic provisions and seismic design requirements in Minimum Design Loads for Buildings and Other Structures: ASCE/SEI 7-10 (ASCE 2010), is not fully established. 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 because seismic design was not considered in the development process of the DM. Thus, it is critical to explore the impact of the key issues that undergird the DM, namely, geometric nonlinearity, initial geometric imperfections, and inelastic behaviour due to residual stresses on the seismic behaviour of typical steel buildings before the DM is extended to seismic design.

An even more powerful method of analysing non-seismic steel frames, an extension of the direct analysis method has recently been developed. It is termed “Extended Direct Analysis (or EDA)” (Lu, 2009, [4]). EDA not only considers all the factors in the AISC direct analysis method, but it also considers frame plasticity with the dependable member strengths. Moreover, since it considers the dependable strength of a structure, the model reasonably realistically represents the real structure. However, for seismic design the effects of frame out-of-straightness are not considered.

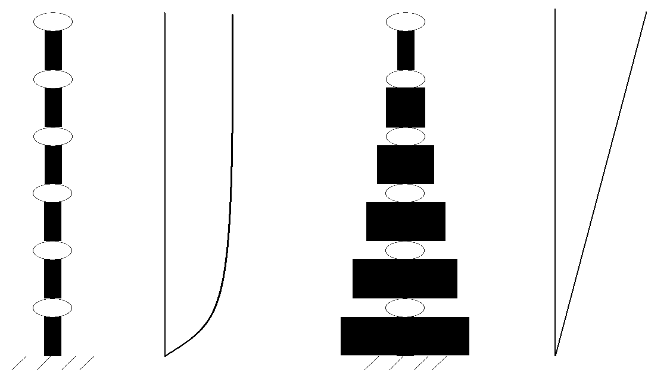
Moreover, for structures in seismic regions, methods to evaluate the likely demands on structures have generally been developed based on the response of initial perfectly straight structures. Few studies have been conducted to systematically evaluate the effect of buildings out-of-straightness on its seismic response and the dynamic stability of structures (Masuno et al., 2011; Yeow et al. 2013). However, they did not study the effect of different target interstorey drifts in their work and they consider only a constant target interstorey drift of 1.8%.

Therefore, there is a need to know how an undamaged building with a specified initial out-of-straightness and how one which is damaged and out-of-straightness due to an earthquake is likely to behave in a subsequent event. This study draws motivation from the issues presented above and aims to address it by answer to the following question:

How does target inter-storey drifts design influence the seismic response of structures with different levels of out-of-straightness?

2 RELATED STUDIES

Sadashiva et al. (2009) conducted studies to evaluate the effect of various types of vertical irregularity on structural response during seismic excitations. Studies have been conducted to evaluate the effects of vertical mass irregularity, and stiffness-strength configurations for different 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 1. Continuous columns were used with the shear-type model to obtain realistic drifts.



Constant Stiffness (CS) Constant Interstory Drifts (CISD)

Figure 1. The Two Classes of Stiffness Distribution Models (Sadashiva et al., 2009)

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. Because out-of-straightness building structures such as those described in this study also have an eccentric moment it would also be expected that these structures also have a tendency for larger displacements in the direction in which they are leaning.

Moreover, Masuno et al. (2011) studied the effect of out-of plumb in steel structures. They considered the Shear-Flexural Beam (SFB) model as shown in Figure 2. 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 shear beam at ith floor was computed using Equation 1 where E=Elastic Modulus; H_i=storey height of the i^{th} floor level; I_i=moment of inertia at the i^{th} floor level; and K_{oi}=initial stiffness of the i^{th} floor level. Masuno et al. pointed out (i) greater initial out-of-plumb generally causes greater response increases relative to structures with no initial out-of-plumb, (ii) structures with a greater number of storeys and those with greater design ductility's also tend to have greater response.

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

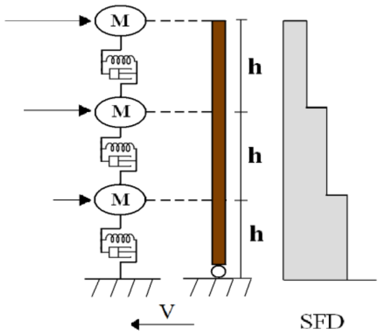


Figure 2. Shear Flexural Beam model (Masuno et al., 2011)

3 MODELLING AND EVALUATION APPROACH

The models used in the study by Masuno et al. (2010) are also used in this study. The model is 10-stories steel 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= 4m. The structure stiffness distribution is designed with the CISD Ratio.

The basic structure was designed as an ordinary building in Wellington close to the fault on site class C. Structures were designed with target inter-story drifts of 1.5% 1.8% and 2% and target design ductility of 4 according to the Equivalent Static Method in NZS1170.5 (2004). The out-of-straightness of 1%, 2%, and are considered in this study. These structures were entered into the programme in their deformed configuration before the seismic analysis started.

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. The dynamic inelastic time history computer programme RUAUMOKO 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. Bi-linear hysteresis loop with bi-linear factor of 1% was used for shear beams and continuous column of the model. Critical damping of 5% is adopted from study of Sadashiva et al. (2009). P-delta effects were considered.

The analysis results from RUAUMOKO were divided in two major groups; models perfectly straight; and models initially out-of-straight. By assuming that the distributions of the peak and residual interstorey drifts ratio (ISDR) are lognormal (Cornell et al. 2002), the median is found using Equation 2.

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

where $x_i = \text{peak or residual interstorey drift ratio (ISDR) due to } i^{th} \text{ record}$

$n = \text{total number of earthquake records considered.}$

4 EFFECT OF OUT-OF-STRAIGHTENESS

Figure 3 indicates that for a 10 story steel structure the residual displacement increased with increasing target design drift and out-of-straightness. For this CISDR model, the peak drift occurred at the base of the structure as shown in Figure 4.

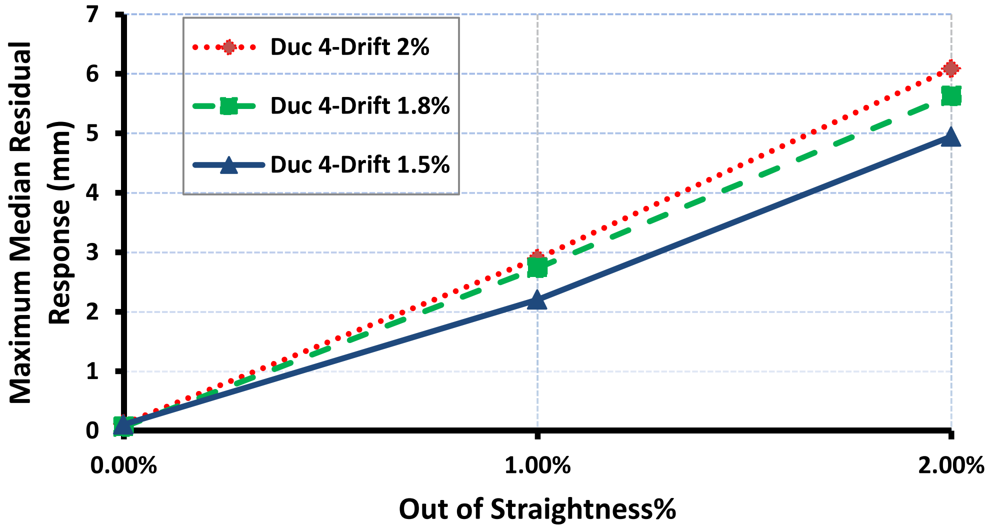


Figure 3. Effect of Drift Design on Residual Response of structures with ductility of 4

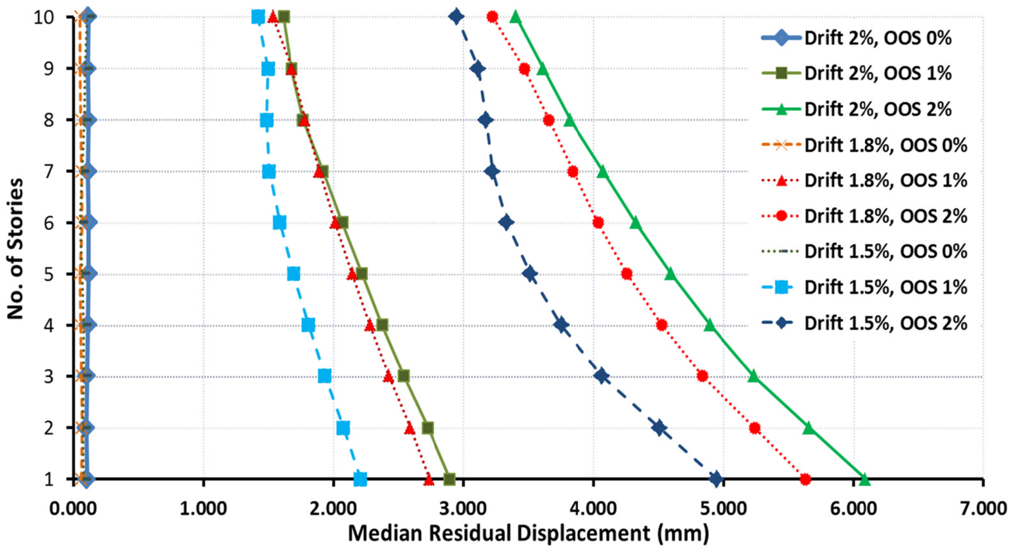


Figure 4. Comparison of median residual response of structures with different target drift designs and out-of-straightness.

5 CONCLUSION

A number of analyses were conducted on SFB-type structures to evaluate the effect of target drift design on seismic response of structures with different level of out-of straightness. It was shown that greater target drift design generally causes greater response increases relative to structures with no initial out-of-straightness. Information developed allows the likely change in peak and residual displacements to be evaluated for specific structures.

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