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Residual Stress Effects on the Seismic Performance of Low-Rise Steel Frames

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ABSTRACT: In non-seismic plastic design of steel structures, initial residual stresses in members affect the frame tangent stiffness and the lateral strength. This effect can be simply considered by using the *Extended Direct Analysis* (EDA) approach as part of design process. However, for the design of frames subject to earthquake, the effect of residual stresses is generally ignored, except in the final column design check. This paper looks at the effect of residual stresses on the seismic performance. Pushover and push-pull analyses were performed on a single cantilever column with nonlinear beam-column fibre sections under moderate compressive axial load. In addition, incremental dynamic analyses were performed with 20 SAC earthquake records to consider the dynamic behaviour. The results show that while the initial residual stresses do have some effect on structural behaviour at the first yielding, the post-yielding behaviour is not affected.

1 INTRODUCTION

Many analysis techniques can be used for design steel frame structures. These methods are varied from the most basic first-order elastic analysis to rational second-order inelastic analysis. Traditional first-order elastic analysis methods can give the design moment from both sway and non-sway cases as shown in Figure 1. Modifications are then used to account for a number of effects such as geometric nonlinearity, initial imperfections and plasticity effects. On the contrary, a second-order inelastic method can consider many effects together in one analysis. It eliminates the need to modify the analysis results but it requires more sophisticated software and more information to be input into the computer.

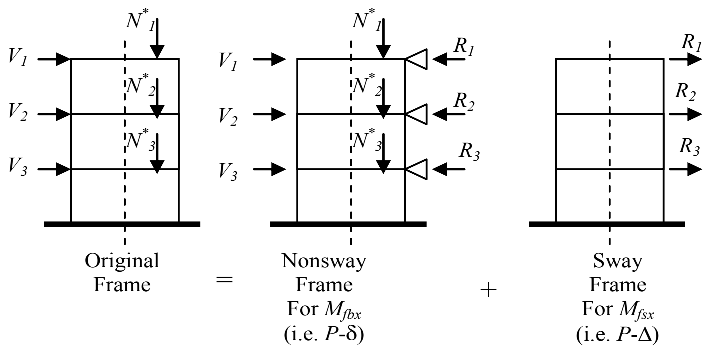


Figure 1. Obtaining Design Moment from Non-sway and Sway Moments

Direct Analysis Method (DM), which has been incorporated in the 2005 AISC Specification (2005), is a newly developed method to estimate the frame elastic moments directly. DM is based on second-order elastic analysis with notional loads to consider geometric imperfections and stiffness reduction factor to account for initial residual stresses. The advantages of DM over the traditional methods are that it eliminates the need to compute column effective lengths; and the secondary design actions can be captured directly by the analysis since both initial stress effects and out-of plumb have been considered in the analysis. However, further modifications are still required to check the frame capacity.

Extended Direct Analysis (EDA) (Lu 2009), which is an extension of the AISC DM approach, has recently been developed. It considers not only the factors mentioned in the Direct Analysis but also the possibility of plastic hinging, axial-moment interaction and the dependable strength of a structure. Since EDA has considered all these factors in the analysis, the results of analysis are reasonable realistic. This means that, in an analysis, the structure is unsatisfactory if the structural model fails and collapse occurs under the applied factored loads

These methods, described above, are used for analysing structures subjecting to monotonic loadings. They may not be suitable for analysing structures subjecting to the cyclic wind or earthquake loadings. Moreover, the initial residual stresses and out-of-plumb effects are not considered directly in the seismic design process. Therefore, there is a need to exam the significance of these effects on steel structures.

This paper addresses the degree of importance of initial residual stress effects on the seismic performance of low-rise steel structures, whereas the significance of the out-of-plumb effects has been studied by Masuno (2010, 2011). This paper answers the following questions:

1. What is the response of steel frames subjected to cyclic loading due to wind when peak strength is not reached?
2. What is the response of steel frames subjected to earthquake loading with large deformations?
3. How significant the initial residual stress effects affect the seismic performance of steel frame structures?

2 RELATED STUDIES

Studies of the effects of initial residual stresses on seismic performance have undertaken by Okazaki, Parkolap and Fahnestock (2009). The main objective of this research is to enhance the functionality of current DM from simply statically monotonic analysis to dynamical cyclic seismic design. These includes 1) clarifying how the Direct Analysis addresses seismic effects; 2) evaluating how the DM includes plastic hinging for seismic loading; and 3) identifying research needs related to the interface of the DM and seismic design requirements. Their preliminary analysis is mainly to evaluate the degree of significance of effects of initial residual stresses on cyclic behaviour.

Their analyses were conducted by evaluating the seismic response of 3-story, 6-story and 9-story steel frame structures. These special moment resisting frames (SMRFs) were obtained from the SAC project. Also, the dimensions, section sizes, weight and any additional details of the structures considered in the research are based on the pre-Northridge design models reported by Gupta and Krawinkler (1999). SAP2000 (CSI 2009) and OpenSEES (2006) were the main analysis packages used. Fibre elements allowed the plasticity to form gradually across the section and along the member length were used in the OpenSEES models. The distributions of initial residual stress from Galambos and Ketter (1959) were assigned to the fibre model in OpenSEES. A bilinear nonlinear material behaviour with concentrated plastic hinge model was used in SAP2000. The strain hardening coefficients were 2% for OpenSEES but 4% for SAP2000. The material yielding stresses used were the same for both programmes.

Okazaki compared five different monotonic methods. These include plastic analysis, direct elastic-plastic hinge analysis with concentrated plastic hinges, second-order distributed plasticity analysis, second-order analysis with concentrated hinges, and first-order analysis with concentrated plastic hinges. The cyclic behaviour based on the push-pull analysis focused on the comparison of the structural response with and without the initial residual stresses and initial imperfections. Each model was subjected to three earthquake records representing three different localities in US.

Based on the results from both monotonic and cyclic push-pull analysis, they concluded that the initial residual stresses and initial imperfections would accelerate frame collapse in cases when deformation concentrates in a small number of stories.

3 MODEL DESCRIPTIONS

3.1 Analysis Model and Methodology

A 3.2m tall 200UC59.5 single cantilever column was analysed in this study. The analysis is performed by OpenSEES, an analytical package enabling to perform second-order inelastic analysis. The column is subjected to an axial compression force, approximating 0.355 times of the section compressive strength, N_s, at top of the column as the base cases. Other axial force values are also used. The whole system is considered as a single degree of freedom system. The seismic weight of the system is 5100kg concentrating at the top. The structural period is 0.5s after the gravity force is applied. Rayleigh constant damping is used.

Pushover and time-history analysis were performed. A serious of time-history analysis with scaling from elastic region to collapse, also known as Incremental Dynamic Analysis (IDA), were conducted with 20 SAC (SEAOC-ATC-CUREE) (2000) earthquake records. Both analyses are performed after the gravity load is applied.

3.2 Residual Stress Model

The initial residual stresses distribution pattern used is based on ECCS (1984) model as shown in Figure 2 below. The model is based on the idealised initial residual stress patterns of hot-rolled I-sections which have been cooled with their webs parallel to the ground and then cold straightened. It should be noted that this research is focusing on the hot-rolled I-section only and the welded section is not studied. The negative value denotes that the section is initially in compression. The maximum compressive residual stresses are located at the edges of the flange and centre of the web whereas joints of web and flange are in tension initially. The initial residual stress, σ_r is calculated as γf_y where γ is residual stress ratio and f_y is the specified material yielding stress.

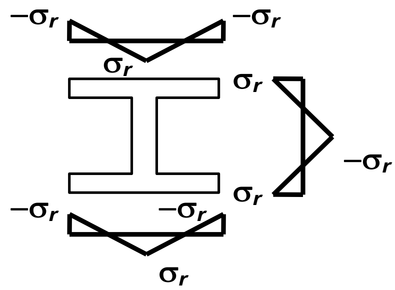


Figure 2. Distribution of Initial Residual Stresses Model

3.3 Section Model

A fibre section with quadrilateral elements is used to incorporate the initial residual distribution into the section. The section is divided into $2i+1$ discritizations along the length of flange and along the clear length of web as illustrated in Figure 3 for an I-section. Each fibre is allocated different initial stress value according to the initial residual stress model above. Equations 1 and 2 are used to calculate the residual stress values for each fibre where b_f is flange width, d is depth of the section and x is the distance from the axes to the centre of each fibre. The combination of fibre section and corotational transformation enable the analysis to take account for axial-moment interaction.

$$\sigma_{r,i} = -\frac{2\sigma_r x}{b_f/2} + \sigma_r \quad \text{for flange} \qquad \text{Eq. 1}$$

$$\sigma_{r,i} = \frac{2\sigma_r x}{d/2} - \sigma_r \quad \text{for web} \qquad \text{Eq. 2}$$

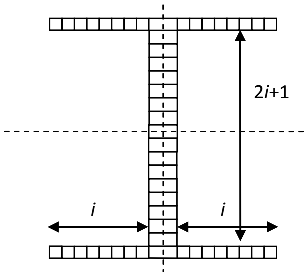


Figure 3. Model of Fibre Section

3.4 Material Stress-Strain Relationship

Steel stress-strain relationship is "Giuffre-Menegotto-Pinto Model with Isotropic Strain Hardening" (2006). It is an inbuilt material command which called Steel02 in OpenSEES. The parameters of this relationship are 0, 20, 0.925, 0.15, 0, 1, 0, 1 according to the sequence of this command. This setting gives smooth transition from elastic to plastic region and no strain-hardening in the post-yield region. Ignoring strain-hardening will result in conservative recommendations. In addition, the stress-strain relationship is the same for both positive and negative directions.

3.5 Element Model

Nonlinear beam column elements from OpenSEES are applied. They used a force formulation to consider the spread of plasticity along the length of element. Also, the integration is based on the Gauss-Lobatto quadrature rule where two integration points are located at the element ends. In this study, each member is subdivided into 8 sub-elements with five integration points in each sub-element.

4 MONOTONIC BEHAVIOUR FROM PUSHOVER ANALYSIS

Figure 4 presents the force-displacement relationship of the monotonic responses for the 6 cases where are categorised into three subgroups according to the magnitudes of applied compression axial forces. Two initial residual stress ratios, γ = 0.0 and 0.5, are presents for each axial force group. The three magnitudes of applied compression axial force are $N = 0.355N_s$, $N = 0.5N_s$ and $N = 0.7N_s$. From the figures, it can be seen that the difference of maximum applied lateral forces between γ = 0.0 and 0.5 is only 0.201kN (0.66% to the γ = 0.0 case) for compression axial force, N, of $0.355N_s$ but the differences increase to 1.515kN (7.73%) for $N = 0.5N_s$ and 2.926kN (36.15%) for $N = 0.7N_s$. The differences of maximum lateral displacement between γ = 0.0 and 0.5 are 2.67mm (5.88% to the γ = 0.0 case), 6.03mm (18.23%) and 4.36mm (22.85%) for N = 0.355Ns, 0.5Ns and 0.7Ns respectively.

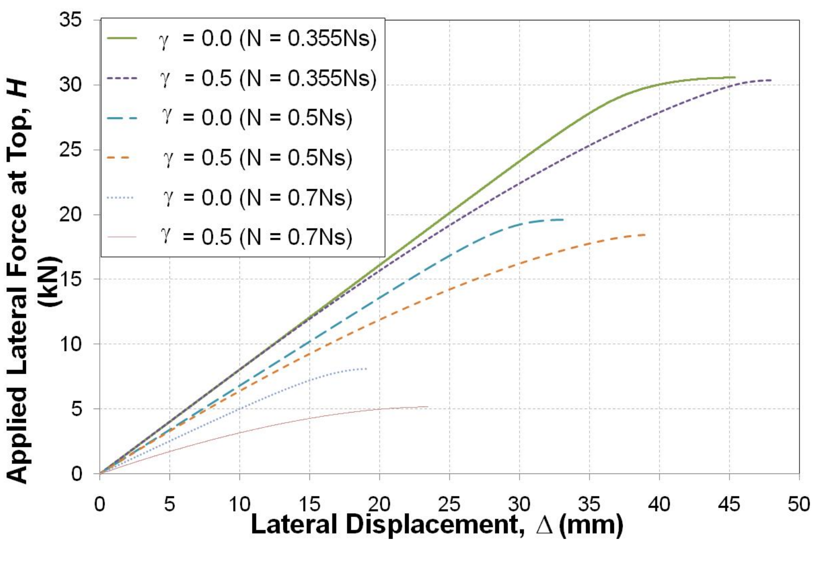


Figure 4. Effect of initial residual stress on monotonic behaviour

From the above observations, it can be seen that the structural strength is related to both the magnitudes of applied compression axial force and the initial residual stress values. Structures with high axial force and large initial residual stress value have the most decrease in the lateral applied force. The result also showed that the degree of influence on the maximum lateral force is dependent on the magnitude of applied axial force as the differences between γ = 0.0 and 0.5 increases with increasing applied axial forces.

5 SEISMIC RESPONSES

5.1 Static push-pull behaviour

Static push-pull analysis with displacement control was performed for the column to understand the complete cyclic behaviour before consideration of the seismic responses. It should be noted that the applied compression axial force, *N*, is 0.3*N*s instead of 0.355*N*s as stated previously. From Figure 5, the initial residual stress effect is similar to the monotonic behaviour. It only affects the structural behaviour at the first yielding. Also, the differences can only be observed in the first cycle in both negative and positive directions. Afterwards, the structural behaviour is not affected by the initial residual stresses effect as indicated by the overlapping of all three curves.

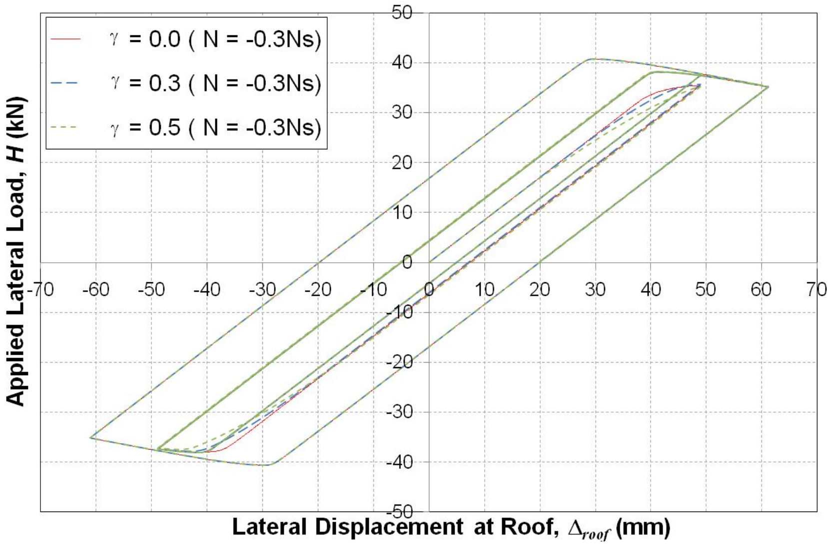
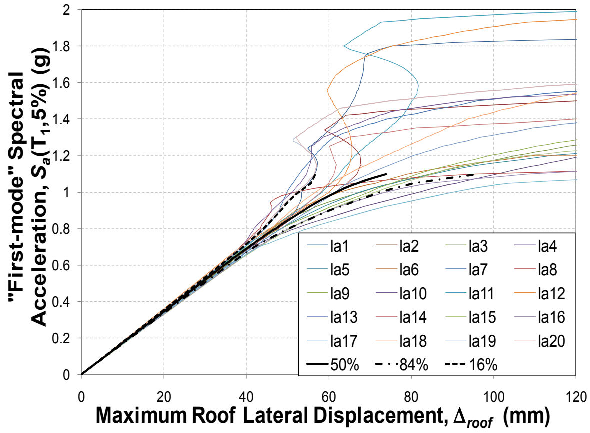


Figure 5. Static cyclic response of a cantilever column

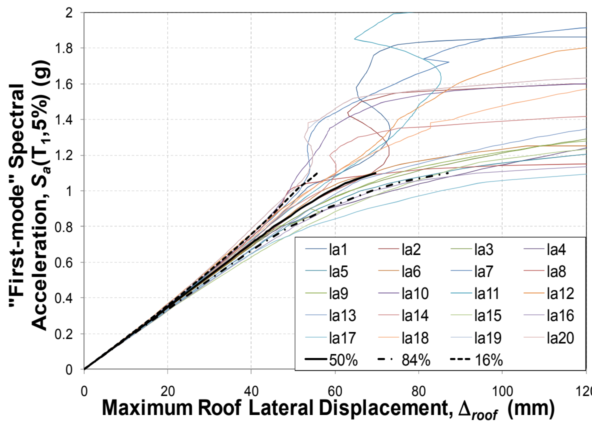
It can also be seen from the figure that the overall strength of the system is decreased as the deflection increases as shown by the negative slope of the curves at the plastic ranges. This is due to the *P*-delta effects where the axial compressive force causing the system to deform further.

5.2 Seismic Responses

Figure 6 shows the plots for all incremental dynamic analysis from 20 SAC records for a structure with an applied compressive axial force, *N*, of $0.355N_s$ with no initial residual stress, γ = 0.0, and with the residual stresses, γ = 0.5. The complete plots of 16%, 50% and 84% confidence levels are also given for each figure as shown by the thicker lines. Based on the result of individual records, both cases, γ = 0.0 and γ = 0.5, reach approximately the same maximum "First-mode" spectral acceleration, S_a, which is about 2.0g. The S_a causing the first yielding of the column among all 20 SAC records is approximately 0.5g for γ = 0.0 and 0.3g for γ = 0.5. These were obtained by visual estimation directly from the plot of each individual record. The yield point is taken as the first point where the gradient of the line changes. The responses of the column after yielding can be categorised into two types. The first type is that the strength of the column is decreasing with increasing the ground motion shaking. The other type is the weaving behaviour where the displacement of column decreases and then increases until it collapses as shown in Figure 6 below.



a) γ = 0.0



b) γ = 0.5

Figure 6. Plots for the results of incremental dynamic analysis for two residual stress ratios

Figure 7 plots the 16%, 50% and 84% confidence levels for both initial residual stress cases for N/N_s = 0.355. In the figure, the plots for 16% and 84% confidence levels only show up to the point where the weaving was observed in the plot of 16% confidence level as shown in Figures 6a and 6b. From the results, all three confidence levels show that the column with initial residual stresses, i.e. γ = 0.5, has slightly greater strength than the column with no initial residual stress such as γ = 0.0. For this suite of records, the overall difference in response is very small.

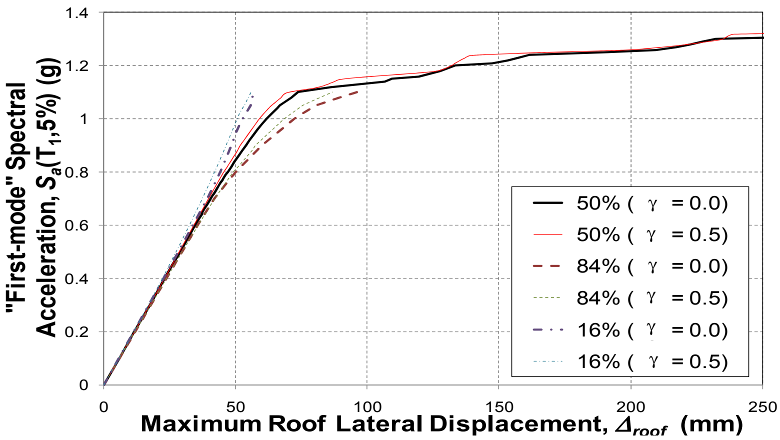


Figure 7. Comparison of the mean values of IDA for γ = 0.0 and γ = 0.5

6 CONCLUSIONS

From both monotonic and dynamic analysis of a single cantilever column with and without initial residual stresses, it was found that:

1) The initial residual stresses tend to affect the monotonic behaviour of structures. The degree of influence of initial residual stress effect is dependent on the magnitude of compression axial force. The strength of structures decreases significantly due to initial residual stresses when high compression axial forces are applied.

2) The initial compressive residual stresses of up to $0.5f_y$ on a column with an applied axial force of $0.3N_s$ do not affect the cyclic push-pull structural responses when the deformations are large. The effect of initial residual stresses was eliminated after the structure moves into the plastic regions.

3) Time-history analysis of a cantilever steel column with an applied axial force of $0.355N_s$ shows that the seismic performance is not significantly affected for initial residual stresses of up to $0.5f_y$.

7 FUTURE RESEARCH

Further study is currently being conducted on other column aspect ratios, and on columns in frames.

8 ACKNOWLEDGEMENTS

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