

NLTHA and Pushover Analysis for Steel Frames with Flag-shaped Hysteretic Braces

J.B. McInerney

University of Cambridge, UK

J.C. Wilson

McMaster University, Canada



SUMMARY:

In this study, non-linear time history and pushover analysis of 1, 2, 4, and 8 storey chevron-braced steel frame models was carried out for braces having flag-shaped and bilinear hysteresis characteristics. For the NLTHA each frame was subjected to an ensemble of ground motions to determine their mean responses. The NLTHA revealed that frames with flag-shaped braces experienced lower residual drifts and those with bilinear braces experienced lower accelerations. However, the behaviour of the frames was generally governed by the backbone curve of the brace hysteresis defined by a post-yielding stiffness parameter, a normalized yield force, and a normalized stiffness. Increasing these parameters generally decreased interstorey drift and increased base shear – trends also evident from the pushover analyses. An energy dissipation parameter had relatively little effect on the response – further supporting the utility of pushover analyses.

Keywords: Flag-shaped hysteresis, bilinear hysteresis, braced steel frame, NLTHA, pushover analysis

1. INTRODUCTION

In this study, non-linear time history analyses (NLTHA) and pushover analyses of four chevron-braced steel frame building models were carried out using the programs Ruaumoko[®] (Carr 2007) and SAP2000[®] (Computers and Structures 2009) respectively. The braces were modelled to emulate flag-shaped and bilinear hysteretic energy dissipation devices (EDD). In actual braces the flag-shaped hysteresis can be implemented using shape-memory alloy components (Krumme et al. 1995) or steel and aramid components (Christopoulos et al. 2008). Braces active in both tension and compression (T-C) and tension only (T-O) were modelled. For the NLTHA each frame model was subjected to twenty earthquake ground motions and the responses were summarized via several response indices including mean normalized maximum interstorey drift and mean normalized maximum base shear. Similar studies by others investigating the seismic response of steel frames with fluid viscous damping braces (Diciceli and Mehta 2007) and SMA braces (McCormick et al. 2007) have been conducted. In this paper, the results for interstorey drift and base shear are highlighted. Pushover analysis was also carried out to investigate drift and base shear and to evaluate its efficacy in comparison to NLTHA.

2. PARAMETRIC STUDY

2.1. Non-linear Time History Analyses

For the NLTHA, four chevron-braced steel frames were analysed using Ruaumoko[®]. These were the same frames used by Diciceli and Mehta (2007) and are shown in Fig. 2.1. The frames were proportioned to provide a decreasing lateral strength as the number of stories increased, allowing the frames to exhibit non-linear behaviour under moderate to high intensity ground motions. Beams and columns were modeled to exhibit elasto-plastic behaviour by defining potential plastic moment hinges with corresponding yield values located at the ends of the beams and columns where moments were greatest. Potential plastic axial force behaviour was also accommodated in the beams and columns. The braces were modelled to exhibit only axial T-C or T-O behaviour and were fully described by a set of hysteretic parameters.

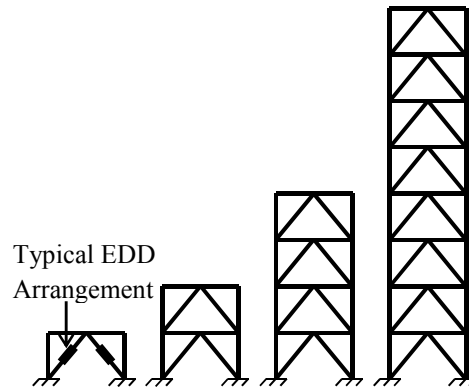


Figure 2.1. Frame models (after Dicleli and Mehta 2007)

Fig. 2.2 illustrates the bilinear and flag-shaped hysteresees and their defining parameters. The bilinear hysteresis is uniquely defined by three parameters: a normalized yield force parameter η , a normalized initial stiffness parameter θ , and a post-yield stiffness parameter α . The flag-shaped (e.g. SMA) hysteresis is uniquely defined by the same three parameters η , θ , α , plus an energy-dissipation parameter β that describes the depth of the flag loop. The parametric study was defined by

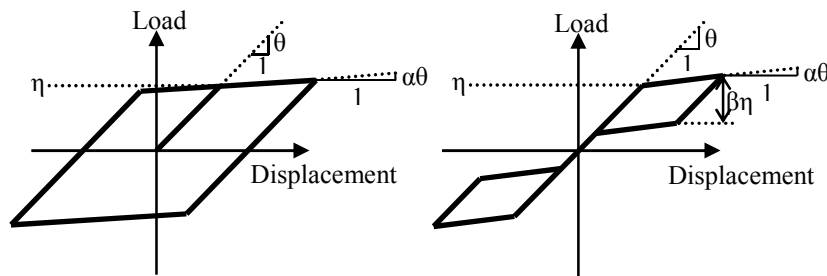


Figure 2.2. Idealized hysteresis for braces with bilinear (left) and flag-shaped (right) and normalized yield force and stiffness parameters (after Christopoulos et al. 2002)

establishing four values for the normalized brace yield force η ; three values for the normalized initial stiffness of the brace θ ; two values for the post-yielding stiffness parameter α ; and two values for the energy-dissipation parameter β . For the flag-shaped braces, this resulted in a total of 48 unique brace models for each frame and bracing type. For the bilinear hysteretic braces, this resulted in a total of 24 unique brace models for each frame and bracing type, as there was no energy-dissipation parameter. Since each of the four frames was studied comprising T-C and T-O braces, a total of 576 unique models were defined. Each frame was subjected to an ensemble of twenty ground motions to determine their mean responses (and standard deviations) as measured by several response indices. Therefore, a total of 11,520 NLTH analyses were conducted using Ruaumoko[®].

The force at first yield and the stiffness were assigned a range of values over which the hysteresis is effective in controlling response. These are reported here as normalized values η and θ , respectively. Force at first yield is normalized by dividing by the weight of the frame W ($=1638\text{kN}$ and was evenly distributed to each storey level) giving η values ranging from about 0.03 to 0.34 of W . Stiffnesses were normalized by dividing by the initial lateral stiffness of the un-braced 1-storey frame ($=22.3\text{kN/mm}$) giving θ values ranging from about 2 to 22. Values of α were taken to be 0.0 (elasto-plastic) and 0.25. A lower limit on β is 0.0 which creates a non-linear elastic hysteresis. An upper limit on the value of β is 1.0 which ensures the recentering quality of the hysteresis. In this study values for β were taken to be 0.5 and 1.0. Table 2.1 summarizes the models and system values used in this study.

The earthquake ensemble used in this study was comprised of 20 California ground motions and was the same used by Christopoulos et al. (2002). Each record was scaled to minimize the square of the

error between a smooth target spectrum and its own 5% damped response spectrum at five period values: 0.1, 0.25, 0.5, 1.0, and 2.0s. This resulted in a mean of the twenty scaled spectra that matched the target spectrum reasonably well over the 0.1s to 2.0s range. A value of 5% inherent damping was used throughout this study. The initial elastic periods of the frames ranged from 0.13s to 1.42s as summarized in Table 2.2.

For a single ground motion, the response index of interest was recorded for each storey in each frame. These maximum values were averaged to obtain a mean maximum value for that particular frame and ground motion. This was done so that response index comparisons could more easily be made between different frames. Because of its nature, base shear did not have values for each storey level, only values for each frame. The 20 mean maximum values for each frame (one for each of the 20 ground motions) were then averaged to give a final single mean maximum value for the frame characterized by a unique combination of the η , θ , α , and β parameter set. Only samples of the drift and base shear results are presented here. Interstorey drift and base shear, which were normalized using storey height h ($=3.6\text{m}$) and frame weight respectively, are key design indices and limiting them in buildings is seismically advantageous. Sample results from the same study for residual interstorey drift and acceleration can be found in McInerney and Wilson (2012) and complete results for the entire NLTHA are provided in McInerney (2010).

Table 2.1. Summary listing of all model and system values in the parametric study

| Frame | Bracing for each frame | | Hysteretic parameters for each frame | | | |
|----------|---------------------------|---------------|--------------------------------------|---------|--------|----------|
| | Hysteresis | Configuration | α | β | η | θ |
| 1-Storey | Flag-Shaped & Bilinear | T-C & T-O | 0.0 | 0.5 | 0.03 | 2.24 |
| 2-Storey | | | | | 0.12 | |
| 4-Storey | | | | | 0.21 | |
| 8-Storey | | | | | 0.34 | |

2.2. Pushover Analysis

The static pushover analysis of the same frames as those in the NLTHA was conducted using SAP2000[®]. Plastic hinges were incorporated into the model similar to the NLTHA. The frames were monotonically loaded one-way and so only the α , η , and θ hysteretic brace parameters were needed to fully describe the behaviour of the braces. This also meant that the frames with bilinear hysteretic braces and the frames with flag-shaped hysteretic braces were described by the same pushover curve. For each of the four frames, T-C and T-O braces were used along with the same three values for θ , four values for η , and two values for α as in the NLTHA, making a total of 192 pushover analyses.

The Equivalent Static Force Method (ESFM) outlined in the National Building Code of Canada (NBCC), suggests an inverted triangular loading pattern for use in the seismic analysis and design of multi-storey buildings (NRC 2005). This pattern approximates first mode loading during an earthquake and was used in the pushover analyses. Eqn. 2.1 gives the equivalent static force, F_x , to be placed laterally at each storey level, x , in the building:

$$F_x = \frac{(V - F_t)W_x h_x}{\sum_{i=1}^n W_i h_i} \quad (2.1)$$

where V is the base shear to be used, W_x is the weight of level x , and h_x is the height from ground to level x . F_t is a force to be placed at the uppermost level of the building (of n storeys) to emulate the effect of higher modes on the response and is defined in Eqn. 2.2:

$$F_t = 0.07T_a V \leq 0.25V \quad (2.2)$$

where T_a is the fundamental period of the building. The NBCC specifies that if the fundamental period of the building is less than or equal to 0.7s then F_t is to be zero. Table 2.2 gives a summary of

the fundamental periods of the frames used in this study along with percentage values for $0.07T_a$ used in the pushover analyses.

At each time step during the non-linear static pushover tests, the average interstorey drift (averaged over all floors) of the frame was determined and used with the associated base shear at that load step to form one point on the load-displacement curve. Interstorey drift and base shear values were normalized the same way as in the NLTHA. The pushover test for each frame was halted as soon as any one of the following occurred: a collapse mechanism formed leaving the frame, or part thereof, with zero lateral stiffness; the interstorey drift at any level reached 3% (the NBCC 2005 recognizes a maximum allowable interstorey drift of 2.5%); the total lateral force placed on the frame reached $1.6W$ (maximum reasonable lateral force expected considering the uncertainty in ground accelerations); or the axial capacity in any column was reached. Only sample results are presented here and complete results for all pushover analyses are provided in McInerney (2010).

Table 2.2. First mode elastic periods for three normalized stiffness values and higher mode effect coefficients

| Bracing System | Normalized Stiffness θ | First mode elastic period T_s (s) and higher mode effect coefficients $0.07T_s$ (%) | | | |
|----------------|-------------------------------|---|----------|----------|----------|
| | | 1-Storey | 2-Storey | 4-Storey | 8-Storey |
| T-C | 22.39 | 0.13 | 0.16 | 0.24 | 0.52 |
| | 5.60 | 0.23 | 0.28 | 0.38 | 0.65 |
| | 2.24 | 0.33 | 0.4 | 0.54 | 0.84/5.9 |
| T-O | 22.39 | 0.42 | 0.5 | 0.71/5.0 | 1.26/8.8 |
| | 5.60 | 0.44 | 0.54 | 0.77/5.4 | 1.33/9.3 |
| | 2.24 | 0.47 | 0.59 | 0.84/5.9 | 1.42/9.9 |

3. RESULTS

Space limitations in this paper preclude a detailed examination of the full response of these systems observed from the NLTHA and pushover analysis. As an example, however, results of the response of the four storey frame are presented below, and some comments on overall results from the complete parametric study are made in section 3.4.

3.1. NLTHA: Interstorey Drift

3.1.1. Detailed observations

Fig. 3.1 shows the mean normalized maximum interstorey drift as a function of normalized yield force at different normalized stiffnesses for the four storey frame. Responses of the frame with flag-shaped hysteretic braces are on the left and those for the frames with bilinear hysteretic braces are on the right. The responses for the frames with T-C braces are on the top and those for the frames with T-O braces are on the bottom. Variability in the data, resulting from the 20 ground motions used in each analysis, is quantified through the use of vertical bars for plus or minus one standard deviation from the mean.

For all cases interstorey drift decreased for increasing values of η and θ . In most cases, interstorey drift decreased for increasing α except for the T-C case with large η , where α had little effect on interstorey drift. In all cases, β (the energy-dissipation parameter) had very little effect on drift. Interstorey drift was very similar for the flag-shaped and bilinear cases except for the T-O case with large η , where interstorey drift was less for the bilinear case. Interstorey drift was also greater for the frames with T-O braces compared to those with T-C braces. In all cases, interstorey drift decreased for increasing number of storeys. Interstorey drift also became less sensitive to η as η increased and it became less sensitive to both η and θ as the number of storeys increased.

3.1.2. General observations

In general, increasing θ was most effective in reducing drifts. This resulted in larger pre-yield and

post-yield lateral stiffness of the frames. The T-C braces were more effective than the T-O braces in

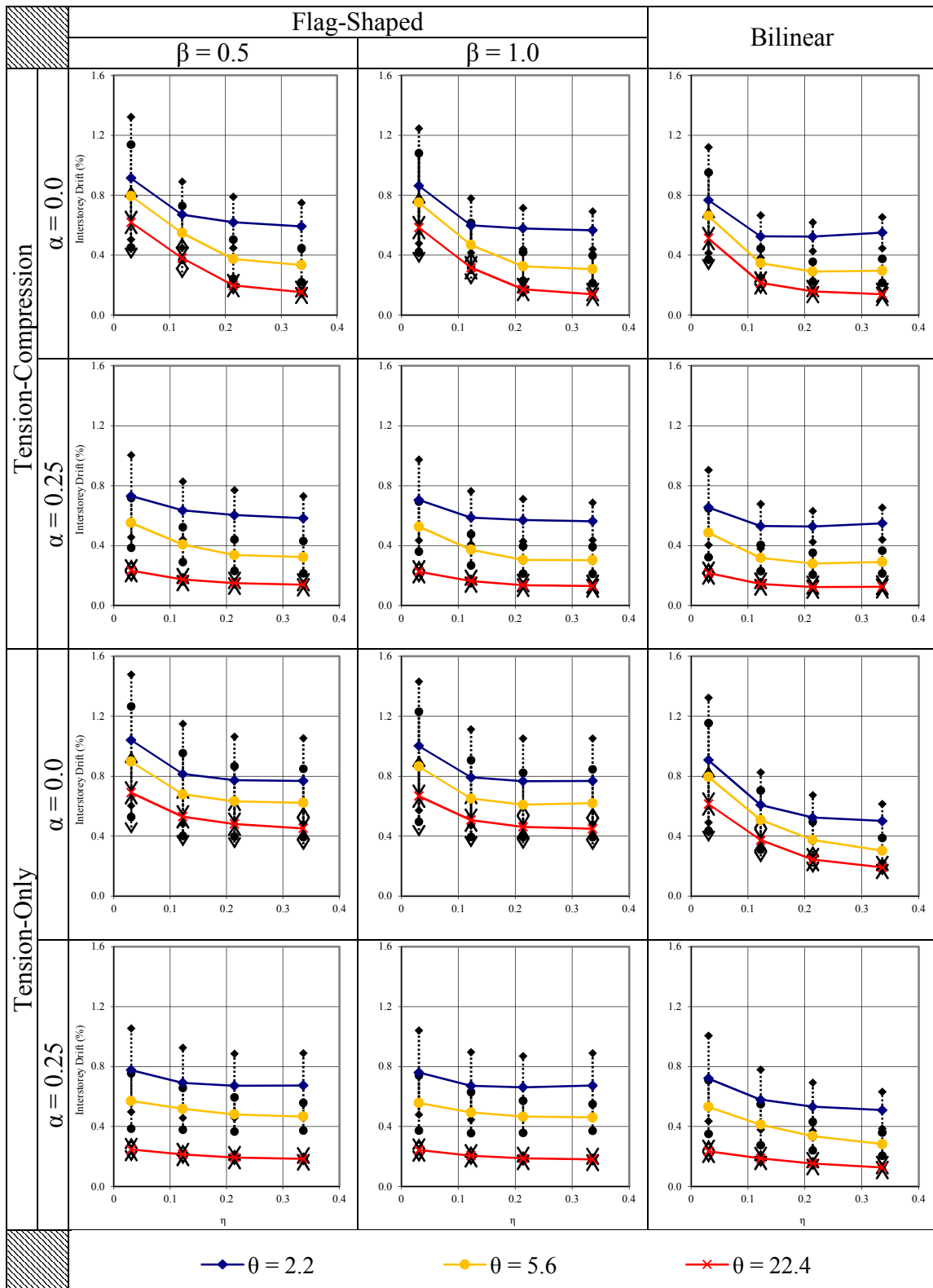


Figure 3.1. NLTHA: Mean normalized maximum interstorey drift plotted as a function of normalized yield force η of the bracing for the 4-storey frame

reducing interstorey drifts. Also, the braces with flag-shaped hysteresses tended to be just as effective in reducing drifts as the braces with bilinear hysteresses.

3.2. NLTHA: Base Shear

3.2.1. Detailed observations

Fig. 3.2 shows mean normalized maximum base shear as a function of normalized yield force at

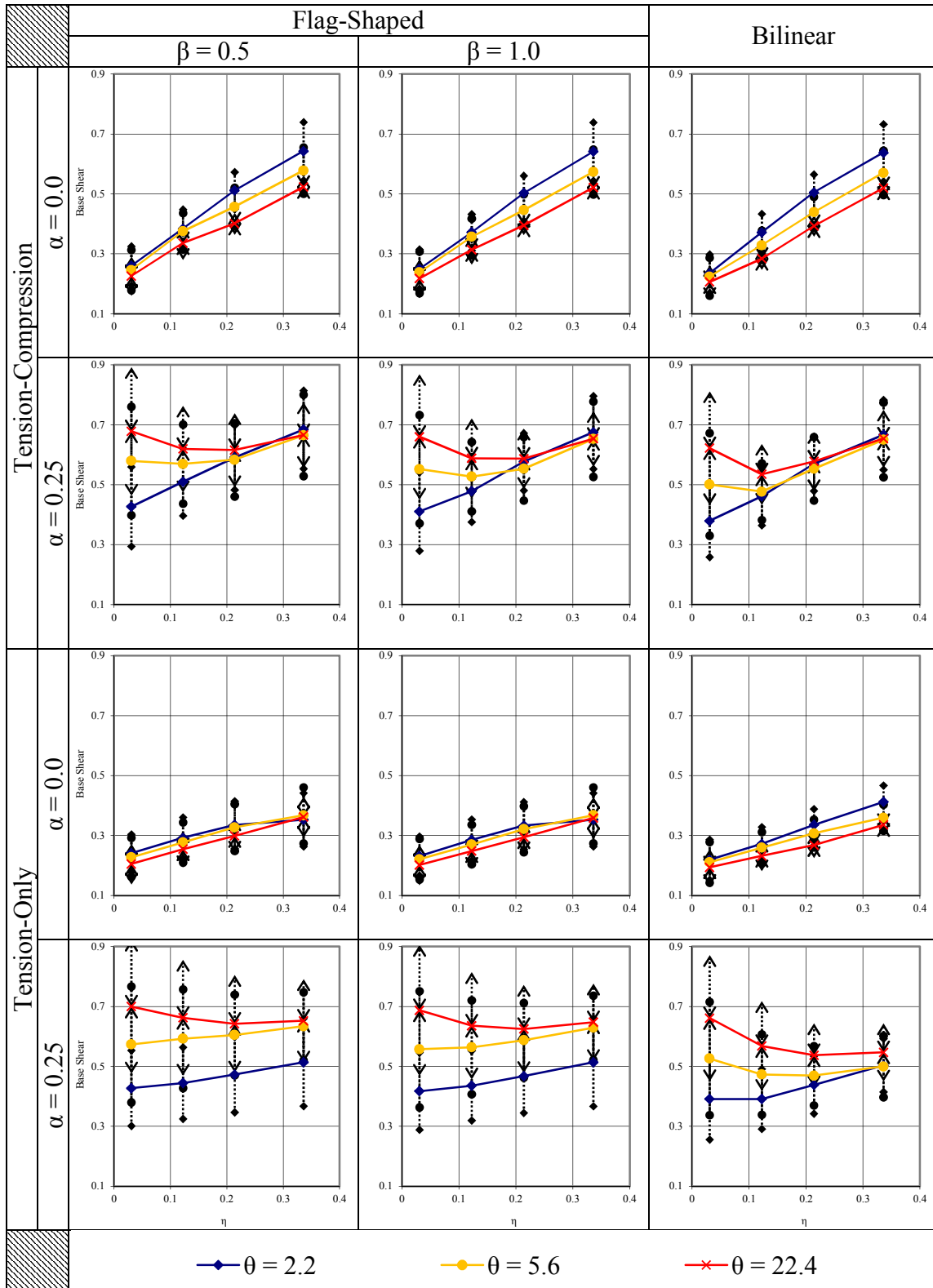


Figure 3.2. NLTHA: Mean normalized maximum base shear plotted as a function of normalized yield force η of the bracing for the 4-storey frame

different normalized stiffnesses for the four storey frame. In most cases, base shear increased for increasing values of η . For $\alpha=0.0$, θ had little effect on base shear except for the T-C case for the lower storey frames with large η where base shear decreased for increasing θ . For $\alpha=0.25$, base shear increased for increasing values of θ in most cases. In all cases, base shear increased for increasing α , and β had no effect on base shear. Base shear was similar for the flag-shaped and bilinear cases except for the T-O case with $\alpha=0.25$ and large η , where base shear was slightly less for the bilinear case. Base shears were lower for the frames with T-O braces compared to the T-C case except for very small η , where they tended to be similar for both of these cases. Base shear tended to decrease for increasing number of storeys. The sensitivity of base shear to η tended to remain constant with increasing number of storeys. For the $\alpha=0.0$ case, base shear became less sensitive to θ with increasing number of storeys and for the $\alpha=0.25$ case, the sensitivity of base shear to θ remained constant.

3.2.2. General observations

For the case where $\alpha=0.0$, decreasing η was most effective in reducing base shears. For the case where $\alpha=0.25$, decreasing θ was most effective in reducing base shears. The frames with T-O braces tended to be more effective in reducing base shears compared to the frames with T-C braces. The braces with flag-shaped hysteresees were just as effective in reducing base shear as the braces with bilinear hysteresees.

3.3. Pushover Analysis

3.3.1. Illustration of yielding sequence of frame

As an example, Fig. 3.3 illustrates the final pre-collapse state of a particular 4-storey frame with T-C braces during its pushover analysis. The displaced shape shown is exaggerated five times. The lateral loading at this final state was 75kN, 150kN, 225kN, and 300kN at the top of the first, second, third, and fourth storeys, respectively. The circles on the braces indicate that axial yielding has occurred while those on the columns and beams indicate flexural yielding or hinging. For this particular analysis, the sequence of yielding was as follows: [1] braces at the two lower storeys, [2] braces at the third storey, [3] braces at the fourth storey, [4] beam at the second storey, [5] column bases at the first storey, [6] beam at the third storey, and [7] beam at the fourth storey. The final hinge formation that created a collapse state (not shown on the figure) was characterized by hinging at the tops of the second storey columns.

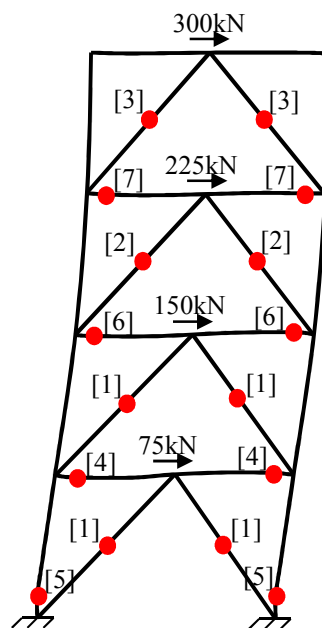


Figure 3.3. Pushover analysis: Final pre-collapse state of 4-storey frame with T-C braces, $\eta=0.12$, $\theta=5.6$, and $\alpha=0.0$ (sequence of brace yielding and hinge formation shown in square brackets)

3.3.2. Detailed observations

Fig. 3.4 summarizes the pushover results for the four storey frame: normalized lateral load (or equivalently, normalized base shear) as a function of mean normalized interstorey drift at different normalized yield forces. Results for each normalized stiffness value are shown in different columns. Mean normalized interstorey drift decreased and normalized base shear increased for increasing values of η . For $\alpha=0.0$, θ had little effect on interstorey drift or base shear except for large η where interstorey drift decreased and base shear increased for increasing θ . For $\alpha=0.25$, interstorey drift decreased and base shear increased for increasing θ . Interstorey drift decreased and base shear increased for increasing α . Interstorey drift was lower for the frames with T-C braces and base shear was lower for the frames with T-O braces except for the $\alpha=0.0$ case with small η where drift and base shear were essentially the same for the frames with T-C and T-O braces. In most cases, interstorey drift and base shear tended to decrease for increasing number of storeys. For $\alpha=0.0$, the sensitivity of interstorey drift and base shear to η remained constant with increasing θ and number of storeys; while for $\alpha=0.25$, the sensitivity of interstorey drift and base shear to η decreased with increasing θ and number of storeys. Interstorey drift and base shear were also less sensitive to η and θ for the T-O case compared to the T-C case.

3.3.3. General observations

In general, the first yield was characterized by yielding of the braces, and subsequent yields were characterized by the flexural hinging in the columns and beams. However, the sequence in which the plastic hinges formed became increasingly complex as the number of storeys – and hence the number of plastic hinges – increased. For $\alpha=0.0$, increasing η was most effective in minimizing interstorey drift; while for $\alpha=0.25$, increasing θ was most effective in minimizing interstorey drift. For $\alpha=0.0$, decreasing η was most effective in minimizing base shear; while for $\alpha=0.25$, decreasing θ was most effective in minimizing base shear. The T-C braces were more effective in reducing interstorey drifts than the T-O braces, and the T-O braces were more effective in reducing base shear compared to the T-C braces.

3.4. Summary of Results of Parametric Study

The seismic responses of the frames were more significantly affected by η (the yield force parameter) and θ (the initial stiffness parameter) than by α (the post-yielding stiffness parameter) or β (the energy dissipation parameter). In fact, β had little effect on response. Increasing α , η , or θ tended to decrease interstorey drift but also had the effect of increasing base shear. This trend was clearly evident in both the NLTHA and pushover results. The NLTHA also revealed that the frames with bilinear braces tended to have lower storey accelerations and the frames with flag-shaped braces tended to have lower residual drifts. It is obviously not possible to deduce this trend from the pushover analyses. However, the responses of the frames with flag-shaped hysteretic braces, as measured by interstorey drift and base shear, were very similar to those frames with the bilinear hysteretic braces, further illustrating the dominance of the hysteresis backbone and the potential of pushover analyses.

The frames with T-O braces, in most cases, did not perform as well as the frames with T-C braces. However, the frames with T-O braces were more effective in reducing base shears. The trend of reduced base shear and increased drift for the T-O case was evident in both the NLTHA and pushover analysis results. For the frames in this study, response index values tended to decrease for increasing number of storeys. The pushover analyses also highlighted the less obvious trend of reduced sensitivity of interstorey drift and base shear to η for large α and θ , evident in the NLTHA results.

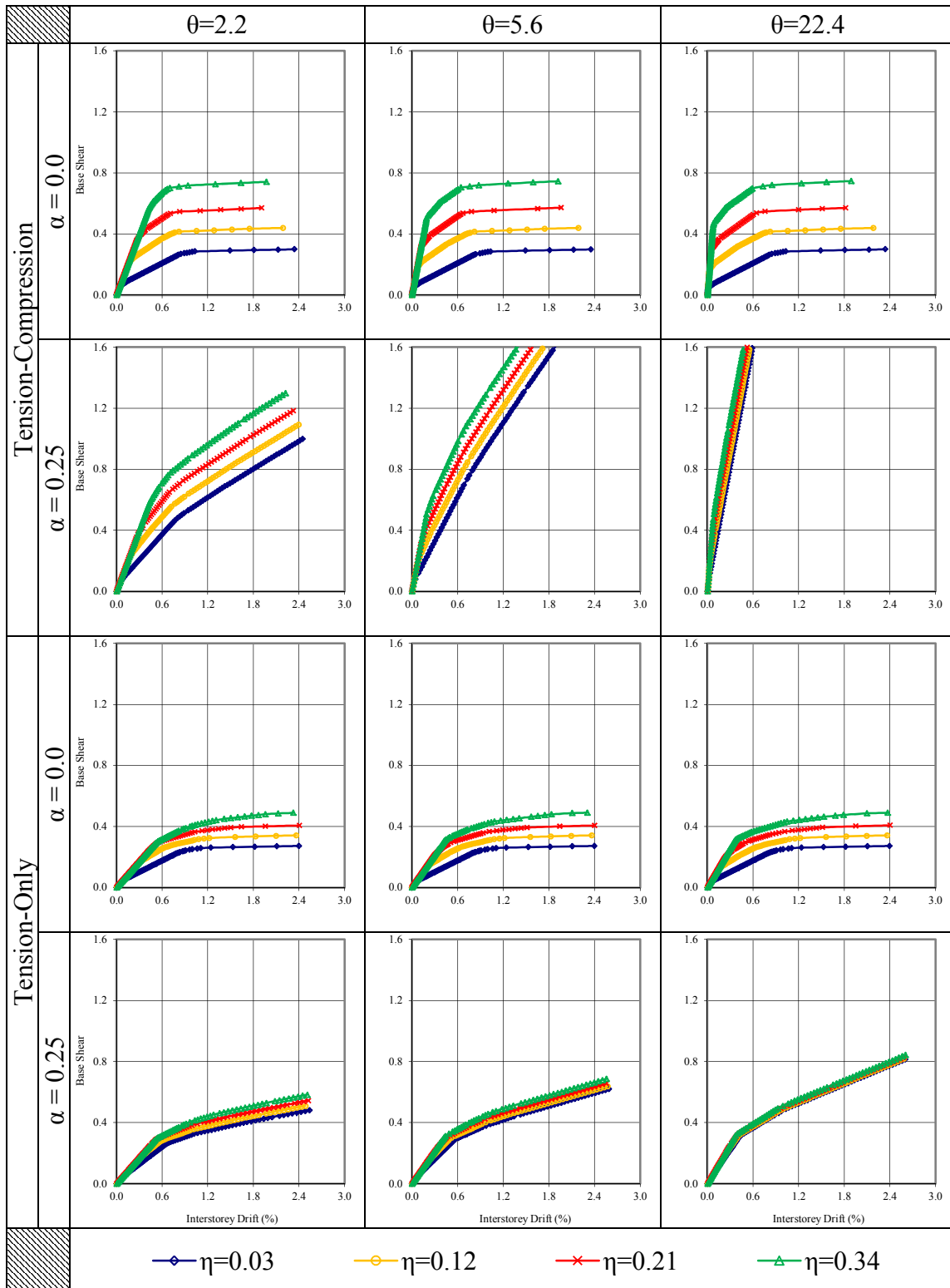


Figure 3.4. Pushover Analysis: Mean normalized base shear plotted as a function of mean normalized interstorey drift for the 4-storey frame

4. CONCLUSIONS

The following conclusions are drawn regarding the overall behaviour and utility of chevron braces with either bilinear or flag-shaped hysteretic characteristics in enhancing, and the ability of pushover

analysis to predict, the seismic performance of low-to-mid-rise steel frame structures:

1. The hysteretic seismic behaviour of chevron braced frames is largely governed by the backbone curve of the brace hysteresis. This was evidenced by the strong effect of α , η , and θ , and the very weak effect of β on the response of the frames showing the utility of pushover analyses in helping to predict seismic response.
2. Increasing α , η , or θ tended to decrease interstorey drift and increase base shear.
3. The flag-shaped and bilinear brace systems performed with equal efficiency in controlling interstorey drift and base shear of the frame structures. However, the flag-shaped braces were found to be more effective in reducing residual interstorey drift and the bilinear braces were more effective in reducing accelerations. This suggests that mixed bracing systems could possibly be used to advantage, where flag-shaped braces could be used to control residual displacements and bilinear braces to reduce accelerations.
4. T-C braces were generally more effective in reducing interstorey drift and T-O braces were more effective in reducing base shear.
5. The pushover analysis successfully predicted many of the trends evident from the NLTHA. Although not done in this study, these trends could be used to help determine advantageous brace parameter values suitable for parametric study.

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