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Research Paper

Effect of High Axial Load on Overstrength Factor of Intermediate Links in EBFs

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ABSTRACT

Eccentric bracing frames (EBFs) are one of the most suitable seismic resistance systems due to their high strength, ductility, and energy dissipation. In some EBF configurations, due to loading patterns or structural geometry, the link member can be subjected to a high axial load. The presence of high compressive axial loads increases the occurrence of buckling and thus reduces both its strength and ductility. Most of the studies conducted have focused on short links, and as mentioned in the commentary of the AISC seismic regulations, the effect of axial load on the behavior of intermediate and long links has not been sufficiently investigated, which highlights the need for further study. In this research, numerical modeling is first validated by experimental results. Subsequently, the overstrength factor of intermediate links made from European I-shaped sections subjected to axial loads is examined. The results indicate that the overstrength factor of intermediate links is lower than the prescribed value of 1.5 in the provisions.

Keywords:
Eccentrically braced frame; Intermediate link; Overstrength factor; High axial load; Finite element modelling

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1. Introduction

Eccentrically braced frames (EBFs) serve as an appropriate seismic resistance system that utilizes capacity-based design principles. During seismic loading, the plastic deformation is limited to the link beam, while other members are designed to behave elastically based on the yielding force of the link. To achive this desired behavior, the forces arising from the yielding of the link are ampilified by an overstrength factor. Therefore, the design of the link and its overstrength factor significantly influence the design of other members and the overall behavior of the frame. The presence of axial force is one of the influential factors in the behavior of the link and its overstrength factor. Due to the plastic deformation and significant rotation of the link beam, as well as the constraints caused by the concrete slab, tensile or compressive axial force is generated in the link.

Links in eccentric bracing frames (EBFs) are classified into three categories based on their length (e). A link is termed a short link if $e < 1.6\ (M_p/V_p)$, a long link if $e < 1.6\ (M_p/V_p)$, and an intermediate link if e falls between these values. Short links exhibit higher strength and ductility, but intermediate and long links are more commonly used due to their suitability for openings and architectural applications. Here, M_p represents the flexural strength, and V_p represents the shear strength of the link.

The link overstrength factor is defined according to Equation (1), where $V_{\max}$ is the maximum shear force of the link in cyclic loading, and V_e is the expected shear strength of the link.

$$\Omega = V_{max}/V_e \qquad (1)$$

In early experimental studies by Popov et al. (Engelhardt & Popov, 1992; Kasai & Popov, 1986a), a value of $\Omega = 1.5$ was suggested for link design. This value is still accepted in many seismic design codes, including AISC (341-16, 2016) and Eurocode 3 (de Normalizaciton, 2005). However, subsequent studies have shown that a constant value of Ω may not be appropriate for all links with different cross-sections and lengths. Hu et al. (Hu et al., 2018) explored finite elements for very short link beams, finding an overstrength factor as high as 1.9. This discrepancy raises concerns about potentially unsafe system designs. Aziz and Amanat (Aziz & Amanat, 2022) conducted numerical studies on links with I-shaped and box sections, highlighting that box sections tend to possess significantly greater overstrength factors compared to I-shaped sections. Al-Masabha (Almasabha, 2022) compiled shear link experimental results, revealing that the overstrength factor suggested by seismic codes could underestimate their actual values. Ozkilich (Ozkilikc, 2022) studied 150 long links to assess the effect of overstrength factors. The results showed that the value of Ω specified in AISC seismic guidelines might not be adequately conservative. In their studies on American I-shaped sections (W-sections), Mojarad et al. (Mojarad et al., 2017, 2019; Mojarad et al., 2020) demonstrated that the cross-sectional geometry can impact the link's behavior. Specifically, cross-sections with stocky flanges exhibit superior performance compared to other sections.

Axial force is a significant parameter influencing link design and affecting its seismic performance.

Dastmalchi (Dastmalchi, 2014) utilized nonlinear analysis to emphasize the significant influence of axial force when the link is connected to the column in EBFs. Furthermore, a finite element analysis was conducted on 22 link specimens to examine the impact of high axial force on their shear capacity. The study revealed that the shear capacity provided by AISC seismic provisions was non-conservative for links under high axial load. Mannheim and Popov (Manheim & Popov, 1983) conducted a study that further highlighted the significance of axial force in contributing to link instability. They emphasized the importance of reducing the shear capacity of the link when subjected to axial force. Kasai and Popov (Kasai & Popov, 1986b) investigated the behavior of I-shaped links with varying lengths under axial force. Their study revealed that longer links experienced premature failure due to the combined effects of bending moments, axial force, and normal stresses. To mitigate the impact of high axial force, they proposed modifications to enhance the link's shear strength, which have been incorporated into design provisions such as AISC 341 (341-16, 2016) and Eurocode 8 (Code, 2005). In their research, Della Corte et al. (Della Corte et al., 2013) investigated the influence of axial restraints on the tensile axial load in short links. Their numerical analysis revealed that very short links with ideal axial restraints can attain shear overstrength values of up to 2, surpassing the typical overstrength value of 1.5. Manganiello et al. (Manganiello et al., 2021) explored the impact of axial restraints on assessing link overstrength and ultimate rotation. Their study introduced empirical formulations to accurately evaluate short and very short links using European I-shaped sections under the influence of axial restraints. Ghafari et al. (Ghafari, et al., 2024) investigated the overstrength factor of intermediate links under axial loads using finite element modeling. The results showed that the presence of axial force in the link negatively impacts its seismic performance, leading to a decrease in strength and ductility.

In accordance with the commentary of AISC seismic provisions, the influence of axial load on the behavior of intermediate and long links remains unexplored. Therefore, the primary objective of this study is to investigate the overstrength factor (Ω) of intermediate links under different axial loads using numerical simulations. A comprehensive analysis is conducted on a total of 72 intermediate links, utilizing European I-shaped sections, and the results are presented and discussed.

2. Finite Element Modelling and Verification

In order to validate the accuracy of the finite element modeling, it is crucial to compare the response of the numerical models with that of the corresponding experimental specimens. The numerical models are simulated using the commercial software Abaqus (ABAQUS, 2014). Similar to previous numerical studies, this analysis does not take into account the effects of residual stress and low-cycle fatigue (Liu et al., 2020; Mohebkhah & Azandariani, 2020; Tashakori et al., 2019). In steel profiles, the shell element can be employed due to its small thickness compared to the other two dimensions. By utilizing the shell element, the stress in the direction of thickness is disregarded, resulting in reduced computational efforts. In this section, S4R elements are utilized, offering 3 degrees of freedom in translation and 3 degrees of freedom in rotation for each node. This element is well-suited for capturing large deformation behavior. To account for nonlinear geometric effects such as local buckling and P-δ effects caused by axial load, the Nlgeom option in Abaqus (ABAQUS, 2014) is utilized. To enhance computational efficiency, the reduced integration method is implemented.

The ASTM A992 steel is utilized in accordance with the experimental specimen (Arce, 2002). The material exhibits elastic properties, including a modulus of elasticity of 29,000 ksi and a Poisson's ratio of 0.3. The yield criterion adopts the Von Mises yield surface and an associated flow rule. Nonlinear kinematic hardening is implemented for plasticity definition, following the recommendations of Kaufmann et al. (Kaufmann et al., 2001). The boundary conditions for the isolated link are modeled following the Richards' approach (Richards, 2004). As depicted in Figure (1), the specific boundary conditions for the left and right ends of the link are implemented. Similar to the test setup by Kasai and Popov (Kasai & Popov, 1986b), a compressive axial load is applied to the left end of the link. These boundary conditions ensure accurate simulation of the loading condition.

The deformed shape and hysteresis response of the shear force versus the link rotation for the experimental especimen (UTA 6b) (Arce, 2002) and its corresponding numerical model are presented in Figure (2). The depicted consistency between the numerical model and the experimental results verifies the accuracy of the modeling process.

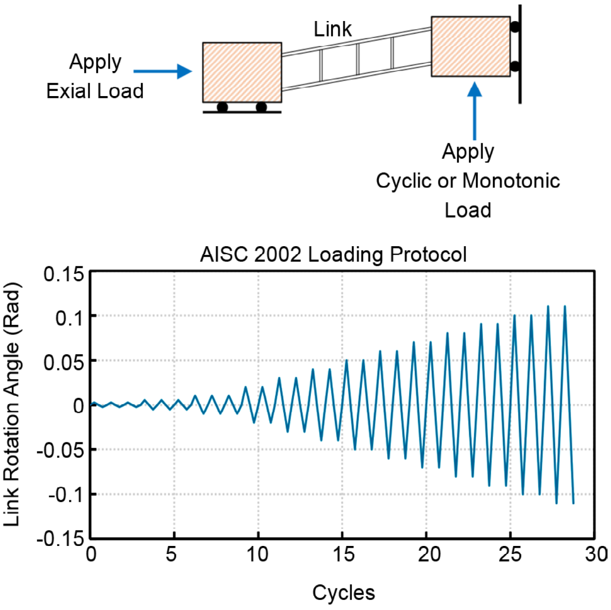


Figure 1. Boundary conditions (Richards, 2004) and loading protocol used in experiment (Arce, 2002).

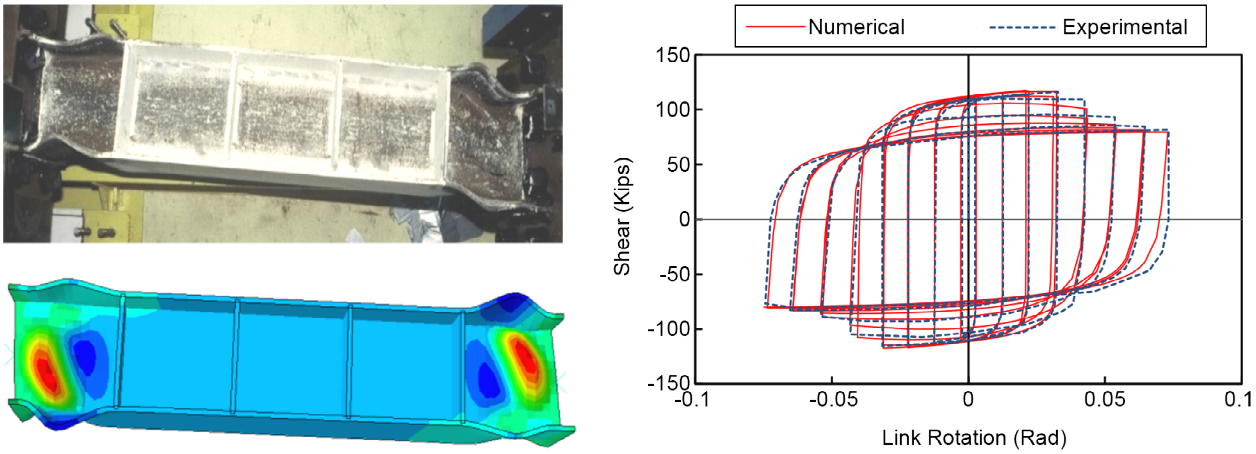


Figure 2. Deformed shape and hysteresis curve of experimental specimen and numerical model.

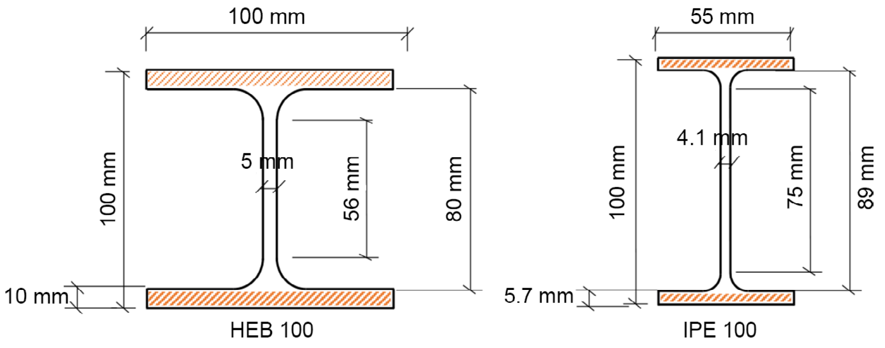


Figure 3. Cross-section geometry of European I-shaped beams.

3. Parametric Study

After validating the finite element model, a nonlinear analysis was conducted to examine the overstrength factor of European I-shaped sections. Figure (3) shows the cross-section geometry of two samples of IPE and IPB beams. Previous studies have indicated that sections with thick flanges exhibit a variable overstrength factor (Okazaki et al., 2005; Okazaki et al., 2009; Richards, 2004). In sections with a thick flange, the shear strength tolerated by the flanges can be substantial, resulting in an increased overstrength factor of the link. To investigate this further, a total of 72 models of I-shaped intermediate links with different cross-sections (HEB 100, HEB 280, HEB 600, IPE 100, IPE 270, and IPE 600) were chosen. These particular sections were carefully selected to encompass a wide range of section characteristics.

To consider the effect of compressive axial force, the link models are analyzed once without axial force and then under axial loads ratio (P_u/Py) of 0.15, 0.30, and 0.45, where P_u is the required axial strength and P_y is the axial strength of the link. According to the AISC seismic provisions (341-16, 2016), when the axial load ratio is greater than 0.15, its effect should be considered in design ($P_u/P_y \geq 0.15$). Additionally, to account for the effect of the intermediate link length (e), three lengths of 1.8 (P_u/Py), 2.0 (P_u/Py), and 2.3 (P_u/Py) have been used to properly cover the range of the intermediate link. To calculate the overstrength factor (Ω), the links are subjected to cyclic loading, and the maximum shear force obtained from the hysteresis curve is determined. Based on Equation (1), the link overstrength is obtained by dividing this value by the expected shear capacity of the link (V_e). The expected shear capacity of the link, V_e, is defined by Equation (2), where V_p is the plastic shear strenght and M_p is the plastic flexurel sterength accroding to Equations (3) and (4), respectively. In these equations, F_{ye} is the expected yield stress, d is the section depth, t_f is the flange thickness, and t_w is the flange thickness.

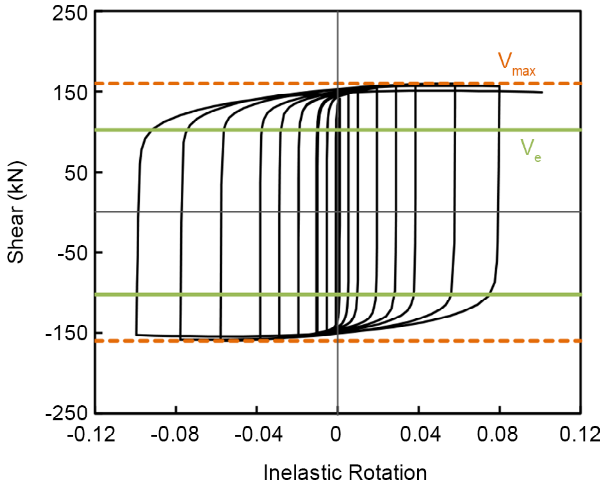
$$V_e = min\left\{V_p, \frac{2M_p}{e}\right\} \tag{2}$$

$$V_p = 0.6F_{ye}\left(d - 2t_f\right)t_w\sqrt{1-\left(P_u / P_y\right)^2} \tag{3}$$

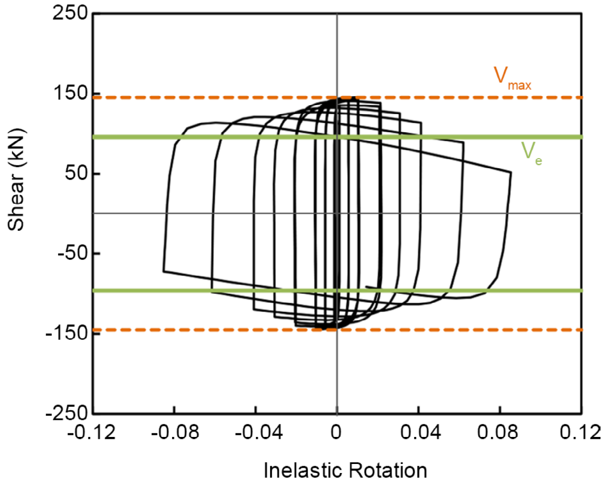
$$M_p = F_{ye}Z\left(\frac{1-\left(P_u / P_y\right)}{0.85}\right) \tag{4}$$

3. Results and Discussion

Figure (4) shows the hysteresis response of an intermediate link beam with an IPE 100 section, once without axial force and once under an axial load with a ratio of $P_u/P_y=0.35$. As evident, the presence of compressive axial force reduces the ductility and strength of the link. According to the hysteresis response in Figure (4), the overstrength factor is obtained by dividing the maximum shear force developed in the link (V_{max}) by the expected shear strength of the link (V_e). The results obtained from the finite element analysis for intermediate links made of IPE and IPB sections with different lengths and various axial forces are summarized in Table (1). These results are also depicted in Figure (5). The dashed line represents the overstrength factor of 1.5 as per the AISC seismic provisions. It can be seen that in almost all models, the obtained overstrength factor is less than the value required by the AISC provisions. The smaller overstrength factor of intermediate links may be attributed to shear-bending interaction, as mentioned in previous studies (Mohebkhah & Chegeni, 2014; Richards, 2004). In shear links, the yield criterion is based on the shear yielding of the web, whereas in intermediate links, simultaneous shear and bending yielding occurs, leading to reduced link performance.



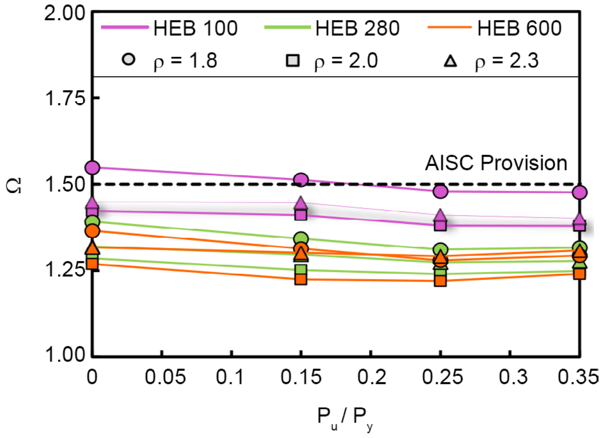
(a) Without Axial Load ($P_u / P_y = 0.0$)



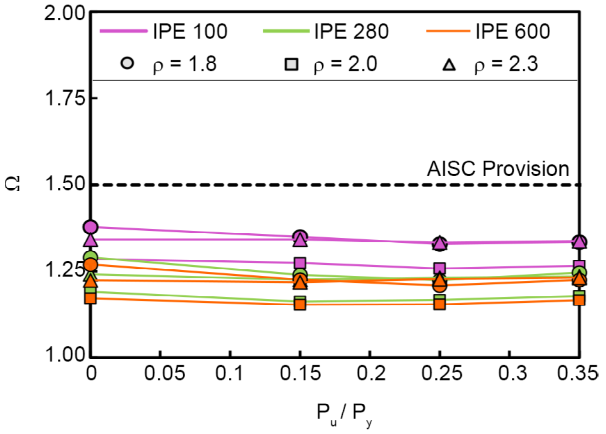
(a) With Axial Load ($P_u / P_y = 0.35$)

Figure 4. Hysteresis response of an intermediate link with HEB 100 section.

Another observation is the effect of the link's cross-section on the overstrength factor. According to Figure (5), links with an IPB cross-section have a larger overstrength factor than those with IPE sections. As mentioned earlier, links with a thick



HEB Intermediate Link



IPE Intermediate Link

Figure 5. Numerical results of the overstrength factor (Ω) of intermediate links.

Table 1. The overstrength factor (Ω) for different link length ratio of $e/(M_p/V_p)$ and axial load ratio, P_u/P_y.

P_u/P_y	HEB 100			HEB 280			HEB 600		
	$e/(M_p/V_p)$			$e/(M_p/V_p)$			$e/(M_p/V_p)$		
	1.8	2.0	2.3	1.8	2.0	2.3	1.8	2.0	2.3
0.0	1.55	1.42	1.45	1.39	1.29	1.32	1.37	1.27	1.32
0.15	1.51	1.41	1.45	1.34	1.25	1.30	1.31	1.22	1.30
0.25	1.48	1.38	1.41	1.31	1.24	1.27	1.27	1.22	1.29
0.35	1.48	1.38	1.40	1.32	1.25	1.28	1.28	1.24	1.31
P_u/P_y	IPE 100			IPE 270			IPE 600		
	$e/(M_p/V_p)$			$e/(M_p/V_p)$			$e/(M_p/V_p)$		
	1.8	2.0	2.3	1.8	2.0	2.3	1.8	2.0	2.3
0.0	1.38	1.29	1.34	1.29	1.19	1.24	1.27	1.17	1.22
0.15	1.35	1.27	1.34	1.24	1.16	1.23	1.23	1.15	1.22
0.25	1.33	1.26	1.33	1.22	1.17	1.23	1.21	1.15	1.23
0.35	1.33	1.27	1.34	1.24	1.18	1.23	1.23	1.17	1.23

flange can also contribute to shear resistance. Compared to IPE sections, IPB sections have a larger flange area relative to the section area, providing greater shear capacity. Although Figure (4) shows that compressive axial force significantly reduces the ductility of the link, Figure (5) indicates that the presence of axial force causes only a slight reduction in the overstrength factor of the intermediate link.

6. Conclusion

According to capacity-based design principles, the link overstrength (Ω) is crucial in the seismic design of eccentrically braced frames (EBFs). One of the factors that can affect the performance of the link is the presence of axial force. According to the AISC provisions, few studies have been conducted on the effect of axial force on the behavior of intermediate and long links, highlighting the need for further research. In this study, using finite element modeling, the cyclic behavior of 72 intermediate link models made of European I-shaped sections under different length and axial load ratios was investigated.

The findings are summarized as follows:

- The overstrength factor obtained is less than the required value of 1.5 in the AISC provisions. According to capacity-based design principles, this issue can lead to the uneconomical design of other capacity-based designed members.
- The overstrength factor varies depending on the type of cross-section of the link. In IPB sections, which have a significant flange thickness compared to IPE sections, the overstrength factor obtained is larger.
- Although the presence of axial force reduces the strength and ductility of the intermediate link, with the increase of axial force, the overstrength factor of the intermediate link decreases slightly.
- The overstrength factor of 1.5 in the AISC provisions is suggested based on experimental results conducted on American wide-flange sections (W-sections). The smaller overstrength factor of intermediate links with European sections compared to the recommended value of 1.5 in the code indicates the need for further investigation into the influence of the link's section.

Given the critical importance of correctly designing the link, it is recommended to further investigate the effect of axial force on other influencing factors in the link design, such as shear resistance, inelastic rotation, and energy absorption.

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