EVALUATION THE EFFECTOF LINK BEAMS' STIFFENERS WITH DIFFERENT CROSS-SECTIONS

SamiraEBRAHIMI
PHD Student in Earthquake engineering, Tehran University, Tehran, Iran
samira.ebrahimi@ut.ac.ir

HamzehSHAKIB
Professor, TarbiatModares University, Tehran, Iran
shakib@modares.ac.ir

Masoud SOLTANI MOHAMMADI
Associate professor, TarbiatModares University, Tehran, Iran
msoltani@modares.ac.ir

Keywords: Link Beam, Stiffener, Cross-Section

ABSTRACT

Link beams of eccentrically braced frames similar to ductile fuses, in addition to avoiding bracing buckling, attract earthquake energies. Link beams' stiffenershave significant effect in earthquake energy dissipation and their suitable arrangement, causes increasing the rotation capacity of link beams.

In this investigation, link beams with tubular and I-shaped cross-sections that are similar in area, moment of inertia, length and stiffener spacing, were compared together and the effect of link beam section and its stiffeners on the rotation capacityof link beams has been studied. Also in this study, tubular link beams for different values of flange compactness ratio and web compactness ratio were compared together and this question has been answered that the flange compactness ratio has more impact on the rotation capacity of tubular link beams or web compactness ratio?In this investigation, the link beams were modelled in ABAQUS and in order to loading, AISC-2005 loading protocol was used. In this modelling, shell elements for flanges, webs and stiffeners have been utilized and also the nonlinear kinematic hardening plasticity material model has been used.

The result of this investigation indicates that, if link beams with various cross-sections have geometrical similarity, I-shaped link beams will have approximately two times more rotation capacity than tubular link beams and it will be more significant with increasing of flange compactness ratio and link beamlength. Also it can be concluded that flange compactness ratio has more impact on the rotation capacity of tubular link beams, in a way that for one web compactness ratio, with increasing of flange compactness ratio, the rotation capacity decreases approximately 69% but for one flange compactness ratio, with increasing of web compactness ratio, the rotation capacity decreases approximately 36%.

INTRODUCTION

Eccentrically braced frames (EBFs) by covering the advantages of moment-resisting frames (MRFs) and concentrically braced frames (CBFs) have been used as seismic load resisting systems in buildings for more than three decades. In eccentrically braced frames (EBFs), the link beams transmit bracing forces through themselves into the columns and other bracings and, in the end, create dominant forces in the bracings. Link beams, similar to ductile fuses, in addition to avoiding bracing buckling, attract earthquake energies. In EBF systems, failure and yielding should happen in the link beams, and other members of the structure must remain in elastic behavior. On the other hand, link beams prevent transmitting of more forces to the other members by yielding (Roeder and Popov 1978), therefore, these link beams are so important.

Numerous investigations were done on link beam length by different scientists (Kasai and Popov1986a; Boscoand Rossi 2009), have shown that link beams with length less than 1.6Mp/Vp (where, Mp is the plastic moment strength and Vp is the plastic shear strength), called short link beams, are dominated by shear web yielding. Those longer than 2.6Mp/Vp, called long link beams, are dominated by flexural yielding. Link beams with lengths between these limits, called intermediate link beams, experience both flexural and shear yielding simultaneously.

Investigations have shown that the convenient arraying of stiffeners in the web of link beams causes delay of web buckling and increases energy dissipation capabilities of the system, so formulas have been derived for stiffener spacing of web and their dimensions by different scientists (Hjelmstad and Popov 1983; Malley and Popov 1984; Kasai and Popov 1986b). I-shaped and tubular cross-sections are used in link beams of eccentrically braced frames. In bridge piers and towers, link beams with I-shaped cross-sections or wide flange require lateral bracings to prevent lateral torsional buckling, however, because of numerous problems of providing lateral bracings, the use of them has been limited (Dusicka et al., 2002; Itani 1997; Berman and Bruneau2005).

Berman and Burunue presented a model for tubular link beams in 2007. In their model, tubular link beams' stiffeners are connected to the flange and the web from the outside around and using stiffeners connected to the web of tubular link beams from inside is acceptable, if flange stiffeners have no significant impact on flange buckling (Berman and Burunue 2007). I-shaped link beams' stiffeners are connected to the web from two sides.

In this investigation, link beams with tubular and I-shaped cross-sections were compared together and the effect of link beam section and its stiffeners on the rotation capacity of link beams has been studied. Also in this study, this question has been answered that the flange compactness ratio has more impact on the rotation capacity of tubular link beams or web compactness ratio?It should be noted that link beams with tubular and I-shaped cross-sections are similar in area, moment of inertia, length and stiffener spacing.

DESIGN EQUATIONS FOR LINK BEAMS WITH VARIOUS SECTIONS

In the link beams with various cross-sections, usually the shearing force is tolerated by the link beam web and the moment by the link beam flange. Tubular and I-shaped link beams are shown in Fig. 1.

(a)(b)

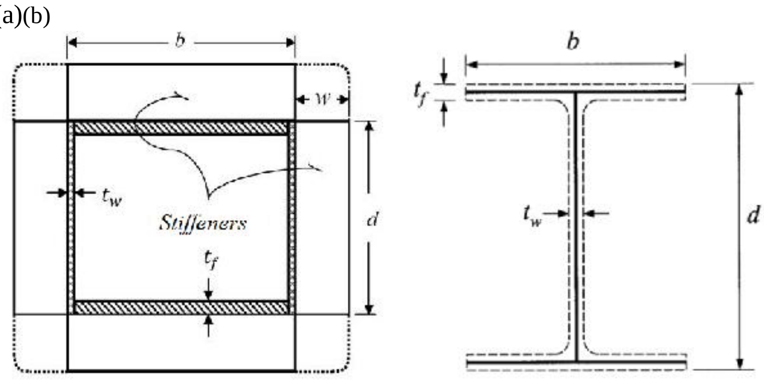

Figure 1.Cross-sections of (a) tubular (b) I-shaped link beams.

The plastic shear strength and the plastic moment strength of such cross-sections can be written as:
The plastic shear strength, V_P, for tubular cross-sections:

$$V_P = \frac{2}{\sqrt{3}} F_{yw} t_w (d - 2t_f) \tag{1}$$

The plastic moment strength, M_p, for tubular cross-sections:

$$M_p = F_{yf} t_f (b - 2t_w)(d - t_f) + F_{yw} \frac{t_w d^2}{2} \tag{2}$$

The plastic shear strength, V_P, for I-shaped cross-sections:

$$V_P = \frac{1}{\sqrt{3}} F_{yw} t_w (d - 2t_f) \tag{3}$$

The plastic moment strength,Mp, for I-shaped cross-sections:

$$M_p = F_{yf} t_f b(d - t_f) + F_{yw} \frac{t_w (d - 2t_f)^2}{4} \tag{4}$$

Where,$F_{yw}$is the web yield strength, F_{yf} is the flange yield strength,$t_w$is the web thickness,$t_f$is the flange thickness, b is the flange width and d is the web depth (Berman and Bruneau 2007; AISC 2005).

STIFFENER SPACING

Web buckling of link beams in EBFs cause rapid strength and stiffness degradation, and this significantly impedes the energy dissipation capabilities of the system. Web stiffeners can be used to delay web buckling beyond a certain rotation level.

Boundary conditions of the web sides that adjacent to the flanges and stiffeners were used in stiffener spacing formula. The stiffener spacing of link beams with various cross-sections is as follows:

a) I-shaped link beam (Kasai and Popov 1986c):

$$a = \begin{cases} 30t_w - \frac{d}{5} \Rightarrow \circ \le 1.6 \\ 52t_w - \frac{d}{5} \Rightarrow \circ = 2.6 \end{cases} \rightarrow a \le d \tag{5}$$

b) Tubular link beam (Berman and Bruneau, 2005):

$$a = \begin{cases} 20t_w - \frac{d}{8} \Rightarrow \circ \le 1.6 \\ 37t_w - \frac{d}{8} \Rightarrow \circ = 2.6 \end{cases} \rightarrow a \le d \tag{6}$$

$$\circ = \frac{e}{Mp/Vp} \tag{7}$$

Where,a is stiffener spacing, p is the normalized link beam length, e is the link beam length and the other terms are as previously defined.

The above stiffener spacing is applicable for shear and intermediate link beams. For flexural link beams (ρ>2.6), stiffeners are only used in the distance of 1.5b at both ends of the link beams because of flange buckling (Engelhardt and Popov 1992).Linear interpolation is used in link beams with any case of cross-section and stiffener arraying, for normalized link beams lengths that are between 1.6 and 2.6.

STIFFENER SIZING

Stiffener sizing must be appropriate to bear the force generated in the stiffeners. The stiffener sizing of link beams with various cross-sections is as follows:

a) I-shaped link beam (AISC 2005):

$$\begin{cases} w \le \frac{b}{2} - t_w \\ t_s \ge 0.75 t_w or 8mm \end{cases} \tag{8}$$

b) Tubular link beam (Berman and Bruneau 2007):

$$A_{st} = \frac{F_{uw} t_w a}{0.828 F_{yst}} \left[1 - \frac{a/d}{\sqrt{1 + \left(a/d\right)^2}} \right] \quad (9)$$

$$A_{st} = w t_s \quad (10)$$

Additionally, to prevent stiffener buckling, web stiffeners should satisfy the minimum moment of inertia requirements given in Appendix F2.3 of the AISC LRFD Specifications (AISC 1980), namely:

$$j = \frac{2.5}{\left(\frac{a}{d}\right)^2} \geq 0.5 \quad (11)$$

where

Where,I_{st} is the stiffener moment of inertia that is equal to $\frac{(w^3 t_s)}{3}$.

Where, $t_s$is the stiffener thickness, w is the stiffener width, F_{yst} is the stiffener yield strength and F_{uw} is the ultimate strength of link beam web.

DEFINITION OF LINK BEAM SPECIMENS

In this investigation, link beams with I-shaped and tubular cross-sections have been considered with flange compactness ratios of 8, 17 and 24, web compactness ratios of 12, 16 and 24 (note that these compactness ratios for I-shaped cross-sections are 6, 8 and 12) and normalized link beam lengths of 1.2, 1.6, 2.1 and 3. The tubular specimens were set to the flange thickness of 16 mm and the web thickness of 8 mm. Also the I-shaped specimens were set to the flange thickness of 16 mm and the web thickness of 16 mm.

In all of the specimens, ASTM A572 Gr. 50 steel was used, and the related stress-strain curves are shown in Fig. 2.

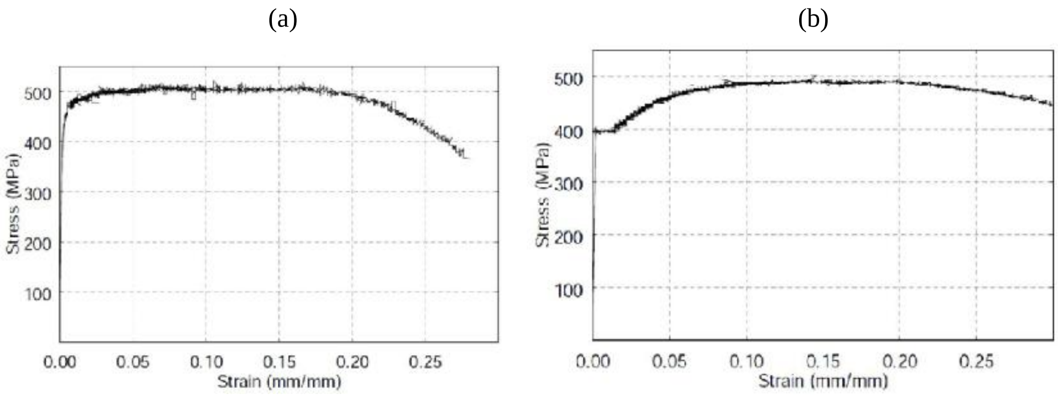

Figure 2.Stress-strain curves of (a) web material (b) flange and stiffener material.

Here, are tried to compare the behaviour of tubular and I-shaped link beams. For this purpose, tubular and I-shaped link beams with equal area, moment of inertia, length and stiffener spacing were considered. For calculating the stiffener spacing in both sections, stiffener spacing of tubular link beams was used and stiffener sizing for each section was calculated separately .Because of executive problems, using of I-shaped cross-section stiffeners that have width nearly equal to half a flange width, is impossible for tubular link beams.

FINITE ELEMENT MODELS

The link beams were modelled in ABAQUS. In this modelling, shell elements for flanges, webs and stiffeners were utilized. And also the nonlinear kinematic hardening plasticity material model was used. Boundary conditions were considered similar to the model of Richards and Uangas shown in Fig. 3 (Richards and Uang2005).

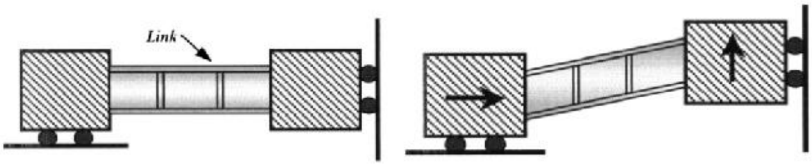

Figure 3.Boundary conditions (a) model before loading (b) deformation of model after loading.

For applying loads, AISC 2005 protocol was applied that is the application of vertical displacement at the link beam end.

DEFINING MODEL INELASTIC ROTATION CAPACITY

For determining the inelastic rotation capacity of link beam, a backbone curve of the shear force versus inelastic rotation hysteresis was used. The inelastic rotation capacity, γ_p, was defined as the point where the backbone curve degraded below %80 of the maximum shear.

VERIFICATION

For validating the numerical studies done, the experimental results of Berman and Bruneau have been utilized. In their investigation, a single storey frame and a span with the height of 3150 mm, width of 3660 mm and a tubular link beam with the below dimensions have been considered.

$d = b$=150 *mm*, t_f=16 mm, t_w=8 *mm*,*e* 460 *mm*, *a* 152 *mm*, *w* 64 *mm*, t_s=10 *mm.*

ASTM A572, Gr. 50 steel was used for the web, flange and stiffeners material. The material applied for the flanges and the stiffeners had the yield stress (F_{yf}) and the ultimate stress (F_{uf}) of 393 MPa and 490 MPa, respectively. The material applied for the webs had the yield stress (F_{yw}) and the ultimate stress (F_{uw}) of 448 MPa and 510 MPa, respectively. This cross-section had the plastic shear (V_p), the plastic moment (M_p) and link beam length (e) of 495 KN, 158 KN-m and 456 mm, respectively. So the normalized link beam length is ρ=1.44, then link beam is shear.

In their investigation, was used ATC-24 protocol for loading, which is horizontally applied at the top of each column. For studying the results validity, the model similar to the motioned model was built in ABAQUS and its hysteresis curve was compared to the hysteresis curve of Berman and Bruneau(Fig. 4) (Berman and Burunue 2007).

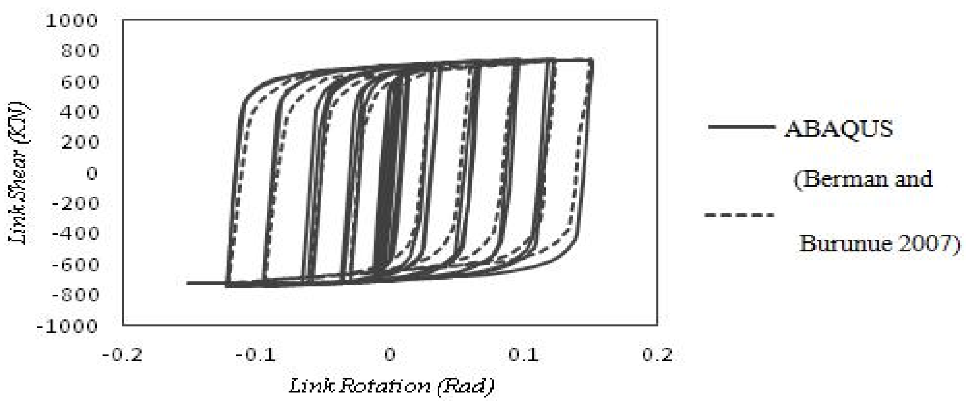

Figure 4. Comparison of the model built in ABAQUS and the experimental results of Berman and Bruneau.

Comparison of two curves shows that the models built in ABAQUS enjoy reasonable validity.

INVESTIGATION OF THE RESULTS OF FINITE ELEMENT MODELS

In this paper, link beams with tubular and I-shaped cross-sections were compared together and the effect of link beam section and its stiffeners on the rotation capacity of link beams has been studied.Table 1 gives rotation capacity of the link beams with tubular and I-shaped cross-sections for different values of flange compactness ratio, web compactness ratio and normalized link beam length (p).

Table 1. Stiffener spacing and rotation capacity of the link beams

Section	$\frac{b'}{t_f}$	$\frac{d'}{t_w}$ (T)	$\frac{d'}{t_w}$ (I)	γu (rad) ρ=1.2		γu (rad) ρ=1.6		γu (rad) ρ=2.1		γu (rad) ρ=3	
				(T)	(I)	(T)	(I)	(T)	(I)	(T)	(I)
S1	8	12	6	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
S2	8	16	8	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
S3	8	24	12	0.2	0.2	0.2	0.2	0.2	0.2	0.16	0.2
S4	17	12	6	0.2	0.2	0.2	0.2	0.2	0.2	0.066	0.2
S5	17	16	8	0.2	0.2	0.2	0.2	0.11	0.2	0.057	0.2
S6	17	24	12	0.2	0.2	0.2	0.2	0.2	0.2	0.041	0.2
S7	24	12	6	0.2	0.2	0.093	0.2	0.082	0.2	0.04	0.047
S8	24	16	8	0.2	0.2	0.082	0.2	0.05	0.2	0.03	0.046
S9	24	24	12	0.2	0.2	0.11	0.2	0.039	0.2	0.021	0.044

In Table 1, b' and d', are $b - 2t_w$ and $d - 2t_f$ for tubular link beams, respectively and, $b - t_w$ and $d - 2t_f$ for I-shaped link beams, respectively. Where, $\frac{b'}{t_f}$ is the flange compactness ratio, $\frac{d'}{t_w}$ is the web compactness ratio.

It can be concluded from Table 1 that, if link beams with various cross-sections have geometrical similarity, I-shaped link beams will have approximately two times more rotation capacity than tubular link beams and it will be more significant with increasing of flange compactness ratio and link beam length.This preference is because of the better performance of I-shaped link beams' web comparing to tubular link beams' web. In I-shaped link beams, both sides of the web is surrounded from up and down by flanges and from around by stiffeners, leading to creation of clamped boundary conditions around the web. But in tubular link beams, one side of the web is surrounded from up and down by flanges and from around by stiffeners. In this state, simply supported boundary conditions are created around the web. Clamped boundary conditions in around of I-shaped link beams' web cause delay local buckling and achieve more rotation that this preference is more significant in long I-shaped link beams.Fig. 5 shows the link beam shear versus link beam rotation hysteresis curve for S7, ρ=2.1

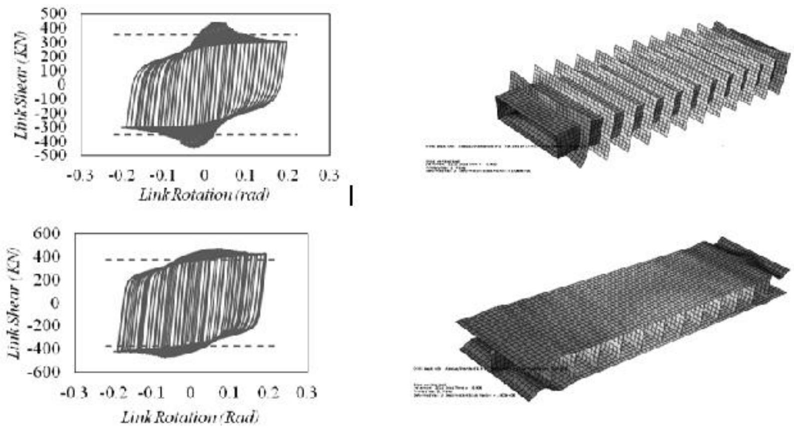

Figure 5.Deformed geometry and the link beam shear versus the link beam rotation hysteresis curve for s_7, ρ=2.1

In finite element models, blacker colours indicate more stress and strain. As a result, more stress and strain exist in both ends of the link beams.

For preventing flange and web buckling of link beams, scientists have considered limitations for flange and web compactness ratios. Here, this question has been answered that which of the flange compactness ratio and web compactness ratio has more impact on the rotation capacity of tubular link beams. It can be concluded from Table 1 that flange compactness ratio has more impact on the rotation capacity of tubular link beams, in a way that for one web compactness ratio, with increasing of flange compactness ratio, the rotation capacity decreases significantly that this decreasing is approximately 69% but for one flange compactness ratio, with increasing of web compactness ratio, the rotation capacity decreases low that this decreasing is approximately 36%.

CONCLUSIONS

The results of this investigation indicate that if tubular and I-shaped link beams having equal area, moment of inertia, length andstiffener spacing, I-shaped link beams will have approximately two times more rotation capacity than tubular link beams and it will be more significant with increasing of flange compactness ratio and link beam length. This preference is because of the better performance of I-shaped link beams' web comparing to tubular link beams' web. In I-shaped link beams, both sides of the web is surrounded from up and down by flanges and from around by stiffeners, leading to creation of clamped boundary conditions around the web. But in tubular link beams, one side of the web is surrounded from up and down by flanges and from around by stiffeners. In this state, simply supported boundary conditions are created around the web. Clamped boundary conditions in around of I-shaped link beams' web cause delay local buckling and achieve more rotation that this preference is more significant in long I-shaped link beams.

The results of evaluation the effect of the flange compactness ratio and web compactness ratio on the rotation capacity of tubular link beams indicate thatthe flange compactness ratio has more impact on the rotation capacity of tubular link beams, in a way that for one web compactness ratio, with increasing of flange compactness ratio, the rotation capacity decreases significantly that this decreasing is approximately 69% but for one flange compactness ratio, with increasing of web compactness ratio, the rotation capacity decreases low that this decreasing is approximately 36%.

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