Study the Feasibility of Transferring the Energy Absorption from Link Beam to Braces in Eccentrically Braced Frames

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ABSTRACT :

Eccentrically braced frame is an effective lateral-resistant system which simultaneously has the advantages of rigidity of concentrically braced frames and ductility of moment-resisting frames. The segment of beam located between two braces is known as link beam. The link beam acts as a fuse and prevents the other members of frame to enter the inelastic range. The link absorbs a significant amount of energy by inelastic deformation. One of the problems of the eccentrically braced frames is the repair of frame after the earthquake. The beam should be replaced since significant inelastic deformations occurred in the link beam. If it becomes possible to transfer the energy absorption from link to braces, the repair will be fast and less expensive, since the replacement of braces is very simple comparing to the replacement of beams. In this study, lower strength steel is used for the braces according to the general concept of easy-going steel (EGS). The brace yields in less displacement and the amount of energy absorption increase significantly. The maximum acceptable area of braces is obtained as a function of area, height and inertia moment of beam, geometrical properties of frame and yield stress ratio of constructional steel and EGS. Then a finite element model was developed according to an experimental test carried out by Berman et al. on an eccentrically braced steel frame and the results of the finite element model and the experiment were compared and good agreement was achieved. Having verified the model, pushover analysis was conducted for various frame models. The results confirmed that energy absorption transfer from link beam to braces is feasible.

KEYWORDS: Eccentrically Braced Frame, Link Beam, Energy Absorption, Yielding, Easy-Going Steel

1.INTRODUCTION

Seismic resistant eccentrically braced frames (EBFs) are a lateral load resisting system that are capable of combining high stiffness in the elastic range with good ductility and energy dissipation capacity in the inelastic range. In this system, the segment of beam placed between the braces absorbs the earthquake energy by large inelastic deformations and other members essentially remain elastic.

Although the large inelastic deformation of the link can dissipate large amounts of earthquake energy, the repair of the system will be hard and expensive, since the deformed beam should be replaced by a new one while the floor load is tolerated by jacks or other devices. Moreover, the large deformation of link beam will cause damages to the floor slab which should be also repaired after the earthquake.

In this paper, the feasibility of transferring the energy absorption from the link beam to the braces is studied. In other words, the energy absorption is tried to be limited in the braces and other members maintain in the elastic range. In this manner, the deformed frame will be easier and cheaper to be repaired. Classic and finite element methods are used in this study.

2. CLASSIC METHOD

As it can be seen from figure 1, the beam-to-column and column-to-base connections are assumed to be pinned connections. Furthermore, bending moments in the braces are ignored.

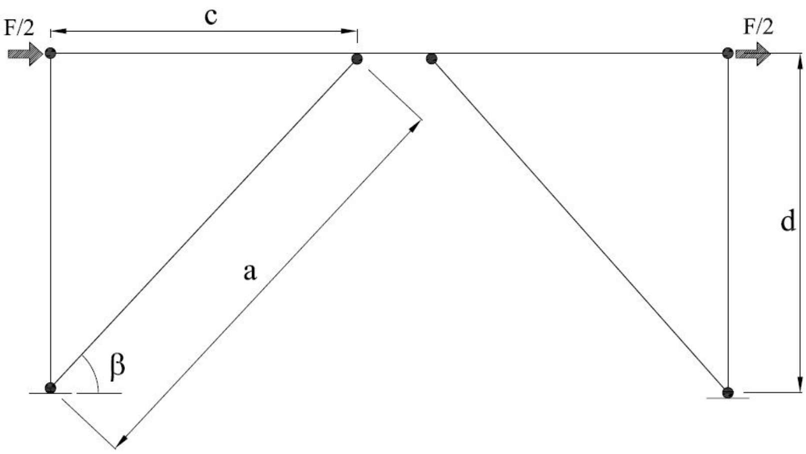

Figure 1: The geometry of a K-shape eccentrically braced frame

A force of magnitude F is applied to the frame and the drift U can be obtained by classic methods as equation 1.

$$U = \frac{F}{E}\left(\frac{a^3}{2.c^2.A_b} + \frac{c}{2.A_g} + \frac{d^2.(b-2.c)^2}{12I_g.b}\right) = \frac{F}{E}N \qquad (1)$$

Where F is the applied force, E is the elasticity modulus, a is the length of the braces, d is the length of the column, b is the width of frame, A_b is the cross section area of the braces, A_g and I_g are the cross section area and the moment of inertia of the beam respectively. To avoid the repetition of the long terms in the parenthesis, the summation of the three terms in the parenthesis is assumed to be N. The rotation angle of the link beam can be calculated by equation 2.

$$\gamma = \frac{F.N}{E.d}.(\frac{b}{b-2.c}) \qquad (2)$$

The value of shear and bending moment in the link beam and the brace axial force can be calculated by writing the equilibrium equations. Link shear, link bending moment and brace axial force can be calculated by equations 3, 4 and 5 respectively.

$$\text{Link shear} = \frac{F.d}{b} \tag{3}$$

$$\text{Link maximum bending moment} = \frac{F.d(b-2.c)}{2.b} \tag{4}$$

$$\text{Brace force} = \frac{F.a}{2.c} \tag{5}$$

By means of Von Mises yield criteria, the shear and bending moment in the link beam should satisfy the equation 6 to prevent the yield in any point of the link beam.

$$\sigma_y > \sqrt{3.\left(\frac{M^2 y^2}{2.I_g^2} + \frac{V^2 q^2}{I_g^2 .t^2}\right)} \tag{6}$$

where V and M are shear and the maximum bending moment of link beam respectively. The fist moment of area, q, should be calculated for the variable height y. The thickness of the cross section at the height y is equal to t.

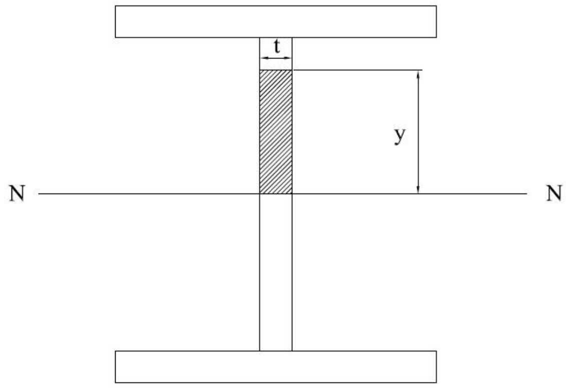

Figure 2: Cross section of link beam

In the case of short link beams, where the shear is predominant, the bending moment can be ignored. The critical point of the link beam is on the neutral axis, since the maximum shear in the height of the beam section occurs in this place. Ignoring the effect of bending moment, the equation 7 should be satisfied for an I-shaped link beam to prevent the yield of link at any point.

$$F < \frac{8\sqrt{3} I_g \sigma_y b}{3h^2 d} \tag{7}$$

Where h is the height of I-shaped beam.

The purpose of this paper is to transfer the energy absorption from the link beam to the braces. Therefore, it is desirable that the braces be fully yielded before yielding begins in the link beam. If all of the brace cross section is assumed to be yielded, the applied force on the frame should satisfy equation 8.

$$F \geq \frac{2c\sigma_y A_b}{a} \tag{8}$$

From equations 7 and 8, it can be concluded that the applied force on the frame should satisfy equation 9 to prevent the yield of link beam and enable the braces to be fully yielded.

$$\frac{2c\sigma_y A_b}{a} \leq F < \frac{8\sqrt{3}I_g \sigma_y b}{3h^2 d} \tag{9}$$

It is acceptable that after the occurrence of yielding in all of the brace cross sections the yielding begins in the link beam. Equation 10 should be satisfied to assure that the beginning of yield in the link beam is after the full yield of braces.

$$A_b < \frac{4.\sqrt{3}}{3}.\frac{b.a}{d.c}.\frac{I_g}{h^2} \tag{10}$$

Where A_b is the cross section area of the braces, and I_g is the moment of inertia of the beam. The geometrical characteristics of the frame a, b, c and d are defined before. The section height of the beam is equal to h. This equation determines the maximum cross section area of the brace to prevent the yielding of the link beam. As it can be seen from figure3, this area depends on the height and moment of inertia of the beam and also on the width to height ratio of the frame.

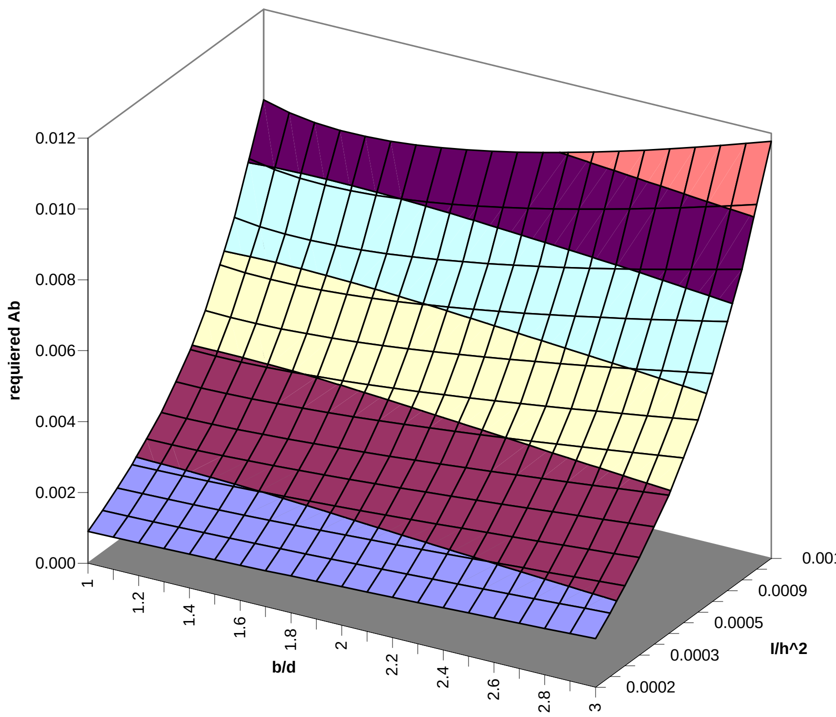

Figure 3: Maximum acceptable cross section area of braces

It is desirable to prevent the buckling of compressive brace before the brace is fully yielded. In other words, elastic buckling of braces is not acceptable. To prevent elastic buckling of the compressive brace, equation 11 should be satisfied.

$$I_b > \frac{F.a^3}{2.\pi^2.E.c} \tag{11}$$

So the equation 10 should be satisfied to prevent the yield of link beam and equation 11 should be satisfied to prevent the elastic buckling of the braces. In other words, for a specific section of beam, the cross section of brace should be less than $\frac{4.\sqrt{3}}{3}.\frac{b.a}{d.c}.\frac{I_g}{h^2}$ and the moment of inertia of the brace should be greater than $\frac{F.a^3}{2.\pi^2.E.c}$.

The purpose of this article is to limit the energy absorption of a frame to occur just in braces, so the beam segment outside of the link beam should not yield. This part of the beam is under axial force and bending moment. The maximum moment occurs in the vicinity of the link beam. The stress in the beam can be calculated by equation 12.

$$\sigma = \frac{F/2}{A_{Beam}} \pm \frac{M.y}{I_{Beam}} \tag{12}$$

Using Von Mises yield criteria, equation 13 is obtained to prevent the yield of the beam segment out of the link beam before the full yielding occurs in the braces. The corresponding surface which shows the maximum acceptable brace area is shown in figure 4.

$$A_{Brace} \le \sqrt{\frac{2}{3}}.\frac{a}{c}.\frac{1}{\left(\frac{1}{A_{Beam}} + \frac{d(b-2.c).h}{4.b.I_{Beam}}\right)} \tag{13}$$

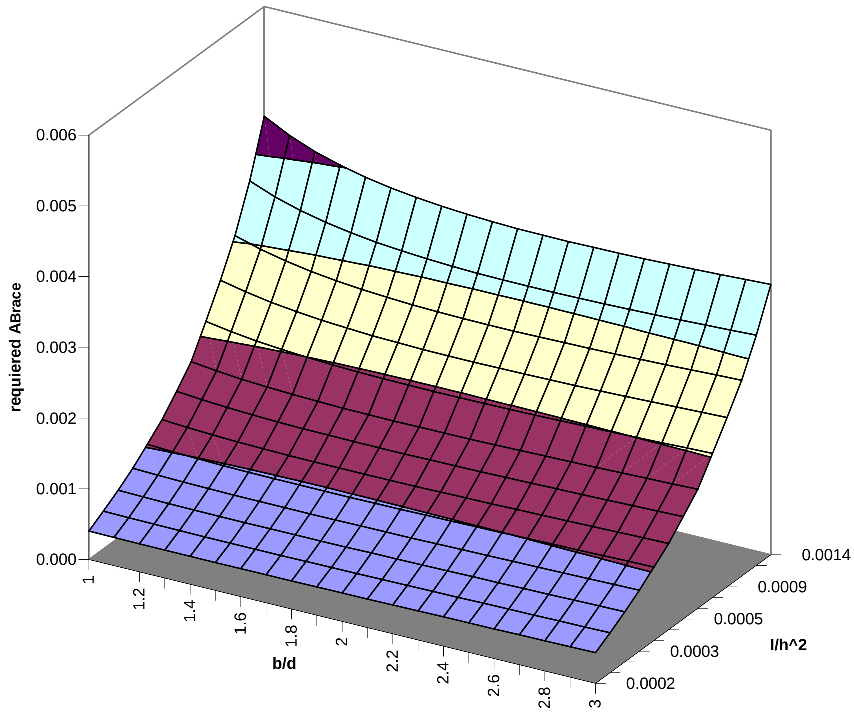

Figure 4 : maximum acceptable brace area to prevent the yield of beam segment out side of the link

A useful method to increase the energy absorption of the braces is to use lower strength steel for the braces. According to the general concept of easy-going steel, this lower strength steel is called Easy-going steel (EGS). The best EGS which is suggested for the braces is pure iron with yield stress between 90 N/mm^2 to 120 N/mm^2. The percentage of the typical elements added to iron to make steel like Carbon, Manganese, Silicon and Chromium are much lower in easy-going steel (EGS) compared to other constructional steels.

The elasticity modulus of EGS is equal to that of other constructional steels. This significantly increases the EGS ductility, since the member made of EGS yields in smaller displacements and its energy absorption is increased. Stress-strain curves of constructional steel (ST37) and Iron (EGS) are shown in figure 4.

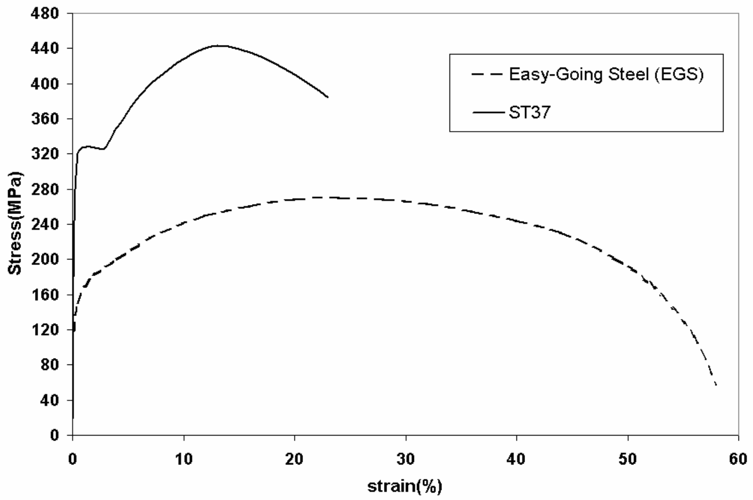

Figure 4: Stress-strain curve for Iron (EGS) and constructional steel

EGS is preferable to constructional steel or high-strength steel due to the following reasons:

- EGS has significantly higher ductility than other constructional steels.
- The elasticity modulus is equal for EGS and other constructional steels.
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Since the ultimate load carrying capacity should not change when EGS is used, the thickness of members should be increased because of the lower yield stress of EGS. So the thickness of structural members made of EGS is greater compared to the thickness of the same members made of common constructional steel.

If the yield stress of EGS is assumed to be equal to $k.\sigma_y$, wher σ_y is the yield stress of constructional steel, equation 12 can be derived from equation 10.

$$A_{Brace} < \frac{4.\sqrt{3}}{3}.\frac{I_g}{h^2}.\frac{b.a}{c.d}.\frac{1}{k} \tag{14}$$

As it can be seen, the limitation of brace area is relaxed in this case, since the ratio 1/k is more than unity. Furthermore, when the thickness of brace is increased because of using EGS instead of constructional steel, the moment of inertia of the brace increases consequently. This will relax the limitation exists for I_b. Equation 13 can also be written in the form of equation 15.

$$A_{Brace} \leq \sqrt{\frac{2}{3}}.\frac{a}{c}.\frac{1}{\left(\frac{1}{A_{Beam}} + \frac{d(b-2.c).h}{4.b.I_{Beam}}\right)}.\frac{1}{k} \tag{15}$$

After the full yield of the braces, they are permitted to buckle. So the amount of F in equation 11 is substituted by the amount of force which can fully yield the braces. Equation 13 is obtained in this way.

$$I_{Brace} > \frac{k.\sigma_y.A_b.a^3}{\pi^2.E} \tag{16}$$

3.FINITE ELEMENT MODELING

After obtaining the classic equations, finite element method is used to verify the obtained results. ABAQUS finite element program is used to develop finite element models. 2D beam elements were used in the models. The finite element model is verified by the results of an experimental test carried out by Berman and Bruneau in 2006. The results are compared in figure 5. As it can be seen, there is a good agreement between the results of finite element model and the results of the experimental test and there are just some little differences. Since 2D beam elements are used, the finite element model has more stiffness compared to the real frame.

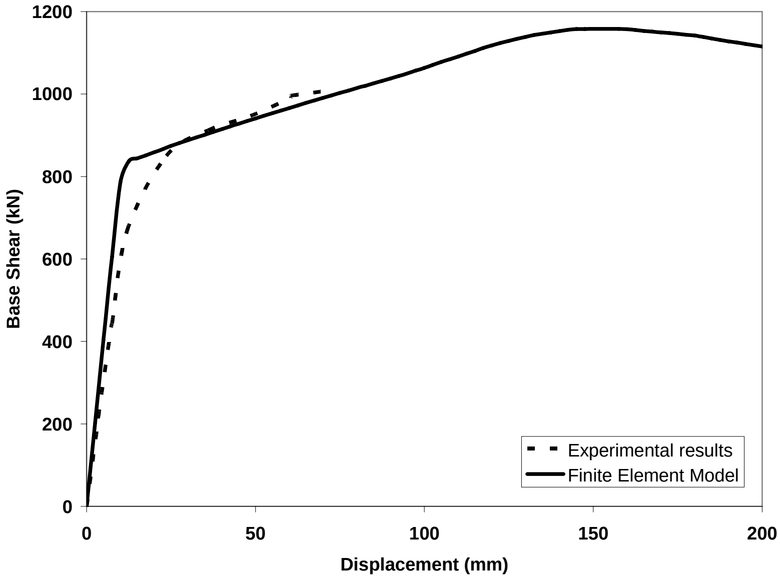

Figure 5: Comparison between the results of the experimental test and the finite element model

The assumed properties for constructional steel and EGS are tabulated in table 1. As it can be seen the ratio k is equal to 2 in this study.

Table 1: Material properties used in finite element models

Material	E (MPa)	σ_y(MPa)	$\sigma_{ultimate}$(MPa)	Ultimate strain
Constructional Steel	206000	240	360	0.22
EGS	206000	120	250	0.45

Finite element models with various width-to-height ratios were developed. Pushover analysis is carried out for the models and behavior of the frames is accurately studied. The maximum brace section area is calculated by the equations mentioned below. As it was anticipated, the link beam and the beam segment out of the link beam yielded after the full yielding of the braces.

A sample finite element model is shown in figure 6. As it can be seen, the maximum stress in the beam is less than the yield stress (240 MPa) while the braces reached to their yield stress (120 MPa). In this point, the drift of the frame is equal to 1.25%.

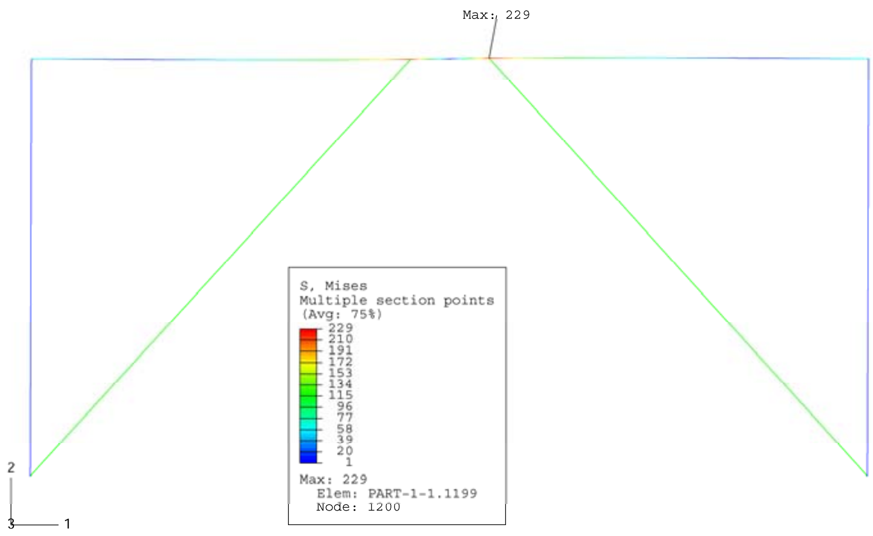

Figure 6: Mises stress in the frame members

Conclusion

In this paper, the feasibility of transferring the energy absorption from the link beam to braces in an eccentrically braced frame is studied. The advantage of this new system is the easy and cheap repair of the frame after a damaging earthquake. The replacing of braces in a frame is much easier than replacing the beam.
Classic and finite element methods are used in this study. Firstly, The maximum acceptable area of braces is obtained as a function of the area, height and inertia moment of beam, geometrical properties of the frame and the yield stress ratio of constructional steel and Easy-Going Steel.
Then finite element models are developed and verified compared to the results of an experimental test. The results of finite element model analysis confirmed that it is possible to transfer the energy absorption from the link beam to the braces in an eccentrically braced frame.

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