Ductility and Ultimate Strength of Eccentric Braced Frame

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Abstract. Eccentrically braced frames have high stiffness against the lateral loads such as earthquake and perfect ability to absorb energy. Link beam, one of the most important parts of the frame, guarantees the required stiffness and ductility of the frame. The role of stiffeners and ductility of the frame depends on the link beam characteristics. The best situation for perfect stiffness and ductility occurs when the link beam works in shear. This is when the role of stiffeners in preventing the early buckling of the web is of a great importance. Placing proper stiffeners on the web of the beam develops the ability of absorbing high amount of energy. In this study the behavior of eccentrically braced frames, role of stiffeners and other parameters of the link beam on the ultimate strength and ductility of the frame are considered using finite elements model and ANSYS software.

Keywords: Ductility, Ultimate Strength, EBF, Finite Element Analysis

1. Introduction

Different methods have been presented to control structures against earthquake loads. The use of moment resisting and trussed frames (CBF) are of the most regular ones. Moment frame has a proper ductility because of the flexural yielding of beam elements. It has a limited rigidity and also its construction is hard. Conversely converged braced frame has high stiffness but because of diagonal wind-brace buckling its failure is brittle and it has low ductility. In order to reduce the deficiencies of moment resisting systems and converged braced frames (CBF) Popov presented the idea of eccentrically braced frames (EBF) in the middle of the 70s. This system has proper stiffness under service loads, which leads to the reduction of deformations in the structure. It also has proper ductility and capability of absorbing energy against immense lateral loads such as strong earthquakes. This is how the ductility and the stiffness, which are two main requisite of the structure against lateral loads, guaranteed. Nowadays the use of eccentrically braced frames is widespread because of high energy absorbing ability at the time of earthquakes, noticeable stiffness and more architectural facilities. Many investigations have been carried out on the behavior of link beam and its failure mechanism in recent two decades [5]-[7]. Hystersis behavior of an eccentrically braced frame, influences of gap between the stiffeners, thickness of stiffeners, beam flange and web thickness and the length of link beam are considered in this paper.

2. Eccentrically Bracing

In the EBF system, instead of wind-braced connection with the intersection point of beam and column or wind-braced axis intersection it connects to the beam at a point with eccentricity (e). Link beam which is between column and wind-braced (one diagonal) or between two wind-braced (two diagonal) acts as a fuse which prevents the applying of excessive force to windtights and also their buckling. Axial loads of diagonal windtights shift to the column or they transfer to another windtight in the form of shear or moment and link beam deforms nonlinearly during several cyclic loading and energy absorbing takes place in a way that happens in restrained frames. Short link beams yield in shear phase but flexural yielding happens in long ones. Yielding criterion of link beam is presented by Popove and Kasay as follow:

$$e < 1.6 Mp/Vp \qquad \text{Shear yielding} \qquad (1)$$
$$1.6 Mp/Vp < e < 2.5 Mp/Vp \qquad \text{Flexure-shear yielding} \qquad (2)$$
$$e > 2.5 Mp/Vp \qquad \text{Flexure yielding} \qquad (3)$$

In these relationships, M_p and V_p are the plastic moment and plastic shear of link beam section respectively. Shear yielding mechanism of short link beams is better than the flexural one in long beams because shear force is constant throughout the length of link beam. Also nonlinear shear strain is distributed uniformly all through that which leads to large nonlinear rotation of link beam without the development of great local strains.
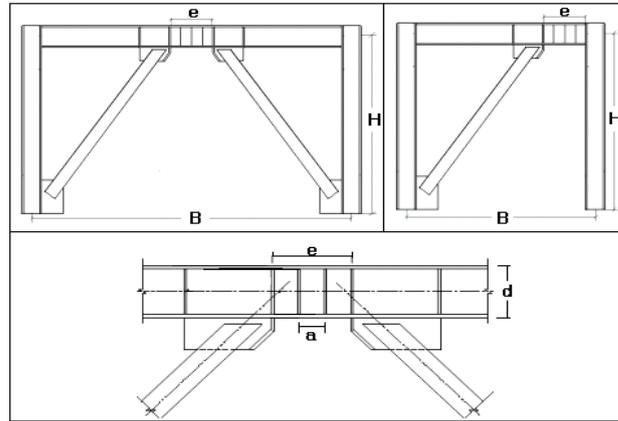

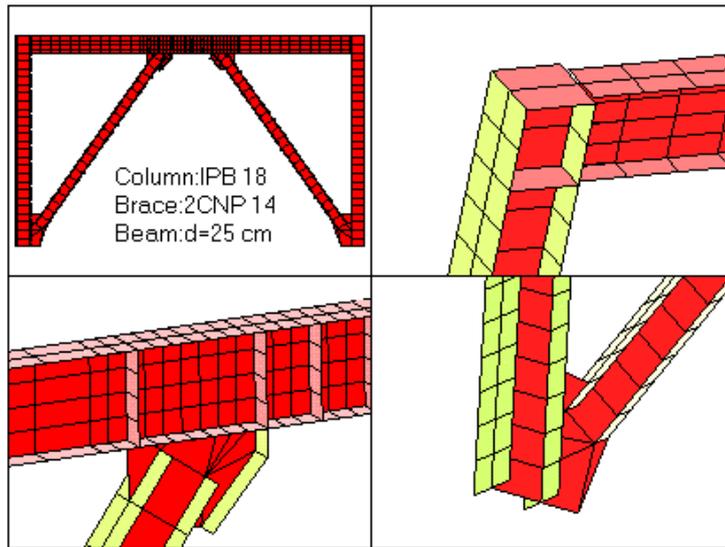Fig. 1: EBF bracing and link beam specifications

Fig. 2: Model and connections specifications

3. Ductility and Relative Over Strength

When a structure is under excessive lateral forces or strong earthquakes, large deformations are developed in that and many parts of it may yield. the earthquake energy is partially absorbed by yielded parts but most of the times the structure remains stable. Therefore it should have the ability of bearing the deformations caused by lateral forces of earthquakes. This ability is implied by a parameter named as ductility (μ) which is equal with the quotient of maximum frame deformation (Δ_u) to its yielding limit deformation (Δ_y).

$$\mu = \Delta_u / \Delta_y \qquad (4)$$

Another important parameter in determining behavior factor of the structure is relative ultra strength (Ω) which is the quotient of total yielding force of structure at verge of collapse (F_u) to the force that leads to the formation of the first plastic hinge in the structure (F_y).

$$\Omega = F_u / F_y \qquad (5)$$

4. Modeling and Numerical Studies

Finite element method (FEM) was used to model the system under study. The method makes i This is the basis of using ANSYS software. The selected element for modeling is 4 joints, membrane shell 181 with 6 degrees of freedom in each joint which is one of the elements that converge rapidly in nonlinear situations. The abilities of this element are explained in reference [2]. Assumptions in modeling are as follows:

1. Large deformations of the joints are considered.

2. Influences of axial forces on elements buckling are taken into account.

3. Von-Misses yielding Criteria is used in the model.

4. Hardening is isotropic.

In order to control the accuracy of modeling and used assumptions in this article, first the shear link beam whose specifications and laboratory results are available in references [1] is modeled with ANSYS software. Histerzies diagram resulted from analysis and experiments is shown in Figure (3). According to diagrams, results are approximately similar and existing differences are the outcome of modeling and loading details.

One story frame with one span whose width and height are respectively 5 and 3 meters is assumed for modeling and numerical studies. It is designed in a way that buckling windtights and failure of columns will not proceed the failure of link beam (Fig. 2). The used modulus of elasticity and Poisson's ratio are respectively $2*10^6$ kg/cm^2 and 0.3. considered strain-stress diagram is shown in (Fig. 4). In order to investigate Histerzies behavior, loading history like (Fig. 5) is applied to the samples (first step of loading begins with regards to the moment of samples yielding and the amount of increasing in each step is 1200 kg). Thickness of stiffeners (t_s), space between them (a), height of link beam (d), thickness of beam flange (t_f), thickness of beam web (t_w) and the length of link beam (e) are other parameters of link beam.

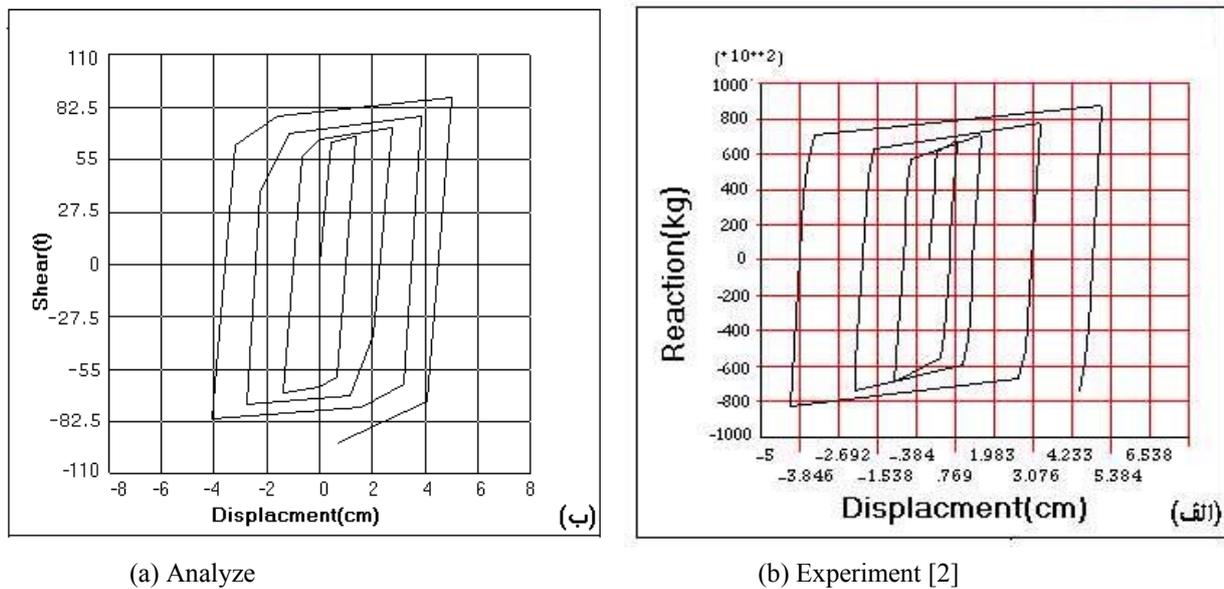(a) Analyze   (b) Experiment [2]

Fig. 3: Histerzies diagram

4.1. Eccentrically Braced Frame with Shear Link Beam

In this situation the amount of e is considered 60 cm and with gradual increasing of loads stresses in frame and link beam are observed. With observation of stresses it is revealed that stress in stiffeners is nearly zero till the yielding second of web and after that stress in link beam stiffeners rapidly increases. Critical points of stress in stiffeners are the place of connection with flanges. The extent of stress gradually decreases from the point of connection with the flange to the center of stiffeners. It is remarkable to exclaim that stiffeners have little role in yielding force, yielding displacement and elastic stiffness of the frame (Fig. 6). The effects of stiffeners are revealed after yielding of link beam web, which are as follow:

1. Postponing nonlinear buckling of web.

2. Participating in the increase of web loading.

3. Increasing plastic stiffness of the frame.

4. Preventing brittle and sudden failure of link beam.
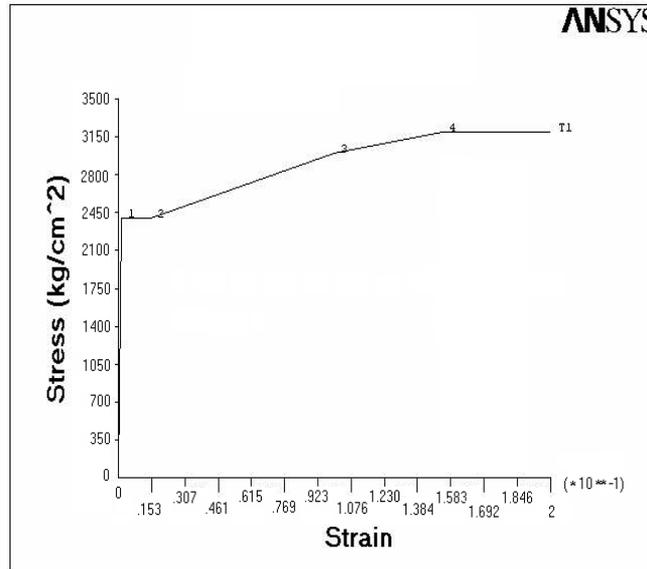
5. Increasing ductility and ultra strength of the frame.
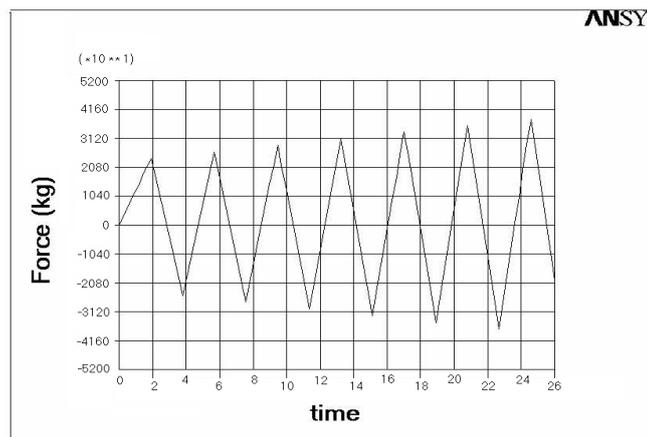

Fig. 4: Stress strain diagram of steel

Fig. 5: History of loading on frame

4.1.1. Gap Between Stiffeners

In order to investigate the influences of gap between link beam stiffeners of web on the behavior of frame, they are changed from 10 cm to 60 cm and analysis is performed under alternative loading. By inspecting Histerzies diagrams it is observed that with the reduction of gap between stiffeners (a) numbers of loading cycles and consequently energy absorbing of system increase (Fig. 8). It is also revealed by stress inspection that energy absorbing is performed only by link beam web. Flanges and stiffeners of link beam prevent brittle failure and precocious buckling of the web since flanges do not allow sudden movement of frame because of their elastic function. In this situation frame stiffness id guaranteed by flanges and the length of link beam and ductility is ensured by the web of link beam. Ultra strength diagrams in figure 7 shows a relatively linear relation at ordinary spaces between stiffeners. After increasing the space from a limit (30-cm) relative ultra strength is constant and the existence of stiffeners is of no value. By placing stiffeners in equal spaces the maximum energy absorbing takes place in link beam. They should be completely welded to the flanges and web.
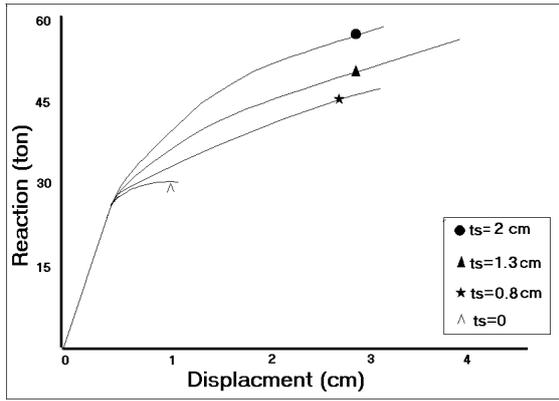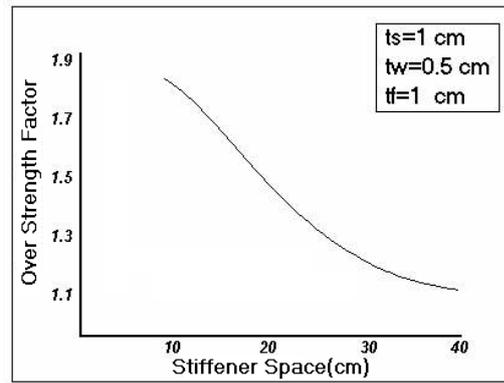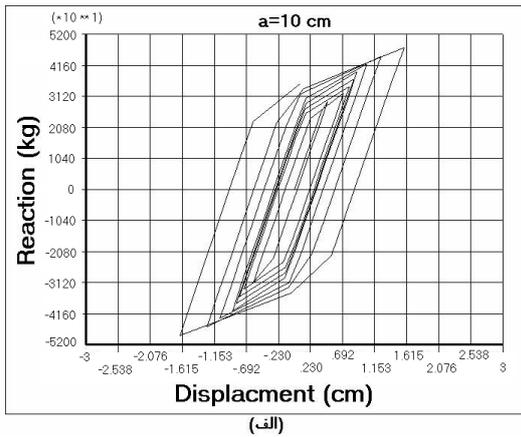
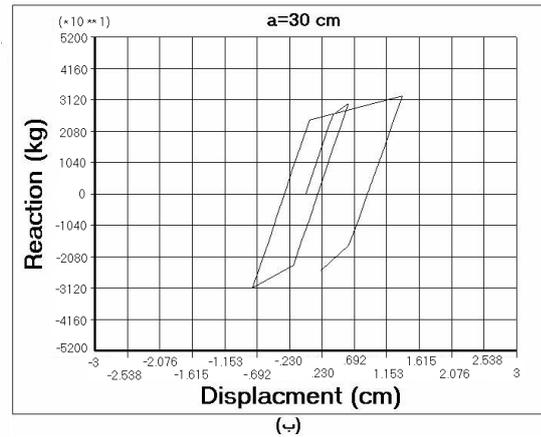Fig. 6: Different thickness of stiffeners

Fig. 7: Different spaces between stiffeners

(a) stiffeners spaces 10 cm

(b) stiffeners spaces 30 cm

Fig. 8: Histerzies diagram of frame

4.1.2. Thickness of Stiffeners

Based on SEAOC [9] and NEHRP [10] codes, vertical stiffeners are sufficient for beams with depth less than 60 cm. According to that the thickness of stiffeners are varied from .6 cm to 2.4 cm. With regards to diagrams shown in Fig. 9 it is observed that frame behavior improves by increasing the thickness of stiffeners since stiffeners with low thickness ($t_s < 1$ cm) do not function properly because of the buckling. Thickness increasing of the stiffeners will lead to the better connection of flanges and strain reduction in link beam web. If the gap between the stiffeners is taken into account, unlimited increase in stiffeners thickness causes the reduction of ductility and relative ultra strength. Curves peak (Fig.9) depends on the gap between stiffeners so that more space between stiffeners requires less thickness to achieve the maximum ductility.
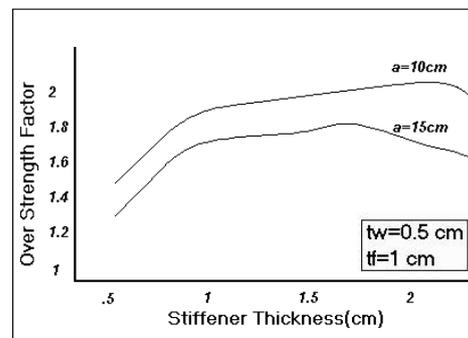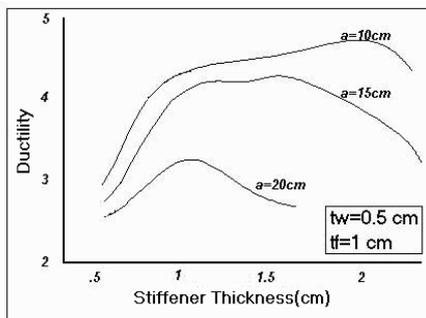

Fig. 9: Relative overstrength and ductility diagram of frame with changing the thickness of link beam stiffeners

4.1.3. Web Thickness of the Beam

Web thickness varies from 0.3 cm to 0.9 cm which is equivalent to the ratio variation of d/t from 25 to 77. By increasing the thickness of the web, yielding displacement of the frame reduces and its yielding force increases but stiffness remains constant. Histerzies diagrams for 0.4 and 0.6 cm of web thickness are

presented in Fig10. According to the diagrams it is observed that a stiffener with 0.4 cm thickness causes more energy absorbing and both ductility and ultra strength increase. It can be concluded that web thickness decreasing leads to the optimization of the design.

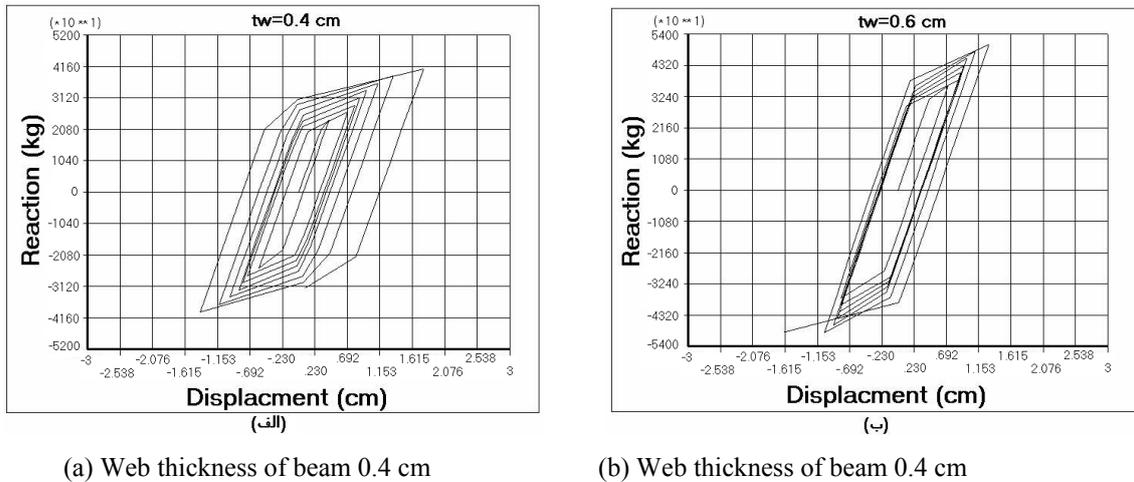(a) Web thickness of beam 0.4 cm   (b) Web thickness of beam 0.4 cm

Fig. 10: Histerzies diagram of frame

Over Strength diagram against the variation of web thickness is shown in Figure 11. According to that the curve increasing between 0.3 cm to 0.45 cm is because of the precocious buckling of web.

4.1.4. Flange Thickness of the Beam

Flange thickness variation are assumed to be between .8 cm to 1.4 cm. Frame stiffness increases due to the increase of flange thickness but its yielding force remains constant. Figure 12 shows the approximate linear increase of ultra strength, which is the consequent of plastic moment increasing. By comparing the results with Figure 11 it is observed that influences of flange thickness are not as important as web thickness and that is why shear rules the mechanism. The increase of flange thickness more than 1.3 cm does not affect the overstrength because web buckling in link beam.
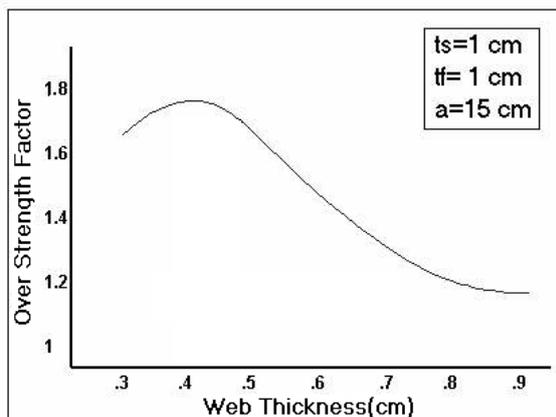

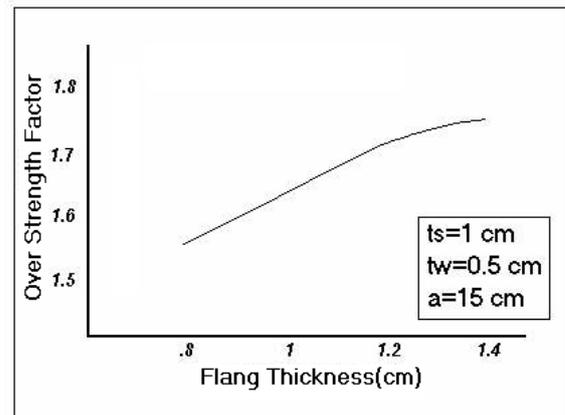Fig. 11: Frame with Changing Thickness of Link Beam Web   Fig. 12: Changing Thickness of Link Beam Flange

4.2. Flexural Link Beam

The amount of e is considered 180 cm. Observation of link beam stresses shows that flanges completely yield and shear is not ruling. Energy absorbing of flanges in this situation is less than that in shear link beam situation because of the premature buckling of flanges. The precocious buckling of flanges can partly be controlled by placing stiffeners in link beam web but it is not efficient because of its torsion. However using two stiffeners at each end side of link beam $1.5b_f$ and $0.75 b_f$ space is proper [4].

4.3. Flexural-Shear Link Beam

The amount of e is considered 120 cm. Stress inspection link beam shows that the web is yielded all through the length of link beam and flanges are also yielded at two ends of that. Web strain is higher at the ends of connection than any other points. So there is the need of two way stiffeners at the ends of link beam with 0.75 b_f and 1.5b_f gap in order to postpone the buckling of flanges, and one way stiffener in the middle of link beam to delay web buckling which its distance is assigned with regards to the rotation of link beam.

5. Conclusions

Eccentrically braced frame analysis leads to the following results:

1. Energy absorbing takes place by the link beam web when the beam works in shear and placing proper stiffeners on web leads to the complete use of strain hardening. Flanges and stiffeners do not have any role in absorbing energy but they help the web for better functioning and the failure is ductile.

2. Stiffeners do not affect the elastic stiffness and period of the structure but plastic stiffness of frame increased.

3. The increase of stiffeners thickness leads to the increase of link beam energy absorbing but after a limit (this limit depends on the parameters of link beam) it is useless and cause the improper function of that.

4. In the state of shear link beam the effects of web thickness is more than the flanges' and selecting less thickness (to a limit which shear needs of the beam is satisfied and stiffeners prevent premature buckling of the web) makes the design more economic, but by (e) increasing the opposite relation takes place and the flange thickness influences will be more.

6. References

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