Investigation of seismic behavior of steel coupling beams in hybrid coupled structures

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ABSTRACT
Seismic response of hybrid coupled wall systems in which steel beams used instead of concrete beams to couple reinforced concrete walls depends significantly on behavior of coupling beams. They must be detailed such that provide the necessary ductility and deformability for the walls to achieve the desirable efficient response. This paper introduces a new and simple model of steel coupling beam that can be used instead of conventional steel coupling beam with standard stiffener, designed based on Iranian code for steel structure design criteria that is similar to AISC criteria. A collection of parametric, and analytical studies was carried out to investigate the effects of various form of stiffeners in the web of the beam by Abaqus Software. Analysis results show that diagonal web stiffener is capable to increase shear link performance in terms of stiffness, strength and energy dissipation.

KEYWORDS
Coupling beam; Diagonal Stiffener; Standard Stiffener.

INTRODUCTION
Coupled shear wall systems that created with coupling of two individual wall piers have been shown to be very efficient in resisting seismic loads. This system exhibits significant lateral stiffness and strength if the openings in the core wall are placed in a regular pattern over the height of the building, and the coupling beams are designed and proportioned properly. Without the coupling, the overturning moment of the structure is resisted by flexural in the wall piers, and the energy introduced to the structure through a seismic event is dissipated by the flexural deformations of the wall piers. When the walls are coupled (via the coupling beams), The wall axial forces due to shear forces in the coupling beams creating a couple that acts to resist a large percentage of the total overturning moment rather than the individual wall piers. Therefore a more stiffeness system is obtained (Fortney, 2005). In order for to obtain the desired behavior of this systems, the coupling beams must be sufficiently strong and stiff, yield before the wall piers, behave in a ductile manner, and exhibit significant energy absorbing characteristics, The hysteretic characteristics of coupling beams, therefore, may substantially affect the overall response of a coupled wall system(Harries et al, 2001).
Low capacity and two major mechanism of failure i.e. diagonal tension and sliding shear in conventionally reinforced concrete coupling beams and also increasing both construction time and cost and designing of impractically deep members due to limited shear capacity of RC coupling beams lead to using of steel coupling beam instead of concrete beam (Fortney, 2004, 2007, El-Tawil et al, 2010).
Ends of the beams are embedded in the two adjacent walls and The resulting system (reinforced concrete walls coupled by steel structural beams) is termed hybrid coupled wall (HCW) system.

Steel coupling beams possess the necessary combination of stiffness, strength, and ductility needed for providing the stable hysteretic response required of coupling beams(El-Tawil et al 2002).
Since the Mechanisms that involve well-controlled inelastic shear deformation in steel coupling beams are generally more ductile than those involving flexure-related plastic hinge deformations, When architectural constraints permit, short coupling beams, which dissipate energy primarily through inelastic shear distortion, are preferred to longer coupling beams that dissipate energy through flexural hinge rotation.(El-Tawil et al, 2010)
Steel coupling beam design is based on a collection of last studies, such as the way proposed by harries (Harries et al, 1993)
The general design philosophy of the steel coupling beam is to ensure that the flanges of the beam remain elastic while the web yields in shear, and that appropriate slenderness ratios of the flanges and web are used in order to preclude local flange or web buckling, so in determination of dimensions of flanges the contribution of the web should be ignored(Harries et al, 1993,Fortney, 2005).
Yurisman et al (2010) Conducted a numerical and experimental study of shear link behavior, utilizing diagonal stiffener on web of steel profile instead of standard (vertical) stiffener (according to AISC criteria) to increase shear link performance in an eccentric braced frame (EBF) of a steel structure system(Yurisman et al, 2010)
Diagonal Stiffener has not been used in steel coupling beam yet. In this paper the effects of diagonal stiffener in the web of coupling beam instead of vertical stiffener has been investigated.
For validation of coupled wall subassemblage model in this study, the finite element model were verified with experimental results. Then a parametric study was done to obtain the best situation for the diagonal stiffener.

FINITE ELEMENT PARAMETRIC STUDY

For verification of finite element model an experimental specimen reported by Fortney (2005) was Chosen. The specimen is consist of two wall connected with steel coupling beam under cyclic loading (figure1). First a load history of force control impart to the test specimen and then displacement control applied. In this experiment cyclic loading applied up to 4% rotation angle and then monotonic loading were applied to 11% rotation(Fortney,2005).
In this study in order to modelling concrete material of shear wall, damage plasticity model was used. This model uses concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity to represent the inelastic behavior of concrete. It assumes that the main two failure mechanisms are tensile cracking and compressive crushing of the concrete material. Also this model is suitable for desirable loading even cyclic loading, the model takes into consideration the degradation of the elastic stiffness induced by plastic straining both in tension and compression. It also accounts for stiffness recovery effects under cyclic loading (Abaqus manual, 2010)
The bars is modeled with truss element which can transmit only axial force.
In order to model the steel beam material, shell element were used. For the nonlinearity of the selected steel material the available kinematic hardening in the abaqus program was used. since for steel only coupon test data is available, so this data is introduced to the software in the form of a half-cycle data with a hardening of about 1.3%.
The analysis and experimental results has been shown in terms of shear force versus vertical displacement at end of the beam in figure 2. It can be seen, good agreement between the analytical and experimental results in terms of their hysteretic behaviour, so we can say the finite element model has been accurated. The calculated shear capacity of the beam, using measured material properties and relations of code, is 578kN, but the experimental results shows a maximum shear of 994kN at approximately 3% rotation, giving a maximum ratio of applied shear to calculated shear capacity of 1.7. this results further support the accuracy of the FEM, which has a maximum shear of 989kN with a ratio of analysis to experimental shear capacity of 0.99.

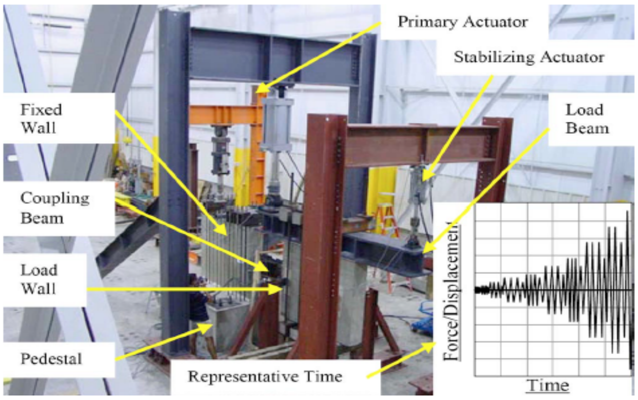


Figure 1. specimen tested by Fortney(2005)

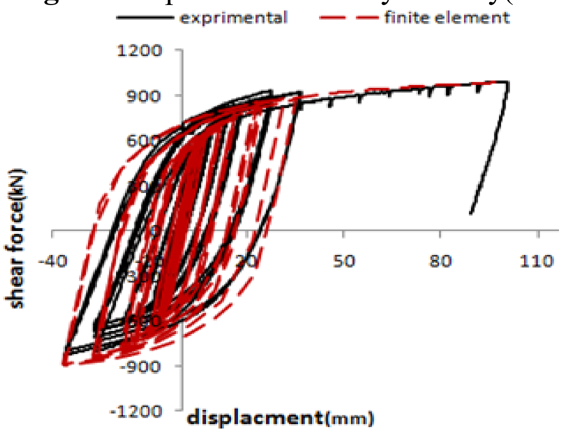


Figure 2. Comparison of analytical and experimental hysteresis curves

Comparison between the behavior of coupling beam with standard and diagonal stiffeners.

The details of models

A 12 story building with hybrid coupled shear wall system designed according to Iranian code of practice for seismic resistance design of buildings (Standard No.2800). Length of beam is 1.8m and building have 3m floor to floor height with 30 N/mm² concrete strength and 240 N/mm² steel strength for beams. Structure has soil of type II. The equivalent lateral force procedure together with elastic structural analysis was used to determine the design forces required for the structural components. Floor dead and live gravity loads are assumed to be 700 kg/m² and 200 kg/m² respectively. The design moment and shear in the 5th floor coupling beam are the largest of those of any floor. Hence, the coupling beams were more important at this location. Design of steel coupling beams with shear critical behaviour is done in accordance with(Harries et al, 1993). Comprehensive details of design are presented in (Omranian,2012)

Since the coupling beam is the primary energy-absorbing element and hence will undergo significant inelastic deformations, its embedment must be capable of developing the full capacity of the coupling beam beam. The design of the concrete embedment of the link beam uses the method developed by Marcakis and Mitchell (1980)(Equation 1)

$$V_c = \frac{0.85\, f_c' b_{eff}\, L_e}{1 + \frac{3.6e}{L_e}}; \quad e = \frac{l}{2} + \frac{L_e}{2} \qquad (1)$$

where l_e = embedment length, b_{eff} = effective width of the resultant concrete stress blocks is taken as the width of the confined wall region, but not greater than 2.5 times the bearing with b_f (flange width) of the embedded member.

In order to determine the dominant behavior of steel beam the nondimensional parameter of $\left(l / (M_n / V_n) \right)$ is examined.

According to (Harries, 2001)

$\left(l/(M_n/V_n) \right) < 1.6$ Shear critical (2)

$1.6 < \left(l/(M_n/V_n) \right) < 2.6$ Shear or flexural critical (3)

$\left(l/(M_n/V_n) \right) > 2.6$ Flexural critical (4)

where M_n=nominal moment resistance of beam

V_n = nominal shear resistance of beam; and

L= span of the beam

The required spacing of the web stiffeners are dependent on the beam rotation demand. The details used in this study are summarized in Table 1.

Table 1. details and dimensions of beam and wall(mm)

beam	Flange width	flange thickness	Web thickness	Depth of beam	Embedment length
	295	38.5	14	497	950
wall		Vertical reinforcment	Horizental reinforcment		
		ϕ_{18} @ 225	ϕ_{16} @180		
remark		$l/(M_n/V_n)$	$1.35 < 1.6$	Shear crtical	

Cyclic loading protocol

The models in this paper were investigated under the cyclic loading. Load history were applied according to the guideline proposed by ATC-24. history of displacement control has shown in figure.3(ATC24, 1992)

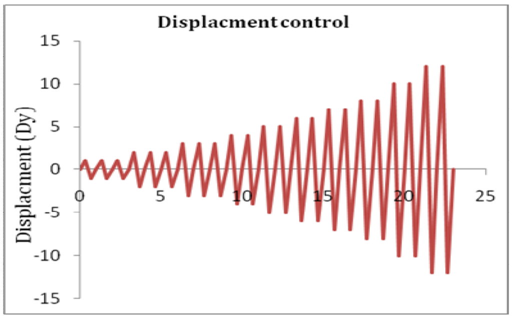


Figure 3. load history of displacement control

RESULTS

The behavior of shear critical coupling beam with diagonal web stiffener (DS) was compared with the behavior of coupling beam with standard stiffener (SS) designed based on Iranian code for steel structure design criteria that is similar to AISC.

Hystertic response

The hystertic curve shear force vs. end of the beam displacement are presented in figure4. It can be seen the installation of diagonal stiffener on the web of coupling beam can increase beam shear capacity, and improve the ability of beam in the energy dissipation.

The analytical capacity (obtained by abaqus) together with rotation angle of coupling beam and also the ratio of analytical capacity to calculated values based on codes have been provided in table 2.

The values of table indicate that the model with the DS has about 25% more shear capacity in comparison with the SS model.

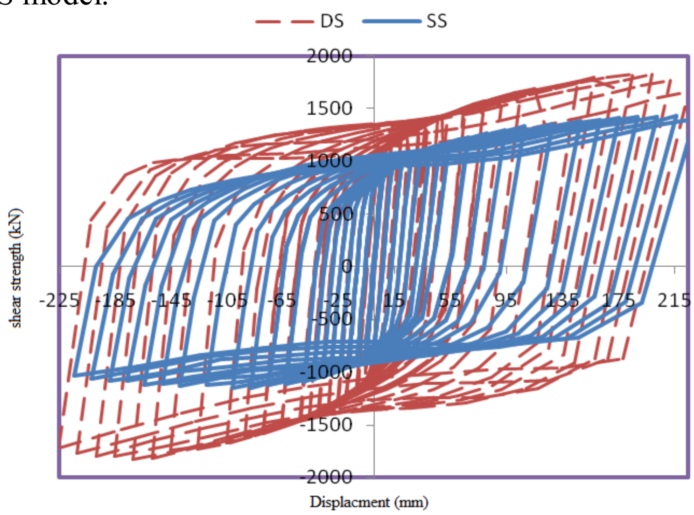


Figure 4. Comparison of diagonal and standard stiffener model hysteresis curves

Table 2. Shear and rotation capacity for DS and SS models

	SS (kN)	DS (kN)
Shear capacity	1432	1829
Rotation angle (%)	12.1	11.1
Ratio	1.6	2.1

Energy dissipation of coupling beam

Dissipated energy of members is an important characteristic in evaluating of seismic performance of a system. The hysteretic response of steel coupling beams is due to yielding of the steel coupling beam outside of the coupled shear wall and the plasticity of the connection region, i.e., the yielding of the beam in the embedded region and the fracture of the surrounding concrete (Park,2006). Figure.5 shows the distribution of dissipated energy by plastic deformation of coupling beam in both models. It can be seen that the model with diagonal stiffener (DS) attract more energy than SS model. For example in rotation angle of 8%, the DS model attracts about 10% more energy than other models.

Stiffness characteristic of models

The system under investigation works similar to a contilver beam. So theorical elastic stiffeness Ke can be obtained from equation 5.

$$K_e = \frac{3EI_{eq}}{l^3} \qquad (5)$$

where $$I_{eq} = \frac{I_b}{1+\frac{3EI_b}{l^2GA}\lambda} \qquad (6)$$

In which I_{eq} is equivalent flexural rigidity regarding the effects of shearing deformation in coupling beam. λ is the cross-section shape factor is defined ratio of plastic section modulus to elastic section modulus. For this system initial stiffeness of beam is 144kN/mm, further calculations is presented in author's thesis (Omranian, 2012). Table 3 shows the initial stiffeness of each of the models. As can be seen from the table 3 stiffeness of DS model is more than SS model. In fact, we can conclude that vertical stiffener has no effect on stiffeness of the model (only 3% more than theory value), but is useful for stability of the system. On the other hand, DS not only increase the stability, but also increase the stiffeness of the system.

Figure 6 shows degradation of peak to peak stiffeness against rotation angle. It can be seen that DS model have more stiffeness in comparison with vertical stiffener.

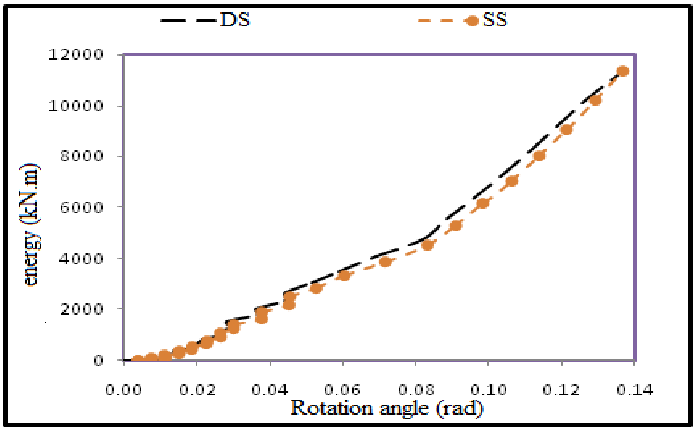


Figure 5. Distribution of dissipated energy

Table3. Values of stiffeness of SS and DS model

	SS (kN)	DS (kN)
Initial stiffeness	149	165.3
Ratio of analysis stiffeness to theory stiffeness	1.03	1.19

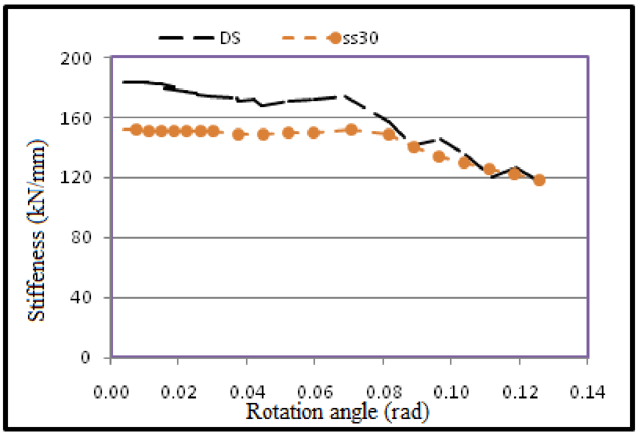


Figure 6. Stiffness characteristics

Finite-Element Parametric Study

In this paper, two nondimensional parameters were used to develop the proposed coupling beam: section compactness ratio ($B = d / t_w$) and diagonal stiffener angle (a). The objective of the parametric study presented in this section is to obtain a optimum situation for diagonal stiffener, whereby system have the best performance in terms of strength, stiffness, and energy dissipation. For the purpose of nomenclature, the beams will be labeled using **a** and **B**, for diagonal angle and section compactness ratio respectively, followed by the numerical values according to Table 4.
SSB model is coupling beam with standard stiffener in any section with according to compactness ratio, for example SS50 is beam with standard stiffener and compactness ratio of 50.
Figure 7 shows the distribution of dissipated energy by plastic deformation of coupling beam in all the models with B=40. It can be seen that the model with diagonal stiffener angle of 30 degree has the maximum dissipated energy about 18% more than DS with angle of 25 degree and about 35% more than SS30. Table 5 shows values of shear capacity with rotation angle of 8% (according to code of practice). Values normalized by value of standard model. It can be seen that the models with diagonal stiffener angle 30 and 35 degree have the higher shear capacity. According to Table 5 increasing section compactness ratios to B=50 beam with standard stiffener withstands higher shear than model with diagonal stiffener. This is due to more buckling in state B=50 in beam with DS. As section compactness ratio is increased, clear length for buckling in DS model is more than model with SS. The degradation of peak to peak stiffeness against rotation angle of B=30 and B=50 are shown Figure 8. It can be seen models with diagonal stiffener have more stiffeness in comparison with vertical stiffener and Model with diagonal angle 30 degree has the best behavior. But as seen

Table4. The models used for parametric study

$\beta = \frac{d}{t_w}$	$\alpha = \tan^{-1}(\frac{s}{d})$					*SS model*
	25	**30**	**35**	**40**	**45**	
30	a25,B30	a30,B30	a35,B30	a40,B30	a45,B30	SS30
35	a25,B35	a30,B35	a35,B35	a40,B35	a45,B35	SS35
40	a25,B40	a30,B40	a35,B40	a40,B40	a45,B40	SS40
50	a25,B50	a30,B50	a35,B50	a40,B45	a45,B50	SS50

in Fig8b, in early load steps all of the diagonal model have more stiffeness than standard model. But after rotation of 6% for DS with a=30 degree and 3% for other arrangement, severe buckling has occured in the web of the beam. As results degradation of stiffeness in SS model is less than DS model. To overcome this problem, the number of diagonal stiffener can be increased. In Fig 9 peak to peak stiffeness and in last row of Table 5, shear capacity for beam with 4 diagonal stiffener has presented. Coupling beam performance is enhanced by increasing the number of diagonal stiffener as shown in Figure 9 and Table 5. As number of diagonals is increased clear length of buckling decreased, thus less buckling occurs.

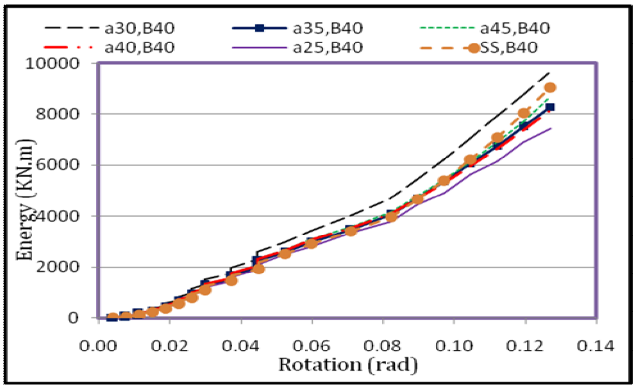


Figure 7. Distribution of dissipated energy

Table5.values of shear capacity.

β \ α	25	30	35	40	45
30	1.12	1.13	1.11	1.07	1.07
35	1.24	1.27	1.25	1.27	1.27
40	1.11	1.13	1.13	1.04	1.04
50	-	0.98	0.96	0.95	0.91
50-4stiff.		1.11			1.06

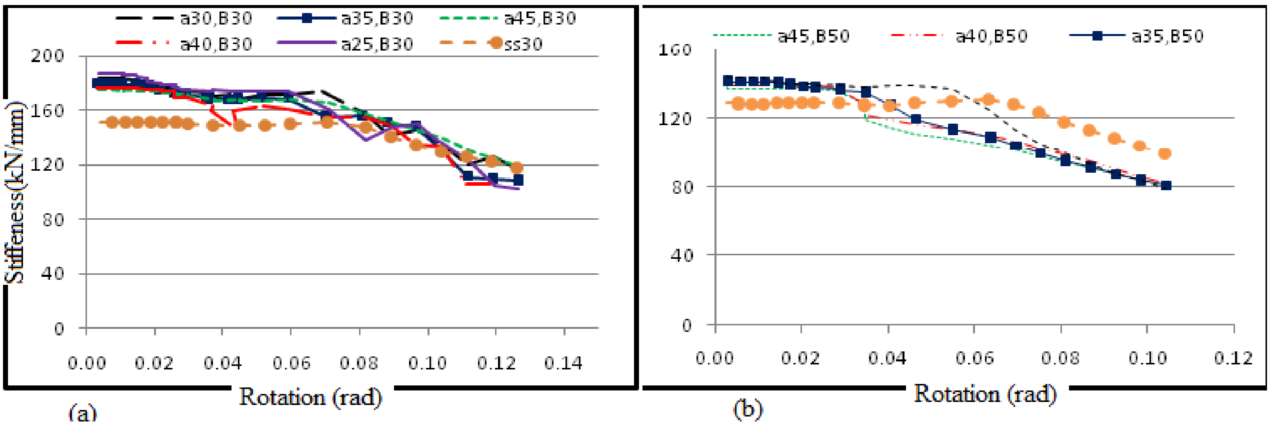
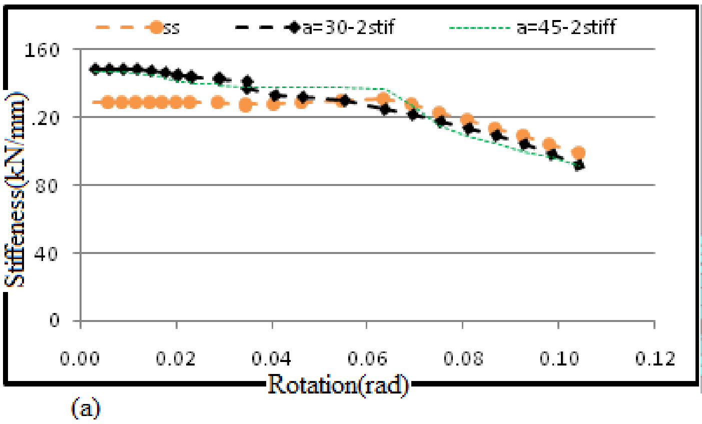


Figure 8. Stiffeness characteristic, a)B=30, b) B=50



(a)

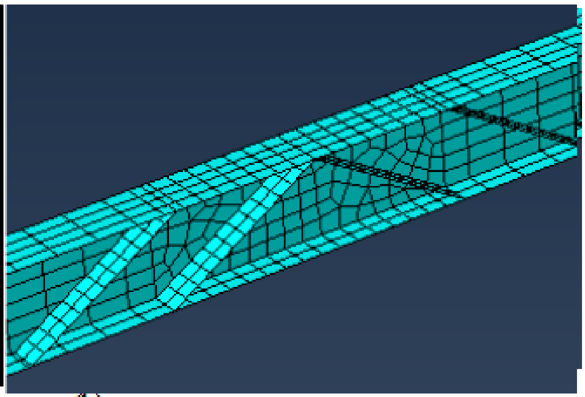

(b)

Figure 9. (a)Stiffeness characteristic (4diagonals),(b)steel coupling beam with 4diagonals

CONCLUSIONS

Based on the results of numerical studies of a proposed steel coupling beam with diagonal stiffener, several conclusions can be drawn as follows:

1- The numerical studies show that the installation of diagonal stiffeners on the web of coupling beams can improve the beam performance in terms of strength, stiffness, and energy dissipation compared with vertical stiffeners.
2- Two nondimensional parameters"section compactness ratio and stiffenss diagonal angle" used to develop proposed beam, on various geometrical conditions showed that, the best performance belongs to the system with diagonal stiffener with angle of 30 degree.
3- For section compactness ratio (B) less than or equal to 40 installation of only two diagonal stiffener on each side of the beam are adequate.
4- For higher section compactness ratio (B=50) number of diagonal stiffener should increase to 4 on each side.

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