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Study of an innovative two-stage control system: Chevron knee bracing & shear panel in series connection

S.M. Zahrai[1a] and A.K. Vosooq[*2]

[1]Center of Excellence for Engineering and Management of Civil Infrastructures, School of Civil Engineering, Faculty of Engineering, The University of Tehran, Iran
[2]Department of Structural Engineering, Faculty of Civil Engineering, Tafresh University, Tafresh, Iran

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Abstract. This paper describes analytical investigation into a new dual function system including a couple of shear links which are connected in series using chevron bracing capable to correlate its performance with magnitude of earthquakes. In this proposed system, called Chevron Knee-Vertical Link Beam braced system (CK-VLB), the inherent hysteretic damping of vertical link beam placed above chevron bracing is exclusively utilized to dissipate the energy of moderate earthquakes through web plastic shear distortion while the rest of the structural elements are in elastic range. Under strong earthquakes, plastic deformation of VLB will be halted via restraining it by Stopper Device (SD) and further imposed displacement subsequently causes yielding of the knee elements located at the bottom of chevron bracing to significantly increase the energy dissipation capacity. In this paper first by studying the knee yielding mode, a suitable shape and angle for diagonal-knee bracing are proposed. Then finite elements models are developed. Monotonic and cyclic analyses have been conducted to compare dissipation capacities on three individual models of passive systems (CK-VLB, knee braced system and SPS system) by General-purpose finite element program ABAQUS in which a bilinear kinematic hardening model is incorporated to trace the material nonlinearity. Also quasi-static cyclic loading based on the guidelines presented in ATC-24 has been imposed to different models of CK-VLB with changing of vertical link beam section in order to find prime effectiveness on structural frames. Results show that CK-VLB system exhibits stable behavior and is capable of dissipating a significant amount of energy in two separate levels of lateral forces due to different probable earthquakes.

Keywords: two-stage earthquake resisting system, vertical link beam, knee elements, stopper device

1. Introduction

Passive structural vibration control has been a simple and effective method in retrofitting structures for more than three decades. The implementation of metallic dampers as structural fuse is a subset of passive control method which has variety of different types like Eccentrically Braced

∗Corresponding author, Senior Structural Engineer at MEWE Consultant, E-mail: vosooq@mewe-ir.com, amirkoorosh@gmail.com
[a]Professor, E-mail: mzahrai@ut.ac.ir

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Frame (EBF) system, Buckling Restrained Braced (BRB) frame, Knee Braced Frame (KBF), Shear Panel System (SPS) etc. Shear-type hysteretic dampers are one type of metallic yield dampers, whose effective mechanism for dissipation of energy input to a structure from an earthquake is through inelastic deformation of the metals (Housner *et al.* 1997). There are many numerical and experimental studies on these systems for deducing of appropriate seismic performance suitability.

To combine stiffness and ductility in steel structures, EBF system is proposed by offsetting either a single brace or adjoining braces from the beam-column joint (Roeder and Popov 1978). This system, which relies on yielding segment of beam between eccentric braces called the "Link", has been shown to provide ductility and energy dissipation under seismic loading. Research on active link has shown in short links, that shear yielding is not significantly influenced by the presence of bending moment (Kasai and Popov 1986). Kasai and Popov (1986) have shown evidence that, for large compression axial forces, flange of link may buckle and cause premature failure. This possibility can be diminished by selecting a small b_f/t_f ratio and a short link length. EBFs have been used widely, and shear links with appropriate stiffening of webs have proven to resist several large cyclic deformations and dissipate considerable amount of energy. Typically, the links have had a wide-flange or I-shape cross-section that requires lateral bracing to prevent lateral torsional buckling. This has limited the use of eccentrically braced frames in bridge piers and towers, as lateral bracing is difficult to develop. To solve the problem, Berman and Bruneau (2007) have suggested a link beam with hybrid tubular cross-section composed of webs and flanges of different thicknesses. Experimental results indicate that the link reached a rotation of 0.15 rad, almost twice the current 0.08 rad limit for wide-flange links, prior to suffering flange fracture without any lateral bracing. However the shear link is a main part of structure which their repairs and replacements might be very complex and expensive. To overcome the trouble of EBFs, Aristizabal-Ochoa (1986) has proposed a bracing system which combines the stiffness of diagonal brace with the ductility of outside frame element called "Knee". Knee Braced Frames (KBFs) are modified form of EBFs, employing a diagonal brace with one end anchored to a knee element. This system however, as originally proposed was not suitable for seismic design because the brace was designed to be slender. Consequently, the brace could buckle and lead to pinching of the hysteresis loops, which is not efficient for energy dissipation. Furthermore, the inelastic cyclic deformations of the brace whose buckling may create a lateral instability problem at the knee-brace joint and cause sudden change to the restoring force of the structure (Balendra *et al.* 1995). Subsequently Balendra *et al.* (1990, 1991) have re-evaluated the system and proposed some modifications to it, at first the knee had been chosen to get yield in flexure whereby buckling of the diagonal brace was prevented. In that way the damage was concentrated in a secondary member which could be easily repaired at minimum cost. Also floor distortions were reduced compared with the case for EBFs.

In the next study by Balendra *et al.* (2001) the different manner of post-yielding behavior of knee element was elected, in which shear yielding was preferred under severe excitation. To achieve this goal, the longer of the two segments of the knee member generated by the intersection of the diagonal brace and the knee member, denoted as l_k was confined to the following condition.

$$l_k < 2\frac{M_P^*}{V_P} \tag{1}$$

Where M_P^* and V_P are reduced plastic moment contributed by flanges only and plastic shear force respectively. To study the inelastic behavior of the lateral load carrying system, a built-up

50×50 mm I-section which had a flange thickness of 6.0 mm and web thickness of 4.4 mm was used for the knee element in one-story frame. The knee was subjected to a shear strain of 0.008 before failure due to tearing of the web was observed. By preventing from local and lateral buckling of the knee element, the frame hysteretic loops were un-pinched and with no deterioration in strength and stiffness. Besides Balendra *et al.* (2001) fulfilled pseudo-dynamic test on a two-story KBF with rolled I-sections as shear type knee elements for investigating to verify the ductile behavior of KBF system, when the latter is subjected to a shear strain that is about 10 times larger than the previous investigation. The test revealed that when the size of knees in both stories was chosen in such a way that the knees are well utilized for energy dissipation, the KBF could dissipate a large amount of energy without any appreciable loss of strength.

Vertical Link Beams (VLBs) could be classified in Shear Panel Systems (SPSs) that are another passive energy dissipation system which recognized as inverted-Y-bracing system in AISC seismic provisions. The proper length of the link in VLB is one of the most important issues. In other words, the inelastic response of the link is strongly influenced by the length of the link as related to the ratio *Mp/Vp* of the link cross-section. When the selected link length is not greater than 1.6*Mp/Vp*, shear yielding will dominate in the inelastic response (AISC 2005). Superiority of the short link beams in comparison with the long link beams has been proven by Engelhardt and Popov (1992) and many others. In investigations done by Buckamp and Vetr, the following constraint was proposed for vertical links with same bending moment at both ends of its length (Boukamp and Vetr 1994).

$$e \leq 1.4\frac{M_P}{V_P} \tag{2}$$

However in practice, the mentioned condition would not exist. Then the following modified constraint was recommended.

$$e \leq \frac{0.7(k+1)M_P}{V_P}\ ;\ \mathrm{k} = \frac{M_2}{M_1} \tag{3}$$

M_1 and M_2 are the upper and lower end moments of the vertical link respectively. According to AISC2002 due to ductility criterion, the steel is used in the links should have yielding stress less than 3500 kg/cm^2 and the rotation of the link through web distortion must be limited to 0.08 radian for short links and 0.02 radian for long links (AISC 2002). Saedi *et al.* (2008) have presented the VLB system with shear panels made of Easy-Going Steel (EGS) having a lower yield stress than common construction steel to improve the seismic behavior of link beam. The study shows that if EGS is used in a link beam, seismic behavior of frame improves noticeably. Using EGS decreases the probability of web and panel buckling to a large extent because of the thickness increase of the sections used in the link beam and the local stability will improve as well. Moreover using EGS on link beam increases the total energy dissipated by the braced frame.

In relation to studies about combination of two energy dissipation dampers in single-degree-of-freedom systems, Vargas and Bruneau (2007) have investigated the seismic performance of single-degree-of-freedom systems with metallic and viscous dampers installed in parallel, to determine the effectiveness or appropriateness of using metallic dampers to mitigate lateral displacements, simultaneously using viscous dampers to reduce acceleration demands in order to protect the nonstructural elements which are vulnerable to excessive floor accelerations in buildings. Parametric analyses have been performed with adding various levels of viscous damping on the equivalent hysteretic damping and on the spectral floor acceleration. Results showed in some instances that adding viscous dampers to strongly inelastic systems can result in increases in floor acceleration (rather than the expected declines). Also it was found that increases in viscous damping reduce the effectiveness of metallic dampers in terms of energy dissipation, since the amplitude of motion is reduced. In some cases, when the amplitude of motion decreases to the point where the system behaves elastically, metallic dampers only work to provide additional lateral stiffness to the system like steel X-bracing systems. Finally, it was observed that adding such viscous dampers in parallel with hysteretic dampers in some cases could worsen the seismic performance of acceleration sensitive equipment and nonstructural component.

In another study related to combination of passive systems, Balendra *et al.* (2001) have proposed a diagonal braced system in steel frames where, the shear yielding knee element was mounted to one end side of the diagonal brace and Slotted Bolted Connection (SBC) was tapped to another end side of the brace. With respect to such assembly, two passive systems were connected in series with each other via a diagonal brace because the total displacement of the frame was obtained from sum of the deformations of the diagonal brace, SBC and the knee. The philosophy of this proposed hybrid system has been expressed in such a way that the inherent hysteretic damping of the knee element maintains the structural integrity in the event of a severe earthquake, while the frictional damping (in the form of SBC) is utilized to dissipate the induced energy in order to meet the serviceability requirements during severe wind storms. When the brace force exceeds the impending frictional force of the SBC, the brace slips with respect to the SBC. The impending frictional force is always kept below from the brace force required to yield the knee. In this way, the knee is always elastic when the SBC is slipping. For assertion of the system capability, the full scale pseudo-dynamic tests were conducted for three types of excitations. These were Sinusoidal base excitation with incremental amplitude after every four cycles, the N-S component of the 1940 El Centro earthquake and simulated wind excitations. The results from the large scale dynamic tests proved the ability of the proposed system in dissipating energy at two different excitation levels. For this specific study, the SBC was activated in the frame drift of 1/1500 and it ceased at the frame drift of 1/560. When the frame was subjected to stronger excitation, the knee started to dissipate energy through shear yielding. The frame hysteretic loops were un-pinched and with no deterioration in strength and stiffness.

Since both of the KBF and SPS systems have had a reliable performance in steel frames, in this paper a parametric numerical study was conducted on proper combination of these two systems in series via chevron bracing. Due to series connection in these two systems, a hybrid seismic performance would be expected from CK-VLB which is able to balance between induced energy from earthquake and energy dissipation capacity.

2. Design procedure

2.1 Vertical link beam

For the reason of hybrid performance of CK-VLB in moderate and severe earthquakes distinctly, the first activation damper (VLB) should be selected weak enough compared with the second one. Post-yielding behavior of VLB strongly depends on its length and section properties. The following statements are generally used for determining yielding mode (AISC 2005):

For shear yielding mode: $e \leq 1.6\frac{M_p}{V_p}$

$$M_P = Z_b F_y \qquad (4)$$

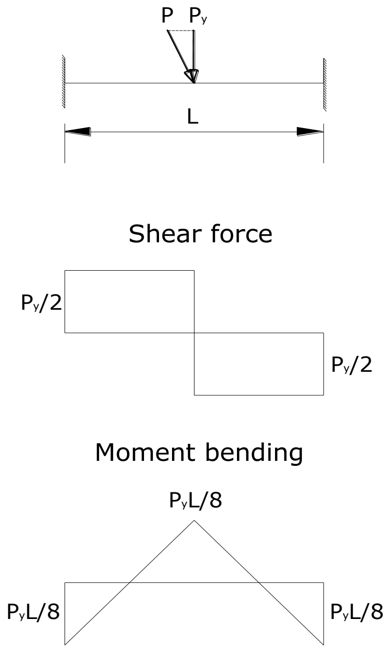

Fig. 1 Knee element in symmetric mode

$$V_P = 0.6F_yA_w \tag{5}$$

If IPE100 with length of 20 cm for instance is selected, then:

$M_P = 39.4 \times 2400 = 94560$ kg.cm, $V_P = 0.6(2400)(10 - (2 \times 0.57)) \times 0.41 = 5230.94$ kg

$e \leq 28.92$ cm

Shear capacity of VLB:

$V_n = \min\{2\frac{M_P}{e}, V_P\} = 5230$ kg

$\phi_V V_n = 0.9(5230) = 4707$ kg

Use a stiffener at middle of the VLB on one side:

Thickness of stiffener $\geq \max(0.8, 0.75t_w)$; $t_{stiff} = 1$ cm

Width $\geq b_f/2 - t_w = 2.34$ cm ; $W_{stiff} = 2.54$ cm

Experimental investigations have shown that as long as the floor beam is prevented against out-of-plane deformations and the shear panel (VLB) is short enough, the out-of-plane instability is not likely to occur in the VLB (Zahrai and Bruneau 1999).

2.2 Knee element

2.2.1 Geometrical investigation

Stress distribution on the web of the knee element will be uniform along its length when the diagonal brace seems to be a symmetry axis of the knee element (Vosooq 2011). In this condition, shear force and bending moment of the knee could be determined from Fig. 1. In such conditions, the knee element can be approximated to a beam with two fixed ends and concentrated force (point

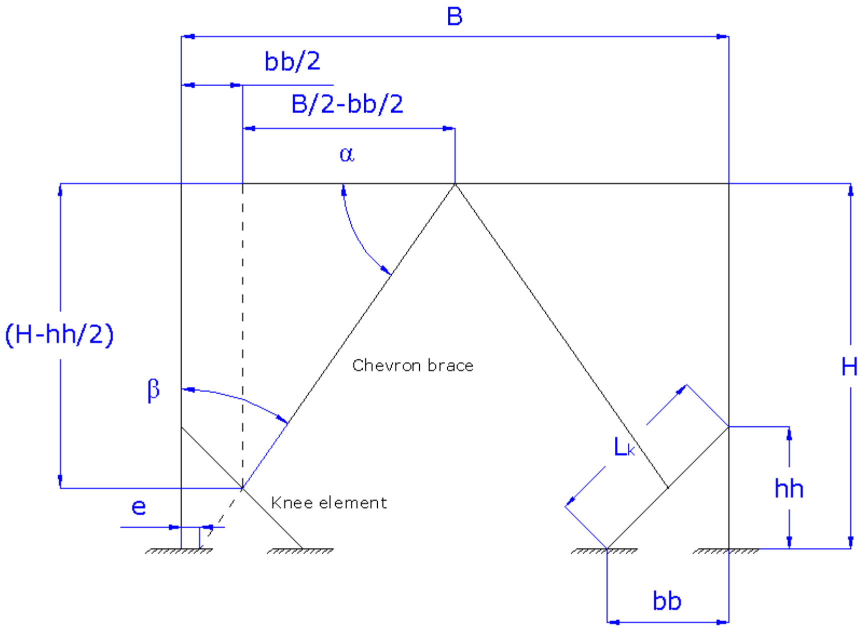

Fig. 2 Effect of B/H on value of eccentricity of brace

load) on mid span. Besides, most capacity of the knee element can be consumed for energy dissipation and the design procedures will be simple.

In this study, the slope of the knee elements in model has been chosen as unit showed in Fig. 2 (*hh* = *bb*) to facilitate cutting and welding in workplace and also being equal in rotational stiffness of ends of element. As mentioned another condition that is very vital and must be applied is the junction of the chevron brace to the middle of the knee element.

According to Fig. 2(a) small amount of eccentricity (*e*) would be appeared on axis of brace because of following geometric conditions. In other words, with placing the knee elements in unit-slope mode and connecting the brace to middle of the knee, some amount of eccentricity may be appeared for the brace line. The magnitude of "*e*" is often too small in usual building frames and can be neglected particularly when the $\frac{B}{H}$ ratio tends to 2 (symmetric case). The value of "*e*" is defined by

$$e = \frac{\frac{\sqrt{2}}{2}L_k\left(\frac{H}{B}\right) - H + \frac{B}{2} - \frac{\sqrt{2}}{4}L_k}{\frac{2H}{B} - \frac{2\sqrt{2}H}{L_k} - \frac{\sqrt{2}L_k}{2B} + 1} \tag{6}$$

L_k, H and B are the length of the knee, height and width of the frame. Regarding Eq. (6), eccentricity is dependent on the length of the knee, height and width of the frame and when the $\frac{B}{H}$ ratio tends to 2 this value will be faded. The effects on each other in the combination of KBF with VLB are another important issue. In Fig. 3 both cases in chevron knee braced frame with and without VLB have been shown. The parameters $\gamma_{(EV=0)}$, γ, E_H and E_V represent respectively angle of brace to the vertical without VLB, angle of brace to the vertical with VLB, horizontal and vertical components due to VLB. The effect of VLB length on other characteristics of frame is illustrated

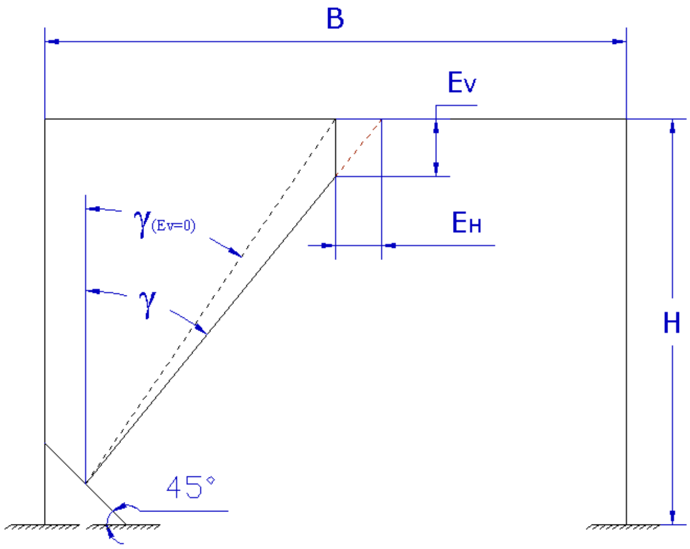

Fig. 3 Effect of added VLB on knee braced frame

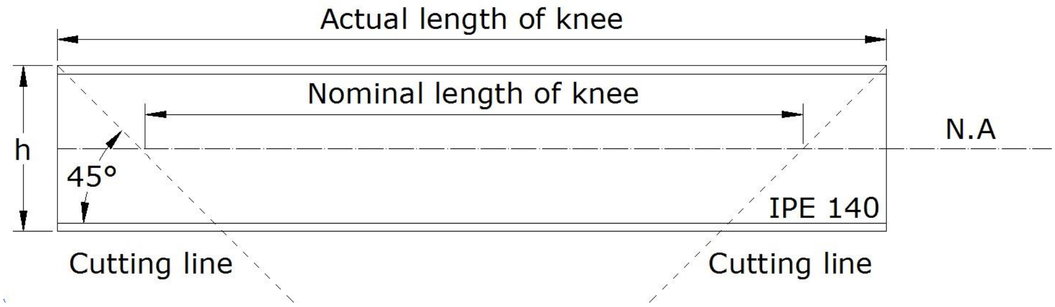

Fig. 4 Fabrication of the knee member

on Eq. (7). This term reveals that when the VLB is added to frame, the angle between brace to knee should be inclined to $\frac{\pi}{4}$ causing the axial force in knee element would be minimum whereby perfect post-yielding behavior of the knee element will be expected.

$$\tan(\gamma) = \frac{B-bb}{2[H-\left(\frac{hh}{2}+E_V\right)]} \tag{7}$$

2.2.2 Knee element design

According to proposed issues, the knee element has been built from IPE140 with symmetry cutting. Fig. 4 shows the specimen in details.

If the knee length is chosen 85cm after fabricating, the nominal length will be 71cm (L-h). To insure that the knee member yields in shear instead of moment, Eq. (1) proposed by Balendra has been used

$l_k < 2\frac{M_P^*}{V_P}$ = 37.12 cm

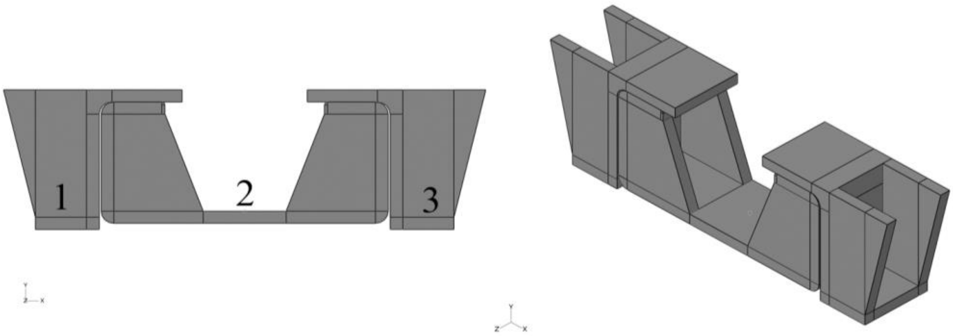

Fig. 5 Shape of the stopper device assembly

If the brace is connected to the middle of the knee, l_k will be obtained 35.5 cm which satisfies the limitation. Shear capacity of knee element:

$V_n = \min\{2\frac{M_P}{e}, V_P\} = 8541.216$ kg

$\phi_V V_n = 0.9(8541.216) = 7687.1$ kg

To prevent of premature failure on knees, stiffeners have been employed in both web sides of knee that described in following sections.

2.3 Stopper device

The design and establishing of the "Stopper Device" (SD) is a fundamental part of the hybrid system efficiency because the CK-VLB system has employed two different passive metallic dampers at end of each chevron bracing vertex only in single panel frame. Hence the performance of the system theoretically is similar to axial springs in series placed along each other. So if there is no contrivance for coordinating between the force distributions of springs, only the spring with smaller stiffness would work and another spring would be almost immobile.

The SD is one type of solution for convenient interaction between metallic dampers connected in series. Based on the geometry of the frame equipped with CK-VLB, the segment of the frame with almost the whole shear force (approximately 80~90% of base shear on single frame) would be the VLB, so initial yielding of the frame would appear in the VLB. In Fig. 5 the SD is shown assembled with three segments. Side segments (1, 3) are set up under the flange beam from upper side and the middle segments (2) is connected to the gusset plate and the VLB from underside and upper side respectively. For this particular study, the VLB rotation angle has been chosen 0.015 through making ±3mm gap between middle and side segments on SD and if the VLB reaches to this angle, the deformation of the VLB will be locked by applying constraint with acting a normal force to the contacting surfaces of SD that touch each other whereby the knees will be superimposed to the system for improvement of energy dissipation capacity.

2.4 Main elements

An equal steel single panel is chosen to place three hysteretic damper systems individually to compare their main seismic parameters via monotonic loading. These systems are KBF, SPS and CK-VLB as shown in Fig. 6. The beam and the columns are wide flange sections IPB140 and

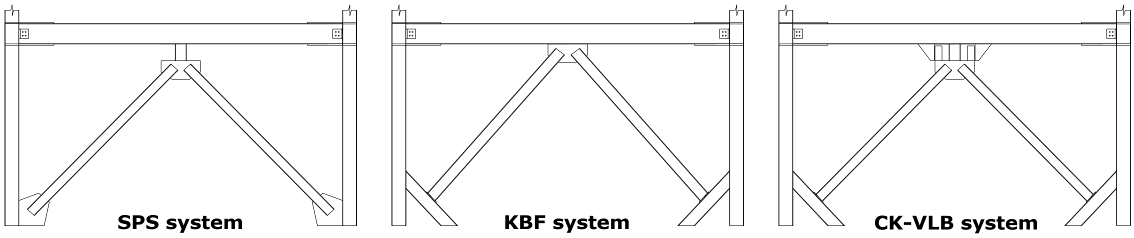

Fig. 6 Schematic shape of three models

Table 1 Summary of the models for monotonic loading test

Model no.	Model name	Number of metallic device	Section of the knees	Length of the knees (cm)	Section of the VLB	Length of the VLB (cm)
1	CK-VLB1	3	IPE 140	71	IPE 100	20
2	CK-VLB2	3	IPE 140	71	IPE 120	20
3	CK-VLB3	3	IPE 140	71	IPE 140	20
4	KBF	2	IPE 140	70.6	-	-
5	SPS	1	-	-	IPE 160	20

IPB120 respectively. These members are designed to remain in elastic range even though the knees go to failure. The chevron brace is 2UNP100 back to back and designed to never buckle in cyclic loadings. The model dimensions were set to a height of 2970mm from N.A of the beam to the base and width of 4260mm between axes of columns. Table 1 shows the summery of the models.

3. Finite element modeling

The general purpose, finite element computer program ABAQUS v6.9 (2009) was used to model the steel frame with CK-VLB and other systems. The software allowed for three dimensional finite elements modeling having the capability of applying nonlinearity in three manners of materials, geometrics and boundary conditions. At first the experimental results have been used to ensure accuracy of the modeling method and the finite element analysis results.

In order to verify numerical results, Zahrai and Moslehitabar's (2006 and 2013) test specifications have been used. The test included single span, single storey steel frame equipped with SPS which was designed and tested under quasi-static loading according to AISC seismic provision (AISC 1997). The finite element program ABAQUS was used to model this specimen. In this step, finite element analysis results are compared to experimental results. Fig. 7 shows the base shear versus lateral displacement of frame for two: numerical and experimental cases. The finite element method results agree with those obtained by experiments.

3.1 Properties definition

The results strongly correlate to the properties of steel that is assigned to the model. This study contains three steel grades for achieving appropriate definition on performance of elements. For

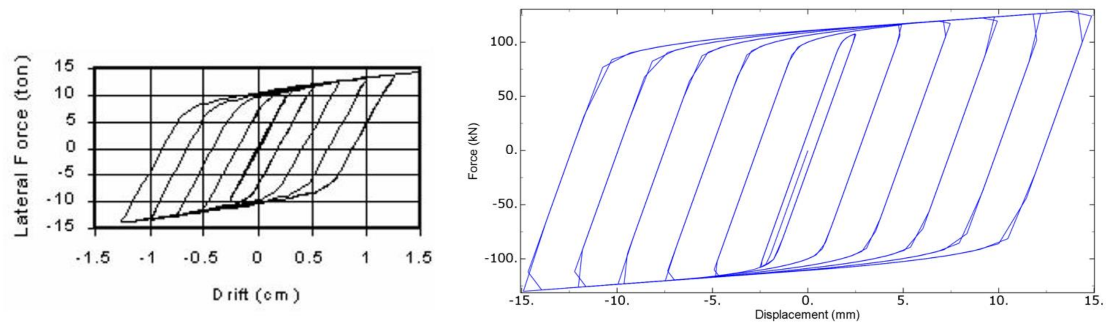

Fig. 7 Base shear- lateral displacement of frame (Left): EXP (Right): FE

Table 2 Properties of steel types using for models

Steel grade	Density (kg/m^3)	Young modulus (kg/cm^2)	Poisson ratio	Yield stress (kg/cm^2)	Failure stress (kg/cm^2)	Analogue plastic strain
Typical steel (ST-37)	7850	2.1×10^6	0.3	2400	3700	0.18
Steel without hardening	7850	2.1×10^6	0.3	2400	2400	0
High strength steel (HSS)*	7850	3.0×10^6	0.3	6900	7600	0.02

* Steel, High Strength Alloy ASTM A-514

whole different frames, the material properties have been completely defined in equal manner in order to compare between their only lateral resistance systems. The properties of elements have been defined in Table 2.

Note that the steel grade without hardening has been used for the main frame (beam, column and braces), the ST-37 grade has been used for definition of metallic dampers and HSS grade has been only used for stopper device in CK-VLB system. Also the classical metal plasticity with Von mises yield surface with associated plastic flow, which allows for isotropic and anisotropic yielding used here. Isotropic hardening is utilized for cases where the straining at each point is essentially in the same direction in strain space throughout the analysis, so the isotropic hardening is utilized for all inclusive material of frames under monotonic loading test and the kinematic hardening is used to simulate the inelastic behavior of materials that are subjected to cyclic loading.

3.2 Assembling and mesh refinement

As mentioned, CK-VLB system has a fundamental part called SD which can create two separate levels of energy dissipation by restricting the exceeding plastic distortion of VLB device. The configurations of SD and mesh density in critical areas are shown in Fig. 8. Also the full view of the frame with CK-VLB system is shown in Fig. 9. In order to proper operation of SD, a contact interaction property with frictionless mode in tangential behavior and hard mode in normal behavior has been applied for in touch surfaces of device. Mesh density has been increased in the susceptible areas with high stress concentrations. To simulate of welded connection types,

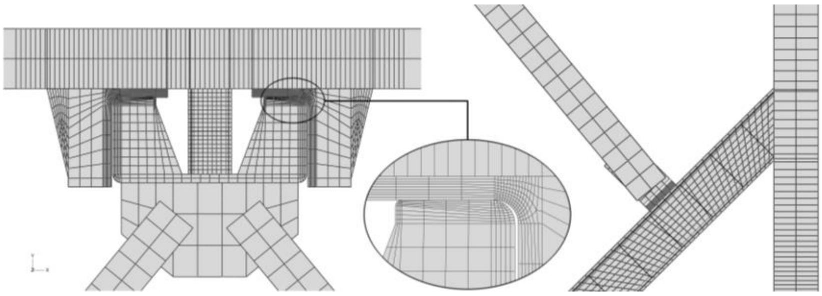

Fig. 8 View of SD and mesh refinement in CK-VLB

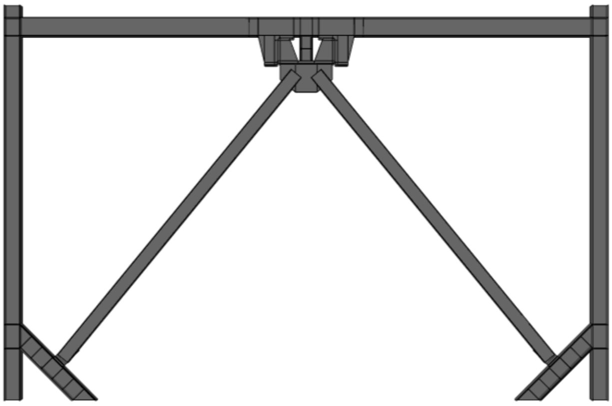

Fig. 9 The full view of frame with CK-VLB system

Table 3 Mesh properties for elements of steel members

Structural type	Mesh type	Family	Number of nodes	Formulation	Integration	Order of interpolation
Column	S4R	Shell	4	Lagrangian	Reduced	Linear
Beam	S4R	Shell	4	Lagrangian	Reduced	Linear
Brace	S4R - T3D2	Shell - truss	4	Lagrangian	Reduced	Linear
VLB device	C3D8	Continuum	8	Lagrangian	Full	Linear
Knee element	C3D8	Continuum	8	Lagrangian	Full	Linear
SD	C3D8R	Continuum	8	Lagrangian	Reduced	Linear
Stiffener	S4R	Shell	4	Lagrangian	Reduced	Linear

surface-based tie constraint has been used that allows for rapid transitions in mesh density within the model. The types and characteristics of mesh elements are addressed in Table 3. Lagrangian formulation and linear order of interpolation were used.

3.3 Lateral loading

Tests were conducted for two types of loadings. Initially the incrementally monotonic lateral force was applied to the beam-to-column joint based on displacement control to compare capacity curves of frames with three different systems as mentioned in Table 1. Then, the quasi-static

Table 4 Loading history for quasi-static loading protocol

Cycle no.	Fraction of Δ_y	Drift (%)
1	0.33	0.033
2	0.33	0.033
3	0.33	0.033
4	0.67	0.067
5	0.67	0.067
6	0.67	0.067
7	1.0	0.1
8	1.0	0.1
9	1.0	0.1
10	2.0	0.2
11	2.0	0.2
12	2.0	0.2
13	3.0	0.3
14	3.0	0.3
15	3.0	0.3
16	4.0	0.4
17	4.0	0.4
18	5.0	0.5
19	5.0	0.5
20	6.0	0.6

loading protocol was used for the frames with CK-VLB1 and CK-VLB2 based on the guidelines presented in ATC-24 (1992). Verification of the (Δ_y) of the frames was obtained from pushover analysis by checking the initial plastic strain on the metallic dampers; the displacement of the frame correlated to first occurrence was assigned to be the yield displacement of the frames. It can be concluded that the yield displacement is 3mm for all frames if existence of VLB is neglected on CK-VLBs and only notation to deformations of knees on frames. Table 4 gives the displacement history of the cyclic loading.

4. Results

4.1 Pushover analysis

The models are subjected to incremental lateral load on beam to column joint by pushover analysis with joint displacement control. The position of knee bracing in KBF system is different and based on recommendations by Mofid and Lotfollahi (2006). Fig. 10 and Fig. 11 respectively show contours of equivalent plastic strains at VLBs and knees. At the end of 5cm lateral displacement of frames, the web of VLB embedded in the SPS system failed at vicinity of flanges, while in the CK-VLB system it still was in intact condition due to application of the SD (Fig. 10).

Also the distribution of plastic deformation in the knee elements was so uniform in CK-VLB unlike the KBF system (Fig. 11). After loading the web of the knees in the KBF system,

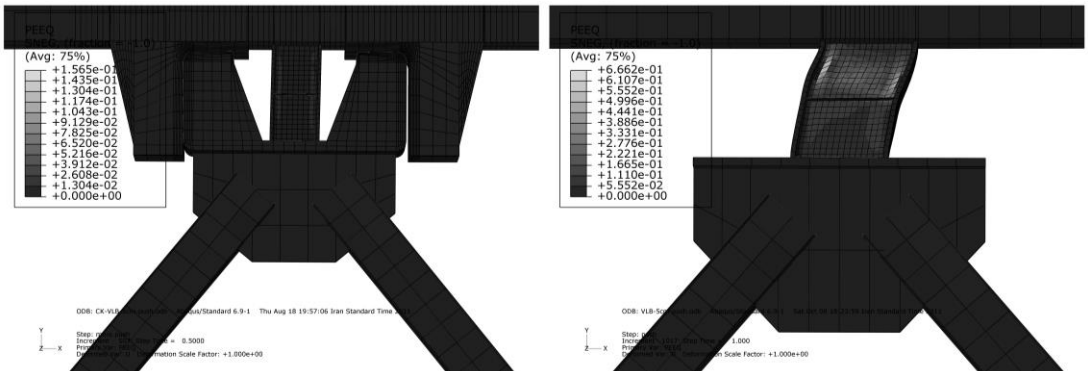

Fig. 10 Quantity of VLB plastic strain (left): CK-VLB (right): SPS

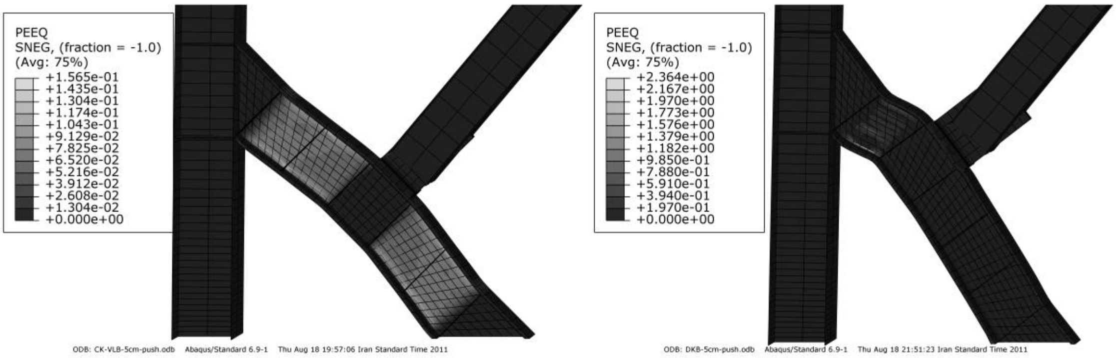

Fig. 11 Quantity of KNEE plastic strain (left): CK-VLB (right): KBF

completely buckled just at one panel of the web that caused premature failure of the knee elements.

The capacity curves resulted from pushover analysis of equal frames with dissimilar metallic dampers are shown in Fig. 12. According to the graphs, the hybrid performance of the CK-VLB ascertain clearly which at the first stage of energy dissipation, by operation of VLB as the first level fuse, the ductility and damping are obtained whereas the second stage has improved the seismic capacities after increasing excitations via yielding of the knee elements. The CK-VLB has achieved to the non-linear performance at 2mm lateral displacement when base shear was 55kN while in the KBF this amount was 230kN at 3.5mm that shows the absorption of energy could be initiated sooner and at lower forces in CK-VLB. Also there is another distinction between behaviors of knees in CK-VLB system; as mentioned above, due to difference of the placement modes in brace-knees segment. In other words, with applying knees in unit-slope mode connecting the diagonal braces to the middle of the knees, the durability of the knees in CK-VLB increased and a logical plastic deformed shape along the webs was observed. The premature failure of the knee elements on KBF system affected on seismic performance through degradation of force-displacement curve when the frame drift exceeded from 1/120.

Fig. 13 shows the total stored energy in main elements of frame equipped with CK-VLB and DKB (Double Knee Brace) systems due to elastic deformations. With early yielding of VLB member on CK-VLB system, the elastic strain energy stays down sorely almost in half of

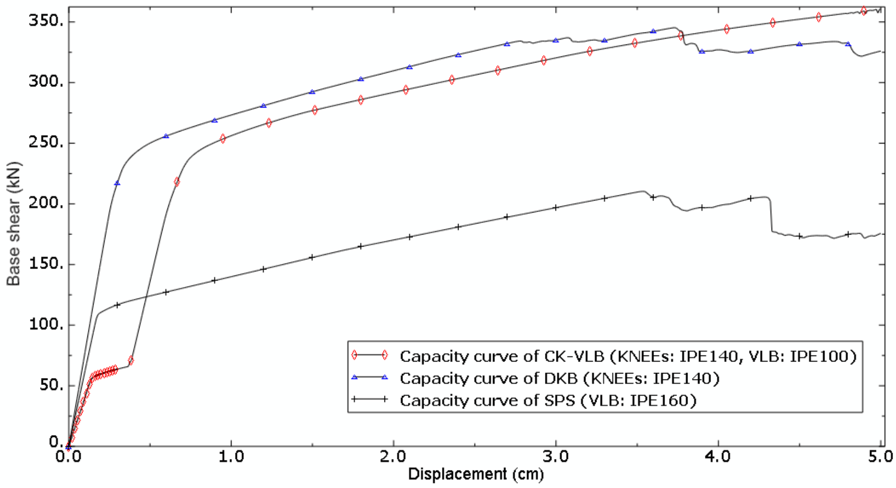

Fig. 12 Lateral performance of frames with different metallic dampers

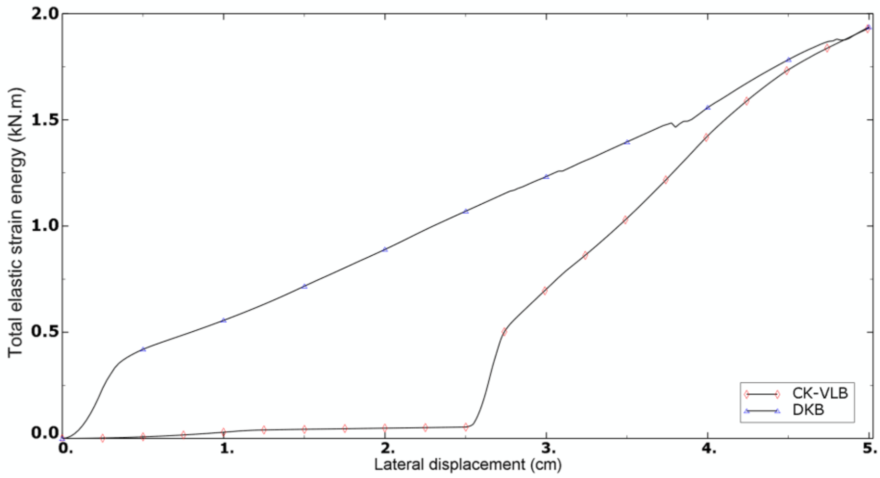

Fig. 13 Elastic strain energy comparison between CK-VLB and DKB models

displacement target compared with DKB system that rises up to 1.1 kN.m. This causes to hold down the internal forces on main elements of frame in most instances and increases durability and endurance. Also a frame with less internal forces has more flexibility in deformations. In Fig. 14 energy dissipation due to plastic deformations of metallic dampers has been indicated on CK-VLB system and SPS system. It is observed from Fig. 14 that CK-VLB system with containing 3 metallic dampers, has a greater value of damped energy (more than 12 kN.m) while SPS system with a greater section size of vertical link beam (refer to Table 1) only has an ability to damp energy about 6.8 kN.m at end of loading process. From results it can be deduced that CK-VLB with combining of vertical link beam and knee elements has a more durability and ductility in main elements in comparison with DKB and it has a greater energy damping ability than that of SPS system.

4.2 Quasi-static cyclic loading analysis

By selecting Δ_y to 3mm, the cyclic displacement same as proposed in Table 4 was imposed to the models with CK-VLB1, 2 and 3. These models only have difference on section size of vertical link beam so it might be possible to find appropriate proportion between two stages of hysteretic performance and distinctions model with variation of section size of vertical link beam. The models were loaded up to 6 times of the drift corresponding to yielding. In CK-VLB1, the initial lateral stiffness of first stage when VLB acted was determined to be 41.22 kN/mm and the second stage of lateral stiffness when the knee elements superimposed was determined to be 55 kN/mm in the elastic range of the cyclic deformations, these two parameters for CK-VLB2 and 3 were obtained 45.3, 55.5 and 48.4, 55 respectively. The first stage yield drift for CK-VLB1 was identified as 0.05% corresponding to a base shear of 58 kN that implies the energy dissipation of the system would start in very small lateral displacements and its second stage yield drift was obtained as 0.3% at the moment of plastic deformation starting in knee elements corresponding to a base shear of 255 kN. The first stage yield drifts for CK-VLB2 and 3 were identified as 0.06% and 0.068% corresponding to base shears of 76 kN and 92.5 kN respectively. Also second stage yield drifts for CK-VLB2 and 3 were obtained same as CK-VLB1 because of equal geometric quantities of knee elements. Figs. 15, 16 and 17 show the corresponding base shear hysteresis versus lateral displacement of the frame for CK-VLB1, CK-VLB2 and CK-VLB3 respectively.

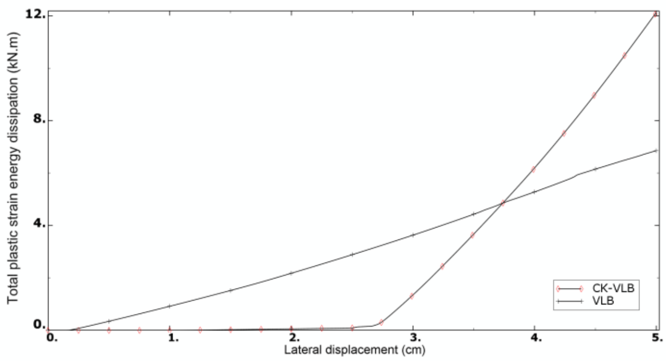

Fig. 14 Plastic energy dissipation comparison between CK-VLB and SPS models

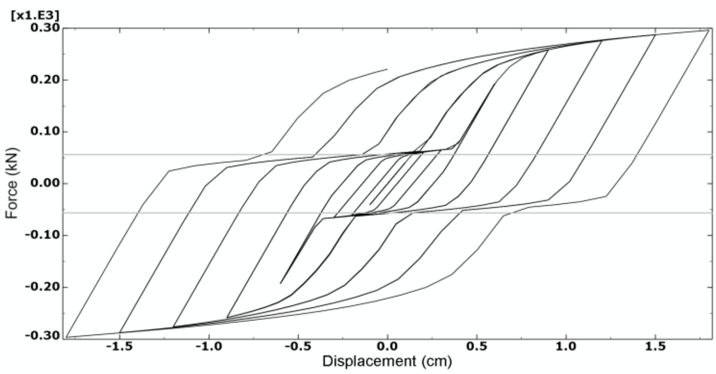

Fig. 15 Hysteresis loops for CK-VLB1 (VLB: IPE100, KNEES: IPE140)

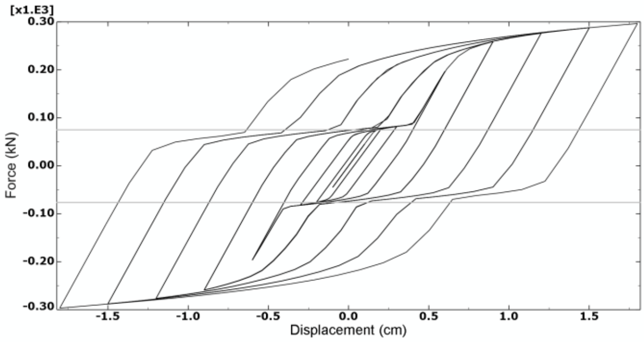

Fig. 16 Hysteresis loops for CK-VLB2 (VLB: IPE120, KNEES: IPE140)

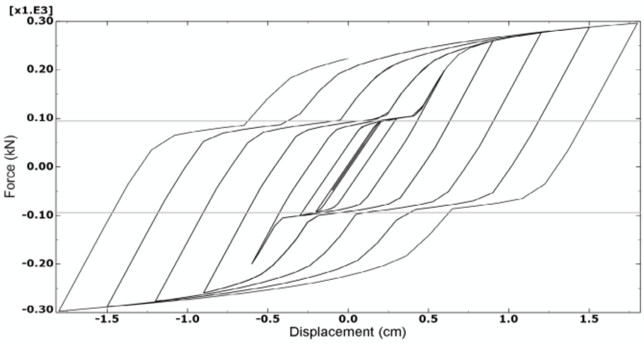

Fig. 17 Hysteresis loops for CK-VLB3 (VLB: IPE140, KNEES: IPE140)

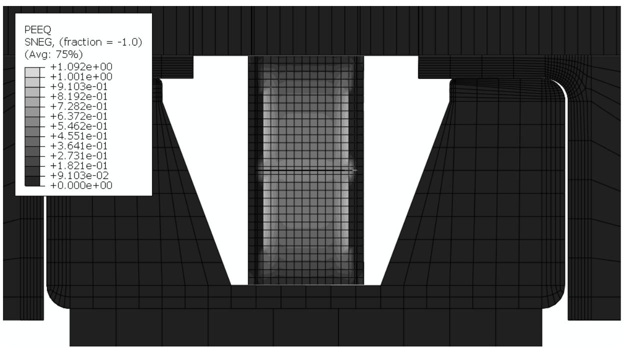

Fig. 18 Plastic strain contour for CK-VLB1 (VLB: IPE100)

According to Figs. 15-17 by increasing section size of VLB on CK-VLB model, the first stage of hysteretic loops created by plastic deformation of VLB, would be larger in their areas whereas the second stage of hysteretic loops would be immutable. Elastic stiffness, yielding force and energy dissipation capacity of system in first stage would be enhanced by increasing section size of VLB. Moreover it is possible to develop balanced proportion of energy absorption of metallic dampers in system. With increasing section size of VLB, the plastic distortions would be decreased regarding to plastic strain contours (Figs. 18-20) and also stability of the VLB for more inelastic deformations would be increased.

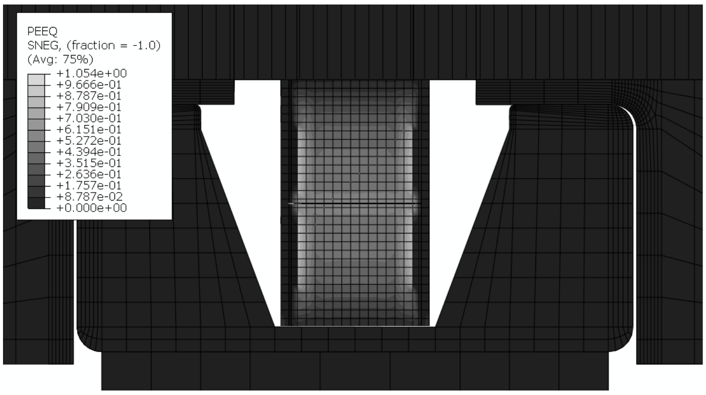

Fig. 19 Plastic strain contour for CK-VLB2 (VLB: IPE120)

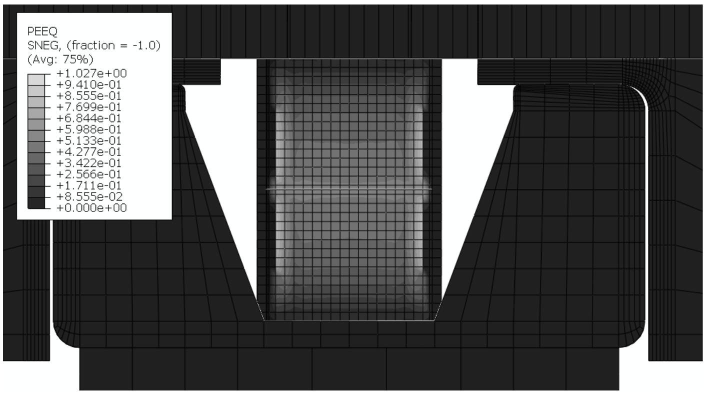

Fig. 20 Plastic strain contour for CK-VLB3 (VLB: IPE140)

5. Conclusions

The authors have presented a new two-stage performance combining system with optimal shape and angles for brace to knee element. It has been shown that with placing the knee elements in unit-slope mode and connecting the brace to middle of the knee, the optimum performance of the knee elements would be expected. In this paper using numerical study, the ability of the proposed system in dissipation energy with two separate levels is proven. Based on results it has been deduced that CK-VLB with combination of vertical link beam and knee elements has a more durability and ductility in main elements in comparison with DKB with larger energy dissipation ability than that of SPS system. Also with increasing section size of VLB, the plastic distortions in web of VLB would be decreased and stability of the VLB for more inelastic deformations would be increased. By built in SD and applying optimal shape and angles, the viability of metallic dampers is improved that lead to durability and increase of energy dissipation capacity.

Acknowledgments

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