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Cyclic testing of innovative two-level control system: Knee brace & vertical link in series in chevron braced steel frames

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Abstract. For further development of passive control systems to dissipate larger seismic energy and prevent the structures from earthquake losses, this paper proposes an innovative two-level control system to improve behavior of chevron braced steel frames. Combining two Knee Braces, KB, and a Vertical Link Beam, VLB, in a chevron braced frame, this system can reliably sustain main shock and aftershocks in steel structures. The performance of this two-level system is examined through a finite element analysis and quasi-static cyclic loading test. The cyclic performances of VLB and KBs alone in chevron braced frames are compared with that of the presented two-level control system. The results show appropriate performance of the proposed system in terms of ductility and energy dissipation in two different excitation levels. The maximum load capacity of the presented system is about 30% and 17% higher than those of the chevron braced frames with KB and VLB alone, respectively. In addition, the maximum energy dissipation of the proposed system is about 78% and 150% higher than those of chevron braced frames with VLB and KB respectively under two separate levels of lateral forces caused by different probable seismic excitations. Finally, high performance under different earthquake levels with competitive cost and quick installation work for the control system can be found as main advantages of the presented system.

Keywords: two-level control system; chevron braced steel frame; knee brace; vertical link beam; energy dissipation; cyclic testing

1. Introduction

During the recent decade, many researchers have investigated various means to find new modern methods to absorb earthquake energy (Silwal *et al*. 2015, Ke and Yam 2016, Shakibabarough *et al*. 2016, Sun *et al*. 2016). The energy dissipation devices dissipate main part of the seismic energy through inelastic deformation mechanisms. Based on earthquake energy dissipation nature, structure control systems are divided into three categories, active (Hochrainer 2015, Li and Liu 2015, Omidi and Mahmoodi 2015), semi-active (Zahrai and Shafieezadeh 2009, Eljajeh and Petkovski 2015, Esteki *et al*. 2015) and passive systems (Hsu *et al*. 2011, Zahrai and Jalali 2014, Mori *et al*. 2015, Zahrai *et al*. 2015, Saeedi *et al*. 2016).

Supplemental energy absorption systems have been recently proposed to improve seismic performance of structures. Extensive research has achieved a better understanding of the effects of supplemental energy dissipation devices on how different structures can sustain earthquakes (Hanson and Soong 2001, Saaed *et al*. 2015). Christopoulos and Filiatrault (2006) also discussed principles of passive supplemental damping and seismic isolation. Accordingly, various passive control devices have been developed and used in structures due to their low manufacturing and operation costs. These absorbers play the main role in controlling the resonance events and fatigue failure. For more energy dissipation and optimum operation of the system at maximum capacity, the passive control systems which can work in desired levels are more appropriate. Takewaki (2011) developed optimal sensitivity design to optimize total damping and its distribution and introduced a variety of passive dampers for building structures under earthquake ground motions. Eccentrically Braced Frame, EBF, as a lateral bearing resistant system shows combinational operation between Knee Braced Frame, KBF, and Concentrically Braced Frame, CBF. This system was initially introduced in order to utilize architecture space and openings optimally. The appropriate operation of this system, in one frame with 1/3 scale was confirmed at California State University at LA. (Roeder and Popov 1978). The KBF and other bracing systems with link beam have been used because of limitations such as necessity of rigid connections in some EBF types, floor distortion due to link beam rotation and increase of other structural parts. Zahrai and Moslehi Tabar (2006) investigated five single span frames having Vertical Link Beam, VLB, under cyclic load using finite element method. Their results showed that vertical link had no impact on sample behavior in absence of stiffener before beam web buckling; however, by applying stiffener, the system performance was improved.

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Chan *et al*. (2009) investigated the shear yielding links with hollow square sections through vertical link. Mofid and Lotfollahi (2006) conducting a numerical study, proposed a model for knee element to obtain a modified chevron braced frame. Kim *et al*. (2012) proposed a new three-layer pillar-type hysteretic damper system for residential houses. The proposed vibration control system has braces, upper and lower frames and a damper unit including hysteretic dampers. The damping capacity of the proposed system was estimated by the logarithmic decrement method for the response amplitudes. A new system for operation in two different levels of lateral load has been reported by Balendra *et al*. (2001). Daneshmand and Hoseini Hashemi (2012) studied the compatibility of their results with AISC instruction by modeling 68 samples of link beams having different lengths. They evaluated various parameters such as web slenderness ratio, with and without single-sided or two-sided stiffeners, distance of stiffeners, and web thickness. The details of rigid connections of special moment resisting frames in energy absorption of structures have been reported by Hoseini Hashemi and Ahmady Jazany (2012) using full scale experimental work.

In some reports, parallel installed system consisting of steel damper and viscous damper decreased the amount of energy dissipation due to viscous damping enhancement of the system (Vargas and Bruneau 2007). Zahrai and Moslehi Tabar (2013) developed an extended mathematical model for evaluation of lateral stiffness of braced frames having VLB. They proposed a mathematical expression to define the geometric properties of the VLB regarding the desired ductility. They found that the ultimate plastic lateral deformation is directly proportional to the link length. Zahrai and Jalali (2014) experimentally and numerically studied cyclic performance of two knee braced single span frame specimens, and discussed some indices to assess the seismic performance of KBFs, including ductility, response reduction factor and energy dissipation capabilities. Zahrai (2015) conducted 5 full scale tests on chevron braced steel frames with VLB to identify the cyclic performance of the proposed narrow flange link beams, and obtained hysteretic damping ratio up to 30%.

Few researchers have recently applied different damping systems in series. Zahrai and Vosooq (2013) applied combination of knee brace and VLB in series installed in chevron braced frames to evaluate a new two-level control system. In their study, the layout and system design are similar to the structure which acts in two-phase during the medium to extreme earthquake occurrences. According to their reports, the system has more energy dissipation capacity compared to VLB system, and begins the energy absorption process faster in comparison with KBF system. Hashemi and Alirezaei (2015) investigated the performance of a combined Knee Brace, KB, and EBF called Eccentrically Knee Brace (EKB), and tested two half-scale specimens. As well as the structural fuse of the frame, the knee element will fail first during a moderate earthquake while in large earthquakes both systems contribute in dissipating energy. In another research, Cheraghi and Zahrai (2016) proposed a multi-level control system with concentric pipes along diagonal brace to decrease seismic response of steel frames. They claimed that the multi-level system could reliably dissipate energy in different excitation energy levels leading to ductility ratios about 15 to 37 and equivalent viscous damping ratios about 36 to 50%. Furthermore, Zahrai and Cheraghi (2017) used their proposed control system to reduce the seismic response of typical 5, 10 and 15-story steel buildings. They showed that the new proposed damper is so effective to improve the seismic behavior of the steel structures under earthquake loading such that the maximum roof acceleration decreased by average of 16%, 14% and 11% compared to bare frames for the 5, 10 and 15-story frames, respectively. To experimentally study the performance of their proposed multi-level pipe in pipe damper, Cheraghi and Zahrai (2017) fabricated two test specimens and investigated the cyclic behavior of dampers.

Another form of multi-level passive control systems is proposed and studied here. In the current study, an innovative type of two-level passive control system entitled Chevron KB-VLB system is proposed to improve performance of steel structures under multiple levels of seismic ground motions. The system consists of two KBs having slotted bolted connection along brace and a VLB in series. This way, a new bracing method is built which shows significant ability to dissipate seismic energy in addition to the capability to sustain against main shock and aftershocks. Two KBs with slotted bolted connection act as the first fuse during moderate earthquakes with lower level forces. On the other hand, the VLB acts as the second fuse to absorb seismic energy induced during severe earthquakes after stoppers are engaged at the knee braces preventing them from further plastic deformations. To investigate the cyclic performance of the proposed system as effective energy absorber under two level excitations, an experimental procedure is presented for three test specimens under cyclic static loading, and the results are used to validate the presented finite element model developed by commercial code ANSYS 13. Finally, the effects of various parameters are evaluated and discussed.

2. Proposed system definition

One of the most inexpensive and simplest methods for passive control of structures is to use VLB, which acts as a subsidiary and ductile fuse in a structure. The VLB is considered vertically between node of chevron bracing and floor beam, and the energy is dissipated through VLB web shear yielding, while other structural elements remain in elastic behavior. According to previous studies, the knee element yielding under shear instead of bending moment causes more stable hysteretic curves and energy dissipation. Hence in this proposed system, the yielding is considered as shear type. On the other hand, shear yielding of knee element is a function of factors such as knee length and angle of incidence with bracing. The overall characteristics of proposed sample are illustrated in Fig. 1. The proposed system consists of two knee segments and a VLB in series, connected through chevron bracing.

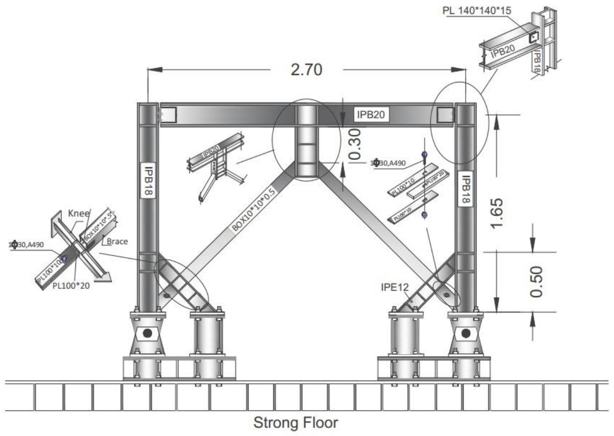


Fig. 1 General geometry of the proposed two-level control system along with its connection details

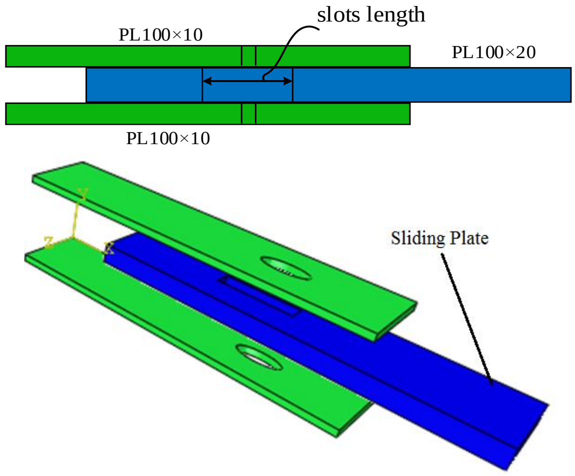


Fig. 2 Proposed slotted bolted stopper details

In this system, design is primarily conducted using yielding of two knee segments acting as the first fuse, while the VLB acts as the second fuse. To consider two-level control operation of the proposed model, it is necessary to provide a system which prevents knee element from excessive deformations after yielding of the first fuse. Thus, for this reason, a slotted bolted stopper mechanism is designed which consists of plates having limited slotted holes as shown in Fig. 2, preventing the first fuse from sustaining excessive inelastic deformations.

3. Design basis and principles

3.1 Knee element design

To maximize energy dissipation capability for the design of knee element, it is necessary to consider three factors such as, providing shear yielding instead of moment yielding, preventing from knee local and lateral buckling that can be done by limiting knee length and the ratio of width to thickness of knee components (Balendra *et al*. 1994).

Furthermore, to prevent the knee from lateral buckling, length limitation is defined for link operation without lateral supports (Leon *et al*. 2011). 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 and to avoid the failure at the moment before shear, the longer of the two segments of the knee member generated by the intersection of the diagonal brace and the knee member, denoted as was confined to the following condition (Ravindra and Galambos 1978, Uniform Building Code 1997),

$$l_k < 2\frac{M_p^*}{V_p},\ M_p^* = t_f b(d-t_f)\sigma_y,\ V_p = t_w(d-t_f)\frac{\sigma_y}{\sqrt{3}} \quad (1)$$

where M_p^* and V_p are reduced plastic moments due to flanges and plastic shear force, respectively. l_k is the maximum length of those two segments of the knee member generated by the intersection of the diagonal brace and the knee member. σ_y, d, t_f, b and t_w present yield stress, depth, flange thickness, flange width and web thickness of knee element, respectively. The International Building Code (Uniform Building Code 1997) specifies minimum regulations for building systems using prescriptive and performance-related provisions.

Although, knee member is considered as the weakest damper in the proposed system, it should be initiated to yield and to dissipate the energy as the first fuse under moderate earthquake. Hence, IPE120 section with 120mm depth, 64mm flange width, 4.4mm web thickness and 6.3mm flange thickness is used.

The best operation condition of knee chevron bracing system occurs when braces are perpendicular to knee segments, and every knee element stands parallel to the other side of brace (Mofid and Lotfollahi 2006). To meet the above condition, length of knee is l_k<317 mm and since the brace goes through the middle of knee, thus the length l_k<173.5 mm is chosen. The selected dimension prevents the knee bracing system from the lateral and local buckling, while premature buckling of the knee web is prevented by adding web stiffeners across the knee length.

3.2 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 for the knee element (Hoseini Hashemi and Alirezaei, 2015). In this condition, shear force and bending moment of the knee element can be approximated to a beam with two fixed ends and concentrated force (point load) on mid-span. Besides, most of the knee element capacity can be consumed for energy dissipation and the design procedures would be simple.

In this study, the slope of the knee elements in model was chosen to be 1 as shown in Fig. 3 to facilitate cutting and welding in workplace and also being equal in rotational stiffness of ends of element. 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 small amount of eccentricity would appear on axis of brace because of following geometric conditions. In other words,

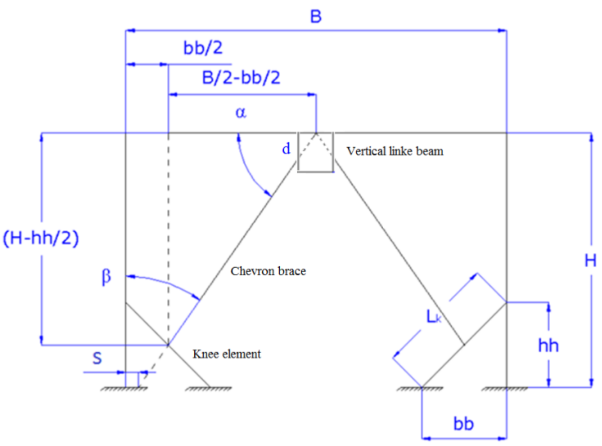


Fig. 3 Geometrical characteristics of the structure

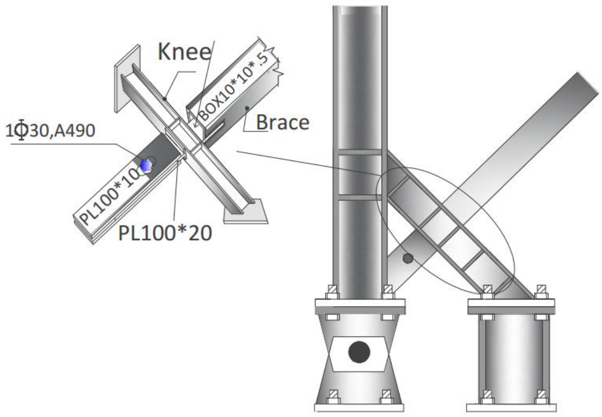


Fig. 4 Schematic of stopping system and slotted bolted connection

with placing the knee element in this slope and connecting the brace to middle of the knee, some amount of eccentricity may be appeared for the brace line. The magnitude of "*s*" is often too small in usual building frames and can be neglected particularly when the ratio tends to 2 (symmetric case). The value of "*s*" is defined by,

$$s=\frac{\frac{\sqrt{2}}{2}L_k\left(\frac{H}{B}\right)-H+\frac{B}{2}-\frac{\sqrt{2}}{4}L_k}{\frac{2H}{B}-\frac{\sqrt{2}H}{2L_k}-\frac{\sqrt{2}L_k}{2H}+1} \tag{3}$$

$$\tan(\beta)=\tan\left(\frac{\pi}{2}-\alpha\right)=\frac{B/2}{H}$$

3.3 VLB design

As long as the knee elements show inelastic behavior of dissipating energy with plastic deformations, the second damper or VLB should remain in elastic zone. After activation of the stopping system as explained later, the second fuse is initiated to work. Therefore, the design of the second fuse is conducted based on a lateral force greater than knee element shear plastic capacity. In addition, for shear yielding of VLB, the length limitation based on the AISC2005 is as follows,

$$e<1.4\frac{M_p^*}{V_p},\qquad M_p^*=Z\sigma_y,\qquad V_p=0.55d\,\sigma_y t_w \tag{4}$$

where *e* and *Z* are the length and plastic modulus of VLB, respectively.

VLB is considered as the second fuse which should yield and enter its inelastic zone after acting stopping system. Hence, IPE 200 section with 190 mm depth, 200mm flange width, 6.5 mm web thickness and 10 mm flange thickness are used for VLB. For this section, $e\leq 735$ mm and by selecting of special length $e=300$ mm, this limitation is satisfied.

3.4 Design of the main member of system

The other main members of CK-VLB system such as braces, columns and beam should remain in elastic range until the end of loading. Thus, a BOX100*5 section, IPB200 and IPB180 profiles are used for the braces, beam and columns, respectively.

3.5 Slotted bolted stopper

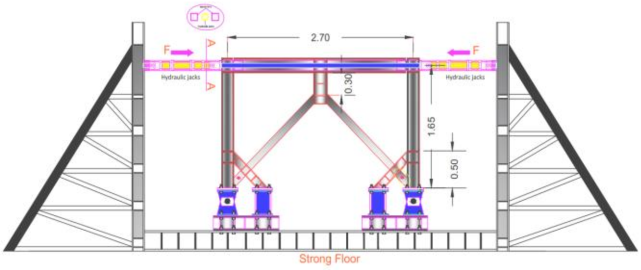
To assign two-level operation for the proposed control system, it is necessary to design a system which prevents knee segments from large plastic deformations and thus to activate the second damper. Therefore, a stopper is designed as presented in Fig. 4. This system contains three plates which are connected to each other in the form of slotted bolted connection. The sliding plate as shown in Fig. 2 is welded to the knee element, and the other two plates are connected to the column constantly. The connection between these plates is frictionless and the slot in central plate leads to limiting the knee movement along braces. For those three test samples, the system behavior is evaluated by changing slot length for controlling knee movement. The plates are connected by A490 high strength bolts having 30mm diameter.

4. Experimental procedure

4.1 Test specimens

Three half scale specimens were tested under cyclic loading in structural laboratory of Iran's BHRC (Building & Housing Research Center). Fig. 5 shows the arrangement of applied system. Two hydraulic jacks with dynamic load capacity of 1000 kN and maximum static 600kN were used for quasi-static applied load within a maximum 30cm displacement. For measurement of relative displacement, Linear Variable Displacement Transducers (LVDTs) with 0.01mm accuracy were used. All data were recorded by data logger TDS602 model constructed by T.M.L Company, Japan. To prevent the tested frames from lateral or out-of-plane movement, two box sections are used (Fig. 5). The stopping system was adjusted by variable slotted bolted connection in three states of 4 mm (CK-VLB1), 7 mm (CK-VLB2), and 10 mm (CK-VLB3).

(a)



(b)

Fig. 5 (a) Photo of test specimen and set-up, (b) Schematic of test specimen and set-up

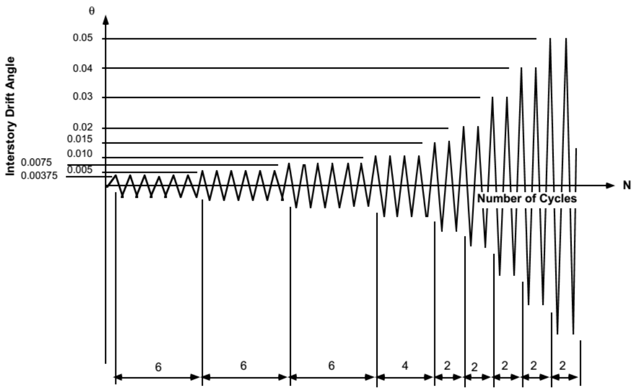


Fig. 6 Applied cyclic loading time history protocol

The constructed specimens were tested under cyclic uniform displacement based on cyclic load protocol of SAC (Jouneghani, Haghollahi *et al*. 2016) as illustrated in Fig. 6. The average rate of loading variation was ranging from 14 mm/min to 28 mm/min.

4.2 Experimental results

In this section, experimental results of the test specimens with Chevron Knee and VLB called CK-VLB are discussed. Firstly, the CK-VLB1 having 4mm of sliding length for stopping system is investigated. The experimental envelope of hysteresis curve of the CK-VLB1 is depicted in Fig. 7 where A, B and C present the points corresponding to the beginning of the knee web shear yielding, start of the stopping system and yielding beginning of the VLB web leading to increase of the system resistance, respectively.

Fig. 8 shows the yielding procedure until the failure of

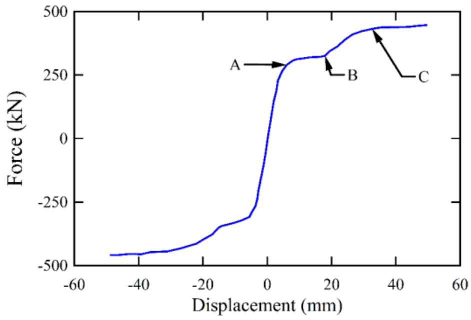


Fig. 7 The experimental pushover curve of the CK-VLB1

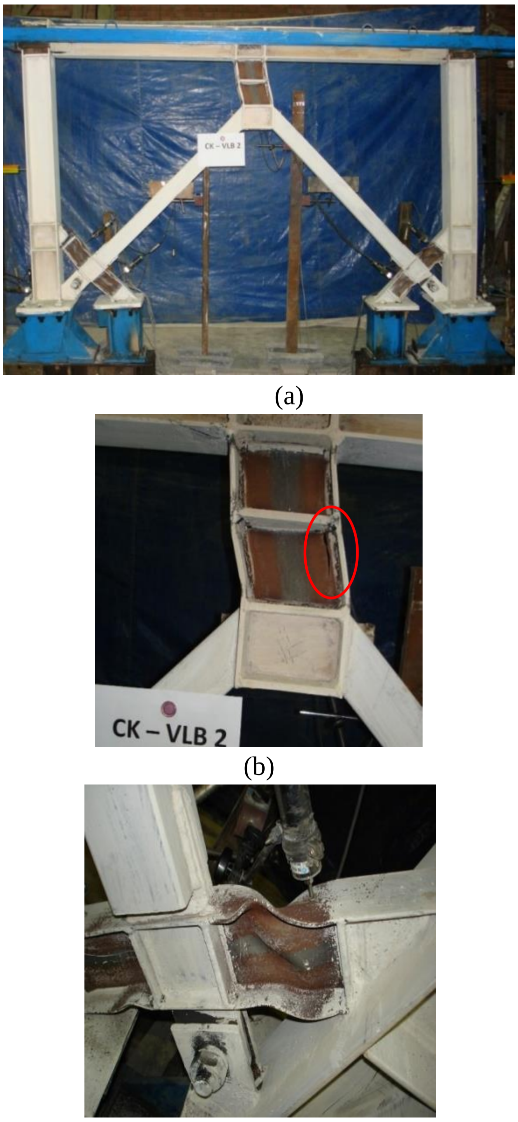
(a)

(b)

(c)

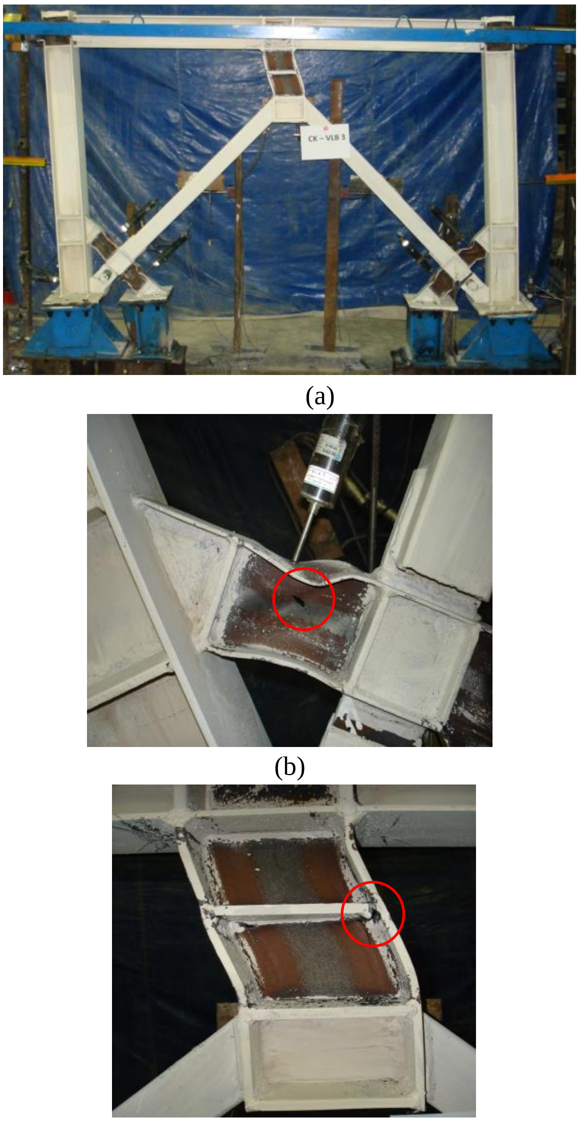
(d)

Fig. 8 Testing Procedure of the first proposed two-level control test specimen CK-VLB1, (a) Beginning of the shear yielding of knee web, (b) complete yielding of knee web and stopper engagement, (c) web yielding of the second fuse, (d) rupture of knee flange at its connection and test termination



(a) (b) (c)

Fig. 9 (a) CK-VLB2 in the end of loading, (b) VLB web failure and (c) yielding of knee links in the end of second sample loading



(a) (b) (c)

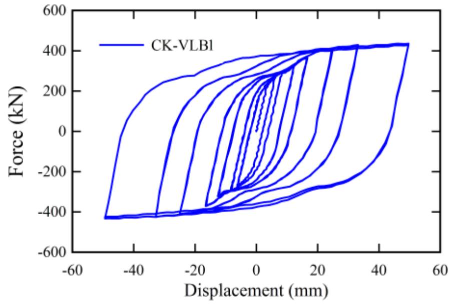
Fig. 10 (a) CK-VLB3 deformation at the end of loading, (b) shear yielding of knee web and (c) vertical link web failure

the CK-VLB1 specimen. In Fig. 8(a), beginning of shear yielding of knee shear link web (first fuse) is shown which occurs at 114 kN corresponding to 6.1 mm lateral displacement. By increasing the applied displacement to the frame, after the stopping system is activated, the VLB enters into plastic zone at 8mm displacement, while the knee web has already yielded entirely. This phenomenon is showed in Fig. 8(b) (point B in Fig. 7). Afterwards, by increasing the applied displacement, the second fuse operates in higher cycle amplitudes at 15 mm displacement. In this condition, the VLB web has local buckling, and its web meets inelastic deformations (Fig. 8(c)).

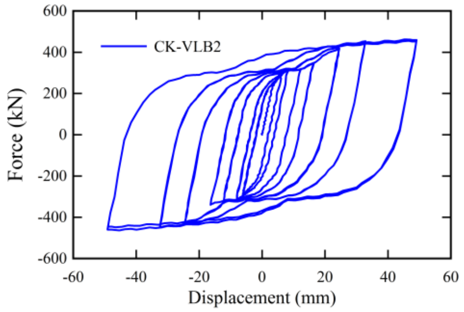
Eventually, at 50 mm displacement due to rupture of the knee flange in its connection location, the test was terminated (Fig. 8(d)). According to the failure mechanism of the system, the first fuse is activated at low-level forces. Then, increase of lateral force toward the second level leads to engagement of the stopping system which activates the VLB. Since this process can be initiated sooner in comparison with conventional systems, and operates in two levels of excitations, it can improve the energy absorption of the proposed model.

In CK- VLB2 sample, the sliding gap of stopping system is 7 mm. Fig. 9 shows the sample after final deformation. The VLB web rupture and knee yielding are presented in Fig. 9(b) and Fig. 9(c), respectively. By comparing failure rate in the CK- VLB1 and CK- VLB2, it is observed that the failure rate in CK- VLB1 is higher because of the small sliding gap. In this case, the VLB faces failure in the web, and knee strength magnitude is more dramatic than that of the first sample. By failure in VLB web, the experiment was terminated as shown in Fig. 9(b).

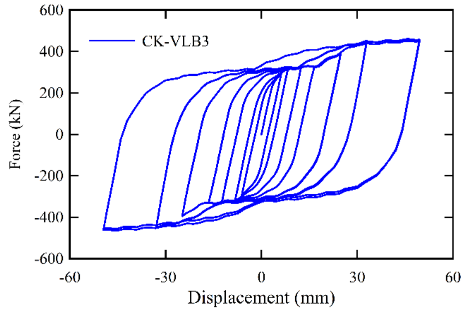
Test details of CK-VLB3 are shown in Fig. 10. In the third sample, the sliding gap of stopping system is 10mm. The shear yielding and rupture of the knee web in the sample is shown in Fig. 10(b). In addition, the VLB web failure and strength reduction, as well as termination of the



(a)



(b)



(c)

Fig. 11 Hysteresis loops of the experimental results for (a) CK- VLB1, (b) CK- VLB2 and (c) CK- VLB3

experiment are presented in Fig. 10(c). For this specimen, the yields of the first and second fuses are initiated at applied forces of 290 kN and 432 kN, respectively.

As shown in Fig. 11, in this sample during the maximum loading cycles and at extremely high displacements (above 50 mm), cracks initiation in the VLB web (Fig. 10) and mild drop in hysteresis curve are visible from Fig. 11(c). Also, this sample failed due to tearing near the VLB web at displacement equal to 32.6 mm.

In Fig. 11, hysteresis loops of CK-VLB1, CK-VLB2 and CK-VLB3 are compared. As shown, by reducing the sliding length of the stopping system, the failure displacement in the VLB and the knee segments are increased. It shows that the larger sliding gap of the stopping system increases the flexibility, and reduces the failure rate in the frames under cyclic loads. The reduction of failure rate in high sliding length is noticeable.

The magnitude of the corresponding loads and lateral displacements for the proposed two-level control systems are listed in Table 1. These parameters consist of the beginning of knee web shear yield, the knee web complete yielding, the second fuse web yielding and the knee flange

Table 1 The magnitude of corresponding lateral loads and displacements for the proposed two-level system

Specimen ID		CK-VLB1	CK-VLB2	CK-VLB3
Beginning of knee web shear yielding	Force (kN)	245	260	290
	Displacement (mm)	4.42	4.72	8
Compelte yielding of knee web and start of stopping operation	Force (kN)	291	320	326
	Displacement (mm)	9.38	17.5	18
yielding of the second fuse web	Force (kN)	406	426	432
	Displacement (mm)	22.9	29.4	32.6
Experiment termination	Displacement (mm)	50	50	50

failure at its connection and the experiment termination. These values are obtained from the hysteresis loops as shown in Figs. 11 and 14.

The test results express that the sliding gap of the stopping system has a great effect on failure rate of the proposed two-level control system. At low values of sliding gap, the system acts as a stiff structure and its ductility and cyclic performance are reduced dramatically. On the other hand, by increasing the sliding gap, the benefits of the proposed system can be shown clearly by improving cyclic performance, i.e. ductility and energy dissipation.

5. Numerical modeling and analysis

5.1 Finite element model

The FEM model was developed using ANSYS-13 commercial code according to the experimental setup. ST37 steel having 210 GPa modulus of elasticity, 0.3 Poisson's ratio and 240 MPa yield stress was used for frame members. The plastic behavior of the materials was modeled by Johnson-Cook strain hardening law.

The knee segments, vertical link, braces, beam, columns and contact surfaces are modeled using 20-node solid elements (SELL181) and 8-node surface elements, respectively. The stopping system, which consists of bolt, nut and related plates, is modeled with SOLID186 20-node structural solid elements that have plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

Contact elements, namely CONTA174 and TARGE170, are created at the interfaces of bolt with plates, bolt with nut and contact surface of the plates. CONTA174 is used to represent contact and sliding between 3D “target” surfaces that is modeled with TARGE170 and a deformable surface, defined by this element. The element is applicable to 3D structural contact analysis and is located on the surfaces of 3D solid elements with mid-side nodes. The element has the same geometric characteristics as the solid element face with which it is connected. Contact occurs when the element surface penetrates to some of the target segment elements (TARGE170) on a specified target surface. Here,

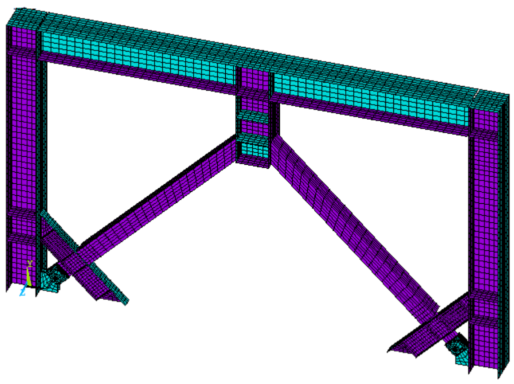


Fig. 12 Finite element model of the proposed two-level control system

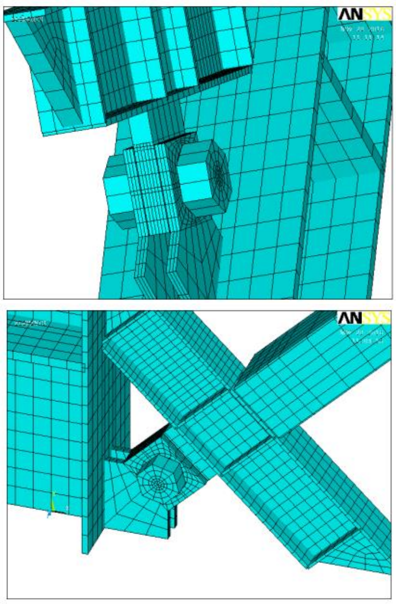


Fig. 13 Detailed meshing for presented stopping mechanism

Coulomb friction law is applied. The contact algorithm used was the ‘‘Lagrange and Penalty Method’’ available in ANSYS 13.0 (ANSYS Inc.). A total number of 32780 elements and the impenetrability constraint of 0.15 are used for this task.

Finite element models of the different parts of the system and applied mesh are shown in Figs. 12 and 13. As observed from Fig. 12, slotted bolted connection generates a displacement limit for the knee, and leads to VLB activation after the engagement of the stopping system. For proper operation of the system, web stiffeners were located in the knee and column intersection as shown in Figs. 12 and 13.

5.2 Result validation

Numerical hysteretic loop was compared to that of experimental results after construction of the primary finite element model. For results verification, the numerical model of the CK-VLB3 was calibrated according to the test specimen. The hysteresis loop obtained from both numerical and experimental results are represented in Fig. 14 for the CK-VLB3. As it can be observed, there is a good

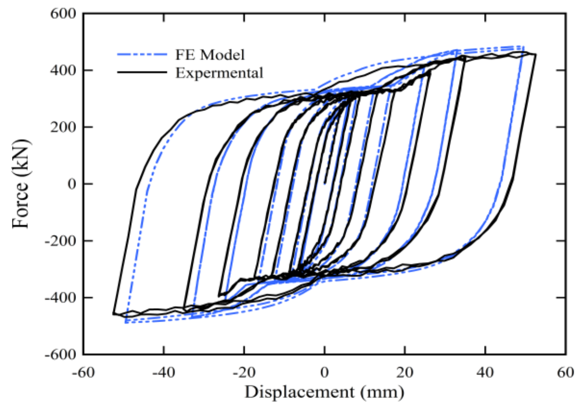


Fig. 14 Hysteresis loop of calibrated numerical model and test results for CK-VLB3

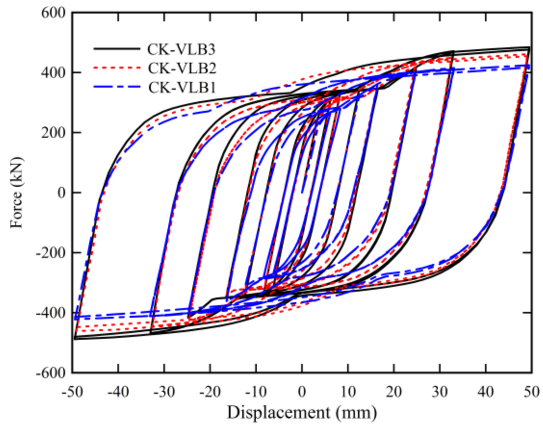


Fig. 15 Numerical hysteretic loops for CK-VLB1, CK-VLB2, and CK-VLB3

agreement between those two hysteresis loops so that the maximum displacement error between experimental and FEM results is about 8%.

5.3 Numerical results

After verifying the finite element model, the hysteretic loops for the proposed samples are extracted, and the obtained results are shown in Fig. 15. In the proposed two-level control system, because of presenting the stopping system in the first fuse and subsequently supporting operation of the second fuse, the dissipation energy is increased in comparison with that of the knee system alone. The first fuse or the knee segment starts to yield in lateral force about 400 kN; afterwards in 570 kN lateral force, the stopping mechanism is started, and the VLB (second fuse) begins to absorb imposed energy. In addition, the proposed two-level control system starts yielding process and energy dissipation sooner in comparison with the VLB alone. Consequently, it can prevent the main components of the structure from failure, and increases the ductility of structure against earthquake. Fig. 16 demonstrates the result comparisons for CK-VLB3 with two KBs and VLB in chevron braced frame under cyclic loads. Area of the hysteresis loop reveals the increase in energy absorption due to the increase of ductile performance of the proposed

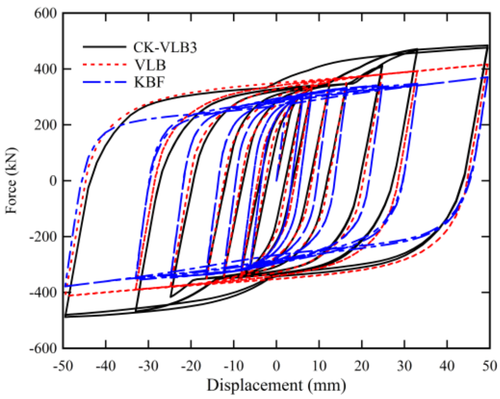


Fig. 16 Comparison between the proposed CK-VLB3 sample model hysteresis curve, KBF and VLB bracing systems

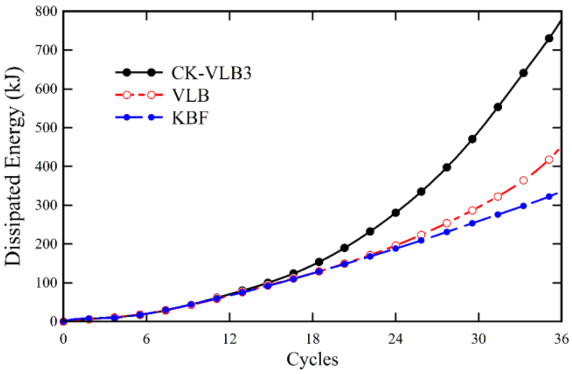


Fig. 17 Comparison of the cumulative dissipated energies of CK-VLB3 with those of vertical link and knee bracing systems

system. According to the observed result, the new two-level control system is capable of better operation compared to the previous existing models of KBF or VLB.

Fig. 17 also shows the variation of cumulative energy dissipated and the number of cycles for CK-VLB3 and the two original models i.e., KBF and VLB. The energy dissipated in each cycle corresponds to the area enclosed by each hysteresis loop. The results show that energy dissipation for all three compared specimens, is similar. For higher displacements due to the engagement of the stopping system, the energy-dissipation performance of the new two-level control system dramatically increases and becomes greater than those of KBF, as well as VLB system. This is a benefit of the new proposed system. Conversely, for CK-VLB3 the analyzed energy dissipation was 78% and 150% higher than those of the VLB and KBF, respectively. Thus, the proposed system can be used as a new alternative for the steel braced frames particularly if subjected to two levels of seismic excitations.

6. Conclusions

In this study, an innovative two-level passive control system was proposed, and its cyclic behavior was evaluated experimentally and numerically. The proposed system consisted of two types of fuses designed to dissipate energy in two different levels of lateral loads. Its behavior was also numerically investigated by nonlinear FEM analyses. A FE model was created in ANSYS and calibrated on the basis of the experimental results observed from the cyclic loading test. The results show that the proposed slotted bolted stopping system has a great effect on the performance of the new system. By increasing the sliding gap, the benefits of the proposed system are shown more clearly improving seismic performance, i.e. ductility and energy dissipation. The stable hysteresis loops with high energy absorption and excellent deformation were obtained in the tested specimens. Cyclic loading results also reveal that two-level control system has higher energy dissipation than KBF, and starts the energy absorption process earlier than VLB. During severe earthquakes, the stopping system is engaged, and the maximum load capability of the proposed system is about 30% and 17% higher than those of the knee and VLB chevron braced systems, respectively. Also, the maximum energy dissipation of the proposed system is 78% and 150% higher than the VLB and KBF, respectively.

The results show that in the proposed system at all levels of seismic loads, the plastic deformations focus in fuses only and other parts of structure remain at elastic zone. The faster initiation of the energy absorption process, the more energy dissipation capacity; moreover, using maximum capacity of the damper components is considered among the benefits of the proposed system. After the earthquake occurrence without damaging the main members, the yielding components can be replaced or repaired easily if needed.

The proposed two-level system can be adjusted for the various design capacities and frame configurations. Therefore, such characteristics make this control system versatile and adaptive for applications in various types of structures.

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