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Parametric study of a proposed hybrid damping system: KE+VLB in Chevron braced frames[1]

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Abstract. In this paper, a new hybrid passive damping system is proposed to improve the seismic performance of steel frame structures under earthquakes in different levels. The hybrid system consists of a chevron braced frame combining two Knee Element (KE) segments with slotted-bolted connections and a Vertical Link Beam (VLB). In order to study the performance of the proposed system, its behavior is studied numerically with nonlinear static and dynamic analyses using finite element method through ABAQUS software. The numerical results are compared with those obtained through the experimental work showing good agreement. Finally, the effect of different geometrical and mechanical parameters on the lateral performance of the proposed frames is investigated. Results show that in moderate and severe seismic loads, the KE and VLB dissipate energy through yielding, respectively. A sharp increase of about 16–40 % in the system capacity takes place compared to the Chevron Knee braced Frame (CKBF) due to operation of the proposed slotted connection. When the yield stress of the VLB is increased from 240 MPa to 690 MPa, ultimate capacity of the structure would improve nearly 17 %. Also, increasing the VLB web thickness from 5 mm to 15 mm, improves the capacity of the structure nearly 16 %.

Key words. Hybrid damping system, energy absorption, vertical link beam, knee element.

1. Introduction

Recently passive energy dissipation systems have been used in various structures as an effective and economical method to decrease damage caused by severe earth-

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quakes. Steel braced system is one of these passive control methods to dissipate the input earthquake energy. In the past decade, different investigations were carried out to modify the steel braced systems. More details can be found in some reviewing references [1–3].

The growth in development and application of the passive energy absorption devices has led to many studies that presented comprehensive discussions on the mathematical modeling, principle of operation, analysis of structures and combining applications of such devices to different structurers e.g., Speicher et al. [4], Zahrai [5] and Ke et al. [6]. In addition, some review references have become recently available on the general topics of additional energy absorption of structural control systems where passive methods were considered [2,3,7].

Achova [8] was the first who proposed the knee braced frame for improvement of the lateral performance and seismic behavior of structures. After that, various researchers showed interest to study the proposed system through experimental work and numerical simulations [9, 10]. Many researchers have conducted such studies including seismic tests [11, 12], eccentrically braced frames tests [13, 14], cyclic tests [15, 16] on the braced frames. Zahrai et al. [17] using a wire rope in parallel to their proposed tension-only braced without pinching, analytically investigated seismic behavior of hybrid tension braced steel frames and developed a suitable approach to improve post-yield stiffness to reduce residual displacements and estimate their energy dissipation capability. Results show that a minor increase in post-yield stiffness can substantially reduce maximum and residual deformations of the hybrid tension only brace. Zhao et al. [18] conducted complementary tests on six half-scale, 2-story chevron CBFs under quasi-static flexural cyclic load and constant axial load. The CBFs exhibited favorable ductility, normal failure mechanism and great deformation capacity. Also, the specimen's hysteretic curves were satisfactory indicating very good energy absorption capacity of the steel braced frames.

Balendra et al. [19] proposed a new two level passive control system containing of knee brace and slotted connection. Also, Lee et al. [20] carried out investigation on hybrid system using a friction and steel strip dampers for improving the seismic performance of steel frames at multi-levels of ground motion. The experimental results of their analysis show appropriate cyclic behavior on connections equipped with new dampers.

In this paper, another innovative system is proposed as a two-level passive control system. It is based on the combination of two Knee Element, KE, segments and a Vertical Link Beam, VLB, in series (KE + VLB) used in a chevron braced steel frame. By employing a slotted connection to KE as the first fuse and utilizing a VLB as the 2nd fuse, a new ductile bracing system is built which shows significant ability to dissipate energy in two earthquake levels. To provide a reliable verification possibility, an experimental setup was built to arrange cyclic loading of the test specimen based on the proposed system. Lateral performance of the proposed system is further studied using nonlinear finite element analysis provided by ABAQUS program. After calibrating and validating the numerical models, the effect of the mechanical and geometrical parameters of the VLB and KE on the lateral performance of the system is investigated with more details.

2. Main idea of the two-level system design

Regarding the fact that increasing the energy dissipation and ductility of structures against seismic loads is essentially necessary, in this paper a new two-level passive control system with capability to change the dynamic characteristics parameters such as stiffness, strength and energy dissipation at different earthquake levels has been deliberated. The proposed system (Fig. 1) consists of a combination in series of KEs as the 1st fuse to dissipate energy in moderate earthquakes and VLB as the second fuse to dissipate energy during the severe seismic loads.

Slotted-bolted connection mechanism is the most important portion of the proposed system (Fig. 1, bottom right part). This mechanism activates whenever the structure encounters with severe loads and makes desired changes in the dynamic characteristic of the structure. As a result, the VLB would begin sustaining the inelastic behavior and subsequently the strength and energy absorption capability of the structure would increase. This leads to improvement in the seismic performance of the presented passive control system.

In this system along with geometrical and mechanical characteristics of the VLB, length of the slot in first fuse influences the performance of the structure against seismic loads. Therefore, the main objective of this paper is to study the above mentioned parameters on the lateral behavior of the proposed two-level control system.

3. Experimental program

To provide solid reliable results for comparison purposes, an experimental setup is built according to the proposed system and a suitable test is carried out. Figure 2 shows the test setup. One specimen was tested under cyclic loading in structural laboratory of Iran BHRC (Building & Housing Research Center). Envelope of the hysteretic behavior would be considered for comparison purposes to validate the numerical models. Servo hydraulic jacks with dynamic load capacity of ± 1000 kN and maximum velocity of 60 mm/s are used for quasi-static load within a maximum displacement of 30 cm. For measurement of relative displacement, linear variable displacement transducers (LVDTs) with 0.01 mm of accuracy are used. All data are recorded by data logger TDS602 model constructed by T. M. L. Company, Japan. To prevent the lateral or out-of-plane movement of tested frame, two box sections are used (Fig. 3). The stopping system is adjusted by constant slotted bolted connection in a state of 4 mm.

The constructed specimen is tested under cyclic uniform displacement based on cyclic load protocol of SAC as illustrated in Fig. 3. The average rate of loading variation is ranging from 14 mm/min to 28 mm/min.

4. Finite element models

In this section, the performance of the proposed system is evaluated using the finite element ABAQUS software and nonlinear static analysis having geometrical

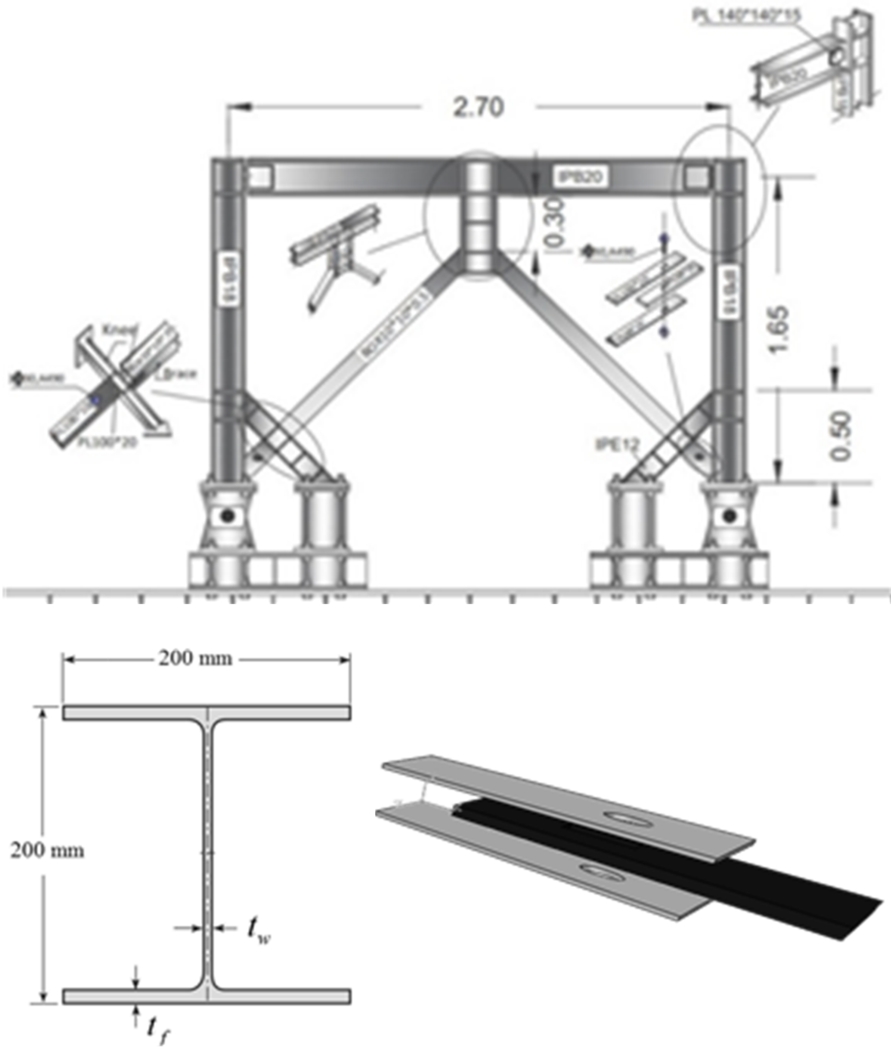

Fig. 1. Two-level system design: top–general geometry of the proposed control system along with its connection, bottom left–geometrical parameters of the VLB, bottom right–proposed slotted-bolted connection mechanism

and material nonlinearities on a 3D model of the structure. As shown in Fig. 1, a single-story steel frame with the height and width of respectively 2.5 m and 3.5 m is considered. Solid element type (C3D8R) is used and the analysis is performed with respect to the effects of large deformations. In order to connect different members of the frame, the Tie constraint is adopted. Interaction and contact between various surfaces are simulated using Contact elements available in the ABAQUS software. A friction coefficient of 0.35 is assigned for such contact surfaces, a normal penalty stiffness factor of 1.0 with a penetration tolerance factor of 0.05 is chosen when

Fig. 2. Photo of the test setup and specimen with the proposed two-level control system

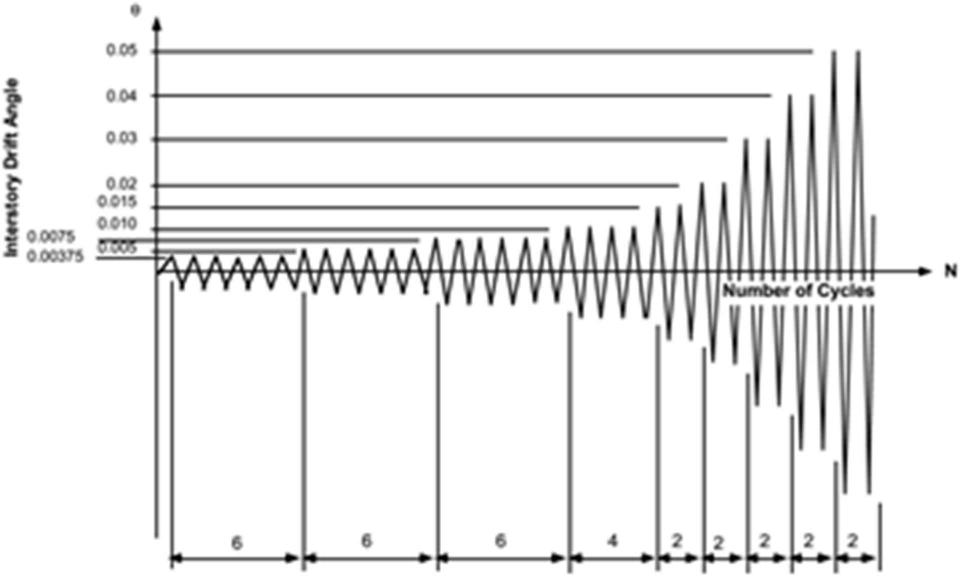

Fig. 3. Applied cyclic loading time history protocol

defining the pair of contact elements, and the close gap option is used to enable the automatic contact adjustment.

4.1. Nonlinear static analysis

The quasi-static displacement-controlled loading shown in Fig. 3, is laterally applied at the upper right column tip and the displacements of the nodes, at the lower boundary of the columns are fixed. Figure 4 shows the FE model of the frame in ABAQUS using a total of 17813 nodes and 24720 elements.

All the simulated samples utilize the VLB with I cross-section. Flange and web

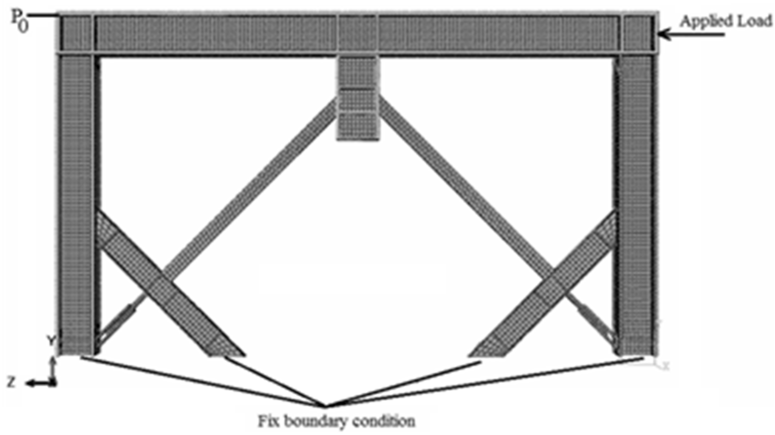

Fig. 4. Finite element model of the proposed two-level control system

thickness and stiffener of the VLB (shown in Fig. 1, bottom left part), i. e. t_f, t_w and t_s are selected as varied parameters. The study is fulfilled through 27 specimens and compared with a standard Chevron Knee Braced Frame (CKBF) as described in Table 1.

It is assumed that all the elements of the system are made by building St-37 steel material with mechanical properties highlighted in Table 2. To investigate the effect of the VLB material on seismic performance of the proposed system, three different types of steel with distinguished yield stress are used (see Table 2).

4.2. Nonlinear dynamic analysis

Three earthquake records of the Erzincan, the Imperial, and the San Francisco are used as ground excitation in dynamic analysis. Automatic time incrementation is used for the dynamic analysis of the earthquake, with the Abaqus/Explicit simulation and a maximum time increment of 6×10^{-4} s. The implicit Newmark-β method available in Abaqus software is used in the incremental dynamic analysis for time stepping, which is unconditionally stable. The analysis is run in double precision to prevent the accumulation of round-off errors.

5. Results and discussion

5.1. Verification of numerical modeling

In order to verify the obtained numerical results and ensure the accuracy of the parameters and specifications used in the FE model, the numerical model of the proposed system (VLB + KE in chevron braced frame) with exactly the same properties as the tested specimen was simulated by ABAQUS software under monotonic load similar to the envelope of the curves obtained from experimental work which is described in section 3.

Table 1. Properties of the numerical case studies

<table>
<tr><th>No.</th><th>Specimen</th><th>Sliding length L (mm)</th><th>Material</th><th>t_{f} (mm)</th><th>t_{w} (mm)</th><th>t_{s} (mm)</th></tr>
<tr><td>-</td><td>CKBF</td><td>-</td><td>ST-37</td><td>15</td><td>10</td><td>10</td></tr>
<tr><td>-</td><td>VBF</td><td>7</td><td>ST-37</td><td>25</td><td>15</td><td>10</td></tr>
<tr><td>1</td><td>BFL1-01</td><td rowspan="9">4</td><td>ST-37</td><td rowspan="3">15</td><td rowspan="3">10</td><td rowspan="3">10</td></tr>
<tr><td>2</td><td>BFL1-02</td><td>SWH</td></tr>
<tr><td>3</td><td>BFL1-03</td><td>HSS</td></tr>
<tr><td>4</td><td>BFL1-04</td><td rowspan="6">HSS</td><td>15</td><td>10</td><td>20</td></tr>
<tr><td>5</td><td>BFL1-05</td><td>15</td><td>10</td><td>15</td></tr>
<tr><td>6</td><td>BFL1-06</td><td>15</td><td>10</td><td>5</td></tr>
<tr><td>7</td><td>BFL1-07</td><td>15</td><td>15</td><td>10</td></tr>
<tr><td>8</td><td>BFL1-08</td><td>15</td><td>10</td><td>10</td></tr>
<tr><td>9</td><td>BFL1-09</td><td>15</td><td>5</td><td>10</td></tr>
<tr><td>10</td><td>BFL2-01</td><td rowspan="9">8</td><td>ST-37</td><td rowspan="3">15</td><td rowspan="3">10</td><td rowspan="3">10</td></tr>
<tr><td>11</td><td>BFL2-02</td><td>SWH</td></tr>
<tr><td>12</td><td>BFL2-03</td><td>HSS</td></tr>
<tr><td>13</td><td>BFL2-04</td><td rowspan="6">HSS</td><td>15</td><td>10</td><td>20</td></tr>
<tr><td>14</td><td>BFL2-05</td><td>15</td><td>10</td><td>15</td></tr>
<tr><td>15</td><td>BFL2-06</td><td>15</td><td>10</td><td>5</td></tr>
<tr><td>16</td><td>BFL2-07</td><td>15</td><td>15</td><td>10</td></tr>
<tr><td>17</td><td>BFL2-08</td><td>15</td><td>10</td><td>10</td></tr>
<tr><td>18</td><td>BFL2-09</td><td>15</td><td>5</td><td>10</td></tr>
<tr><td>19</td><td>BFL3-01</td><td rowspan="9">12</td><td>ST-37</td><td rowspan="3">15</td><td rowspan="3">10</td><td rowspan="3">10</td></tr>
<tr><td>20</td><td>BFL3-02</td><td>SWH</td></tr>
<tr><td>21</td><td>BFL3-03</td><td>HSS</td></tr>
<tr><td>22</td><td>BFL3-04</td><td rowspan="6">HSS</td><td>15</td><td>10</td><td>20</td></tr>
<tr><td>23</td><td>BFL3-05</td><td>15</td><td>10</td><td>15</td></tr>
<tr><td>24</td><td>BFL3-06</td><td>15</td><td>10</td><td>5</td></tr>
<tr><td>25</td><td>BFL3-07</td><td>15</td><td>15</td><td>10</td></tr>
<tr><td>26</td><td>BFL3-08</td><td>15</td><td>10</td><td>10</td></tr>
<tr><td>27</td><td>BFL3-09</td><td>15</td><td>5</td><td>10</td></tr>
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Table 2. Mechanical properties of the steel types used for the numerical models

Steel grade	Density (kg/m^3)	Young modulus (GPa)	Poisson ratio	Yield stress F_{y} (MPa)	Failure stress F_{u} (MPa)	Elongation (%)
Typical steel (ST-37)	7850	210	0.28	240	370	0.18
Steel without hardening (SWH)	7850	205	0.29	316	451	0.06
High strength steel (HSS)	7850	208	0.27	690	760	0.02

The obtained pushover curve is compared with that of experimental results as demonstrated in Fig. 5. As it can be observed, there is a good agreement between two pushover curves. For verification purposes of the numerical results, the FE model was calibrated according to the test specimen. In the experimental envelope curve A, B and C present the points corresponding to the beginning of the web shear yielding of the knee element, start of the stopping system operation and yielding beginning of the VLB web, respectively.

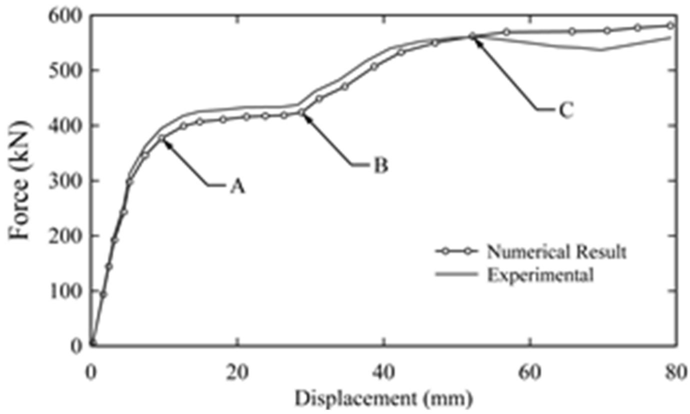

Fig. 5. Finite element model of the proposed two-level control system

In Fig. 6, the VLB appearance after yielding under the applied load is compared between experimental and simulation results. It is clear that the simulation can predict the experimental output with fairly good accuracy. As observed, the yielding takes place only in the first and second fuses while other components of the structure remain elastic.

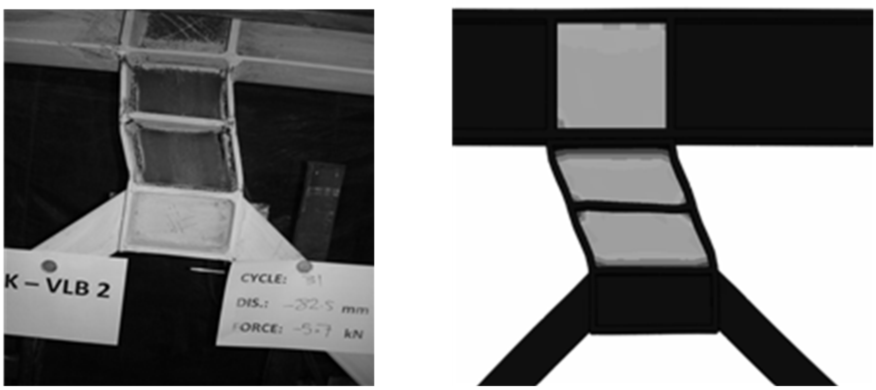

Fig. 6. VLB appearance after yielding: left–experimental specimen, right–simulation model

5.2. Parametric investigation

After validating the simulation accuracy hereafter this study is devoted to investigate the effect of different parameters on the pushover curves and performance of the proposed two-level passive control system. As presented in Table 2, the specimens are classified in three groups: BFL1, BFL2 and BFL3 having slot length of 4 mm, 8 mm and 12 mm, respectively.

In Fig. 7 the pushover curves corresponding to the BFL1 and CKBF specimens are shown. The comparison between BFL1-03 and CKBF shows that application of slot stopping system causes the capacity of the structure to increase about 40 %. It is observed that for the case of moderate lateral loading and related displacements less than 12 mm (point A in Fig. 7a), the knee element acts as the first fuse and starts to dissipate the imposed energy. With more increase of the applied load, the stopping system gets engaged such that in point B the VLB acts as the second fuse. Therefore, for the next steps with higher loads (after point B), the second fuse operation results in considerable augmentation of the energy absorption capacity of the structure compared to the traditional knee brace system.

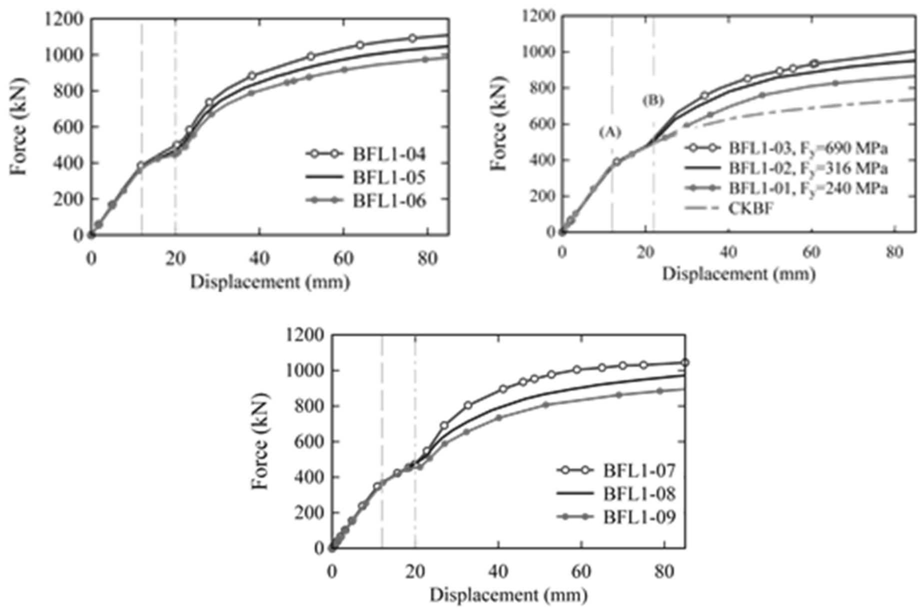

Fig. 7. Effect of different parameters pertaining to the VLB on the pushover curves of the BFL1 group for: top left–different material, top right–different stiffener thickness and bottom–different web thickness

The effect of the yield stress of the VLB material is examined through simulation with three different values for the yield stress. The results can be observed in Fig. 7, top left part. When the yield stress increases from 240 MPa (BFL1-01) to 690 MPa (BFL1-03), ultimate capacity of the structure augments nearly 17 %. It can be inferred that the geometrical and mechanical properties of the VLB affect considerably on the performance of the proposed system against seismic loads.

Because absorption and dissipation of energy are caused by shear yielding of the knee elements and VLB, thus the cross-section geometry of the fuses can impact sensibly the performance of the system. In this regard the web and stiffener thickness are varied for BFL1-04 to BFL1-09 according to Table 2. The pushover curves of these specimens are depicted in Figs. 7, top left and bottom parts). As shown, when the web thickness is increased from 5 mm to 15 mm, the capacity of the structure increases nearly 16 %. As expected, for the case of moderate lateral loads the second fuse web thickness has no effect on the structure stiffness. However, it can increase the system strength for higher lateral loads.

Similar results were obtained for different value of the slot length of the slot stopping system. These results can be observed in Figs. 8 and 9 where the pushover curves have been depicted for slots of 8 mm and 12 mm in length.

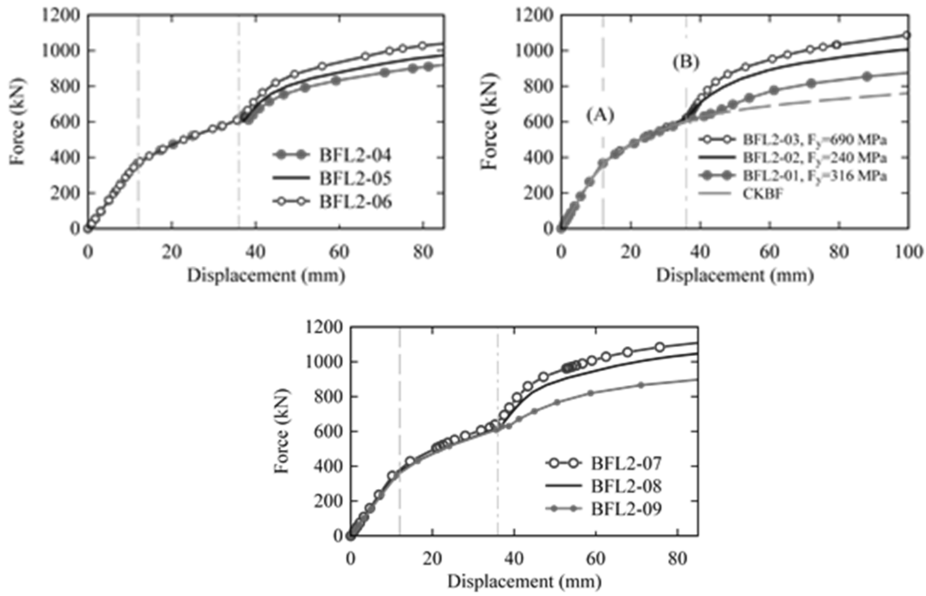

Fig. 8. Effect of the different parameters pertaining to the VLB on the pushover curves of the BFL2 group for: top left–different material, top right–different stiffener thickness and bottom–different web thickness

In Fig. 10 the pushover curves corresponding to BFL1-03, BFL2-03 and BFL3-03 are compared to the traditional CKBF. Figure 10 indicates that when the slot length of the slot-stopping system increases the second fuse starts to operate in higher level of loads and causes the ultimate capacity of the proposed system to be increased significantly. For instance, the ultimate displacement of BFL1-03, BFL2-03 and BFL3-03 are 90 mm, 100 mm and 150 mm, respectively. Therefore, in line with the increase of the slot length of the slot-stopping system, the structure stiffness is significantly improved resulting in desired performance of the structure against sever seismic loads.

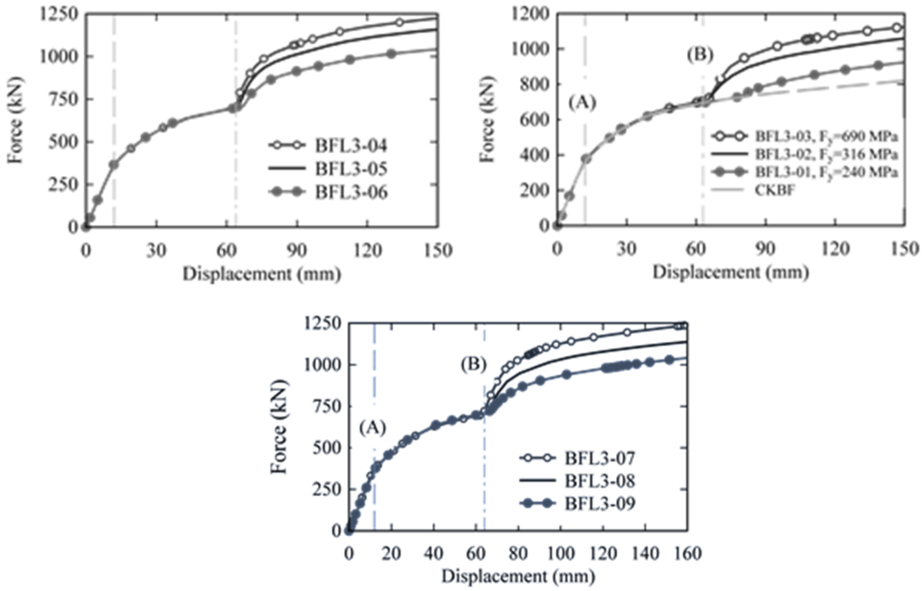

Fig. 9. Effect of the different parameters pertaining to the VLB on the pushover curves of the BFL3 group for: top left–different material, top right–different stiffener thickness and bottom–different web thickness

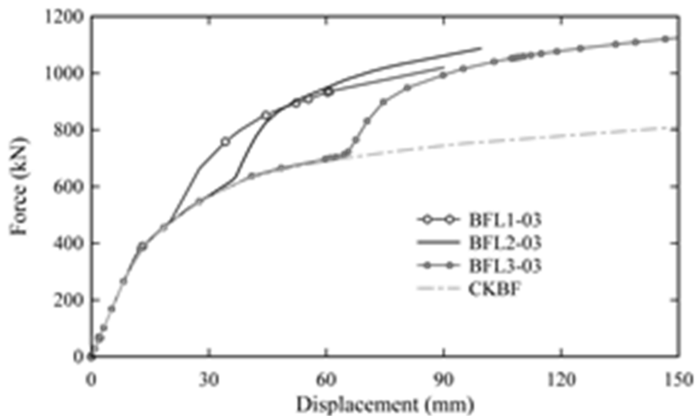

Fig. 10. Pushover curves of the BFL1-03, BFL2-03 and BFL3-03 specimens

The distribution of plastic deformation and final configuration of the proposed system are shown in Fig. 11. It is observed that for the case of moderate loads, the knee element yields (Fig. 11, top part) and consequently the VLB as the reserve fuse remains intact. At the end of 16 cm lateral displacement of frame, the knee elements fail at vicinity of flanges, while the VLB system still is in intact condition. However, for higher level of loading after 22 cm lateral displacement of the frame, the VLB tends to yield (Fig. 11, bottom part) causing significant energy dissipation. It is observed that yielding takes place only in the fuses while the other members of the structure such as beams and columns remain in the elastic zone.

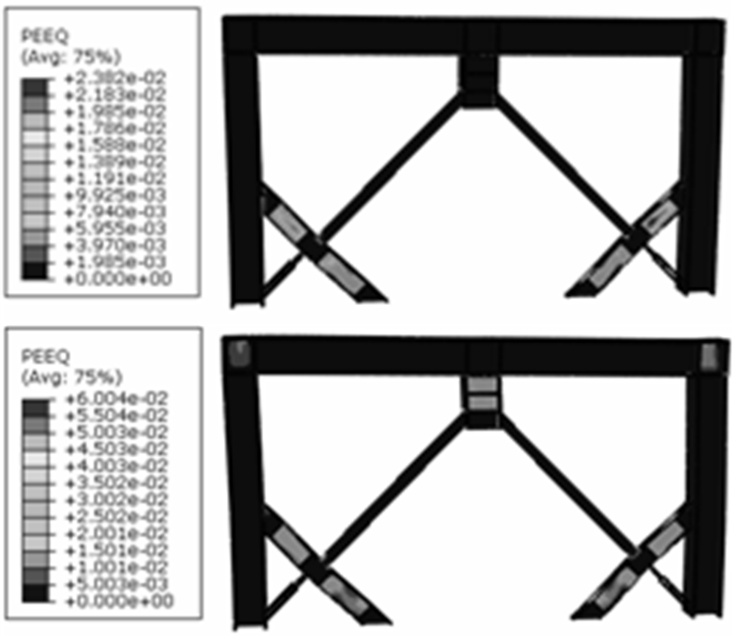

Fig. 11. Plastic strain distribution and final configuration of the BFL1-01 specimen: left–first fuse yield at 398 kN and right–final configuration and the second fuse yield at 800 kN

5.3. Nonlinear dynamic time history analysis

In this section, nonlinear dynamic time history analysis of the proposed hybrid damper system under seismic loading using the horizontal component of earthquake records of the 1906 San Francisco in the United States, 1979 Imperial valley in Aeropuerto Mexicali and the 1992 Erzincan in Turkey with maximum ground acceleration of respectively 0.15 g, 0.37 g and 0.47 g is evaluated.

According to the results of nonlinear static analysis and evaluation of the proposed system performance, high energy absorption and acceptable behavior with a suitable ductility are observed in all investigated specimens. In order to evaluate the seismic performance of the proposed system, samples of BFL1-03 with specification given in Table 1 for which the improvement of seismic behavior of structures is assessed. Fig. 12 compares the history of lateral displacement responses of the point P0 at the BFL1-03 frame under the San Francisco, Imperial Valley and Erzincan earthquakes, respectively. The solid lines are the response of the frame using the proposed hybrid braced system, whereas the dashed lines are the frame response without the proposed system. The results show that adding the proposed system to the braced framing system decreases the maximum amplitude of the structures. As seen from

Fig. 12, the proposed system reduces the maximum amplitude of the structures the San Francisco, Imperial Valley and Erzincan earthquakes up to 16.3 %, 19.2 % and 11.5 %, respectively. Therefore, in three cases, the proposed system is effective in reducing the maximum amplitude that can ensure good dynamic behavior within a wide range of earthquakes from moderate to strong.

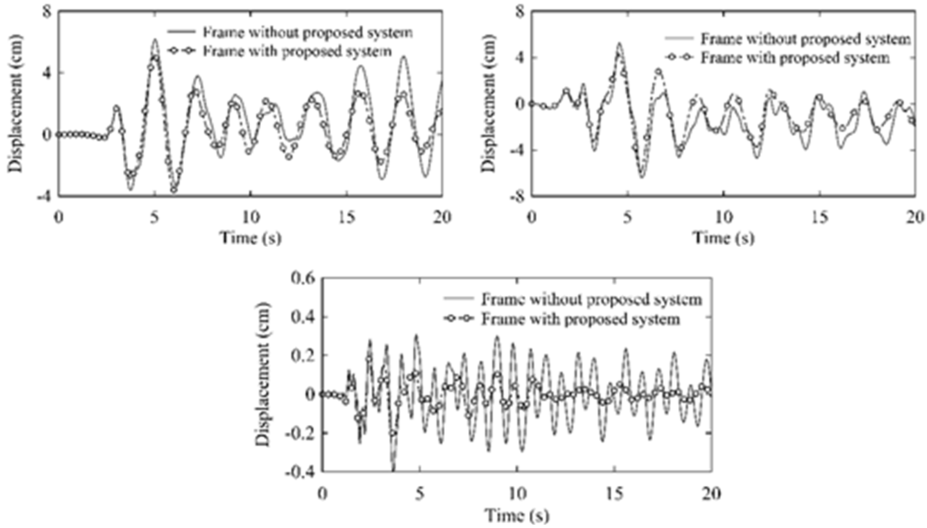

Fig. 12. Time history graphs of the horizontal displacements of the point P0 at the BFL1-03 frame under: top left–San Francisco, top right–Imperial Valley and bottom–Erzincan earthquakes

6. Conclusion

In this paper, a two-level passive control system was proposed to improve the seismic performance of chevron braced framing structures. The new system is based on the combination of VLB and knee brace with slot-stopping technique used in a chevron braced frame. The nonlinear static and dynamic finite element analysis available in ABAQUS software was applied for parametric study on the lateral behavior of the structure. The numerical procedure was evaluated through an experimental verification showing good agreement.

The results indicate that the two-level characteristic with variable stiffness and strength can absorb and dissipate seismic energy in the different earthquake levels. Nearly 40 % improvement in load capacity of the structure over the traditional knee bracing system can be achieved by the proposed two-level control system. When the web thickness is increased from 5 mm to 15 mm, the capacity of the system increases nearly 16 %. Ultimate yield stress of the steel material and thicknesses of the web and stiffener of the VLB can impact the system performance against seismic loads. It is worthy to note that the structure performance is improved with properly selecting these parameters. It was observed that by increasing the slot length, the second fuse operates in higher loads resulting in significant increase of the structure ultimate strength. Examination of the stress contours indicate that in the proposed system only the mounted fuses yield and other parts of the structure experience elastic behavior. The results show that adding the proposed system to the braced framing system decreases the maximum amplitude of the structures under the earthquake loads. It seems that the proposed multi-level bracing system demonstrates desired performance despite its applicability, simplicity and fairly low cost, and can be a good alternative for traditional knee bracing system to improve the seismic performance of braced structures

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