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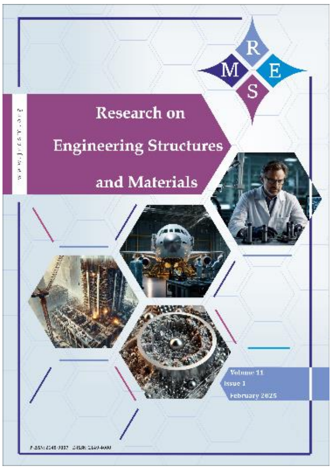

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Research Article

Enhancing the seismic performance of a concentrically braced reinforced concrete frame using an I-shaped shear link made of low yield point steel

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Abstract

The experience of previous earthquakes has shown that reinforced concrete frames are susceptible to earthquake damage; therefore, several techniques have been suggested by researchers to enhance their efficiency. Although the reinforcement of RC frames with concentric braces does enhance the frame's stiffness and lateral resistance, it does not have much effect on its ductility. Hence, in this article, an I-shaped shear link as a damper is investigated with the aim of strengthening RC frames. This damper designed for ease of production and post-earthquake replacement, not only improves the frame's stiffness and resistance, but also augments its ductility and plastic behavior. Considering that the damage is expected to be limited in the damper, other structural components will remain in the elastic region. Although the addition of such dampers increases the ductility, it reduces the stiffness of the system. To compensate for this weakness, the damper using low yield point (LYP) steel is discussed and investigated. Furthermore, the effect of the thickness of the damper flanges on the seismic behavior of the frame is examined. The results show that the use of LYP steel in the construction of the studied shear damper can improve the stiffness and resistance of the reinforced concrete frame as well as the amount of energy dissipation. However, the mere use of LYP steel does not guarantee the improvement of the frame's behavior, and this is subject to the thickness of the damper's flanges.

1. Introduction

During recent severe earthquakes, reinforced concrete (RC) structures experienced structural damage at various levels due to the lack of ductility, insufficient strength, etc. [1-3]. Consequently, the losses caused by these major earthquakes highlight the importance of further investigation to enhance the seismic performance of RC structures.

The improvement of the seismic response of RC buildings using the base isolation technique has been studied by various researchers, including Kontoni & Farghaly [4], Farghaly & Kontoni [5], and Belbachir *et al.* [6]. The mitigating effect of tuned mass dampers (TMDs) on the seismic response of RC high-rise buildings, considering soil-structure interaction (SSI), has been investigated by Kontoni & Farghaly [4], Farghaly & Kontoni [5], etc. Moreover, the mitigation of seismic pounding between RC high-rise buildings, considering SSI, through the use of base isolation, tuned mass dampers (TMDs) and pounding tuned mass dampers (PTMDs) has been explored by Farghaly & Kontoni [5]

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and Farghaly & Kontoni [7]. In reinforced concrete buildings with a moment frame system, seismic energy is dissipated by relying on the formation of plastic joints at both ends of the beam [8]. Considering that the floor beam, in addition to the task of energy absorption and lateral load, is also responsible for gravity load, so it is highly difficult to replace and repair it after an earthquake. On the other hand, the lateral and gravity loads increase its vulnerability.

In many reinforced concrete buildings, a change of use or a change in seismic requirements, damages caused after an earthquake, or the need to change the area or the number of floors of the buildings, confirm the necessity of retrofitting the buildings. In general, the strengthening of reinforced concrete buildings is done by two methods: local and general strengthening. Local reinforcements include the use of FRP [9,10], the use of steel jackets [11-13], the use of concrete jackets [14-16], the use of UHPC concretes to strengthen joints [17-19], and it is also the use of SMA [20,21], which usually do not have a significant effect on the stiffness and lateral strength of the structure. In cases where a structure needs to increase its stiffness or strength, only using the general strengthening method including the addition of structural elements such as steel shear wall [22-24], concrete shear wall [24-27], concentric brace [28-30], eccentric brace [30-33], BRB brace [34-36], and dampers [37-41] are prevalent. Although the addition of concrete shear walls increases the stiffness and lateral resistance, it brings disadvantages such as increasing the weight of the structure, complexity of implementation and formatting, and disturbance in the use of the building. Furthermore, despite the efficiency and adaptability of steel shear walls, employing steel sheets as the primary load-bearing component leads to the transmission of high stresses to the surrounding frame. This requires beams and columns with a high moment of inertia, which may sometimes be unachievable. It should be noted that convergent braces also do not perform well against bidirectional loads, so it has not been accepted as a successful method, particularly in areas with a high risk of earthquakes. On the other hand, the eccentrically braced frame (EBF) system is another method which has exhibited good ductility during previous earthquakes. Nevertheless, due to the fact that the connecting beam is integrated into the floor beam in this system, repairing or replacing the connecting beam after a severe earthquake is complicated [42]. Also, the shear capacity of the connecting beam causes significant axial forces to be applied to the columns around the brace, which must be considered in the design and seismic analysis process. Researchers addressed the complexities related to the construction and design of the diverging system by employing a perpendicular shear link at the junction of the beam and braces (beneath the beam). In the new system with vertical shear link (V-EBF), the shear link is not subjected to axial loading and this system is known as an alternative strategy for improving the seismic behavior and strengthening of reinforced concrete buildings. After the initiative of V-EBF, some researchers have suggested metal dampers such as added stiffness and damping dampers (ADAS), oval added stiffness and damping (EDAS), triangular added stiffness and damping (TADAS), U-shaped, ring, box and other types of dampers, in order to improve the behavior of convergent frame braces (CBF).

In the last few decades, the philosophy of designing important buildings against earthquakes has shifted from traditional and conventional methods, which are solely focused on increasing the strength and stiffness of the structure, to the use of energy dissipation systems. In the modern approach to designing structures, engineers constantly strive to enhance the structure's plasticity by utilizing some items of equipment known as dampers and energy absorbers. In this design philosophy, dampers act as a fuse and are yielded earlier than the rest of the members in order to prevent the occurrence of large non-linear deformations in the main members. This design approach is especially important in regions with high seismic activity, as it not only ensures the stability of the structure during an earthquake, but also allows for the replacement of energy-absorbing components without damaging the remaining primary elements. As a result, the costs associated with repairing and reconstructing structures after an earthquake could be significantly reduced. By incorporating energy dissipation systems in a well-planned and suitable design, numerous benefits can be attained in both the construction of new buildings and the retrofitting of existing ones. With regard to these advantages, the following can be mentioned: increasing the damping and energy absorption of the structure, significantly reducing the acceleration and relative displacement of the floors, minimizing disruptions in structural service, reducing destructive deformations in structural and non-structural components, and minimizing damages related to internal equipment. These advantages encompass a significant increase in the structure's damping and energy dissipation, leading to a considerable reduction in floor acceleration and relative displacement.

There are various types of dampers, including friction dampers, viscous dampers, metal dampers, buckling dampers, and others. Energy dissipation in the mentioned systems has different mechanisms compared to each other. Among the existing steel dampers, shear dampers are of more interest due to their ease of construction, installation, repair and replacement after an earthquake, as well as their favorable performance in seismic behavior confirmed by laboratory and numerical studies. With the addition of a damper to the bracing member, the stiffness is obtained from the sum of the stiffness of the equivalent series springs. Based on this, although the utilization of shear dampers directly connected to the braces can prevent the buckling of the diagonal members within the concentric frame and enhance the system's energy absorption capacity, this approach simultaneously reduces the elastic stiffness of the lateral load-bearing system.

In this study, the effect of using LYP steel, in an I-shaped shear link, as a method to increase the seismic performance of the RC frame in terms of ultimate strength, stiffness, energy absorption and ductility is investigated. For the considered I-shaped shear link used as a damper, twelve models with different thicknesses of the damper's flanges and also various combinations of steel types (ST37 and LYP) have been compared to determine to what extent the RC frame is influenced and in which cases its seismic performance is notably improved.

2. Damper Details

Although the acceptable performance of the damper under seismic loading is an important factor in evaluating the damper as a ductile element under the influence of seismic loads, the ease of construction, installation, and replacement after an earthquake are also considered as other important factors in the assessment of the damper. Thus, the damper shown in Figure 1 is suggested to strengthen the reinforced concrete frames, which fulfills both important factors of ease of construction and installation. As shown in Figure 1, these dampers are connected to the beginning of the concentrically braced elements, and by being yielded before the beam elements prevent their buckling. Therefore, it is expected to act like a ductile fuse. Also, their placement is such that they can be easily replaced after a severe earthquake.

For the construction of this damper, the use of both ST37 steel and LYP steel is feasible. The use of low yield point (LYP) steel is preferred for two reasons: 1) Although the system strength using low yield point steel is equal to that of conventional steels, the shear displacement of the system using LYP steel is less than that of other high carbon steels. 2) The ductility and energy dissipation capacity of LYP steel are much higher than conventional steel.

According to AISC 341-16, the damper's performance as a shear link is classified into three modes: Shear mechanism in the case that $\rho \leq 1.6$, shear-flexural mechanism in the case that

2.6 > ρ > 1.6, and flexural mechanism by ρ ≥ 2.6, where $\rho = \frac{e}{M_p/V_p}$. Studies in this field [43-46] have indicated that I-shaped links with shear yielding demonstrate better performance than links with flexural yielding; therefore, it is suggested that the proposed damper should be designed in such a way that the shear yielding mode occurs. Regarding article F3.5b.2 of AISC 341-16, design shear strength is determined using the expression of $V_n\phi_v$. Since the shear mechanism used for the damper is $V_n = V_p$, in this case, according to AISC 341-16 regulations, its shear strength is calculated from Equation (1):

$$V_p = 0.6\,F_{yw}A_w \tag{1}$$

In Equation (1), the net section area of the web, A_w, equals bt_w, where b is the net depth of the web, and t_w is the web thickness. Additionally, F_{yw} stands for yield stress of the steel material utilized in the web.

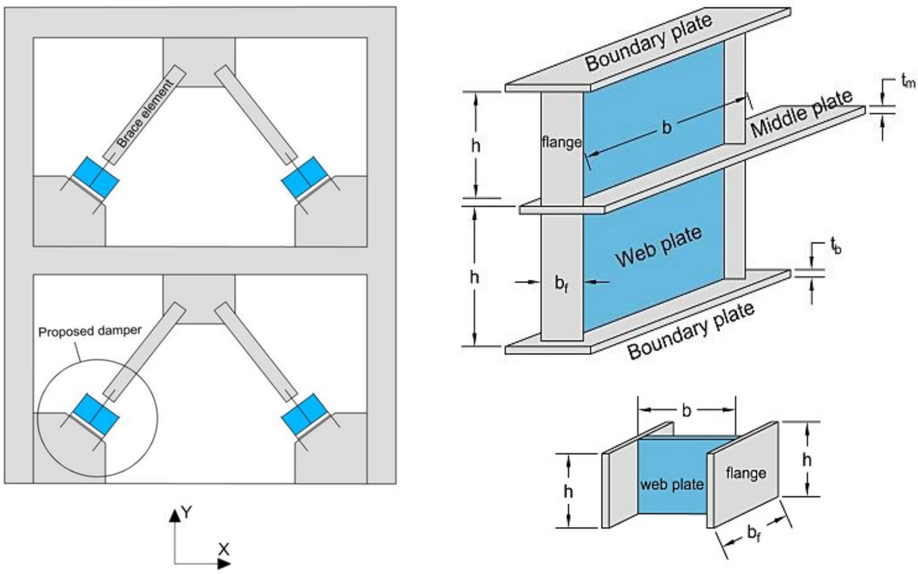


Fig. 1. Proposed damper

Although in AISC 341-16, the flange strength in shear capacity is ignored, in this article, referring to previous studies [47-50], the contribution of the flange in the shear capacity of the damper has been considered. Since two I-shaped dampers are utilized in the construction of the damper, a factor of 2 is applied; therefore, the shear capacity (V_d) of the damper is suggested as follows:

$$V_d = 2(V_p+V_f) \tag{2}$$

In the above relationship, V_f is the shear capacity of the flange, which can be calculated from Equation (3).

$$V_f = \frac{4M_f}{h} \tag{3}$$

In above Equation (3), h represents the shear link height, which is shown in Figure 1. Additionally, M_f denotes the flexural capacity of the damper flange, which is obtained from

Equation (4), where F_{yf} represents the yield stress of the material of the flanges. Moreover, b_f and t_f stand for flanges width and thickness, respectively.

$$M_f = \frac{b_f t_f^2}{4} F_{yf} \tag{4}$$

$$V_{design} = max \begin{cases} 1.25 R_y V_d \\ \Omega V_d \end{cases} \tag{5}$$

After designing the shear damper, the brace has been designed for the intensified force according to Equation (5). The purpose of brace design for a force greater than the capacity of the damper is to yield the damper before the diagonal of the damper to ensure the fuse-like operation of the damper. In the above relation, R_y and Ω are the ratio of ultimate stress to the yield stress of the damper material, and the over-strength factor of the damper, respectively.

3. Method of Study

In this article, a fixed thickness of 6 mm was considered for the damper web in all the examined models in the case that the steel type used is ST37, because when the steel material is changed to LYP, the thickness corresponding to the yield stress needs to be modified. Other dimensions of the damper such as the height of the web and the width of the flanges are unchanged in the studied models, while the thickness effect of the flange was examined in different cases with different steel materials. First, a damper was designed as a base model, in which the thickness of the web is 6 mm, the thickness of the flange is 20 mm, the width of the flange is 150 mm, and the depth of the web is 150 mm. After calculating the shear capacity of the brace using Equation (5), the steel braces within the reinforced concrete frame were designed for the obtained shear force, which was considered 2UNP120 for each brace. Then, the longitudinal and transverse reinforcements of the reinforced concrete frame were designed with the initial assumption of beam and column sections of 400×400 (mm^2).

Table 1. Material properties of steel sections

Material	Yield stress, F_y (MPa)	Ultimate tensile strength, $F_u(MPa)$	Modulus of elasticity, E (MPa)	Ultimate strain
ST37	240	370	200000	0.065
Rebar (Ø10)	486	600	210000	0.15
LYP100	100	257	153100	0.02

The details of reinforcements were designed for the lateral horizontal force resulted from the combined effects of the braces forces designed using ETABS [51] software. Figure 2 illustrates the specific details of the designed frame, and Table 1 provides the material specifications. To assess the impact of flange thickness on the shear strength of the damper, keeping other variables constant, dampers with a flange thickness of 5, 10, and 15 mm were analyzed. Also, to evaluate the effect of the type of steel on the performance of the system, dampers with two types of steel, ST37 and LYP, were investigated. Considering that the yield strength of LYP steel is about 2.4 times less than that of ST37, therefore, when using LYP, the thickness of that section was increased by 2.4 times to keep the shear strength constant. In Figure 2, details related to the dimensions of the concrete frame, the diagonal elements of the brace, and the dimensions and information of the beam and column sections can be observed. Within the ABAQUS [52] software, a single-floor frame (with one opening) was modeled and analyzed from the mentioned frame.

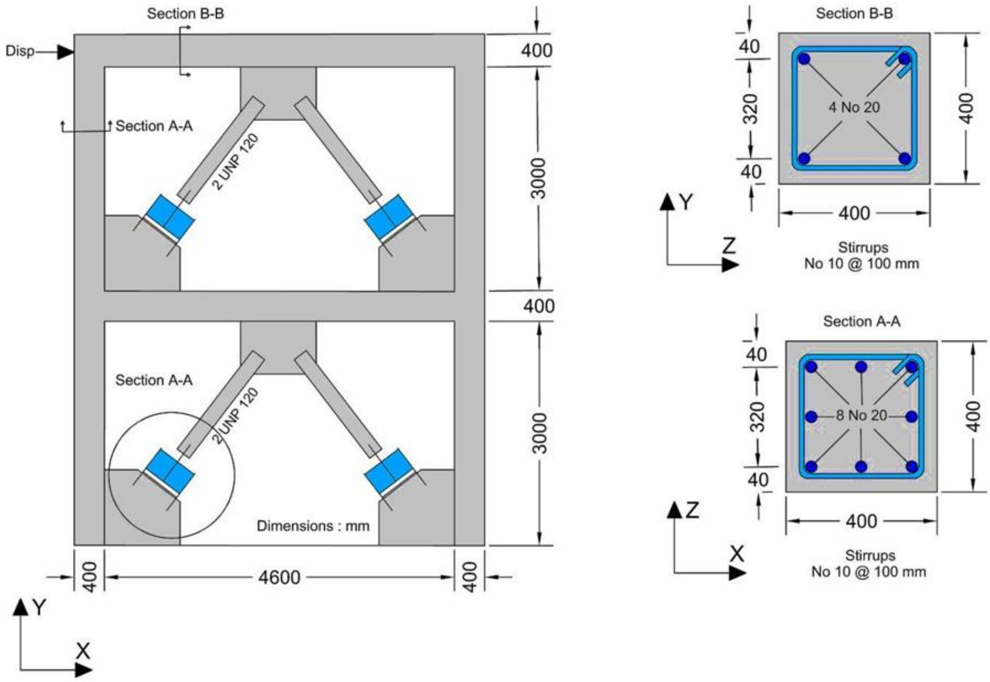


Fig. 2. Details of the frame (Dimensions in mm)

4. Numerical Study

4.1. Numerical Models

As described in the previous section, twelve models were analyzed, and categorized into four groups: 1) three damper models made of ST37 with flange thicknesses of 5mm, 10mm and 15mm, along with a 6mm web thickness; 2) three damper models with flange thicknesses of 5mm, 10mm and 15 mm made of ST37 steel, and the corresponding web thickness of 15 mm made of LYP100 steel; 3) three damper models with flanges and webs made of LYP, featuring flange thicknesses of 5mm, 10mm and 15mm, and a web thickness of 15mm; 4) three damper models with both the web and flanges made of LYP100 material, featuring flange thicknesses of 12mm, 24mm, and 36mm, and a web thickness of 15mm. It is necessary to mention that when changing the steel material from ST37 to LYP100, the corresponding thickness related to the yield stress must be taken into account. In other words, the web thickness of 6mm, which is initially used with ST37 steel, should be adjusted in order to account for the change in steel type to LYP100 with the coefficient $\frac{F_{yw}(\mathrm{ST37})}{F_{yw}(LYP)} = \frac{240}{100} = 2.4$; therefore, when using LYP steel for the damper web, the thickness of the web is increased in this way: $6 \times 2.4 = 14.4 \cong 15mm$. Thus, the thickness of the components whose steel is changed from ST37 to LYP100 is modified in the mentioned way. Since the value of the parameter b, representing the depth of the I-shaped section, is constant in all models, according to Equation (1), the shear capacity in both corresponding cases is equal to each other. Table 2 displays the details related to the thickness and the utilized steel of the damper components in the studied models. In this Table, for each numerical model, a name has been chosen as M_f- t_f- M_w- t_w, which respectively represents the material type of the flange plate, the thickness of the flange plate, the material type of the web plate, and the thickness of the web plate.

Table 2. Properties of models

Model	$t_f(mm)$	$t_w(mm)$	M_f	M_w
S-5-S-6	5	6	ST37	ST37
S-10-S-6	10	6	ST37	ST37
S-15-S-6	15	6	ST37	ST37
S-5-L-15	5	15	ST37	LYP100
S-10-L-15	10	15	ST37	LYP100
S-15-L-15	15	15	ST37	LYP100
L-5-L-15	5	15	LYP100	LYP100
L-10-L-15	10	15	LYP100	LYP100
L-15-L-15	15	15	LYP100	LYP100
L-12-L-15	12	15	LYP100	LYP100
L-24-L-15	24	15	LYP100	LYP100
L-36-L-15	36	15	LYP100	LYP100

4.2. Verification of Finite Element Results

In this article, the ABAQUS [52] software was used to simulate numerical models. In order to ensure the accuracy of the modeling and analysis of the finite element models, the laboratory test of TahamouliRoudsari *et al*. [53] was chosen for validation, which is similar to the model discussed in this article in terms of boundary conditions and the use of steel elements in the concrete frame. In Figure 3, the finite element modeling of the laboratory model derived from the referenced article [53] is displayed.

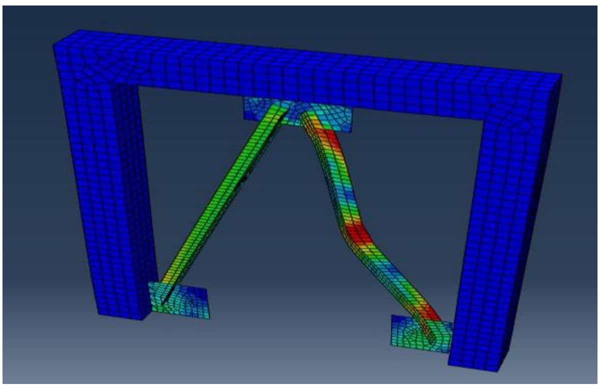


Fig. 3. The stress status of the validated FE model

The geometric and mechanical details, as well as the loading and boundary conditions, were applied according to the referenced paper [53] in the ABAQUS [52] software. Solid elements were used for modeling concrete elements, while shell elements were utilized for modeling the brace and gusset plates. Comparing the experimental results of

TahamouliRoudsari *et al.* [53] and the finite element results, as presented in Figure 4, shows the high accuracy of the FE modeling.

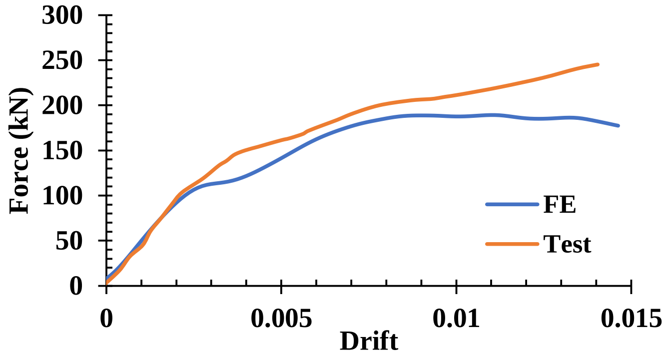


Fig. 4. Comparing the results of the experimental test model with the FE model

5. Results and Discussion

5.1. Investigating the Effect of Flanges Thickness on The Stiffness and Strength of The Studied Frame

The push-over and bilinear curves of the models can be seen in Figures 5, 6 and 8 in terms of investigating the effect of increasing the flanges thickness. In the models of the diagram in Figure 5, a comparison has been made between the models in which all damper components are made of ST37 steel. The diagrams in Figure 6 are related to the models in which the damper web is made of LYP steel, and the damper flanges are made of ST37. The graphs in Figure 8 compare the models in which the entire damper components are made of LYP steel. Also, all the results of the analysis of the models are given in Table 3.

In Figure 5, as the thickness of the damper flanges increases, the slope of the bilinear curves in the elastic region, which represents the stiffness of the frame, also increases. Moreover, the increase in the ultimate strength of the studied frame with the increase in the thickness of the flanges is clearly observable in this diagram. According to Table 3, by increasing the flanges thickness from 5 mm to 10 mm, the frame stiffness is increased by 8 percent. Furthermore, with an increase in the flanges thickness from 5 mm to 15 mm, the percentage increase in stiffness reaches 16%. This indicates that in models where all the damper components are made from ST37, the frame stiffness is improved by increasing the flanges thickness from 5 mm to 15 mm. Regarding the system shear strength, based on Table 3, it can be inferred that a rise in the flanges thickness from 5 mm to 10 mm results in a 13% growth in shear strength. This percentage increase in strength, when the flanges thickness of damper changes from 5 mm to 15 mm, reaches 25%. Therefore, in the group of models where all damper components are made of ST37, the final strength of the frame improves with an increase in the thickness of the flanges.

According to the graphs in Figure 6, it can be seen that with the growth in the thickness of the damper flanges, the stiffness of the system is grown. Although the stiffness of the system in this group, in which the damper is made of LYP, is increased with the rise of the thickness of the flanges, the ultimate strength of the system is decreased. As the values in Table 3 show, the stiffness of the frame rises by 5% as the thickness of the damper flanges is increased from 5 mm to 10 mm, and this stiffness growth in the case where the thickness of the damper flanges is increased from 5 mm to 15 mm, is reached 11 percent. However, by increasing the thickness from 5 mm to 10 mm, the shear strength of the system has decreased by 3%, and by increasing the thickness of the damper flanges from 5 mm to 15 mm, the system strength has declined by 13%. With regard to Figure 7, it is evident that with an increase in the thickness of LYP flanges from 5mm to 10 mm, the ultimate strength, stiffness, and energy absorption grow by a percentage of 2-5%. Furthermore, in model L-15-L-15, despite a negligible decrease in the ultimate strength compared to model L-5-L-15, the stiffness and energy absorption of the frame show a rise of 9% and 7%, respectively.

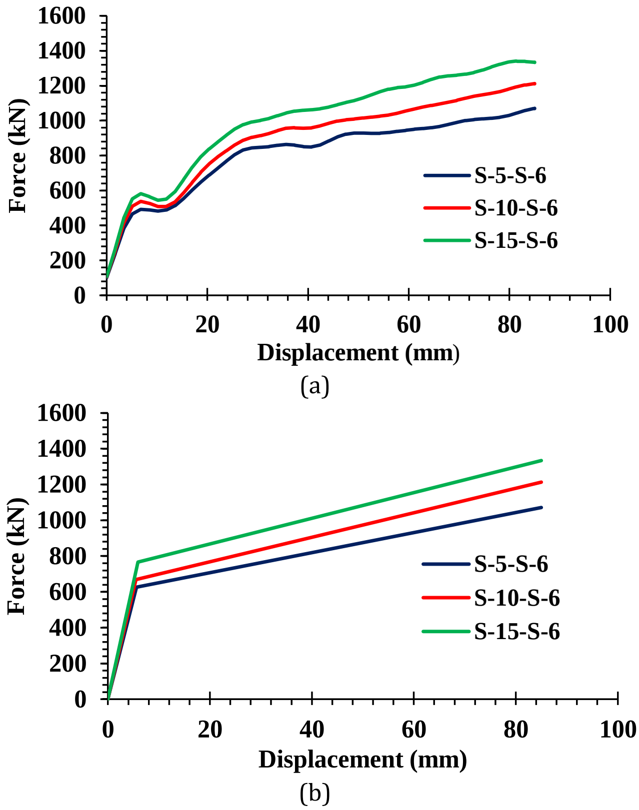


Fig. 5. Comparing the models whose dampers are made from ST37: (a) push-over curves, (b) bilinear graphs of (a)

By analyzing the graphs in Figure 8, it can be observed that by increasing the thickness of the damper flanges from 12 mm (thickness corresponding to 5 mm in the state of flanges made from ST37) to 24 and 36 mm (thicknesses corresponding to 10 and 15 mm in the state of flanges made from ST37, respectively), the stiffness of the frame is grown. The results in Table 3 show that with the rise in thickness from 12 mm to 24 mm, the stiffness of the frame is increased by 12%. In addition, when the thickness of flanges changes from 12 mm to 36 mm, the percentage increase in the frame stiffness reaches 22 percent.

Additionally, the frame shear strength is reduced by 7% with the increase in the thickness of the flanges from 12 mm to 24 mm. However, with the growth in the thickness of the flanges from 12 to 36 mm, the system shear strength shows a slight increase of 1%. Thus, in the comparison made for Figures 5, 6, and 8, it is concluded that the stiffness rises with the growth in the thickness of the flanges. However, considering the impact of increasing the flanges thickness on system strength in Figures 6 and 8, it can be inferred that while the increase in flanges thickness contributes to a decrease in frame strength, this reduction is generally not a significant magnitude. Consequently, increasing the thickness of the flanges within the range of 5 to 15 mm notably enhances the stiffness and strength of the analyzed frame in most models.

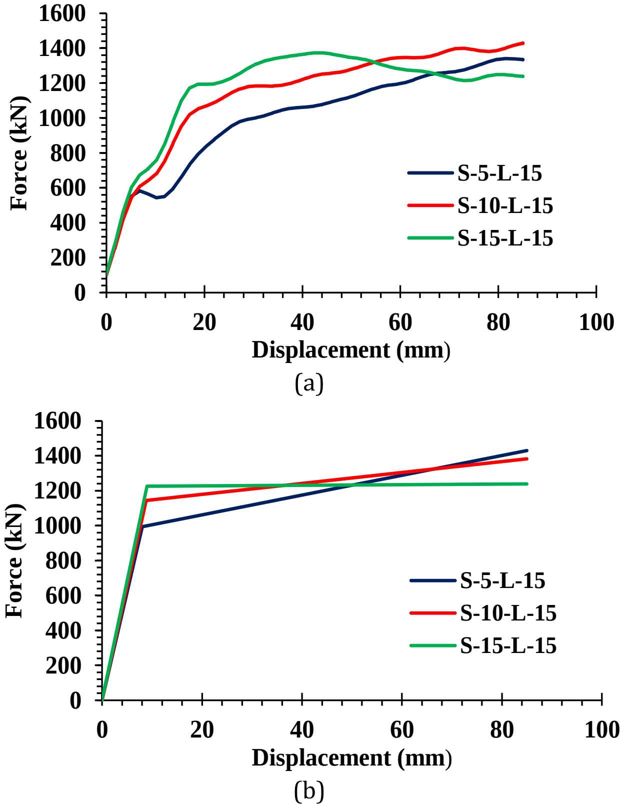
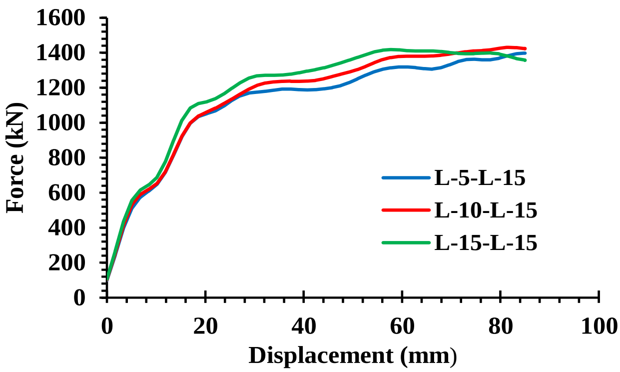
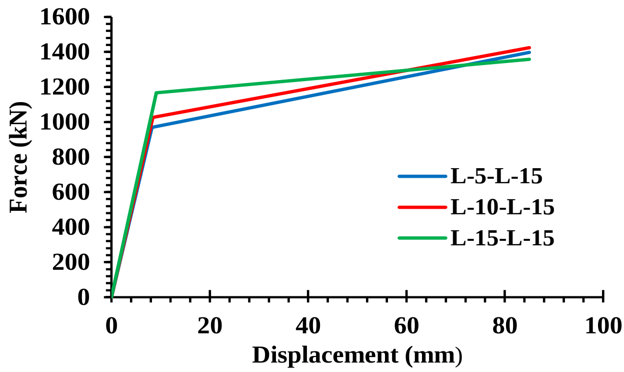


Fig. 6. Comparing the models whose webs of dampers are only made from LYP: (a) push-over curves, (b) bilinear graphs of (a)

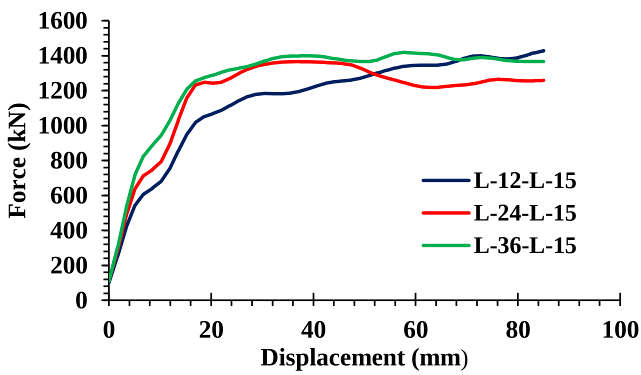


(a)

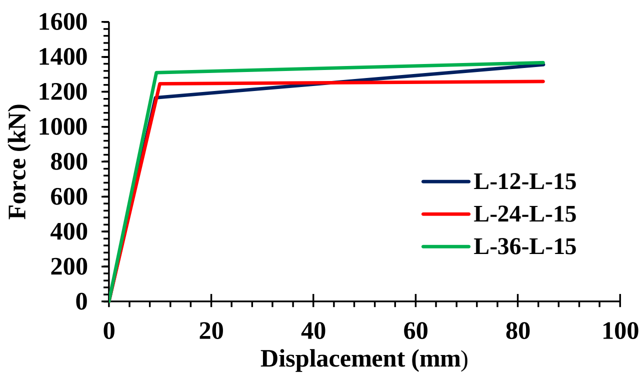


(b)

Fig. 7. Comparing the models whose all plates of dampers are made from LYP: (a) push-over curves, (b) bilinear graphs of (a)



(a)



(b)

Fig. 8. Comparing the models whose all plates of dampers are made from LYP: (a) push-over curves, (b) bilinear graphs of (a)

Table 3. Comparison of values based on increasing thickness of damper's flanges

Model	Ultimate strength, V_u (kN)	ψ^*	Stiffness, K $(\frac{kN}{mm})$	ψ^*	Energy absorption, EA (kN.mm)	ψ^*
S-5-S-6	1071.07		111.97		69173.37	
S-10-S-6	1212.41	1.13	121.42	1.08	76624.23	1.11
S-15-S-6	1334.32	1.25	129.9	1.16	85364.20	1.23
S-5-L-15	1429.48		123.47		97219.09	
S-10-L-15	1383.14	0.97	129.86	1.05	101297.78	1.04
S-15-L-15	1238.69	0.87	136.49	1.11	99172.13	1.02
L-5-L-15	1398.27		117.68		94894.65	
L-10-L-15	1424.61	1.02	122.34	1.04	98176.37	1.03
L-15-L-15	1358.46	0.97	128.47	1.09	101185.11	1.07
L-12-L-15	1355.99		128.19		101021.76	
L-24-L-15	1258.93	0.93	143.52	1.12	100176.55	0.99
L-36-L-15	1366.79	1.01	156.3	1.22	107409.77	1.06

* The ratio of values to the base model in each category.

5.2. Investigating The Effect of Flanges Thickness on The Behavior Factor and Over-Strength Coefficient of The Studied Frame

In Table 4, the results of the behavior factor and over-strength coefficient related to the investigated models are evident. In the group of models in which the entire damper plates are made of ST37 steel, with the increase in flanges thickness from 5 mm to 10 mm and 15 mm, the coefficient of behavior is increased by a negligible amount of 1% and 3% (respectively). Regarding the over-strength coefficient, by increasing the flanges thickness from 5 mm to 10 mm, no significant effect can be seen in this parameter (one percent decrease).

Table 4. Comparison of behavior factor (R) and over-strength (Ω) based on increasing damper's flange

Model	R	ψ^*	Ω	ψ^*
S-5-S-6	10.37		1.65	
S-10-S-6	10.49	1.01	1.63	0.99
S-15-S-6	10.7	1.03	1.74	1.05
S-5-L-15	11.7		2.37	
S-10-L-15	11.65	0.99	2.6	1.10
S-15-L-15	11.25	0.96	2.65	1.12
L-5-L-15	11.85		2.43	
L-10-L-15	11.83	0.99	2.48	1.02
L-15-L-15	11.72	0.98	2.68	1.10
L-12-L-15	11.72		2.69	
L-24-L-15	11.02	0.94	2.52	0.94
L-36-L-15	10.95	0.93	2.44	0.91

* The ratio of values to the base model in each category.

Also, by increasing the thickness of the flanges from 5 mm to 15 mm, this coefficient is increased by 5 percent. In the second group of models in which only the web plate of the damper is made of LYP, by increasing the thickness of the damper flange from 5 mm to 10 and 15 mm, no significant effect on the behavior coefficient can be seen, while this amount of growth in the thickness of the flanges is led to an increase of about 10% in the over-strength coefficient amount. According to the third group of models with LYP flanges and webs, there is no remarkable improvement in the behavior factor (R) by changing the thickness of the flanges from 5mm to 10mm and 15mm. However, model L-15-L-15 indicates a growth of 10% in the over-strength factor (Ω) in comparison with model L-5-L-15. Also, in the group of models where the entire damper plates are made of LYP, the increase in the thickness of the damper flanges results in a 6-7% decrease in the behavior coefficient. Also, this trend in the thickness of the damper flanges leads to a decrease in the over-strength coefficient (a decrease between 5 and 10%).

5.3. Investigating The Impact of Damper Steel Type on The Strength, Stiffness, And Energy Absorption of The Analyzed Frame

In Figures 9 to 23, the models have been compared to examine the impact of steel type on the structural parameters of the system. Figure 9 clearly demonstrates the positive effect of using LYP steel in the damper. The stiffness of model S-5-L-15 increases by 10% compared to the base model in this group (S-5-S-6). Additionally, the frame strength in this comparison rises by 33%.

In Figure 10, a comparison has been made between the model in which all damper components are made from LYP and the case where all damper components are made of ST37. The positive effect of using steel with low yield stress on stiffness and strength can be seen in this diagram. As it is evident from Table 5, using LYP steel in all damper components results in a 14% growth in system stiffness and a 27% increase in ultimate strength. It can be observed that this process of enhancing stiffness and strength is apparent in the remaining diagrams, except for the model in Figure 22. According to the diagram in Figure 22 and as indicated in Table 5, the model with the characteristic S-15-L-15, compared to the base model of this group (S-15-S-6), has shown a 7% reduction in strength. As a result, it can be generally concluded that when steel with low yield stress is used in the damper components, although in some cases the ultimate strength value may decrease by less than 10%, the system's overall improvement is evident across all comparisons in terms of system stiffness. Moreover, according to Table 5 and the comparative Figures in this section, the system's energy absorption is significantly improved due to the usage of LYP in the damper web or the entire damper, instead of using ST37 steel.

Regarding to Figures 13 to 15, the models in the third group show better performance in terms of energy absorption and ultimate resistance than the ST37 models (the first group of models). In this comparison, the stiffness of the frame is almost constant and without significant change. According to Figures 16 to 18, the third group of models does not show a remarkable difference in ultimate strength, stiffness, and energy absorption when they are compared to the second group peer-to-peer. However, Figure 24 shows that the stress distribution in the third group is significantly better than in the second group. While Figures 19 to 21 and Figure 24 demonstrate that the fourth group of models exhibits higher stiffness and energy absorption compared to the third group, the stress distribution in the studied frame is more favorable when using the third group of damper models.

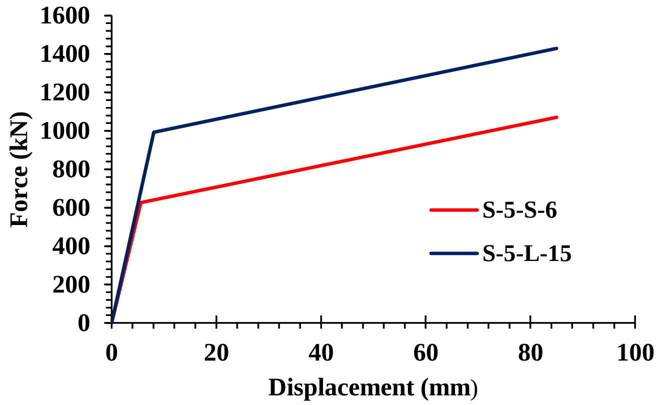


Fig. 9. Comparing S-5-S-6 with S-5-L-15

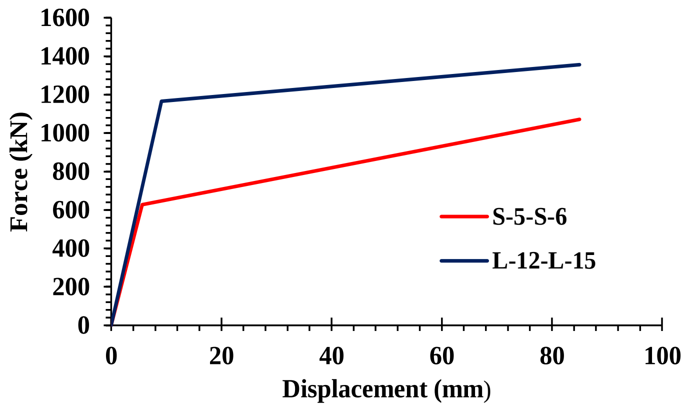


Fig. 10. Comparing S-5-S-6 with L-12-L15

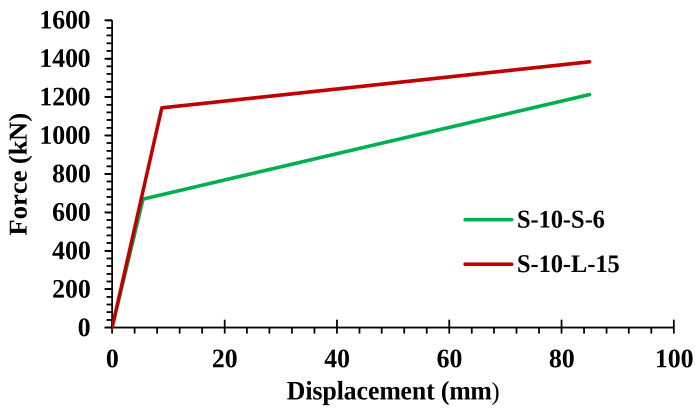


Fig. 11. Comparing S-10-S-6 with S-10- L-15

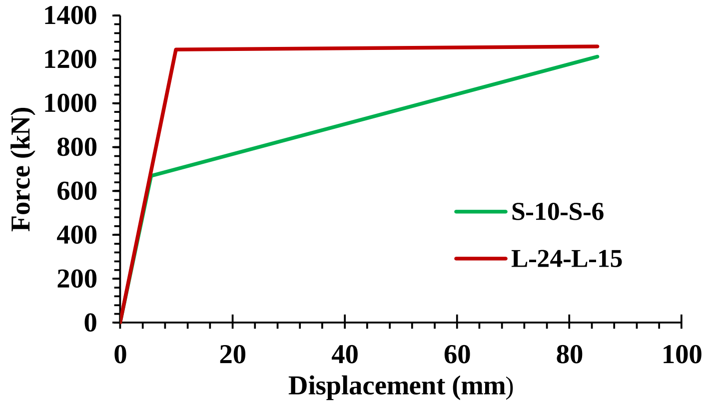


Fig. 12. Comparing S-10-S-6 with L-24-L-15

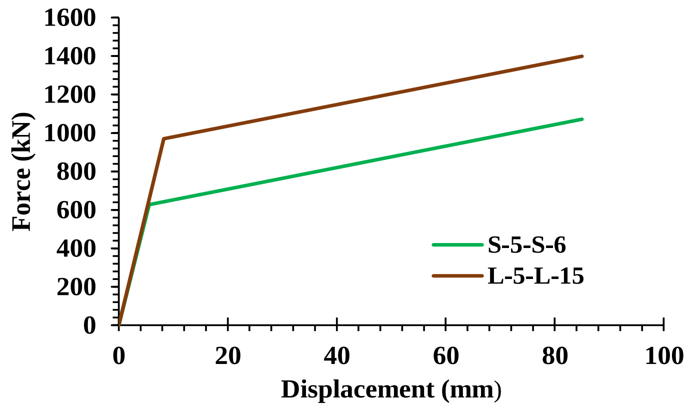


Fig. 13. Comparing S-5-S-6 with L-5-L-15

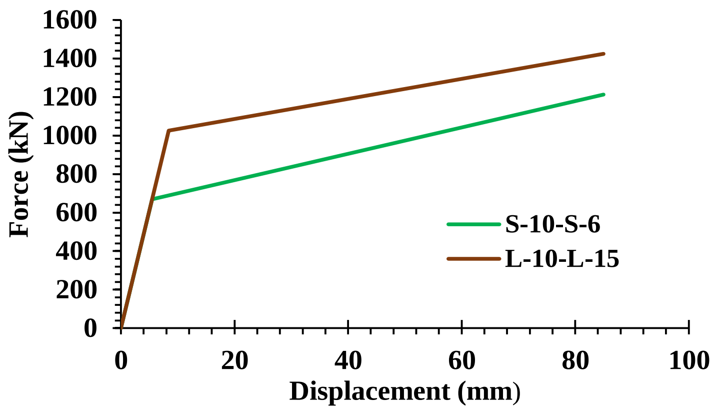


Fig. 14. Comparing S-10-S-6 with L-10-L-15

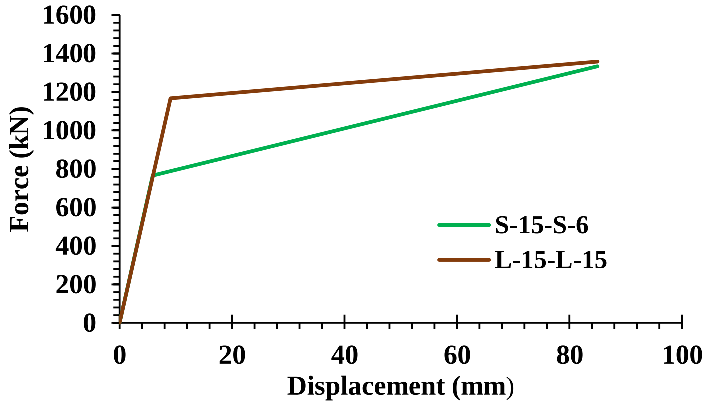


Fig. 15. Comparing S-15-S-6 with L-15-L-15

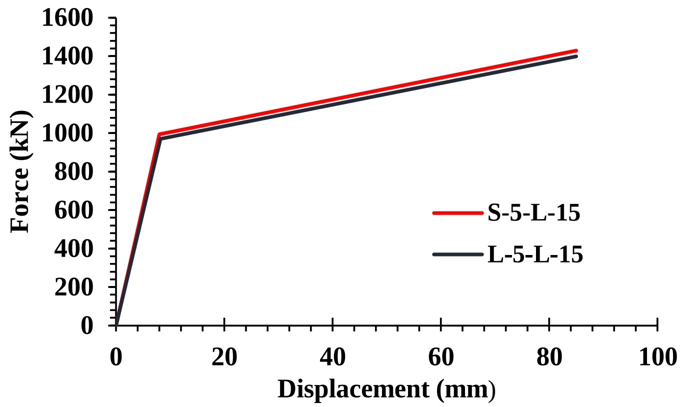


Fig. 16. Comparing S-5-L-15 with L-5-L-15

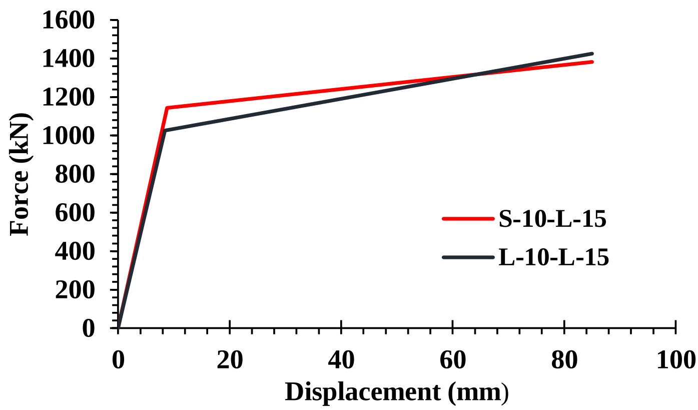


Fig. 17. Comparing S-10-L-15 with L-10-L-15

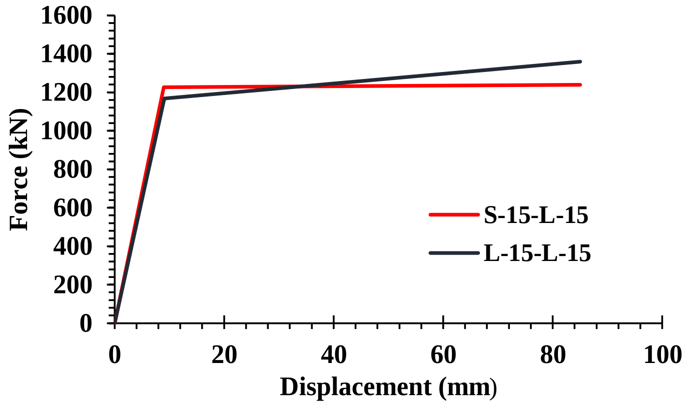


Fig. 18. Comparing S-15-L-15 with L-15-L-15

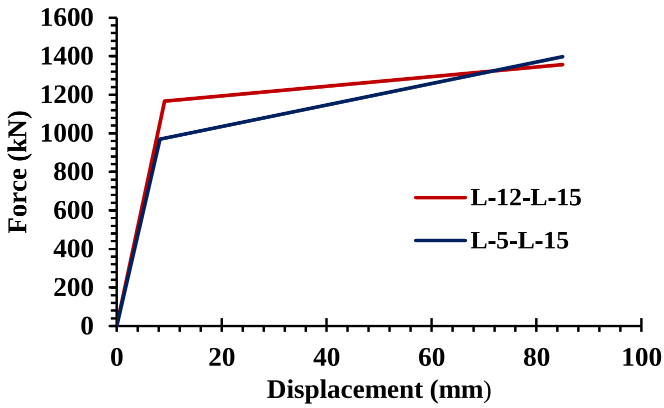


Fig. 19. Comparing L-12-L-15 with L-5-L-15

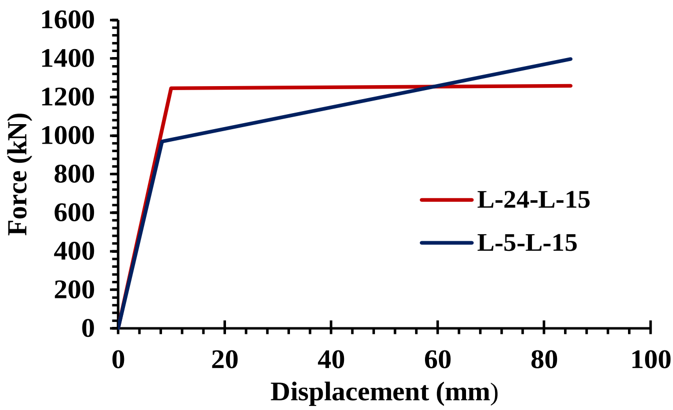


Fig. 20. Comparing L-24-L-15 with L-5-L-15

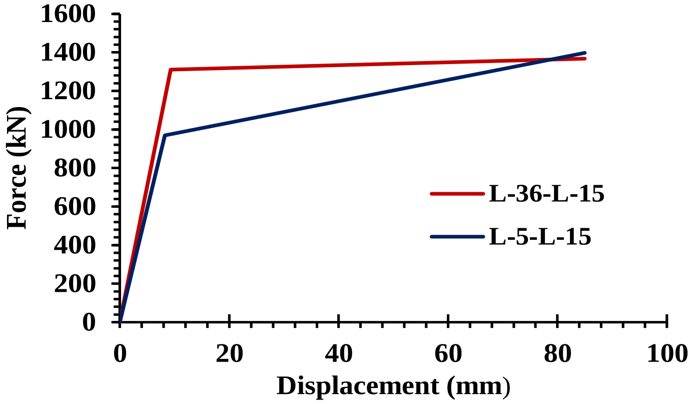


Fig. 21. Comparing L-36-L-15 with L-5-L-15

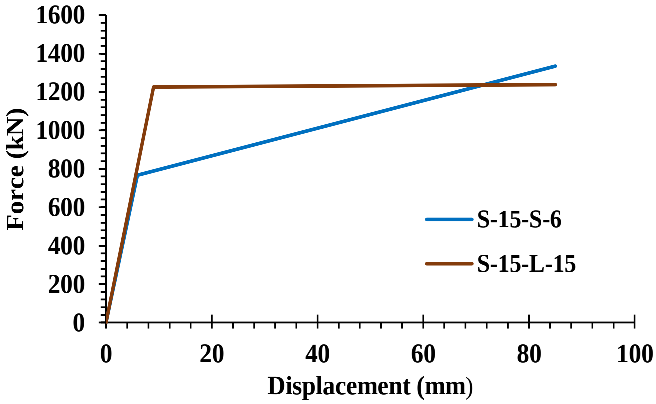


Fig. 22. Comparing S-15-S-6 with S-15-L-15

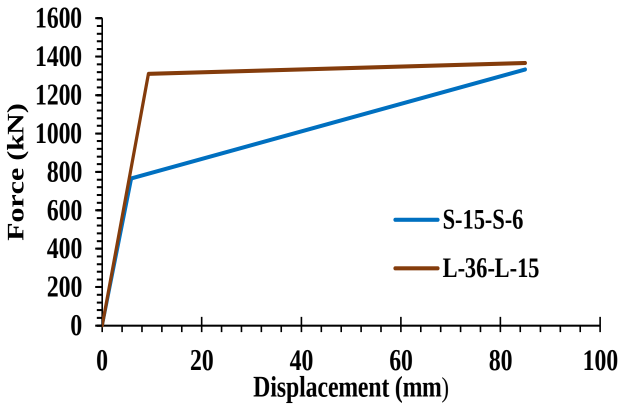


Fig. 23. Comparing S-15-S-6 with L-36-L-15

Table 5. The structural parameters of the LYP damper divided by the parameters of the ST37 damper

Model	Ultimate strength, $V_u(kN)$	ψ^*	ψ^{**}	Stiffness, K $(\frac{kN}{mm})$	ψ^*	ψ^{**}	Energy Absorption, EA (kN.mm)	ψ^*	ψ^{**}
S-5-S-6	1071.07			111.97			69173.37		
S-10-S-6	1212.41			121.42			76624.23		
S-15-S-6	1334.32			129.9			85364.20		
S-5-L-15	1429.48	1.33		123.47	1.10		97219.09	1.41	
S-10-L-15	1383.14	1.14		129.86	1.07		101297.78	1.32	
S-15-L-15	1238.69	0.93		136.49	1.05		99172.13	1.16	
L-5-L-15	1398.27	1.30	0.98	117.68	1.05	0.95	94894.65	1.37	0.98
L-10-L-15	1424.61	1.18	1.03	122.34	1.01	0.94	98176.37	1.28	0.97
L-15-L-15	1358.46	1.02	1.10	128.47	0.99	0.94	101185.11	1.18	1.02
L-12-L-15	1355.99	1.27	0.95	127.98	1.14	1.04	101021.76	1.46	1.04
L-24-L-15	1258.93	1.04	0.91	125.3	1.03	0.96	100176.55	1.31	0.99
L-36-L-15	1366.79	1.02	1.10	140.89	1.08	1.03	107409.77	1.26	1.08

$\boldsymbol{\psi}^*: \left(\frac{S,L-i-L-15}{S-i-S-6}\right)$, $\boldsymbol{\psi}^{**}: \left(\frac{L-i-L-15}{S-i-L-15}\right)$

5.4. Investigating The Impact Of Damper Steel Type on The Behavior Factor and Over-Strength Coefficient of The Analyzed Frame

Referring to Table 6, while the utilization of steel with low yield stress, either in the damper web or in all its components, increases the behavior factor to some extent, the substantial rise in the values of the over-strength coefficient is more significant (approximately an increase of 40% and 60%).

Table 6. Behavior factor (R) and over-strength (Ω) coefficient of the LYP damper divided by factors of the ST37 damper

Model	R	ψ^*	ψ^{**}	Ω	ψ^*	ψ^{**}
S-5-S-6	10.37			1.65		
S-10-S-6	10.49			1.63		
S-15-S-6	10.7			1.74		
S-5-L-15	11.7	1.13		2.37	1.44	
S-10-L-15	11.65	1.11		2.6	1.60	
S-15-L-15	11.25	1.05		2.65	1.52	
L-5-L-15	11.85	1.14	1.01	2.43	1.47	1.03
L-10-L-15	11.83	1.13	1.02	2.48	1.52	0.95
L-15-L-15	11.72	1.10	1.04	2.68	1.54	1.01
L-12-L-15	11.72	1.13	1	2.69	1.63	1.14
L-24-L-15	11.02	1.05	0.946	2.52	1.55	0.97
L-36-L-15	10.95	1.02	0.973	2.44	1.40	0.92

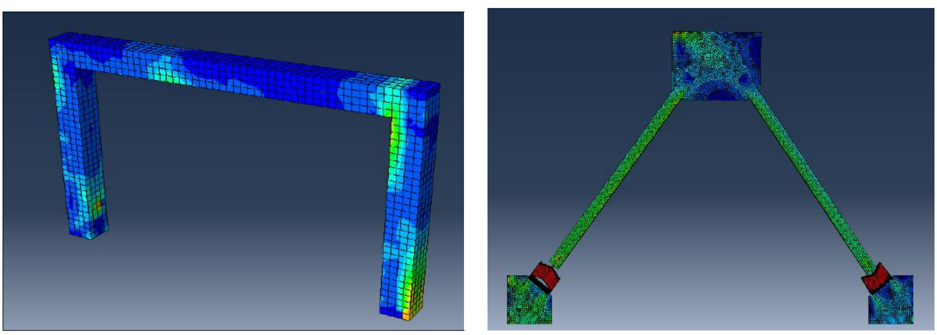
$\boldsymbol{\psi}^*: \left(\frac{S, L-i-L-15}{S-i-S-6}\right)$, $\boldsymbol{\psi}^{**}: \left(\frac{L-i-L-15}{S-i-L-15}\right)$

Consequently, the use of LYP steel instead of ST37 elevates the behavior and over-strength coefficients of the studied frame, and this elevation is more pronounced in the case of the over-strength coefficient.

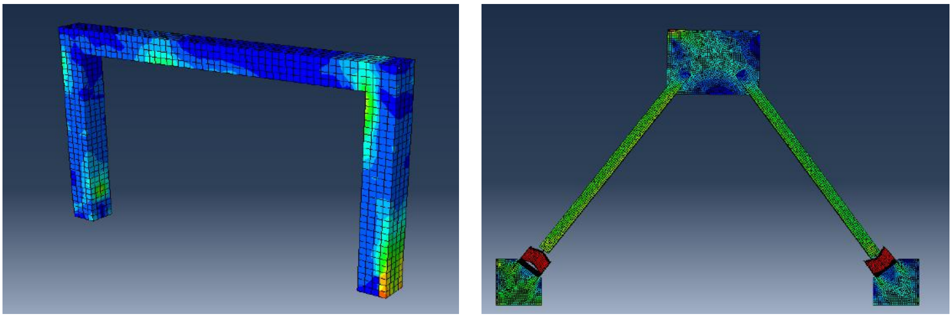
5.5. Reviewing the Stress Distribution In Structural Members

To consider the impact of adding the proposed damper to the RC frame on the stress distribution, the status of the stresses is shown in Figure 24. The stresses in the RC frame and the steel elements are shown separately for each case to provide a clearer understanding of the stress distribution. Referring to Figure 24, in the cases of (a), (b) and (c), the dampers are obviously yielded, whereas the other parts of the structures remain elastic. Since the studied frame in this paper was designed based on the capacity of the damper made of ST37 steel (as described in section 3), in the presented models in which all damper components are made of ST37 steel, the provided equation (5) for the damper design is satisfied, and the damper acts as a ductile fuse, as was shown in Figures 24(a), 24(b), and 24(c).

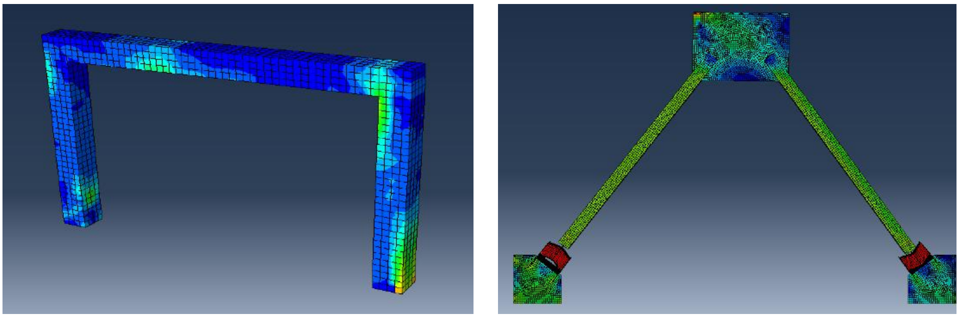
On the other hand, by utilizing LYP steel, in some cases such as (e), (f), (k) and (l), stress is transferred from the damper to the brace elements. This difference in stress distribution of ST37 and LYP models, despite identical shear capacities for ST37 and LYP models, is due to the distinct behavior of LYP steel. In fact, it is expected that based on the equations proposed to predict the shear behavior of each shear plate (or shear link), the shear capacity will be obtained based on the yield stress and its thickness. Therefore, to maintain this shear strength in both types of ST37 and LYP dampers, the same capacity was considered to predict and evaluate their nonlinear behavior. Expected results according to Figure 24 show that owing to the strain-hardening impact of the LYP steel, the ultimate strength of the LYP dampers is greater than the expected value. For this reason, if the LYP damper is designed based on the relationships governing the ST37 damper, the damper may cause buckling of the brace elements. Therefore, the members outside the LYP damper should be designed for amplified forces. Additionally, the LYP models exhibited higher energy absorption, stiffness, ultimate strength, behavior factor, and over-strength compared to the ST37 models, as shown in Table 5, demonstrating LYP effectiveness in enhancing the seismic performance. The LYP models (g), (h) and (i) with lower thickness of flanges indicate better status of stress distribution compared to models (j), (k), and (l), which suggests that the mere use of LYP steel does not guarantee the improvement of the frame's behavior, and this is subject to the thickness of the damper’s flanges.



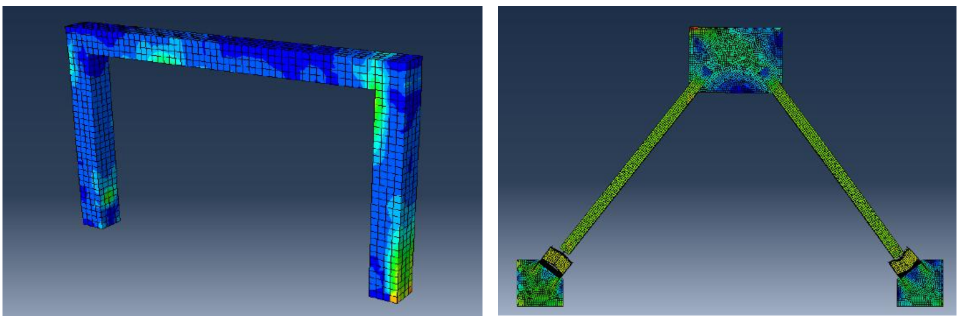
(a) S-5-S-6



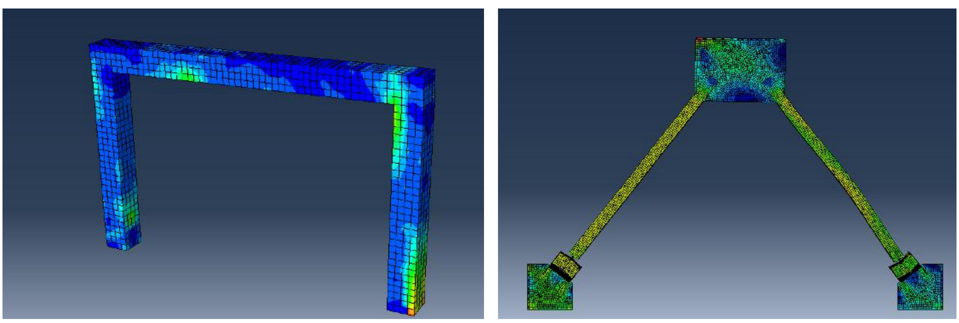
(b) S-10-S-6



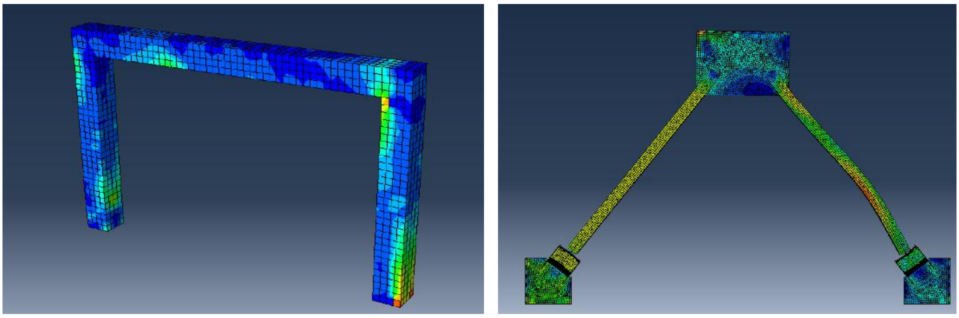
(c) S-15-S-6



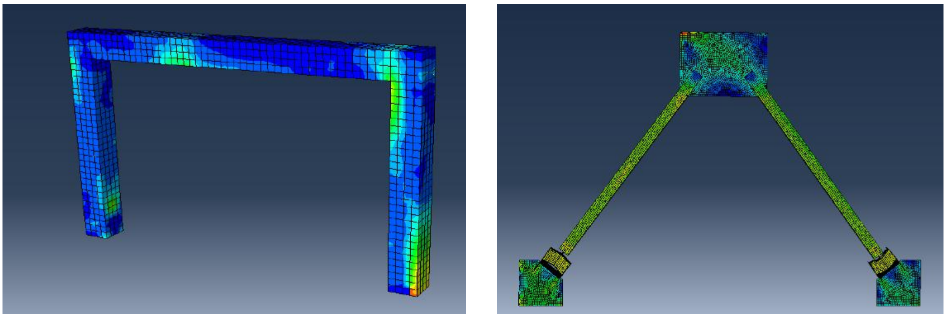
(d) S-5-L-15



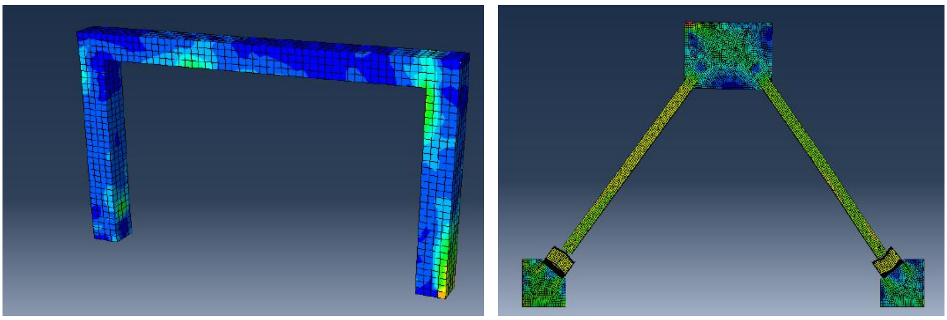
(e) S-10-L-15



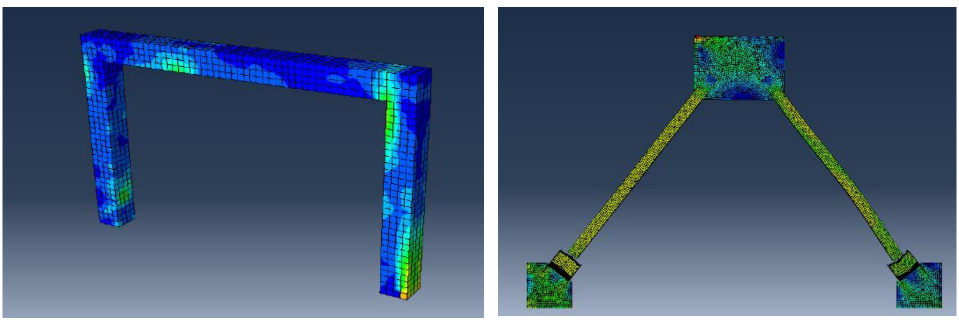
(f) S-15-L-15



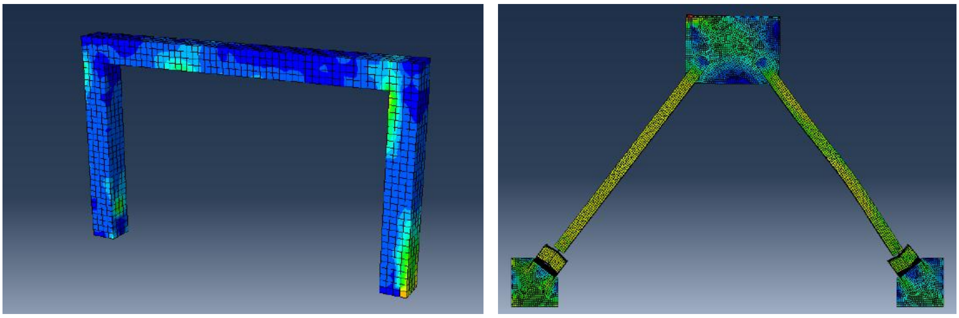
(g) L-5-L-15



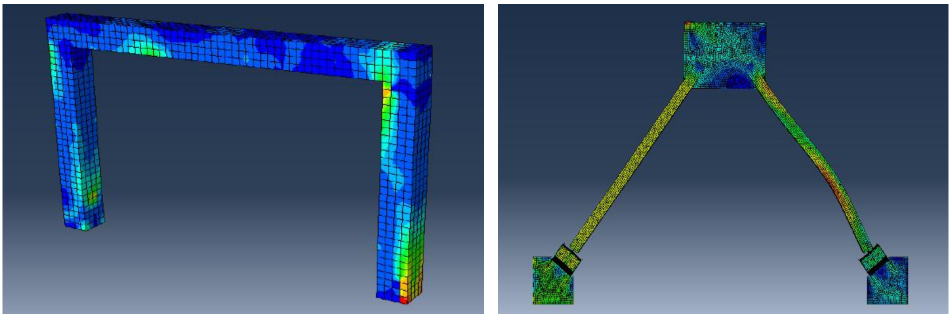
(h) L-10-L-15



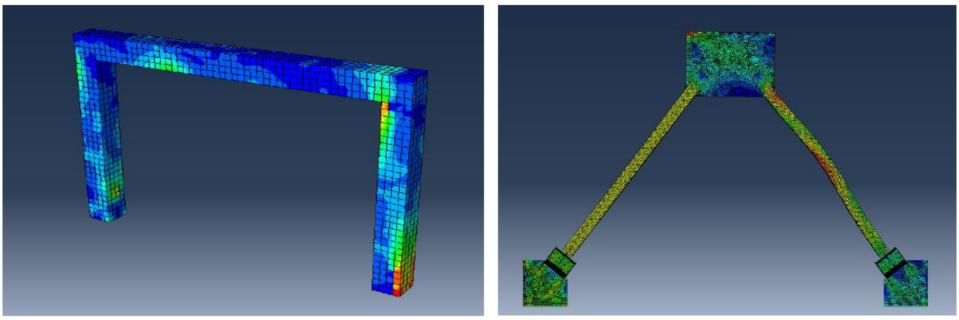
(i) L-15-L-15



(j) L-12-L-15



(k) L-24-L-15



(l) L-36-L-15

Fig. 24. Distribution of stresses

6. Conclusions

In this paper, the effects of the steel type and the thickness of the damper flanges, pertaining to an I-shaped shear link, on the ultimate strength, stiffness, energy absorption, behavior factor, and over-strength coefficient were investigated. The findings are summarized in the following:

- In the group of models where all damper components are made of ST37 steel, an increase in the thickness of damper flanges leads to an increase in the system's stiffness, ultimate strength, and energy absorption. Furthermore, this growth in damper flange thickness indicates an increase in the behavior and over-strength coefficient by 1 to 5 percent.

- With reference to the models where only the damper web is constructed using LYP steel, an increase in the thickness of the damper flanges has led to a decrease in ultimate strength by 3 to 13 percent, while the system's stiffness and energy absorption are increased. Additionally, the behavior coefficient is decreased by 1 to 4 percent, while the additional resistance coefficient is increased by 10 percent.
- In the group of models where the entire damper is made of LYP, increasing the thickness of the damper flanges has resulted in a reduction in strength by approximately 7 percent. Meanwhile, both stiffness and energy absorption are increased. Additionally, there is a decrease of approximately 5 to 10 percent in both the behavior coefficient and the over-strength coefficient.
- Using LYP steel is led to an increase in the parameters of stiffness, ultimate strength, energy absorption, behavior coefficient, and over-strength coefficient. However, the positive impact of using LYP on the energy absorption parameter and the over-strength coefficient is more noticeable. This indicates that the use of LYP steel not only improves the system's stiffness and strength, but also enhances the energy absorption capacity and ductility of the system.
- The LYP models in the third group demonstrate that using LYP steel enhances the seismic behavior of the RC frame in terms of ultimate strength, stiffness, energy absorption, behavior factor, and over-strength compared to the ST37 models.
- A comparison of the third and fourth groups of models reveals that while LYP steel can enhance the seismic behavior of the frame, the degree of improvement is contingent upon the thickness of the damper plates.
- The use of LYP steel in the studied I-shaped shear link has a significant role in enhancing the performance of concentrically braced reinforced concrete frames in terms of ultimate strength, stiffness, ductility, and energy absorption, provided that the related equations for the damper design are satisfied.

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