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Enhancing Seismic Performance of Ductile Moment Frames with Delayed Wire-Rope Bracing Using Middle Steel Plate

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Abstract**—**Moment frames have considerable ductility against cyclic lateral loads and displacements; however, if this feature causes the relative displacement to exceed the permissible limit, it can impose unfavorable hysteretic behavior on the frame. Therefore, adding a bracing system with the capability of preserving the capacity of high energy absorption and controlling displacements without a considerable increase in the stiffness is quite important. This paper investigates the retrofitting of a single storey steel moment frame through a delayed wire-rope bracing system using a middle steel plate. In this model, the steel plate lies where the wire ropes meet, and the model geometry is such that the cables are continuously under tension so that they can take the most advantage of the inherent potential they have in tolerating tensile stress. Using the steel plate also reduces the system stiffness considerably compared to cross bracing systems and preserves the ductile frame's energy absorption capacity. In this research, the software models of delayed wire-rope bracing system have been studied, validated, and compared with other researchers' laboratory test results.

Keywords—Ductile moment frame, delayed wire rope bracing, cyclic loading, hysteresis curve, energy absorption.

I. Introduction

THE seismic retrofitting of the existing structures and strengthening the ones recently built in earthquake-prone areas with the objective of enhancing their safety levels and elongating their exploitation period is of vital importance. The traditional methods of seismic retrofitting of the existing structures such as strengthening beams, columns, and connections, or adding bracings and shear walls are quite costly. On the one hand, harmful effects on the performance and serviceability of the buildings during base excitation must be regarded. Hence, selecting a method, which could solve the aforementioned problems and provide a desirable performance, would improve the retrofitting operations. Therefore, energy dissipation systems for the design and retrofitting of structures have been soaring in the last few decades.

In areas with medium to high seismic risks, steel moment frames are appropriate and common choices to provide the required ductility because the members provide a great amount of energy dissipation capacity due to large plastic deformations. Sometimes, however, the lateral displacements of these frames may exceed the permissible limit during strong earthquakes and cause increased damage [1]; therefore, the use of an appropriate method for the retrofitting of moment frames is quite essential.

Today, considering the knowledge engineers have about the structure behavior under seismic excitation, an appropriate lateral load resisting system should have the highest energy dissipation capacity and the lowest deterioration in the loops of its hysteresis curve. Also, it could ideally transfer lateral forces created by lateral loading to the ground. Local or general buckling, early fatigue in the members under cyclic loading, and opening/closing of cracks are some parameters that can cause disorder in the hysteresis curves [2] and, therefore, the approved seismic codes and regulations such as AISC 2010 [3] try to reduce their effects through considering the structural standards.

A probable disorder in the hysteresis curve is the drop in the frame resistance during the lateral loading cycles. After studying the seismic behavior of inelastic systems, Akkar and Miranda have stated that the decrease in the frame resistance has destructive effects on the lateral stability of the system meaning that steeper falls in the branches of the hysteresis curve will increase the level of the lateral resistance required to prevent the frame collapse [4]. Other researchers have also studied the effects of the stiffness after yield point on the collapse capacity of frames [5], [6].

In recent seismic designs, some structural elements are allowed to have inelastic displacement [6]. Now, if the structure behaves flexibly and the $\mathrm{p}-\Delta$ effects are combined with the plastic displacement, the post-yield tangential stiffness may become negative which means a drop in the resistance. Under such conditions, the structure will tend to continue displacement in a known direction and this can lead to dynamic instabilities in the structure under severe seismic stimulations [6]. The role of the $\mathrm{p}-\Delta$ phenomenon in the frame collapse, which is due to the undesirable effects of the gravity loads under static conditions, has been studied by several researchers and solutions have been suggested to enhance the frame performance under seismic simulations [7]-[11].

As mentioned before, the moment frame's tendency to continue transforming in one direction under seismic loads together with $p-\Delta$ effect is the most serious factors in its collapse. An approach used by researchers to solve this problem is to use bracing systems to adjust stiffness and

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control the frame's lateral displacement. Thus, the study and use of wire-rope systems have been the focus of attention in the recent years. For instance, Razavi [12] used a reverse *V* bracing system in some consecutive stories of a moment frame, Qiang- Jihong [13] investigated the application of wire-ropes to preserve the stability of lamella cylinders, and Moosavi [14] studied the role of bracing connections in preventing buckling and tensile performance of the bracing elements.

Since the last two decades, much emphasis has been placed on the enhancement of ductility and energy dissipation capacity of structures in earthquake-prone areas. Some researchers have addressed the investigation of wire-rope bracing with energy dissipater elements. Using a light energy dissipation center in the center of the wire-rope bracing [15], using dampers that absorb and dissipate energy through the friction force [16], [17], using U-shaped dissipaters [18], using couple energy dampers [19], using elements that are always under tension [20], and combining wire-rope bracing with the cylindrical type [21]-[23] are only some related studies to mention.

In the present study too, the wire-rope bracing has been selected to retrofit the moment frame because adding wire ropes will cause a considerable increase in the frame stiffness due to which the ductility and, hence, the energy dissipation capacity decreases compared to the case without bracing. In other words, it can be stated that the wire-rope bracing, although capable of controlling the lateral displacement within the permissible limits, will balance the merits of such a bracing system because it directs the frame behavior towards stiffness. Therefore, in this research, by adding a steel plate at the meeting point of the wire ropes, not only the frame ductility is preserved, but the main objective of the bracing system, which is to control the frame lateral displacement, is also achieved. This is expected to improve its energy dissipation ability compared to cross bracing. For this purpose, four modeling cases were tried including ductile moment frame system, hybrid system with moment frame and cross cable bracing, hybrid system with delayed wire-rope bracing using pipe and hybrid system with delayed wire-rope bracing using middle plate and the energy dissipation rate of each was checked and calculated.

II. Studying the Performance of Delayed Cable Bracing Using Middle Steel Plate

A. Appearance Delayed Cable Bracing System

For the first time, Hou and Tagawa introduced the concept of the wire-rope bracing with delay along with its theoretical studies [21]. They placed a cylinder at the meeting point of the wire ropes and caused a delay in the wires to start action. The wire ropes used in this model have lengths more than the frame diameter because of the cylinder. This feature causes the frame to use its energy dissipation capacity for small displacements and makes the bracing elements start acting and absorbing the lateral forces as soon as entering the range of large displacements (when one rope takes the shape of a straight line).

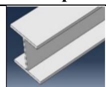
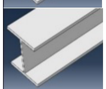
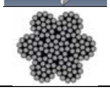
Since the objective of the present research is to substitute a steel plate for cylinder, first the models made in ABAQUS were validated through comparing the results of the finite element analysis with those of the researchers, and the middle steel plate was added after it was confirmed that the model worked correctly. It is worth mentioning that all the details of the software modeling (geometry, materials specifications, conditions of supports, range of loading, position of the constraints, and location of the welding lines) were considered similar to those of Hou and Tagawa [23] which supplemented their own previous works.

B. Initial Models

The first three initial models (Fig. 1) include a simple moment frame, one braced with cross cables, and one braced with cross cables and a cylindrical casing at the point where cables meet. In all the modeling cases, all the frame members (except cables) have been introduced and built as 3*D*, ductile, and rigid; the cables, too, have been introduced to the model as wires with lengths proportional to the middle plate. Next, after validating the correctness of the software outputs, a horizontal rectangular steel plate is substituted for the cylindrical casing. The geometrical specifications of steel plate will be provided next.

Sections used for beams and columns are $H-150 \times 150 \times 7 \times 10$ (class $SN400$B steel) connected with T-shaped elements obtained through cutting $H-300 \times 150 \times 6.5 \times 9$ sections (class $SS400$ steel). For bracing members, we used a 10 mm diameter cable (stainless steel ($SUS316$) strand ($7 * 19$)) with a yield strength = 57.9 *kN* and ultimate strength = 60.2 *kN*. The length and inner diameter of the steel pipe were, respectively, 214 mm and 40 mm. In the frames' design, the philosophy is that, at the failure point, buckling should not occur and failure should be limited to the T-shaped connecting elements. Tables I and II show the specifications of the sections geometries and mechanical specifications of the used steels respectively.

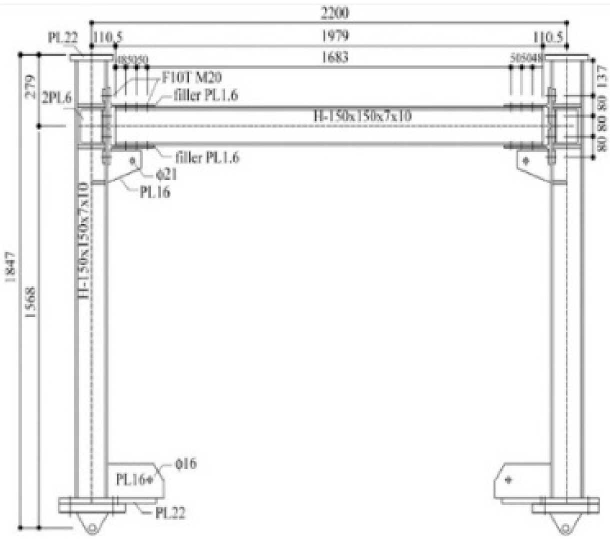
TABLE I
Geometrical Specifications of the Main Sections

Member	Shape	Section	Length (cm)
Column		H150×150×7×10	197.9
Beam		H150×150×7×10	170.3
T member		Cut from H300×150×6.5×9	224
Cable		Strand 7×9	Proportional with middle steel plate

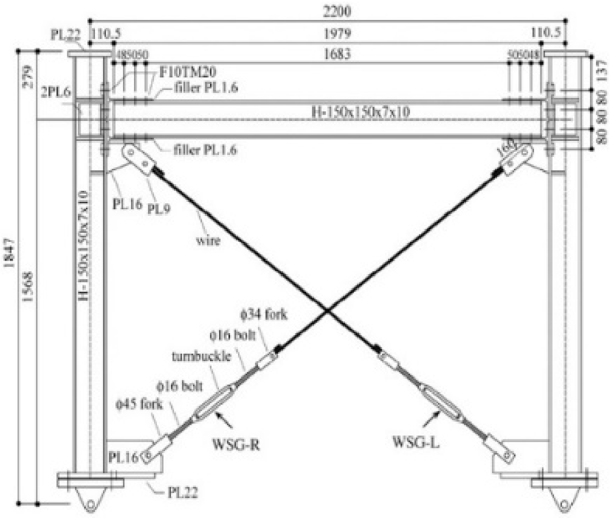
Columns supports are pinned in such a way that all the degrees of freedom (except rotation round the axis perpendicular to the frame plane) are closed and movement outside the frame plane is prevented by constraints fixed on columns tops. As shown in Fig. 2, the load is of the displacement type applied on the columns top plates for symmetry; the displacement cycle range is according to the information in Table III.

TABLE II
MECHANICAL SPECIFICATIONS OF THE USED MATERIALS

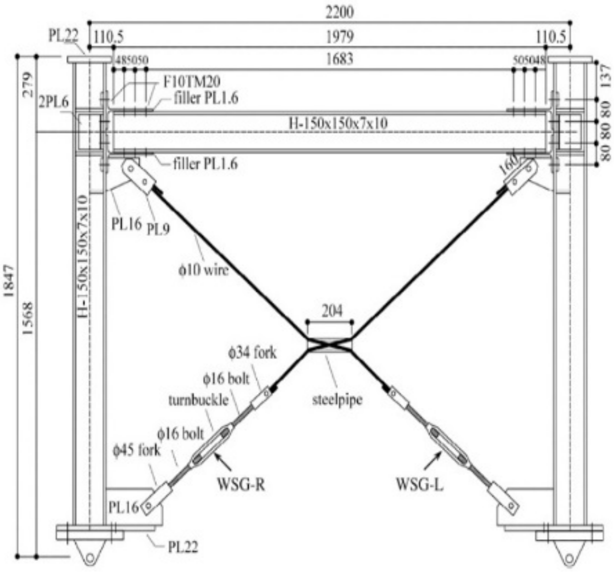
Steel grade	Density ($\frac{kg}{m^3}$)	Young's modulus ($\frac{N}{m^2}$)	Poisson ratio	Plastic property (Mpa)	
$SN400B$	7850	21×10^{10}	0.27	235 500	0 0.33
$SS400$	7860	21×10^{10}	0.26	245 500	0 0.32
$SUS316$	8000	19.3×10^{10}	0.3	–	



(a)



(b)



(c)

Fig. 1 Experimental models of the moment frame: (a) Simple (b) with cable bracing (c) with cable bracing and a cylindrical casing

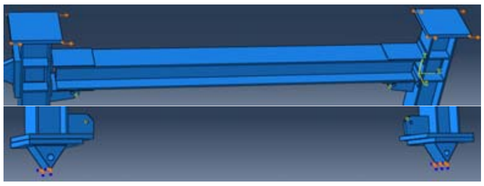


Fig. 2 Conditions of supports

TABLE III
RANGE OF THE DISPLACEMENTS VARIATIONS

Time	Displacement (mm)	Time	Displacement (mm)
0	0	1	0
0.1	20	1.1	-60
0.2	0	1.2	0
0.3	-20	1.3	80
0.4	0	1.4	0
0.5	40	1.5	-80
0.6	0	1.6	0
0.7	-40	1.7	100
0.8	0	1.8	0
0.9	60		

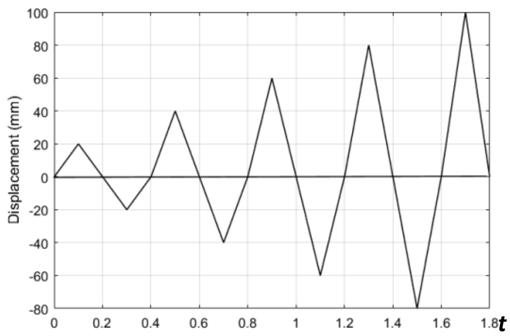
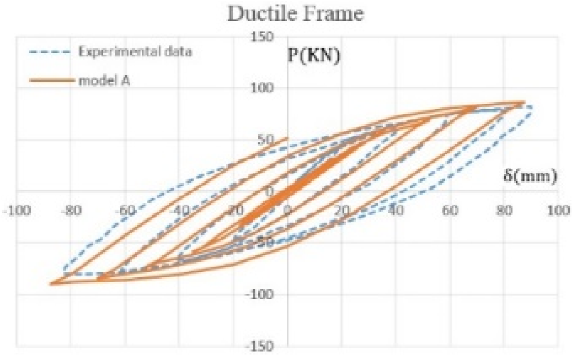


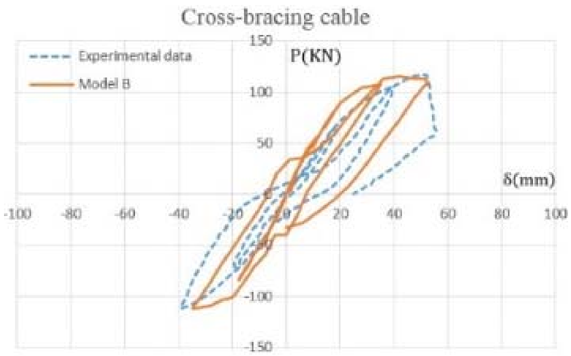
Fig. 3 The history of predefined displacement versus time

C. Validation

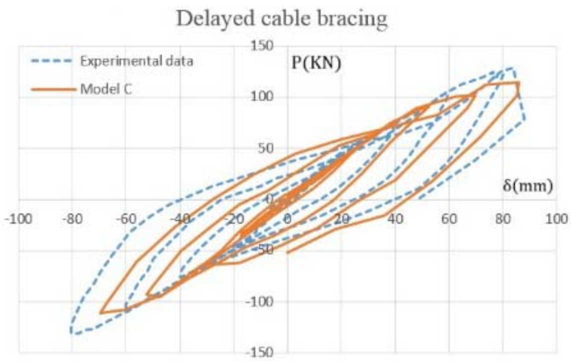
As mentioned before, three different models of moment frames were created in a software environment similar to the experimental models and placed under cyclic displacements according to the data in Table III. Then, the initial stiffness and hysteresis curves were extracted after analyzing the required outputs (forces and displacements at the failure moment). To validate the correctness of the model performance, we will now study the output results found from the finite element analyses of the models and compare them with those of the experimental tests.



(a) Frame A



(b) Frame B



(c) Frame C

Fig. 4 Comparison of the hysteresis curves found from the FE analyses and laboratory data

Fig. 3 shows the diagrams of the displacements of the frames versus the basic shear under the effects of the cyclic displacements. Using these loops, it is possible to find the frame's maximum displacement (δ_{max}) and maximum basic shear (p_{max}). Table IV shows the displacement and basic shear at the failure moment found from laboratory data and finite element analyses. It is worth mentioning that similar to recorded laboratory data, the FEM software has stopped at a point in which the stress and strain in either the cables or the connection elements has reached to the maximum allowable values.

Comparing the load displacement (hysteresis) cycles found from the laboratory data and *FE* analyses indicates the acceptable precision of the software models to explain the frame behavior. As shown in Table IV too, the errors of frame *A* model (created first and basis for other models) to determine maximum displacement and basic shear are 2.8 and 5.2% respectively. Since these error values are acceptable and, hence, the model validity in precise explanation of the frame behavior is confirmed, it is possible now to replace the cylindrical casing with the steel plate which is the central idea of this research.

TABLE IV
RESULTS FROM FE ANALYSES AND LABORATORY DATA

Sample	$P_{max}(KN)$			$\delta_{max}(mm)$		
	Ana.	Exp.	Diff. %	Ana.	Exp.	Diff. %
Frame *A*	86.3	82	5.2	87.5	90	2.8
Frame *B*	115.6	117	1.2	52.5	52	0.96
Frame *C*	118.03	129	8.5	86.22	84	2.6

One reason for studying the idea of replacing the cylindrical casing with the steel plate is its easy execution and availability in different thicknesses. Also in the cases where walls are needed to be placed inside the frame, using a steel plate can have superiority compared to cylinder, because of its smaller in-plane dimensions as well as it needs less space for having rotation.

D. Assembling Rectangular Plate

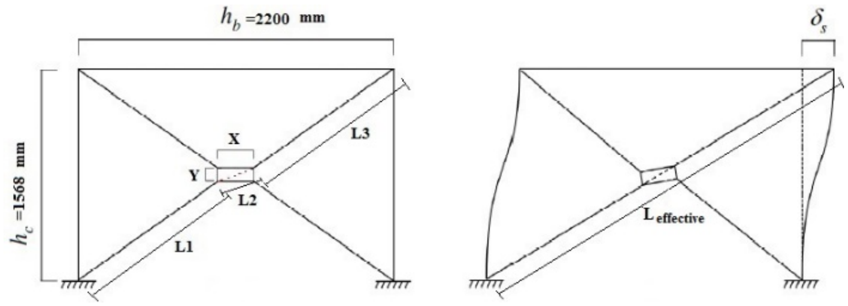
The concept of the bracing system is portrayed in Fig. 4. The wire rope is longer than the frame diagonal. Four wire-ropes are bundled with the middle plate of length *X* and width *Y*. In this system, the bracing system is activated when the lateral displacement of the frame reaches a certain level called δs; in the other words, the bracing members do not act between $\delta < \delta s$, where δ= story drift and δs = story drift at which the diameter frame is effective diameter, as shown in Fig. 4 (b). In this model, the beam members were assumed to be rigid. The effective diameter at which the bracing member starts acting, can be controlled according to the story drift at the same time, δs, and size of the middle plate using:

$$a)\ L_{effective} = L_1 + L_2 + L_3 = 2\sqrt{\left(\frac{h_b - x}{2}\right)^2 + \left(\frac{h_c - y}{2}\right)^2} + \sqrt{x^2 + y^2} \quad (1)$$

$$b)\ L_{effective} = \sqrt{h_c^2 + (h_b + \delta_s)^2} \qquad (2)$$

where h_c and h_b respectively denote the column and beam length. One of the biggest advantages of this system is that, the braced frame can exhibit ductile behavior similar to a moment-resisting frame for small and medium vibration amplitudes. This behavior enables the frame to absorb the seismic energy by the beam and column deformations. But in the large vibration amplitude that led to over the δs lateral displacement of the frame, the bracing member acts and prevents unacceptably large story drift and frame collapse.

For the delayed wire-rope bracing whit pipe, model *C*, bracing member began to operate in δs = 30 mm. So, to be able to compare the performance of the pipe and the plate, we assume that for the delayed wire-rope bracing whit plate, model *D*, story drift δs, has the same value. In this case, $L_{effective} = 2726\ mm$ is obtained from (2). Now, the sides of the plate can be calculated using (1). In this method, while one side of the plate is assumed, the other side also could be simply calculated. In this model, *X* = 300 mm and *Y* = 70 mm are obtained from (1). Fig. 5 shows the hysteresis curve for this model.



(a) Dimensions (b) Deformation at δ = δ *s*

Fig. 5 Delayed wire-rope bracing using middle plate

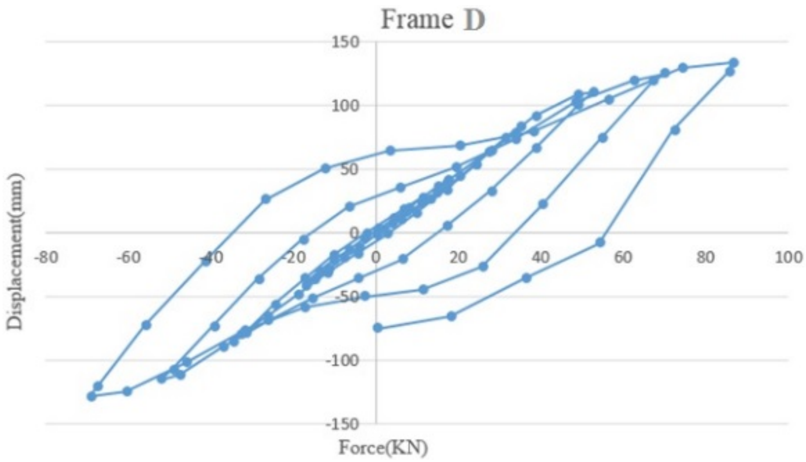
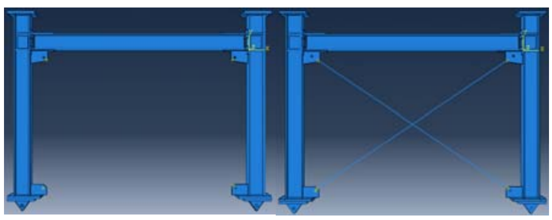


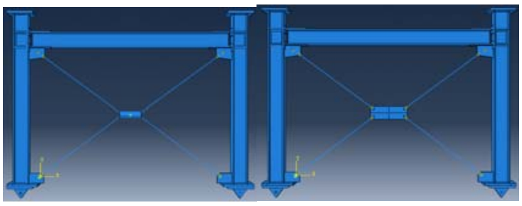
Fig. 6 Hysteresis curve based on model *D*

E. Comparing the Performance of Different Bracing Systems

In this section, the objective is to place horizontal rectangular steel plate at the meeting point of the bracing cables and study the performance of four different types including ductile moment frame system, cross cable bracing system, delayed wire-rope cable bracing with pipe and delayed wire-rope cable bracing with plate. In this paper the aforementioned frames are named as A, B, C and D, respectively. Fig. 6 shows a view of these models. It is worth mentioning that in these models, all the modeling assumptions (frame geometry, mechanical specifications of the materials, conditions of supports, and range of loading) have been considered as the same.



(a) (b)



(c) (d)

Fig. 7 Models made in the software environment (a) Ductile moment frame (b) Moment frame with cross cable bracing (c) Delayed wire-rope cable with pipe (d) Delayed wire-rope cable with plate

Table V shows the results of the separate analyses of these models. The cross cable bracing (model *B*) imposes a large initial stiffness on the moment frame because the tensile cables start functioning at the early stages of the loading and resist the frame's lateral displacement. As shown in Table VI, the cross cable bracing increases the ultimate force ratio to 1.34, and decreases the ratios of the ultimate displacement and energy absorption by 0.6 and 0.433 times respectively to the corresponding values for ductile moment frame. Under these conditions, the frame ductility and its energy absorption capacity are reduced.

Placing the steel plate at the cables' meeting point reduces the frame stiffness compared to the cross cable bracing because the plate can rotate round the axis perpendicular to the frame plane due to its rotational degree of freedom and causes delay in the cables' functioning; gradients of the skeleton curves of frames *A, B, C,* and *D* in Fig. 7 confirm these issues. The cross cable bracing with steel plate has a displacement almost equal to that of model *A* frame. Furthermore, using steel plate increases the ratios of the frame's tolerability of the lateral forces and the energy absorption capacity by 1.55 and 1.72 times respectively; therefore, it can be concluded that the proposed bracing system has a better performance compared with respect to cross bracing ones which are very common in today's designs and constructions. Hence, we can introduce model *D* as the most appropriate among those investigated.

TABLE V
DATA OBTAINED FROM THE ANALYSES

Frame model	Ultimate force (*KN*)	Ultimate displacement (*mm*)	Energy absorption (*J*)
A	86.36	87	12507
B	115.58	52	5418
C	118.03	86	17724
D	133.20	86	21511

TABLE VI
RATIOS OF FORCE, ULTIMATE DISPLACEMENT AND ENERGY ABSORPTION FOR FRAMES *B, C* AND *D* TO THE CORRESPONDING VALUES FOR FRAME *A*

Model	Force ratio	Displacement ratio	Energy absorption ratio
B	1.34	0.6	0.433
C	1.36	0.98	1.417
D	1.55	0.98	1.720

For model *D*, cable strain diagram can show the delayed activate for cables. As shown in Fig. 8, the upper cables strain is almost zero in early times of load cycle. Right and left upper cables experience their first peak strain at time 0.5 and 0.7 respectively. Counterclockwise rotation of the middle plate at the beginning of loading is because of strain values appear earlier in the right upper cable. Based on data reported in Table III, it is seen that while δs is equal to 30 mm, time is approximately reached to 0.5; that means the first bracing member has entered to reaction stage at the time which has been expected from analytical design.

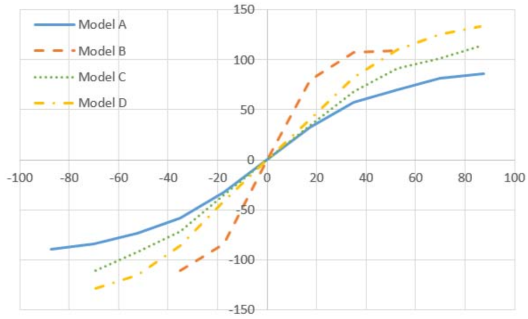


Fig. 8 Skeleton curves for frames *A, B, C,* and *D*

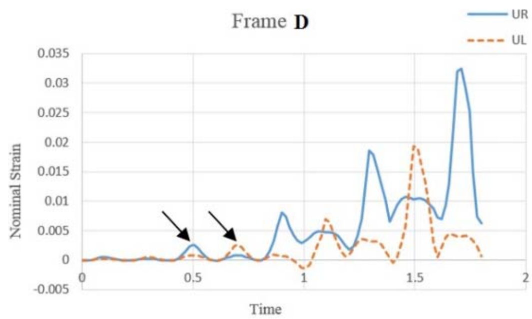


Fig. 9 Strain diagram for the upper cables in model *D*

Adding bracing system to frames will increase the column axial force, in which verification of column strength is needed for preventing the columns from failure, such as buckling, which may be caused by bracing action. But the proposed bracing system (model *D*) restrains the lateral storey displacement within a specified range; Furthermore in columns, it reduces the compression force increase resulting from brace attachment in comparison with cross cable bracing (model *B*). Fig. 9 shows a view of left columns axial force diagrams in the studied models.

One of the concerns regarding bracing system is buckling bracing members. In models presented in this research, the problem of buckling is solved by using cables because the latter are tensile elements that do not work against compression and bending, and placing a steel plate at their junction causes them to be always under tension so that their maximum potential can be used against tensile forces; Fig. 10 shows the performance mechanism of the plate and cables rotation. As shown, when the applied load moves the frame to the right, the cables along direction 1 (35^0 angle) start functioning as the main bracing members, and those along direction 2 (145^0 angle) go under tension due to the middle plate's clockwise rotation; therefore, the cables are always under tension.

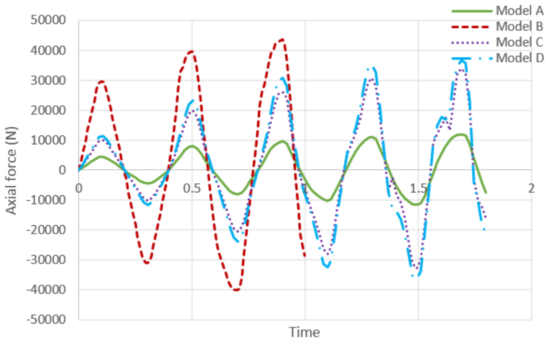


Fig. 10 Axial force to the left columns

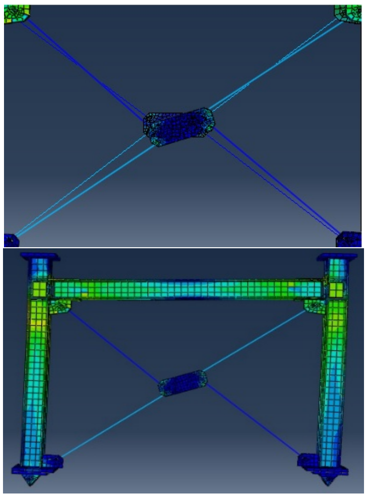


Fig. 11 Performance of the braced moment frame under lateral loading

III. Conclusions

This paper has described a seismic retrofit method for moment resisting frames. The method adopts wire ropes as the bracing member to eliminate buckling. The idea of using steel plate at the meeting point of the bracing cables has been proposed to enhance the performance of moment frames braced with cross cables because the latter alone does not have a desirable seismic performance. Although this type of bracing reduces the frame's lateral displacement, it also reduces the ductility and energy dissipation capacity of the frame due to the high increase in the stiffness which causes more rigidity of the structure. The use of middle plate causes the delay in the activation bracing members; by delaying the brace action, the lateral story strength can be increased without reducing energy dissipation capacity. Results show that using middle the steel plate increases the ratios of the frame's lateral tolerability and energy absorption capacity respectively by 1.55 and 1.72 times greater compared to ductile moment frame. This system could also improve the energy absorption capacity about 20% compared to the delayed wire-rope bracing with pipe. But cross cable bracing system decreases the ratio of energy absorption capacity by 0.433 times compared to the value for ductile moment frame.

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