

# Strength and Ductility of Stiffened Steel Box Columns of Various Cross-Sectional Configurations under Lateral Cyclic Loadings

T. Thevega, K. Rajavijayan, J.A.S.C. Jayasinghe and K.A.S. Susantha

**Abstract:** Stiffened steel columns are widely used in bridge piers due to their structural and constructional efficiency. The bridge pier is one of the main structural components in elevated highway transportation. The ability of structures to survive severe earthquakes depends on both strength and ductility. In this study, the stiffeners with different cross-sectional configurations are introduced to improve the strength, ductility and energy absorption capacity of thin-walled steel box columns. All cross-sections are designed with the same cross-sectional area and height for different stiffener arrangements. The columns are analysed by finite element method, incorporating both material and geometric nonlinearities under constant axial load and lateral cyclic loading. Using the lateral load-lateral displacement behaviour, the cross-section with two middle stiffeners shows high strength and ductility capacity. But examining energy absorption behaviour, the cross-section with corner stiffener shows high capacity among analysed columns. Therefore, by considering strength, ductility and energy absorption capacity, the best cross-section is identified as the cross-section with two middle stiffener arrangement with a particular cross-sectional area compared with other cross-sections. In addition to that, local buckling patterns of the columns are examined at different displacement levels to understand the failure modes.

**Keywords:** Bridge pier, Cyclic loading, Strength, Ductility, Nonlinear finite element analysis, Stiffened steel column, Steel material model

## 1. Introduction

Steel bridge piers, with either circular, square or rectangular cross-sections, are widely used as part of the lateral and vertical force-resisting systems in buildings, offshore platforms, elevated storage tanks and transmission towers, or as cantilever piers in bridges and wind turbines [1]. Steel columns may be superior to the counterparts of reinforced concrete due to the stiffness, lightweight and ductility, especially when limited construction space is preferable [2].

The most common failure mode of steel columns of highway bridge piers is lateral deformation due to local buckling of steel plates when subjected to lateral cyclic loading. Local buckling and global buckling are the main reasons for the reduction in strength and ductility in columns, which causes failure under lateral cyclic loadings.

There are several methods to delay the buckling of steel plates [3]. Commonly used methods are concrete infilling or introducing stiffeners [4], [5], [6], [7]. In the past, many studies have shown that the performance of concrete-filled hollow box sections are not good because local buckling is most likely to occur in box tubes [8]. Although

concrete infilling delays local buckling of steel plates, to make it more effective, longitudinal stiffeners can be welded inside or outside the steel plate [9]. Introducing only the stiffeners could also be used to delay the local buckling of steel bridge piers. Diaphragms can also be placed horizontally along the column to delay local buckling.

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Several experimental studies have been carried out to analyse the behaviour of the column on seismic performance [10], [11]. Those tests were found to be very costly and results were not adequate to make a firm conclusion. Therefore, the analytical procedure is important in this type of investigation.

The aim of this study is to propose an optimum cross-sectional configuration that gives high strength, ductility and energy dissipation capacity of steel bridge piers. For this purpose, stiffened steel columns having different cross-sectional configurations are analysed. The analyses are carried out using a finite element model which considers the effects of both material and geometric nonlinearities. The reliability of prediction of this type of investigation highly depends on the details of the finite element model such as material models, element types and mesh, boundary conditions, solution technique, etc.

When steel material models are considered, yielding criteria and hardening models play a great role. In this study, commonly used three models, namely isotropic, kinematic and combined hardening, are used in the analyses. Analyses are carried out using a finite element program called *ABAQUS*.

## 2. Finite Element Analysis of Steel Column

There are several analytical methods that have been developed to employ nonlinear simulation. The empirical model, plastic hinge model and elasto-plastic finite element model are some of the recognized methods [12]. The finite element methods which account for both geometric and material nonlinearities are comparatively more accurate and the accuracy greatly depends on the ability of the material model to simulate real material behaviour.

In this study, a finite element model is developed in *ABAQUS* for a previously tested stiffened steel box column [13]. The analysis is carried out simulating the same loading pattern of the test with three different material models. The comparisons are made between the test and the predicted results. The material model that gives the best prediction is selected for the subsequent analyses of the different cross-sectional configurations.

### 2.1 Details of the Steel Column

Different cross-sectional configurations are proposed by changing the stiffener arrangement inside the column, as shown in Figure 1. The

selected test specimen has eight stiffeners similar to the cross-section type 4. Cross-sectional details of the specimens are shown in Table 1.

The cross-sectional area is kept constant ( $A_s=12800 \text{ mm}^2$ ) and the height of the columns is 2420 mm. The main plates, stiffeners and diaphragms are of SM490 steel type (Japanese Industrial Standard). Three horizontal diaphragms are provided in an interval of 450mm from the base of the column. All the component plates (i.e., main plates, longitudinal stiffeners and diaphragms) have welded connections.

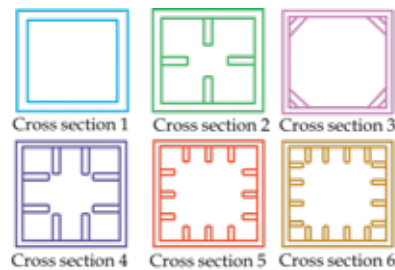


Figure 1 - Different Types of Cross-Section

Table 1 - Cross-Sectional Details of Columns

	$A/\text{mm}^2$					
	12800					
$B, D/\text{mm}$	450	450	450	450	450	450
$t/\text{mm}$	7.2	5.8	5.8	5.8	5.8	5.8
$b_f/\text{mm}$	0	53	83.7	53	36	35
$t_f/\text{mm}$	0	11.7	7.5	5.8	5.8	4.4

### 2.2 Finite Element Model

The steel columns are modeled using a 4-node shell element (S4R) available in *ABAQUS* program. One of the most important aspects that affects accuracy in numerical methods is mesh sensitivity. Usually, when mesh density increases, the quantity of interest starts to converge to a particular value. However, there is a point where a further increase of the number of elements would not yield any benefit in terms of accuracy.

The optimum element mesh is identified after carrying out a series of analyses. Accordingly, very finer mesh is employed near the base where high stresses and local buckling are expected to occur while the upper part is modelled with a coarser mesh to increase the computational efficiency, as shown in Figure 2. The transition from finer to coarser mesh is carried out using the same type of shell element while ensuring the nodal and edge compatibilities.

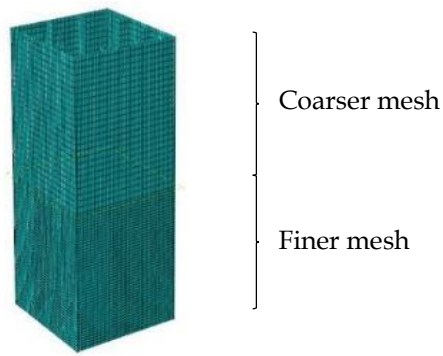


Figure 2 - Finite Element Mesh

### 2.3 Material Model

Modern design specification allows steel structures to deform up to a certain displacement level in the inelastic range, which involves both material and geometrical non-linearity. In a non-linear analysis, the accuracy of the model has a large effect on the reliability of predictions. Yield function, flow rule and hardening are important factors in material non-linearity. There are some yield criterions to define yield surface where material undergoes yielding such as Von Mises, Tresca, Mohr-Coulomb etc. Von Mises yield criterion, which is commonly used in steel material modelling, is used in this study.

The flow rule defines the plastic straining. After yielding, there is a permanent deformation in the material that is plastic deformation. Hardening is defined as the change of yield surface as material yields. There are three different hardening rules that are commonly used [14], namely Isotropic Hardening (IH), Kinematic Hardening (KH) and Combined Hardening (CH).

Bauschinger effect is neglected in the IH model and in the KH model, constant. The isotropic hardening rule states that the yield surface expands proportionally in all directions when yield stress is exceeded. Stress induces an anisotropic effect. That is known as the Bauschinger effect. Kinematic hardening involves a translation of the yield surface. The combined hardening rule states that the yield surface expands and translates in the direction of the stress rising.

In this study, all three types of hardening rules are incorporated together with the elasto-plastic bilinear stress-strain model shown in Figure 3 [15]. Bilinear idealization is made from the tri-linear model by connecting the yield point with the point at 5% strain. The material parameters

corresponding to the tri-linear idealization of SM490 steel is given in Table 2.

Table 2 - Material Properties

Steel type SM490	
Parameter	Value
Yield stress ( $\sigma_y$ )	412 MPa
Young modulus ( $E_s$ )	206000 MPa
Poisson ratio ( $\nu$ )	0.276
$E_{st}/E_y$	7
$E_{st}/E_s$	1/30

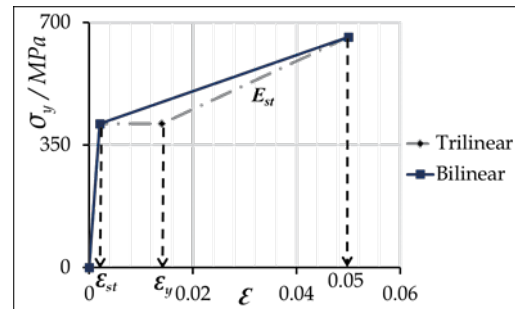


Figure 3 - Steel Material Model (Susantha et al., 2001)

### 2.4 Loading

The loading pattern as adopted in the test arrangement is used in all the analyses [13]. First, the axial load  $P$  is applied as  $0.2P_y$  ( $P_y = A_s \sigma_y$ , where  $A_s$  is the cross-sectional area) at the column top. Then the lateral cyclic displacement is incrementally applied at the column top for all the columns with different cross-sectional configurations, as illustrated in Figure 4.

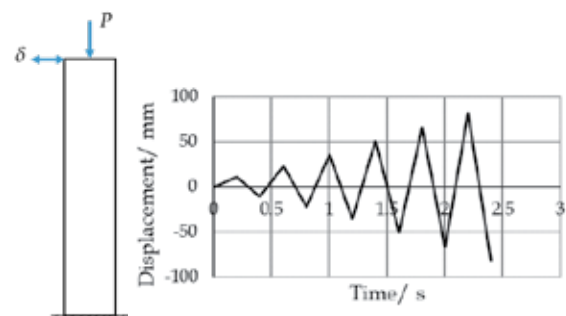


Figure 4 - Loading Arrangement

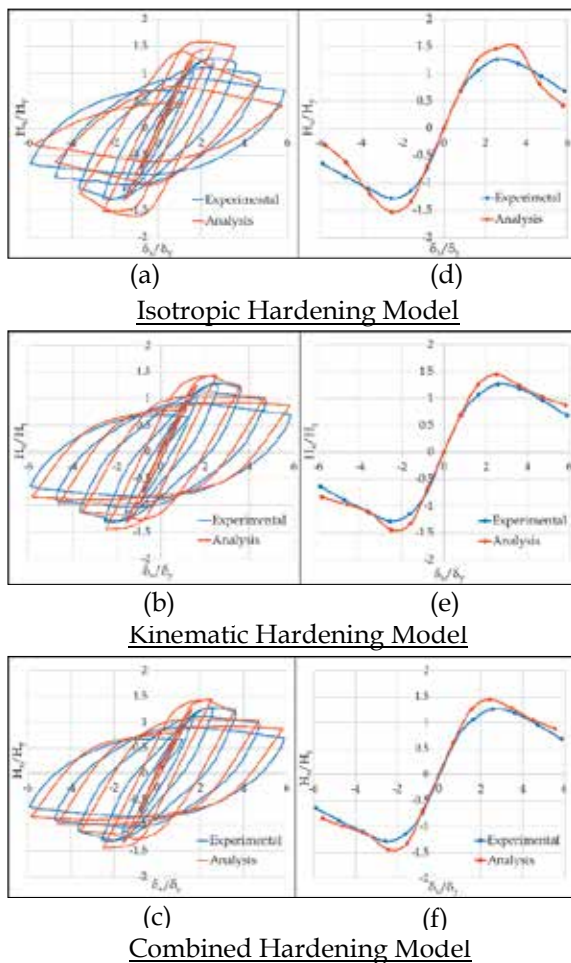
## 3. Results

### 3.1 Validation of the Model

The lateral load-lateral displacement hysteretic curves (normalized by  $H_y$  and  $\delta_y$ ) for all the models are obtained from the analyses. Comparisons (hysteretic curves and envelope curves) of the experimental and predicted relations using IH, KH, and CH material models are shown in Figure 5.



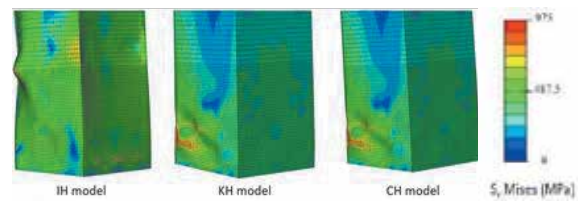
It is visible that the CH model gives comparatively better comparison with experimental results. The high discrepancy of maximum load observed with the IH model is attributed to the isotropic expansion of the yield surface. In the case of comparisons with KH and CH models, the initial stiffness and loading/unloading stiffness are found to be reasonably acceptable. The difference between experimental and analysis for the CH model is smaller than the KH model. In this study, the CH model is identified as the most suitable material model to be used in the rest of the finite element analyses.



**Figure 5 - Lateral Load-Lateral Displacement Relations: Experimental vs Prediction using: (a), (b) and (c) Hysteresis Curves (d), (e) and (f) Envelope Curves**

The deformed shapes obtained at lateral displacement level of 65.6 mm using three material models are shown in Figure 6. It is observed that the magnitude and shape of buckling are different for different material models. Generally, buckling occurs near the base of the column. However, for the IH model, when the lateral displacement is increased it moves up

from the base, possibly due to strain hardening around the base [16].



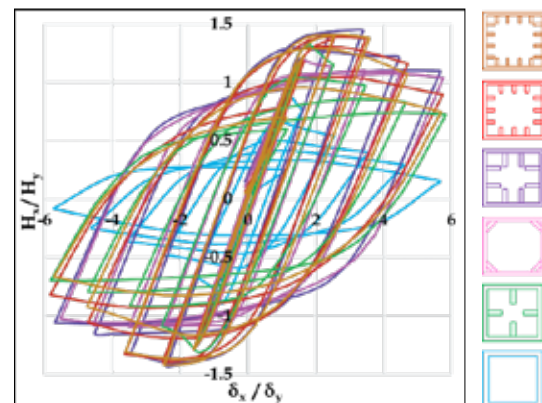
**Figure 6 - Deformed Shapes of the Column**

### 3.2 Strength and Ductility Evaluation of Different Cross-Sectional Configurations

Lateral load-lateral displacement hysteresis curves and envelope curves for different cross-sectional configurations using Combined Hardening (CH) model are shown in Figures 7 and 8, respectively. As seen in these figures, the initial stiffness (load-displacement behaviour) is similar for all the cross-sectional configurations.

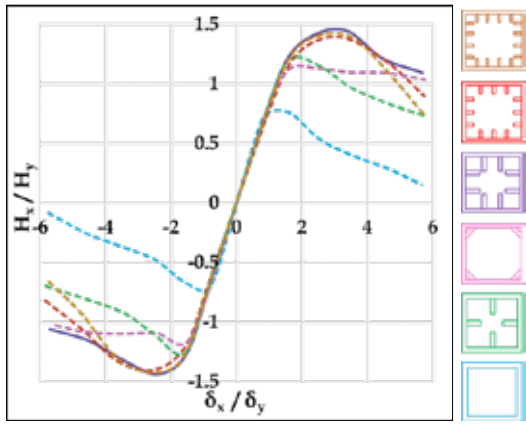
The cross-section 1 experiences faster strength degradation after initiation of local buckling because there are no stiffeners to prevent the buckling. It is clearly observed from the comparison of envelope curves that the stiffness and strength can be improved and the occurrence of local buckling could be delayed by changing the stiffener arrangement, as shown in Figure 8.

The load-carrying capacity of the cross-section 3 decreases smoothly after buckling due to corner strengthening plates even though it could not bear a large lateral load than cross-sections 4, 5 and 6. However, after undergoing a large lateral displacement of around  $4.5 \delta_y$ , it shows better performance than the cross-sections 5 and 6. Among all different cross-sections, the cross-section 4 shows better performance under lateral cyclic loading.



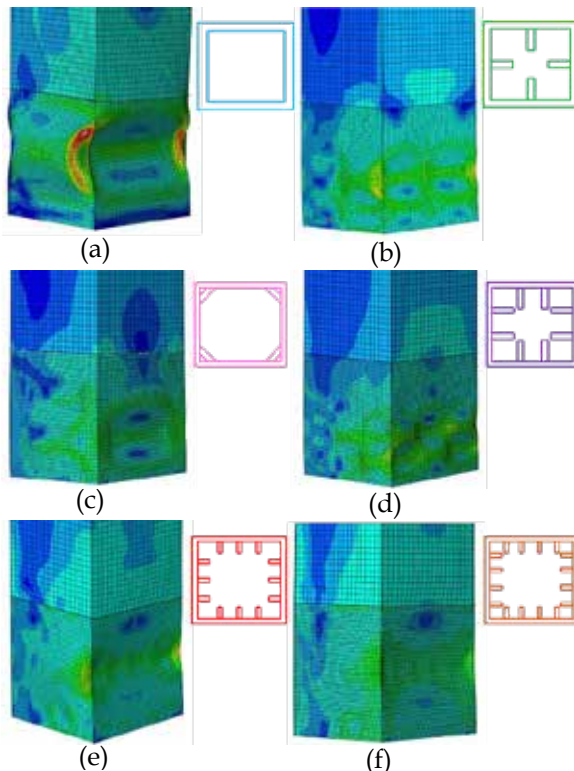
**Figure 7 - Lateral Load-Lateral Displacement Relations (Hysteresis Curves) for Different Cross-Sectional Configurations**





**Figure 8 - Lateral Load-Lateral Displacement Relations (Envelope Curves) for Different Cross-Sectional Configurations**

The deformed shapes are obtained at maximum lateral displacement level ( $\delta = 81.48$  mm) for different cross-sectional configurations in the CH model (see Figure 9). Figure 9(a) shows significant deformation near the base of the unstiffened section. Ductility is the ability of a structure to resist large deformations. The ductility of the column is improved by increasing longitudinal resistance with longitudinal stiffeners. The columns, which have stiffeners in the middle of the plates, show different local buckling patterns. There seems to be a correlation between local buckling patterns and the performance which needs to be studied in a future comprehensive study.



**Figure 9 - Deformed Shape of Different Cross-Sectional Configurations**

### 3.3 Energy Absorption Capacity

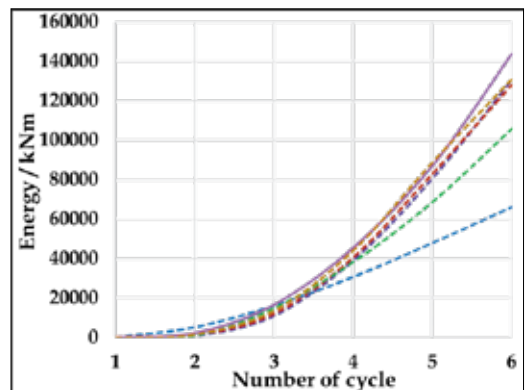
The dissipated energy is a measure of the cyclic behaviour of the structures. A normalized energy absorption ( $E$ ) is defined in Eq. (1) [17].

$$E = \frac{2}{H_y \delta_y} \sum_{n=1}^n E_i \quad \dots(1)$$

In Eq. (1),  $E_i$  = energy absorption in the  $i^{th}$  half-cycle,  $n$  = number of half-cycles (one-half cycle is defined from any zero-lateral load to the subsequent zero-lateral load). The dissipated energy can also be calculated by the summation of the area of full cycles under lateral load-lateral displacement curves. The strength of the column decreases at a controlled rate from cycle to cycle, which is expected to dissipate larger energy under cyclic lateral loading. If the dissipated energy is larger, it is expected to experience higher ductility [18].

Ductility is always a big concern for structures in regions of high seismicity. It seems that more attention should be directed to the problem of poor ductility of the thin-walled steel columns. The energy absorption capacity of the column for different cross-sectional configurations is evaluated under lateral cyclic loadings.

Figure 10 shows the comparison of the variation of cumulative energy absorption with the number of lateral cycles obtained. The dissipated energy is higher for cross-section 6 than cross-sections 1 and 2. However, it is lower than cross-section 3. Further, cross-sections 4, 5 and 6 dissipate nearly same amount of energy. Even though the strength of the column with cross-section 3 is lower than the cross-sections 5 and 6 (see Figure 8), ductility and energy absorption of the column with cross-section 3 is higher than those of cross-sections 5 and 6 (see Figure 10).



**Figure 10 - Energy Absorption Capacity of different Cross-Sectional Configurations**



### 3.4 Effect of Different Lateral Cyclic Loadings with Different Cross-Sectional Configurations

The analyses are carried out for four types of lateral cyclic loading patterns from past literature [1], [2], [11] as illustrated in Figure 11, to investigate the effect of lateral loading patterns on the column behavior. However, lateral displacements are given according to the experimental displacements. Since the actual loading patterns under real earthquake loads are complex, investigation of behavior under different loading patterns is very important.

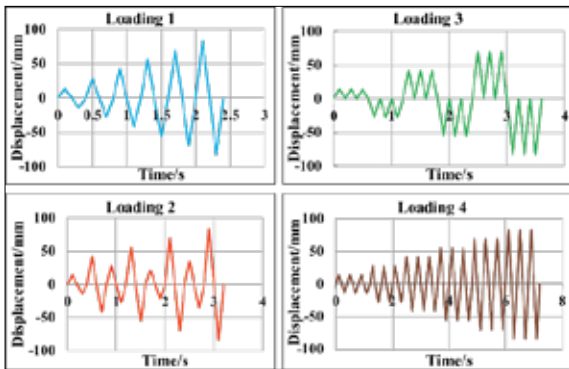
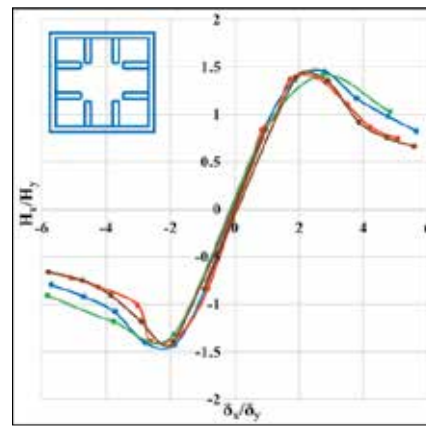


Figure 11 - Different Types of Lateral Cyclic Loadings

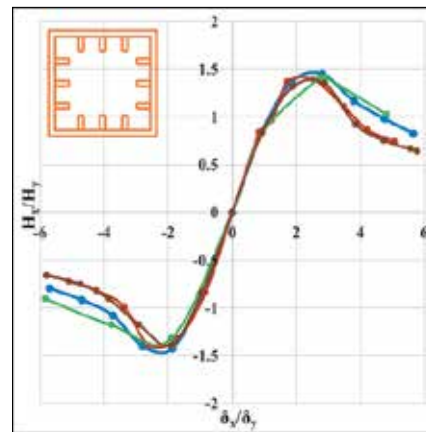
The effects of loading patterns under different cross-sectional configurations are studied. The envelope curves of the corresponding hysteretic curves are shown in Figure 12 for different cross-sections. There is no significant effect on the maximum lateral load for a particular cross-section, but the slope of post-peak curves differs when different loading patterns are used. This is a very important observation because lateral displacements of the column should be predicted using a loading pattern that suits best the actual displacement patterns of the column subjected to a particular earthquake.

### 3.5 Optimum Stiffener Arrangement

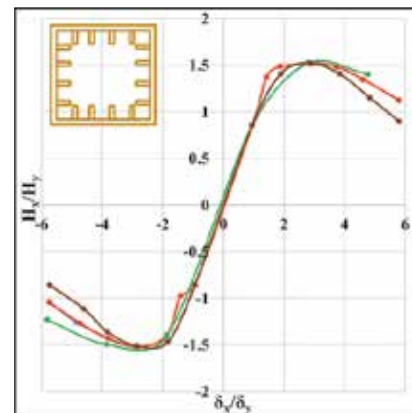
It is clearly visible that the strength, ductility and energy absorption capacity increase with the number of stiffeners but, after a particular number, the performance gradually diminished because when the number of stiffeners increased while keeping steel cross-sectional area constant, the size of the stiffeners becomes significantly small. To check this, an additional cross-sectional configuration (five stiffeners per side) is selected, as shown in Figure 13.



(a)



(b)



(c)

Figure 12 - Lateral Load-Lateral Displacement Relations (Envelope Curves) for different Cross-Sectional Configurations with different Lateral Cyclic Loadings

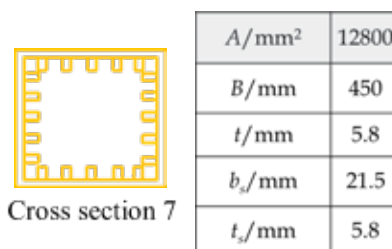
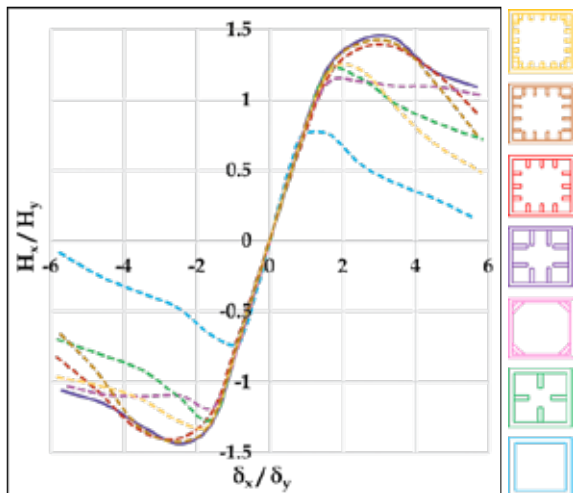


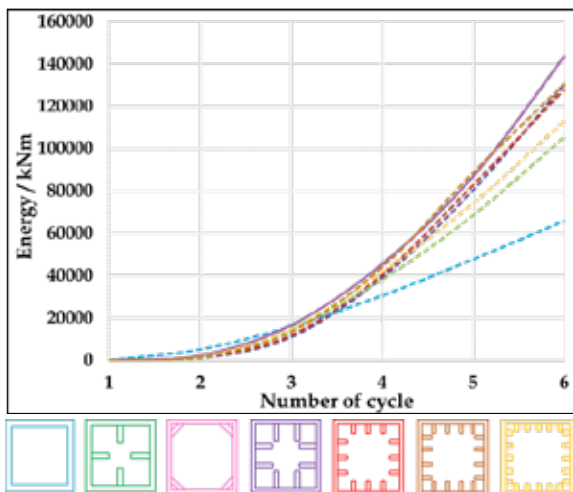
Figure 13 - The Cross-Sectional Details of the Additional Column

When increasing the number of stiffeners from four to five, the strength decreases by 12% (see Figure 14) and energy absorption capacity reduces by 15% (see Figure 15). Up to four stiffener arrangement, buckling occurs at the later part of cycles but for five stiffener arrangement, buckling occurs at the early stage of cycles.

Even though the thickness of the outer plate and thickness of stiffeners are same for the cross-sections 4 and 5, when the length of the stiffeners are reduced by 32% (changing the number of stiffeners with the same cross-sectional area), the strength is reduced by 3% and also energy absorption capacity is reduced by 3%. Based on the performance in terms of strength, ductility and energy absorption ability, the cross-section with two stiffeners per side is identified as the optimum stiffener arrangement out of all the configurations considered in this study.



**Figure 14 -Lateral Load-Lateral Displacement Relations (Envelope Curves) of Optimum Stiffener Arrangement**



**Figure 15 - Energy Absorption Capacity of Optimum Stiffener Arrangement**

## 4. Conclusions

In this study, numerical analysis has been carried out to evaluate the cyclic behaviour of the steel column using finite element analysis. First, the effects of material models on hysteretic response are investigated using three material models. Then, different cross-sectional configurations are introduced with the same cross-sectional area to improve the strength, ductility and buckling behaviour of the column under constant axial and lateral cyclic loading. The followings are the main conclusions of this study;

- The proposed finite element analysis procedure can be used to determine the strength, ductility and energy absorption capacity of a steel column.
- Among the three hardening models, Combined Hardening (CH) model gives better prediction, which is suitable for proposed finite element analyses.
- The cyclic behavior of the steel column is improved with stiffeners. The cross-section 1 does not have stiffeners on the plates to delay the local buckling and to improve the strength of the column.
- Under different lateral cyclic loadings, the performance of the column is dependent on the cross-section.
- The cross-section 3 has only corner plates that helped to increase the ductility significantly compared to other cross-sections. However, the strength increase is not significant in cross-section 3. Therefore, an attempt should be made to check a cross-section with both corner plates and one or several stiffeners per side.
- The cross-section 4 with two middle stiffeners shows better strength and ductility performance in comparison with other cross-sections.
- It is important to have corner stiffeners in the columns to have stable post-peak load-displacement behavior as evident from the lateral load-lateral displacement curves (hysteresis curves and envelope curves) corresponding to the cross-section 3.
- It is important to have stiffeners on the middle of the plates to resist maximum lateral load, that is proved by the lateral load-lateral displacement curves (hysteresis curves and envelope curves) corresponding to cross-sections 4, 5 and 6.



- In stiffened steel columns, strength and ductility increase with the number of stiffeners. However, there is a limitation on the number of stiffeners.
- This method can be used in the bridge construction industry to find the optimum cross-section for a given cross-sectional area by considering lateral performance.

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