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ANALYSIS OF COMPOSITE CONCRETE STEEL COLUMN USING NEW STEEL SECTION

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ANALYSIS OF COMPOSITE CONCRETE STEEL COLUMN USING NEW STEEL SECTION

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Acknowledgments

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1. Abstract

Conventional concrete encased steel composite columns are typically constructed by embedded “W” steel section or other sections identified in the American Institute of Steel Construction “AISC”, positioned in the center of the concrete column cross section or around it. The importance of composite elements is found in their common use in big facilities and construction projects where the need more elements with high compressive capacity and less cost arise. In this research, a new shape of structural steel is proposed which is applicable to columns and can be developed to beams. The model is basically concrete column with steel reinforcement and the proposed steel section embedded, four angles were welded together to form the shape “X”. The equivalent compressive strength capacity of this “X” shape will be equivalent to the compressive strength capacity of conventional steel “W” section having similar dimensions of depth and width. Cost reduction and strength enlargement are the main goals of this paper, proposing a new “X” shape was never done before. It has less steel weight, better buckling and compressive strength than conventional “W” steel section.

Comparative study was done based on results from analyzing three columns, 6 ft long: one conventional “W” section (W4x13), one with two angles (2L 3.5x3x5/15), and one with four angles (4L 2x2x1/4). Finite element analysis was done using ABAQUS software and theoretical analysis using AISC and Eurocode. In addition to a cost analysis on various steel. Cost was calculated based on the column weight, length, and price per pound/foot

It was concluded that the proposed “X” shape steel section is cost efficient and has comparable compressive strength values to the conventional “W” section.

2. Introduction

The need for low-cost construction elements has increased in recent years given the vast developments of quick and intelligent construction processes. Nowadays, composite concrete elements are used more frequently, especially in high-rise buildings (Samarakkody, Thambiratanam, Chan, & Moragaspitiya, 2017). The need ~~of~~ for high strength columns capacity increased, and in order to fulfill such capacity, the column should have a big concrete section, which will reduce the available living space in the building. Bigger sections are more costly and less spacious floor areas are undesirable. Using composite concrete elements replaces the regular reinforced concrete column and reduces the cross-sectional area, hence, sustaining acceptable floor areas, smaller cross-sectional area and higher strength capacity (Park, et al., 2013), (Yarnold & Stoddard, 2020).

The steel-concrete composite column refers to the concrete encased hot-rolled steel section ("I" or "W" sections), or a concrete filled tubular section of hot rolled steel. The most common section is the "W" section, which has been described as the "undisputed star of the steelwork" (Landolfo, Formisano, & Lorenzo, 2017). All steel sections used in construction are summarized in the American Institute of Steel Construction shown in Figure 1 below (AISC, 2016).

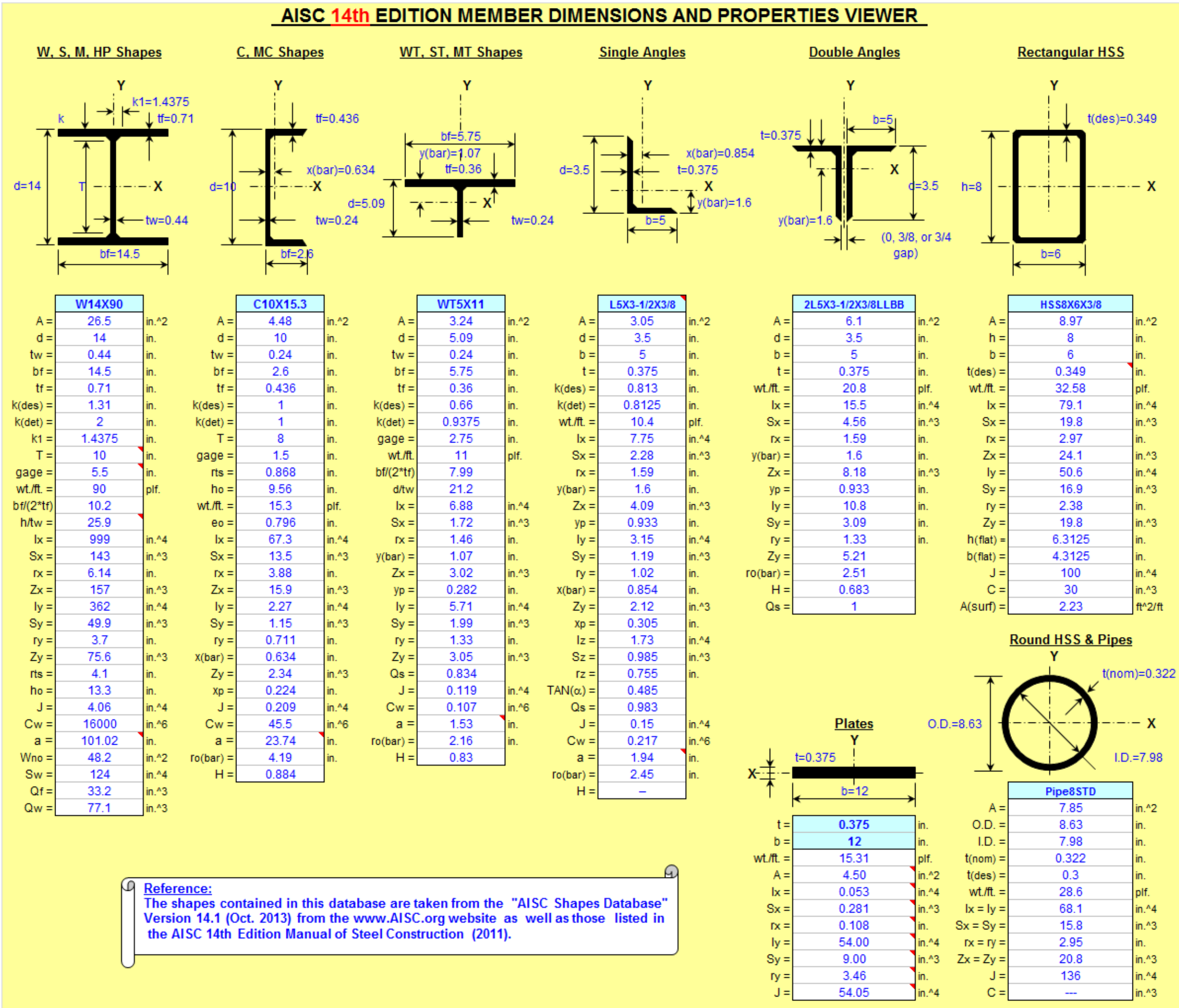

Figure 1 Steel Structural Shapes (AISC, 2016)

In this thesis, cost reduction and strength enlargement were investigated using a newly proposed "X" shape steel section, which has less weight and larger compressive strength than the conventional "W" steel section. The idea of proposing the shape "X" as a steel section came from its geometry. "X" shape has symmetrical dimensions which helps in strength calculations and eliminates having strong and weak axes (X, Y). This paper aims to compare the symmetrical "X" shape with the asymmetrical conventional "W" steel section. As per AISC conventions, compressive strength calculations in columns should be done on a major (strong) x-axis and minor (weak) y-axis to prevent a potential failure due to the weak axis geometric properties. Since an “X” steel section was never proposed before, four angles were used to represent the shape “X”. The weight of steel angles combined as “X” is smaller compared to the “W” section with the same depth and width, which costs less because the price of steel sections is based on its weight.

Many researchers studied the steel sections in ~~the~~ AISC with various concrete strengths and cross sections focusing on compressive and flexural strength along with shear resistance (Bridge & O'Shea, 1998), (Elchalakani & Zhao, 2008), (Goode, Kuranovas, & Kvedaras, 2010), (Campione, 2013) and (Hwang, 2018). In studies mentioned previously, stress-strain and force-moment diagram ~~is~~ was drawn to compare theoretical and experimental results to find similarities and consistency. Furthermore, theoretical analysis for steel sections ~~is~~ was conducted based on two main codes: Eurocode 4 and AISC. (AISC, 2016), (Eurocode4, 2004).

Eurocode 4 provides more accuracy with experimental results than conservative AISC results based on Ellobody & Young (2011), and Ellobody, Young, & Lam (2011). Finite elements analysis was strongly used in many papers to simulate the behavior of structural elements and compare with theoretical or experimental data (Lelkes & Gramblička, 2013), (Park, et al., 2013).

In this thesis, cost reduction and strength enlargement were investigated using a newly proposed “X” shape steel section, which has less weight and larger compressive strength than the conventional “W” steel section. Theoretical analysis using AISC and Eurocode 4, and software simulation using ABAQUS were conducted to verify if the proposed section can present an economical alternative to the conventional “W” steel sections.

The next chapters are organized as follows: Chapter 5 presents a literature review for papers in similar fields. Chapter 6 depicts the methods used to analyze the effectiveness of the proposed X section, and is divided into: theoretical analysis, software analysis, and cost analysis. Chapters 7 and 8 include the conclusion and references. Chapter 9 summarizes tables, figures, universal codes and software steps.

3. Literature Review

In this literature many papers studied the use of steel sections from AISC and calculated the compressive strength of steel sections if used alone or combined with concrete as composite concrete-steel element.

3.a Using Steel Angles.

the use of steel angles in composite steel-concrete columns was studied by Hwang (2018), to increase the performance of compression resistance. “W” steel section was replaced by using four steel angles; to resist axial load and flexural strength. Steel angles are placed internally at the corners of the cross section with concrete cover; to resist the local buckling and fire. Steel angles depend mainly on transverse plates which they are connected by welding or bolting. Transverse plates resist shear and confine the concrete. Prefabricated Steel Reinforced Concrete Column “PSRC” which is the proposed steel angle reinforced column in the paper showed better results than the conventional concrete encased steel composite column (CES), due to higher axial load carrying capacity, and bond strength between angles and concrete.

Figure 2 below shows a comparison between Concrete Encased Steel Column (CES) and PSRC (Prefabricated Steel Reinforced Concrete Column). Figure 2. a. shows the conventional CES where “W” steel column placed and the center of the cross section with longitudinal bars and tie bars placed at the corners. Figure 2.b. and c show the PSRC containing four steel angles placed vertically at the corners, confined by steel plates or bars horizontally and they are bolted or welded with the steel angles.

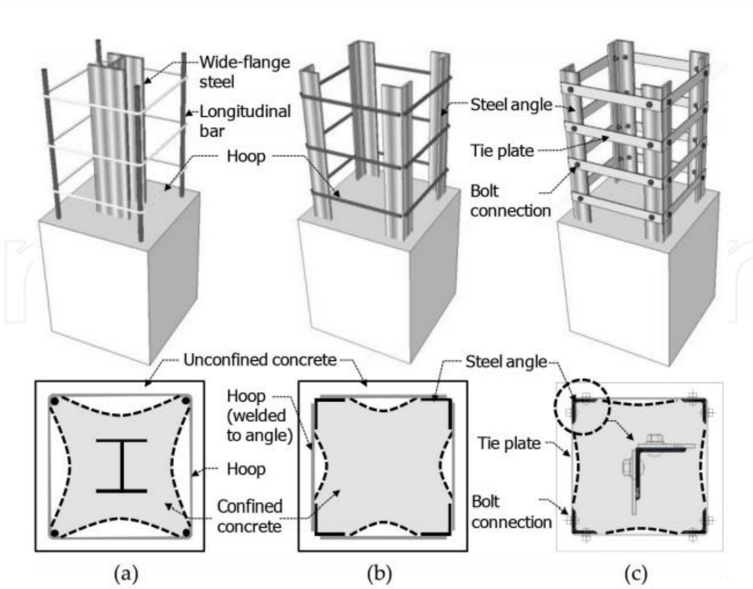

Figure 2 Comparison of CES column and PSRC columns. (a) CES composite column, (b) PSRC composite column (weld connection), (c) PSRC composite column (bolt connection). Hwang (2018)

Figure 3 below shows stress-strain relationship drawn using numerical analysis, where confined concrete achieved higher compressive strength than unconfined concrete. This indicates the reason behind using steel angles to confine the concrete instead of conventional concrete steel composite column where the steel section is confined by concrete not steel.

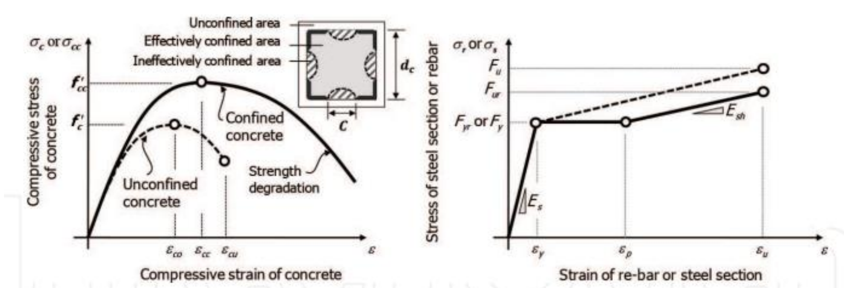

Figure 3 Stress-strain relationship of concrete and steel for numerical analysis (Hwang (2018))

Figure 5 below shows Force-Moments (P-M) interaction diagram, where the solid line is for the PSRC, and dashed line is for the conventional concrete steel composite column. Results proved that the assumption of using steel angles to confine the concrete will achieve higher compressive and moment strength than the conventional concrete steel column.

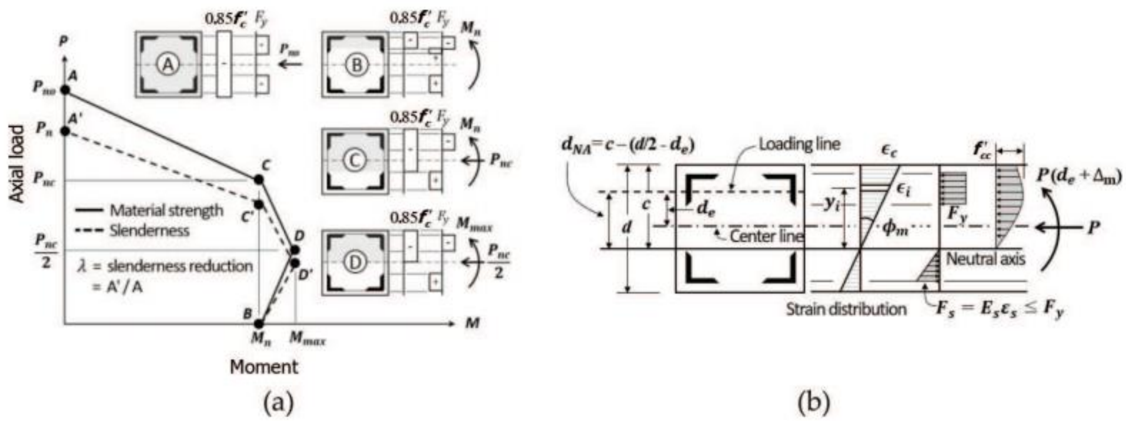

Figure 4 Section analysis methods of PSRC column under eccentric axial loading: (a) P-M interaction diagram and (b) strain-compatibility method. Hwang (2018)

Same column PSRC (Prefabricated Steel Reinforced Column) was studied by Eom, et al. (2014), steel angles were welded with tie bars to achieve shear transfer between steel angles, bond between steel angles and concrete, buckling resistance and lateral confinement (Figure 5). Both tie bars and plates provide the bond to the steel angles and concrete, while steel angles provide resistance for axial load and flexural moment. In addition, concrete cover helps in local buckling and fire resistance (2014).

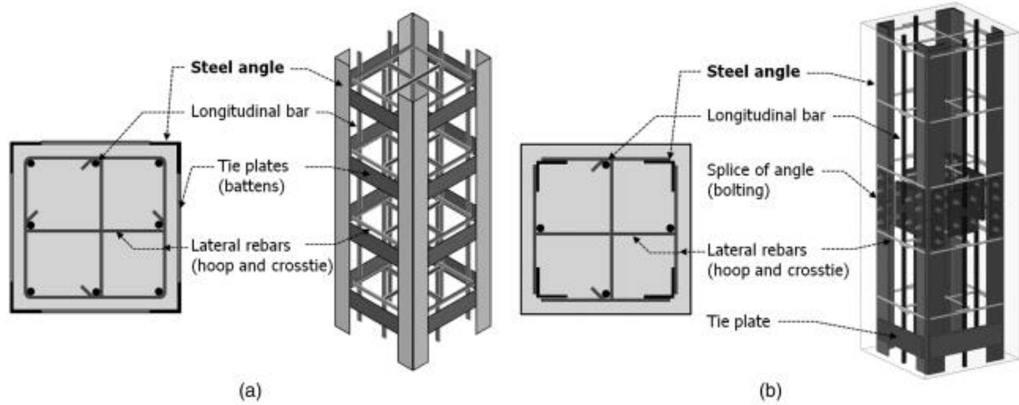

Figure 5 Composite columns using prefabricated steel angles: (a) existing method of retrofitting [data from Poon (1999), Montuori and Piluso (2009), and (Hwang, 2018)ione (2010)]; (b) proposed PSRC composite column (Eom et al. (2014))

The bond strength for the two Prefabricated Steel Reinforced Concrete column “PSRC” from Hwang (2018) and Eom, et al. (2014), between steel angles and concrete is generated by the bearing strength of the transverse reinforcement. When the bond strength is greater than the applied load it showed ductile behavior after flexural yielding without bond failure. The column ultimately fails due to fracture of the steel angles, bond slippage in the steel angles and/ or the fracture of transverse bars (2014).

The two PSRC in (Hwang, 2018) and (Eom, et al., 2014) papers, showed greater flexural strength and stiffness than CES approximately by 30%, peak strength increased due to larger effective compressive area, and deformation capacity under cyclic lateral loading reduced by 20%. On the other hand, transverse bars or plates may cause premature tensile fracture due to connection failure. When the transverse plates are not closely spaced, the PSRC will be vulnerable to premature spalling of the cover due to the smooth surfaces of steel angles, this may lead to degrading of load carrying and deformation capacity. Both studies (Hwang, 2018) and (Eom, et al., 2014) managed to replace the conventional steel section "W" with steel angles placed internally but did not calculate the cost of using steel angles instead of "W" section. Also, the steel angles were placed at the corners not at the center, which will be integrated in this paper. This eliminate failure due to spalling of the cover, because the angles are close to the perimeter of the column.

On the other hand, Campione (2013) studied the use of externally placed steel angles with battens for concrete columns. Eight short columns were subjected to axial load and bending moment, to study their compression behavior. Results indicates that columns achieved very high load carrying capacity and ductility, if adequately designed up to the peak applied load.

Figure 6 shows four specimens of 1250 mm height (4.1 feet): one column without steel angles and the other three is confined with four vertical angles and battens located at different spaces –units are in millimeters-.

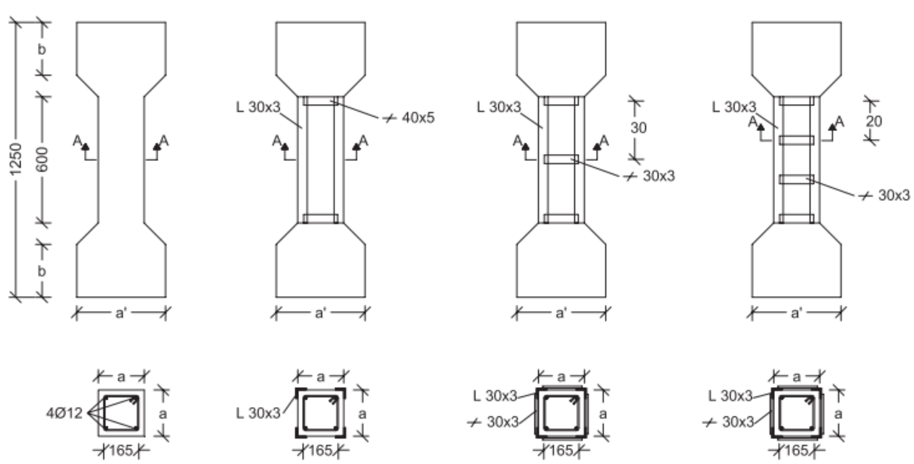

Figure 6 Strengthened specimens with steel angles and steel battens. Campione (2013)

The presence of steel angles and battens prevents buckling of longitudinal bars. Columns with directly loaded angles behave as a composite member. The increase in capacity depends on the geometrical and mechanical properties alongside with the characteristics of the concrete core (2013). Campione studied regular reinforced concrete columns without using steel sections internally but added steel battens around the columns, this could cause delays in construction due to the process of attaching the battens around the columns after pouring and curing of concrete. Also, there was no cost study involved to obtain the results of using more labor hours of welding and material cost.

Kim et al. (2014), focused on maximizing the contribution of high-strength steel in preventing early crushing of the concrete. This study used steel tubes and closely spaced ties for lateral confinement with ultra-high-strength of 200 MPa (29 Ksi) concrete, and high-crushing strain by placing L-shaped steel sections at the corners of the cross section. Early crushing occurred in the ultra-high-strength concrete column and the concrete-encased L-section column. Higher peak strength and flexural stiffness than the conventional concrete-encased H-section columns was concluded (Figure 7).

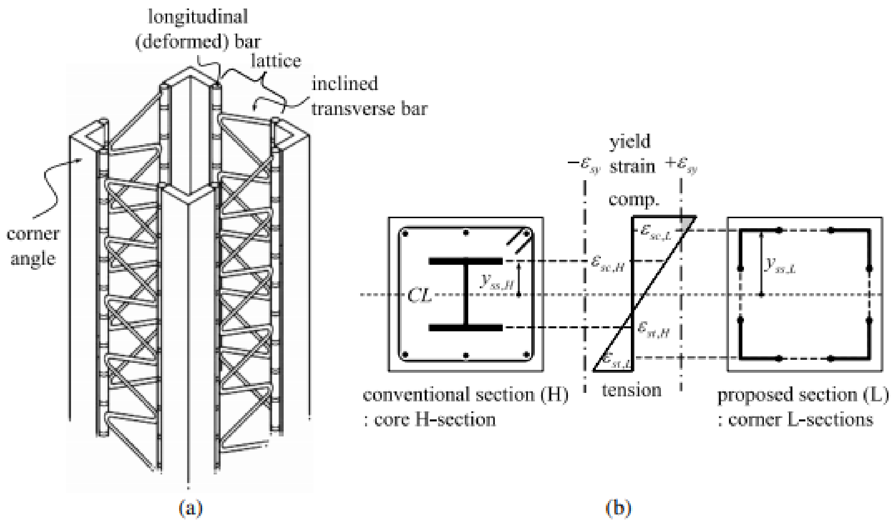

Figure 7 Concrete encased steel column with L corner sections: (a) prefabricated steel section with lattices, (b) strain distribution in steel sections. Kim et al. (2014)

In this paper high compressive strength concrete was used and compared steel angles columns and conventional "W" section. There were no indications were to use such column and for what case in construction, and without doing any cost analysis. The use of such big strength has limitations in construction and require accurate calculations of the cost.

3.b Using Finite Element Analysis.

In this section the structural response and mode of failure for columns was studied by Young and Ellobody (2011), they used finite element method to analyze the strength of columns, and then compared the design strength values using the AISC (2016) and Eurocode4 (2004) for composite columns.

Figure 8 shows Modeling steps of concrete encased steel composite columns (Step (1) Modeling of reinforcement. Step (2) Modeling of unconfined concrete. Step (3) Modeling of encased steel section. Step (4) Modeling of highly confined concrete. Step (5) Modeling of partially confined concrete. Step (6) Modeling of loading plates).

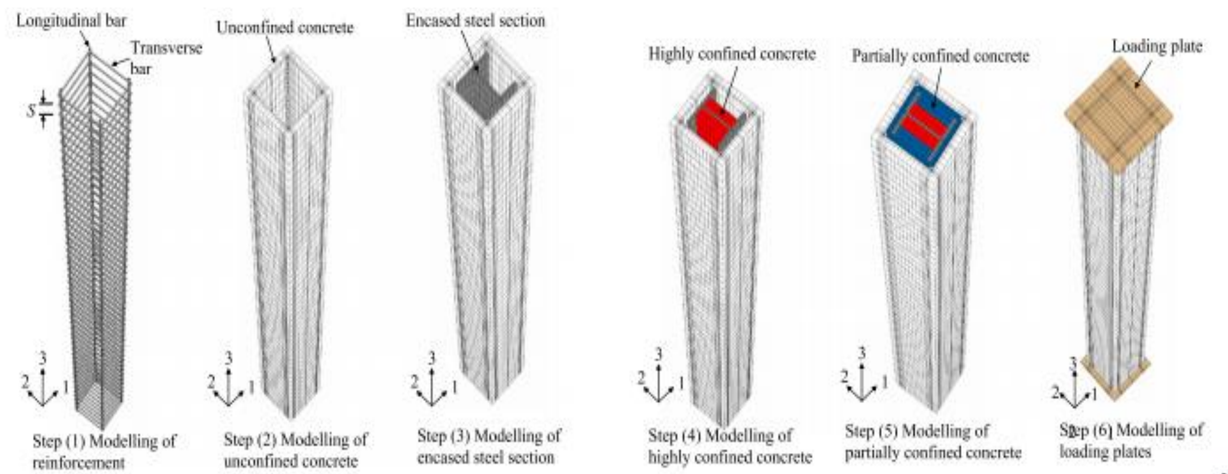

Figure 8 Modelling steps of concrete encased steel composite columns. Young and Ellobody (2010)

This study covered slender, non-slender, stub and long concrete encased steel composite columns. The concrete strength varied from normal to high strength (20 - 110 MPa), (2.9 – 15.95 Ksi). The steel section yields stress also varied from normal to high strength (275 - 690 MPa), (39.9 – 100 Ksi). They modeled the interface between the steel section and concrete, longitudinal and transverse reinforcement bars and the reinforcement bars and concrete. These models allowed the bond behavior to be simulated and the different components to retain their profile during the deformation of the column. The increase in structural steel strength has a small effect on the composite column concrete strength having higher relative slenderness ratios, and this is due to the flexural buckling failure mode (2011).

Generally, it is shown that methods following Eurocode4 (2004) can accurately predict the design strengths for the concrete encased steel composite columns having a concrete cylinder strength of 30 MPa (4.35 Ksi). Otherwise, predictions were generally conservative. The predictions methods according to AISC (2016) were quite conservative for all concrete encased steel composite columns (2011).

In addition, Ellobody & Young did another study with Lam (2011) using a nonlinear 3-D finite element model to analyze eccentrically loaded concrete encased steel composite columns (Figure 9). They also compared the design strengths using the American Institute of Steel Construction “AISC” (2016) and Eurocode4 (2004). These codes are used in structural engineering design for construction element and systems, Eurocode4 (2004) exists in three main countries: United Kingdom, France and Germany and extend all over Europe and other international countries, it is mainly used to design composite steel and concrete structures using the limit state design philosophy since 2004. AISC (2016) exists mainly in the United States and other international countries, it is mainly used to design steel structures and composite elements with steel using the allowable stress design ASD and, load and resistance factor design method LRFD.

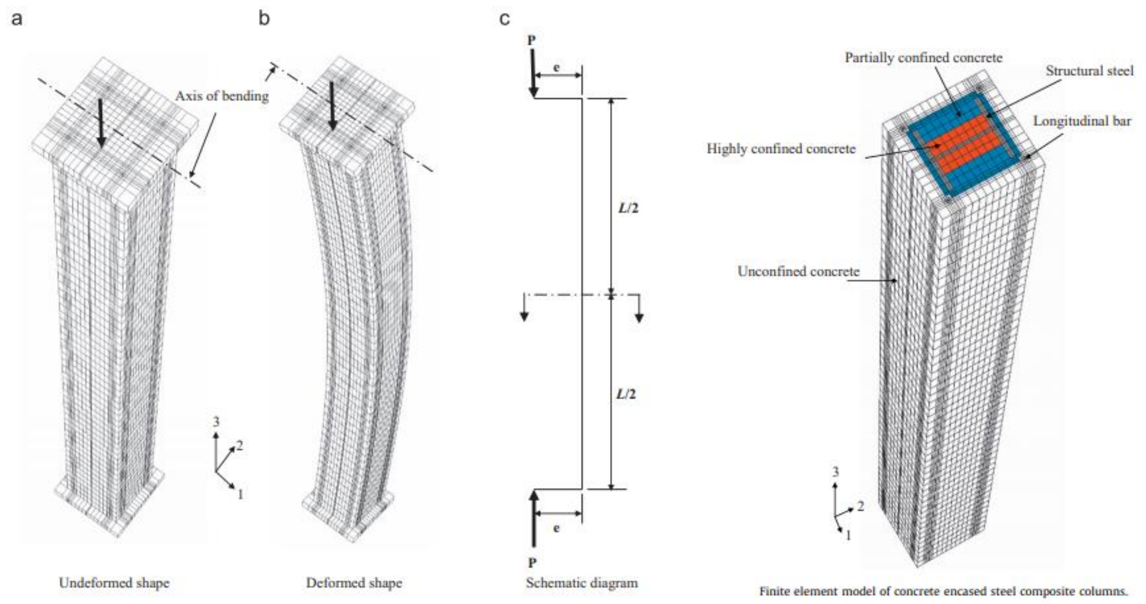

Figure 9 shows finite element model of concrete encased steel composite columns. Ellobody, Young and Lam (2010)

Increasing the structural steel yield stress for eccentrically loaded columns of 0.125 the diameter will have significant effect on columns with concrete strength less than 70 MPa (10.15 Ksi). Higher eccentricity of 0.375 the diameter, columns will have significant effect only on columns with concrete strength higher than 70 MPa (10.15 Ksi), due to the structural steel yield stress increase. The composite column strengths obtained from the finite element analyses were compared with the design strengths calculated using the Eurocode 4 (2004) for composite columns (2011).

Again, it is shown that methods according to Eurocode4 (2004) can accurately predict the eccentric column load as shown in figure 8, while overestimated the moment (2011). This was the reason of adding Eurocode 4 calculations to the theoretical part of this thesis, next to the AISC theoretical calculations of compressive strength. Columns tested in this paper have the axial load concentric with no eccentricity so, both codes will have accurate results of the compressive strength because AISC overestimate the moment due to the eccentric load if applied.

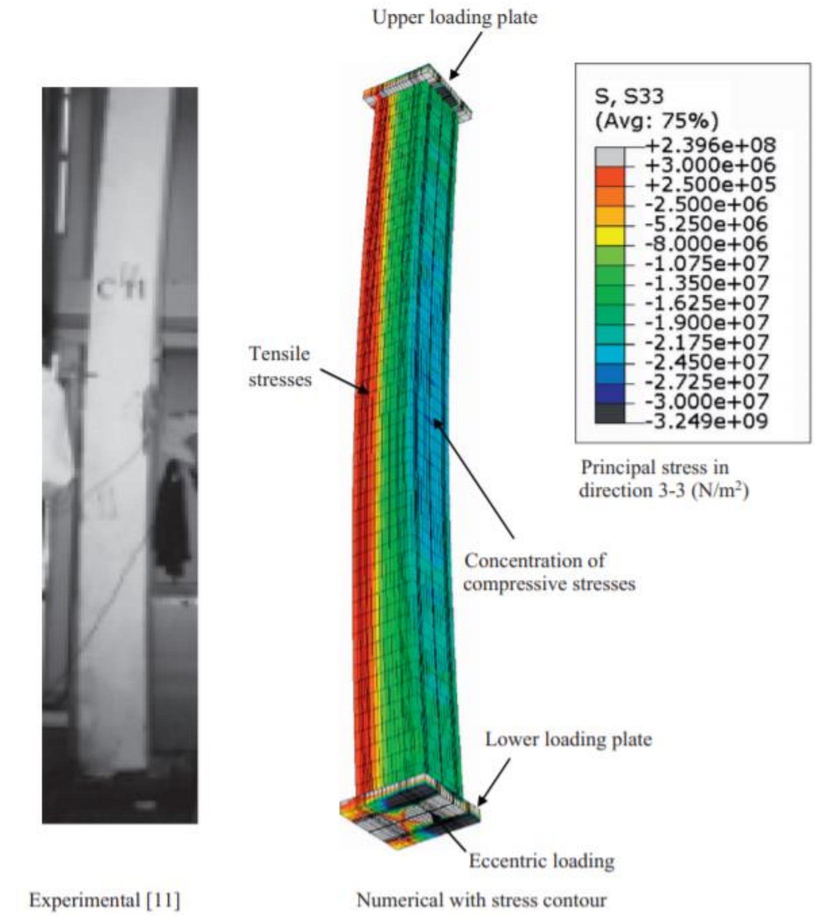

Figure 10 Comparison of deformed shapes at failure for eccentrically loaded concrete encased steel composite column BC5. Ellobody, Young and Lam (2010)

Last paper in this section conducted by Lelkes and Gramblička (2013), they studied theoretical and experimental analysis of composite steel-concrete (SC) columns, which are completely or partially concrete-encased steel members (Figure 11). Theoretical analysis was done using the non-linear software Atena 3D, while the experimental analysis was done by testing 18 columns. Results were analyzed using general design method in Eurocode4 (2004), then they compared it with the model developed by Atena 3D.

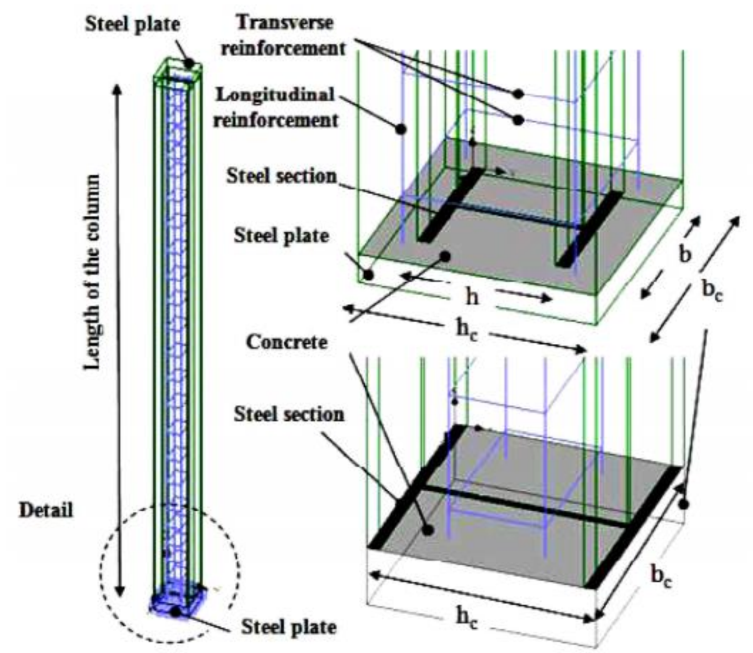

Figure 11 Model of the composite SC columns in software Atena 3D. Lelkes and Gramblicka (2013)

It was concluded that Atena 3D results, for the resistance and force-deflection relationship matched the tested samples analysis, and results from general design method mentioned in Eurocode (2004). This indicates that Atena 3D can be used to predict structural performance before actual lab testing. Using finite element analysis can help in simulate the structural element before testing which can help in theoretical studies, software can satisfy this purpose and give true simulation of using the columns either with steel section or with regular reinforcement.

Papers in this section studied the use of steel section in concrete and compare it to the regular reinforced concrete column by using finite element analysis but did not compare composite to composite concrete-steel columns using different steel sections. Generally, steel sections have greater compressive strength than concrete columns, and composite concrete-steel columns will have better results than regular reinforced column. comparison using steel sections with the help of finite element analysis integrated in this thesis.

3.c Using Steel Tubes section.

Thin-walled steel tubes filled with concrete have been used in tall buildings to improve the economical view of engineers (1998). Concrete Filled Steel Tubes “CFST” combine the advantages of both steel and concrete, ductility, speed of construction, high capacity, high stiffness, and acceptable cost. etc. (2008).

investigated Concrete Filled Steel Tubes “CFST” was investigated by Jiang. A et al. (2013), with a series of bending tests of thin-walled CFST. A total of four specimens were tested, two square specimens and two rectangular specimens, with aspect ratio width to wall thickness from 50 mm to 100 mm (1.97 in to 3.94 in). The load–displacement curves, failure mode and ultimate capacity of test specimens were observed. An analytical model was developed for the thin- walled CFST’s subjected to bending. The model was able to predict the behavior and strengths of test specimens. On the other hand, Han, Yao, and Tao (2007) studied thin-walled concrete filled steel tubes “CFST” under pure torsion using ABAQUS software for the finite element analysis, results showed good agreement with test results.

Figure 12 below shows schematic view of the element division of circular and square section and how torsional moment applies on sections.

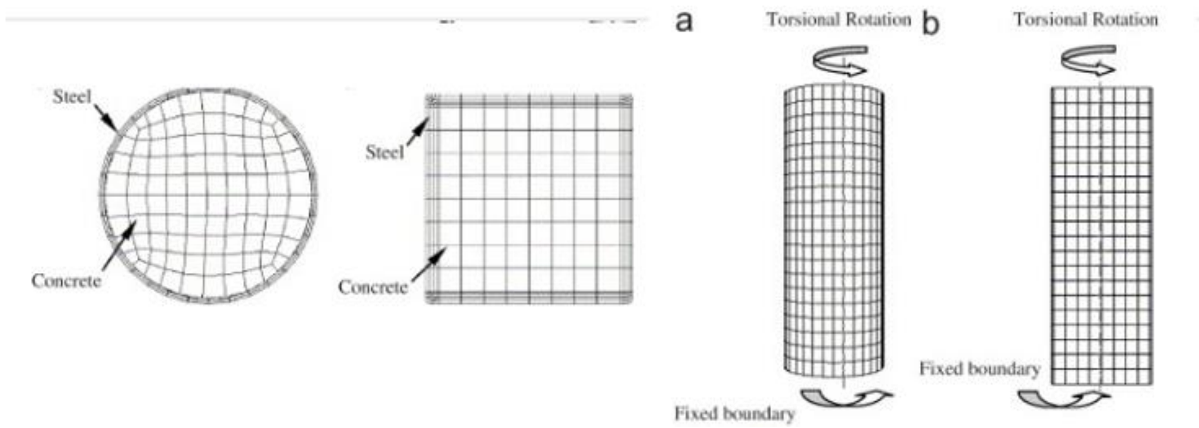

Figure 12 A schematic view of the element division (circular and square). Han, Yao and Tao (2007)

This study used ABAQUS as a software to simulate the specimen before testing which gave good results but, did not study the cost of adding tubes on site before pouring the concrete, and if this will require specific concrete compressive strength. Some columns with small diameter require high slump concrete so it can easily pour and not causing honeycombing, this can create gaps between concrete and tubes which eventually will affect the compressive strength of the column.

Huge number of samples were studied by Goode, Kuranovas and Kvedaras (2010). They tested 1817 of concrete filled steel tubes “CFST” and compared the results with predictions of slender load bearing capacity calculations according to methods suggested by Eurocode4 (2004). The following types of tested CFST’s were analyzed: circular and rectangular hollow section stub and long columns fully filled with concrete, which were with or without applied moments at the ends of specimen. The results showed that Eurocode4 (2004) provide safe methods of strength evaluation.

Figure 13 below shows long CFST (Concrete Filled Steel Tubes) slenderness columns. (a) circular CRST with no moment. (b) circular with moment. (c) square CFST with no moment. (d) square CFST with moment.

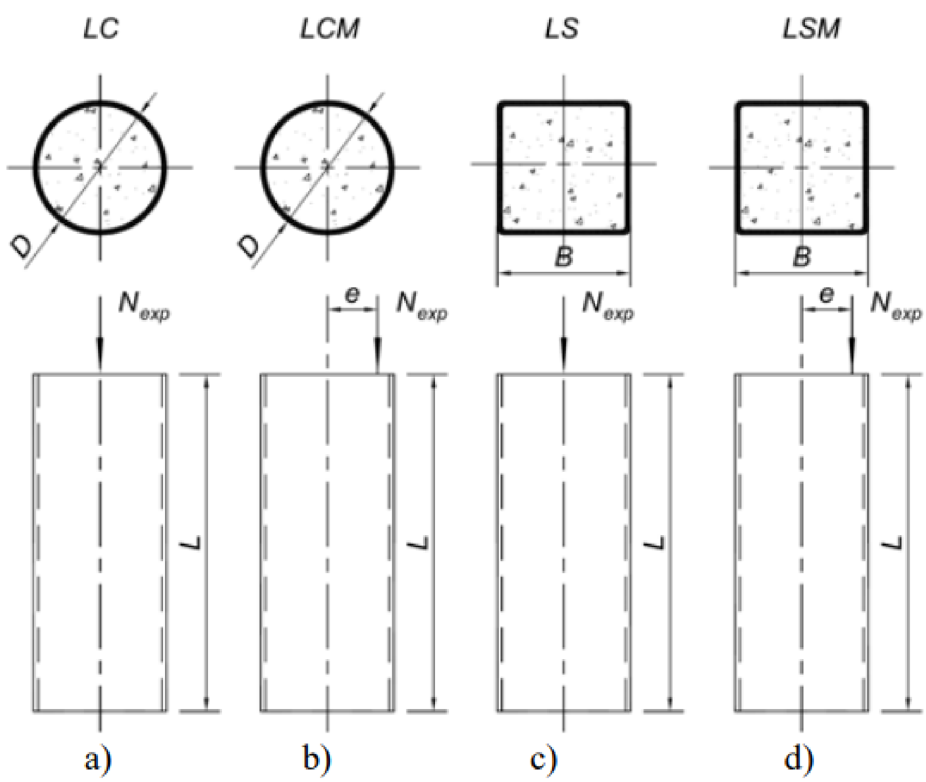

Figure 13 Sections used in Goode, Kuranovas and Kvedaras experiment (2010)

In this paper the vast amount of specimens will help in generalizing and validating the assumption of using Eurocode 4 in calculating the compressive strength, but with no cost comparison between these sections.

3.d Using Steel Fibers in Concrete.

Influence of using steel fibers was studied by Takgoz and Dundar (2012), by testing 16 L-shaped plain and steel fiber columns, subjected to axial load and biaxial moment. Concrete compressive strength, load eccentricity, slenderness effect and steel fiber content were studied through the experimental testing. Nonlinear behavior of the materials was considered and analyzed using “The Moment Magnification Method” suggested by ACI 318 specification (Figure 14).

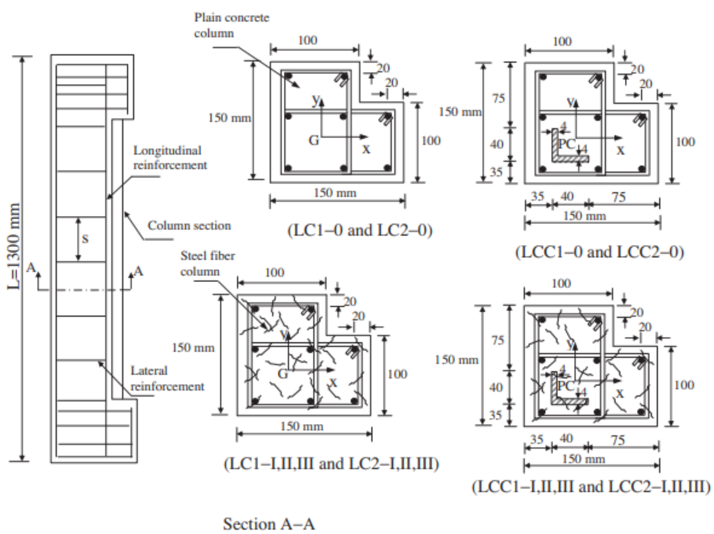

Figure 14 Details of column specimens. Takgoz and Dundar (2012)

The results showed that using steel fibers prevent concrete spalling and provide significant improvement on confinement, ductility, and deformability features. Results indicated that using “The Moment Magnification Method” has given reasonable results for the analysis of reinforced concrete and composite columns subjected to biaxial bending and axial load (2012). Using steel fibers have advantages, but it is a new element added during pouring and will require trained labor or special concrete mix from the batch, the cost of this process was not mentioned. Also, the limitation of using L shaped columns in narrow down the possibilities of using such shape, since construction nowadays, use rectangular, square, and circular shapes. Using fibers in commonly used column shapes and calculating the cost of it can be helpful to compare and see if it worth to use such technology in construction.

Previous papers in this literature proposed new ways of using steel sections, adding material, simulating using finite element software and comparisons to find the best way of increasing the strength properties of columns, but did not conduct cost analysis between the compared sections which integrated in this paper. Also, none of the papers in the engineering or construction field suggested to use the proposed shape steel section "X". This paper compared the use of "X" shape steel section and conventional "W" steel section, cost analysis study was conducted to compare the cost based on similar compressive strength values and dimensions.

This thesis will study the following:

- The effectiveness of the new "X" steel section from structural engineering point of view.
- Cost comparison between the proposed shape steel section "X" and conventional "W" steel section.

4. Methodology

This research proposed the “X” shape steel section. Since there are no molds or existing sections with the same geometry, steel angles were used to represent the proposed shape. “X” section placed at the center of the column with longitudinal reinforcement bars and ties. To answer the research question, the following approaches were used:

3.a Methodology Approach:

Two approaches were used in this paper to make detailed comparison and conclusion.

First, theoretical analysis using universal codes -AISC 360-10 and Eurocode 4- to calculate nominal compressive strength and draw compressive and tensile stress-strain for three specimens. Kent and Park model for confined and unconfined concrete was used to draw stress and strain (Sabau & Onet, 2011). Excel sheet was created to summarize all calculations.

Secondly, finite element analysis using ABAQUS software to apply axial concentric load on three specimens and draw force-deflection curve. All angles were assumed to be one section of the shape “X”, but with dimensions of the angles as in theoretical analysis. All force-deflection curves were combined and compared to observe which section have more compressive strength capacity.

Cost analysis was also conducted to compare steel sections. Material price of the proposed shape section with similar load capacity to the conventional section have less price due to the lighter weight of the used angles than conventional steel “W” section.

Generally, if prefabrication manufacturers have premade mold for the “X” shape, there will be no need for steel angles and welding cost on site or during future experiments.

4.b Methods of Data Collection:

Results were taken from software simulation and from theoretical calculations using existing codes (AISC, EuroCode4 and ABAQUS). Three columns were studied, concrete cross section is eight by eight inches (8x8) and 6 feet long. All specimens have four axial rebars #4, steel section in each column will be positioned in the center.

Column section dimensions were assumed so that failure load of columns will be less than 300 Kips, which is the maximum load that can be applied at OU Fears laboratory in case experimental work is to be done in the future. The following table summarizes the specimens properties.

Table 1 general description of specimens tested in the lab

	Specimen 1	**Specimen 2**	**Specimen 3**
Concrete	8x8x72 (inches)	8x8x72 (inches)	8x8x72 (inches)
Steel Sections	W4x13	2L3.5x3x5/16	4L2x2x1/4
Rebars	4#4	4#4	4#4

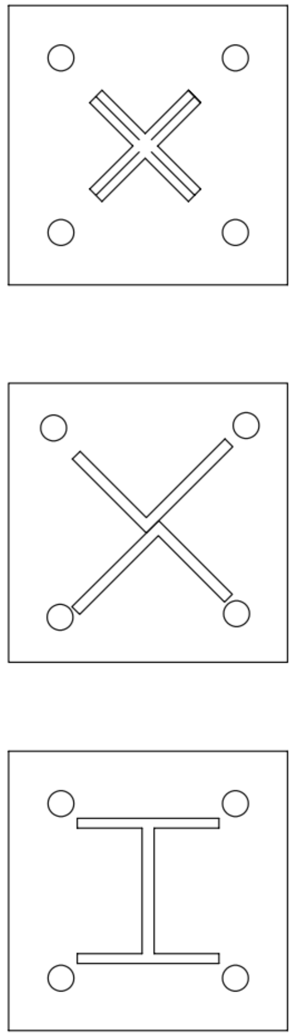

Figure 15 AutoCAD schematic drawings of the three specimens used in this thesis

4.c Methods of Analysis:

Force-deflection curves drawn for each column to check which specimen have higher compressive strength from ABAQUS software. Cost analysis study conducted on the chosen proposed section to compare it with the conventional “W” steel section data and cost using AISC sections properties, and theoretical calculations to calculate the design compressive strength.

5. Analysis

This section covers theoretical analysis on the three specimens using AISC and Eurocode 4, software simulation using ABAQUS software, and Cost analysis on AISC steel sections.

5.a Theoretical Analysis:

Compressive strength calculations were done according to AISC-360 and Eurocode4 on the three specimens, taking in consideration that Eurocode4 calculations can accurately predict the composite concrete steel column behavior as per literature review references. Three columns of 8 by 8 inches and length of 6 feet were analyzed using AISC and Eurocode4 (W4x13 for conventional composite column (first specimen), four steel angles (second specimen) and two angles (third specimen)).

5.a.1. AISC Compressive Strength:

Using AISC 360 (chapter I, section 12), the following two figures 16 and 17 summarize in detail the equations. In addition, an excel sheet created for this purpose and snapshots will be attached also to show the results in Appendix A: AISC.

1b. Compressive Strength

The design compressive strength, $\phi_c P_n$, and allowable compressive strength, P_n/Ω_c, of doubly symmetric axially loaded encased composite members shall be determined for the limit state of flexural buckling based on member slenderness as follows:

$$\phi_c = 0.75 \text{ (LRFD)} \qquad \Omega_c = 2.00 \text{ (ASD)}$$

(a) When $\frac{P_{no}}{P_e} \le 2.25$

$$P_n = P_{no}\left(0.658^{\frac{P_{no}}{P_e}}\right) \tag{I2-2}$$

(b) When $\frac{P_{no}}{P_e} > 2.25$

$$P_n = 0.877 P_e \tag{I2-3}$$

where

P_{no} = $F_y A_s + F_{ysr} A_{sr} + 0.85 f_c' A_c$ (I2-4)

P_e = elastic critical buckling load determined in accordance with Chapter C or Appendix 7, kips (N)

= $\pi^2 (EI_{eff})/L_c^2$ (I2-5)

A_c = area of concrete, in.^{2} (mm^2)

A_s = cross-sectional area of steel section, in.^{2} (mm^2)

E_c = modulus of elasticity of concrete

= $w_c^{1.5}\sqrt{f_c'}$, ksi $\left(0.043 w_c^{1.5}\sqrt{f_c'}, \text{ MPa}\right)$

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AMERICAN INSTITUTE OF STEEL CONSTRUCTION

Figure 16 Compressive strength equation, AISC Chapter I Section 12

16.1-92 AXIAL FORCE [Sect. I2.

EI_{eff} = effective stiffness of composite section, kip-in.^{2} (N-mm^2)

= $E_s I_s + E_s I_{sr} + C_1 E_c I_c$ (I2-6)

C_1 = coefficient for calculation of effective rigidity of an encased composite compression member

= $0.25 + 3\left(\frac{A_s + A_{sr}}{A_g}\right) \le 0.7$ (I2-7)

E_s = modulus of elasticity of steel

= 29,000 ksi (200 000 MPa)

F_y = specified minimum yield stress of steel section, ksi (MPa)

F_{ysr} = specified minimum yield stress of reinforcing bars, ksi (MPa)

I_c = moment of inertia of the concrete section about the elastic neutral axis of the composite section, in.^{4} (mm^4)

I_s = moment of inertia of steel shape about the elastic neutral axis of the composite section, in.^{4} (mm^4)

I_{sr} = moment of inertia of reinforcing bars about the elastic neutral axis of the composite section, in.^{4} (mm^4)

K = effective length factor

L = laterally unbraced length of the member, in. (mm)

L_c = KL = effective length of the member, in. (mm)

f_c' = specified compressive strength of concrete, ksi (MPa)

w_c = weight of concrete per unit volume ($90 \le w_c \le 155$ lb/ft^3 or $1500 \le w_c \le 2500$ kg/m^3)

The available compressive strength need not be less than that specified for the bare steel member, as required by Chapter E.

Figure 17 Compressive strength equation, AISC Chapter I Section 12

The following Tables 2,3 and 4 show the values of compressive strength of all three specimen of conventional steel section W4x13, two angles 2L 3.5x3x5/16 and four angles 4L 2x2x1/4 using the AISC equation shown in Figure 16 and 17.

Table 2 compressive strength values of steel section W4x13 using AISC Chapter I Section 12

Concrete	**fc' (Ksi)**	**4.00**	**Steel Section**	**W 4x13x112**	
	Ec (Ksi)	3606.00		As (in2)	3.83
	Ac (in2)	59.38		Fy (Ksi)	50.00
	Ic (in4)	238.93		Es (Ksi)	29000.00
Section	b (in)	8.00		Is (in4)	3.86
	h (in)	8.00		Ig (in4)	341.33
	Ag (in2)	64.00	Strength Calculations	EI effective	514089.38
Steel Bars	Fysr (Ksi)	60.00		Pe (Kips)	1529.30
	# of Bars	4.00		Pno (Kips)	440.53
	Diameter (in)	0.50		Pno/Pe	0.29
	Asr (in2)	3.83		Pn (Kips)	**390.49**
	Esr (Ksi)	29000.00			
	Isr (in4)	0.01			

Table 3 compressive strength values of steel section 4L2x2x1/4 using AISC Chapter I Section 12

Concrete	**fc' (Ksi)**	**4.00**	**Steel Section**	**4L 2x2x1/4**	
	Ec (Ksi)	3606.00		As (in2)	3.76
	Ac (in2)	59.38		Fy (Ksi)	50.00
	Ic (in4)	238.93		Es (Ksi)	29000.00
Section	b (in)	8.00		Is (in4)	1.40
	h (in)	8.00		EI effective	439922.28
	Ag (in2)	64.00	Strength Calculations	Pe (Kips)	1308.67
Steel Bars	Fysr (Ksi)	60.00		Pno (Kips)	437.27
	# of Bars	4.00		Pno/Pe	0.33
	Diameter (in)	0.50		Pn (Kips)	**380.20**
	Asr (in2)	3.83			
	Esr (Ksi)	29000.00			
	Isr (in4)	0.01			

Table 4 compressive strength values of steel section 2L3.5x3x5/16 using AISC Chapter (I) Section 12

Concrete	**fc' (Ksi)**	**4.00**	**Steel Section**	**2L 3.5x3x5/16**	
	Ec (Ksi)	3606.00		As (in2)	3.86
	Ac (in2)	59.38		Fy (Ksi)	36.00
	Ic (in4)	238.93		Es (Ksi)	29000.00
Section	b (in)	8.00		Is (in4)	4.66
	h (in)	8.00		EI effective	538501.00
	Ag (in2)	64.00	Strength Calculations	Pe (Kips)	1601.92
Steel Bars	Fysr (Ksi)	60.00		Pno (Kips)	441.93
	# of Bars	4.00		Pno/Pe	0.28
	Diameter (in)	0.50		Pn (Kips)	**393.74**
	Asr (in2)	3.83			
	Esr (Ksi)	29000.00			
	Isr (in4)	0.01			

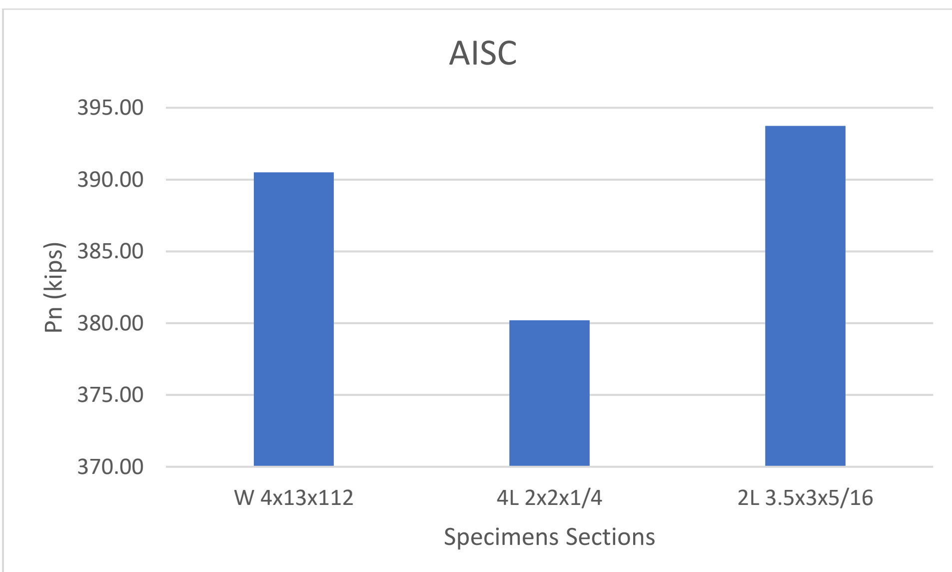

Figure 18 AISC Compressive Strength values

Figure 18 shows that that 2L section has greater compressive strength than 4L and W sections, the difference between 2L and W sections is around 3 kips, and difference between 4L and W is 9 kips, which can be accepted as comparable and similar values. Increasing area of steel or modifying on the “X” shape can produce a stronger section.

5.a.2 Eurocode 4 Compressive Strength:

Using Eurocode4 section 6.7, the following figure 19 summarizes in detail the equations. In addition, an excel sheet created for this purpose and snapshots will be attached also to show the results in Appendix B: Eurocode4.

6.7.3.2 Resistance of cross sections

(1) The plastic resistance to compression $N_{pl,Rd}$ of a composite cross-section should be calculated by adding the plastic resistances of its components:

$$N_{pl,Rd} = A_a f_{yd} + 0{,}85 A_c f_{cd} + A_s f_{sd} \qquad (6.30)$$

Expression (6.30) applies for concrete encased and partially concrete encased steel sections. For concrete filled sections the coefficient 0,85 may be replaced by 1,0.

(2) The resistance of a cross-section to combined compression and bending and the corresponding interaction curve may be calculated assuming rectangular stress blocks as shown in Figure 6.18, taking account of the design shear force V_{Ed} in accordance with (3). The tensile strength of the concrete should be neglected.

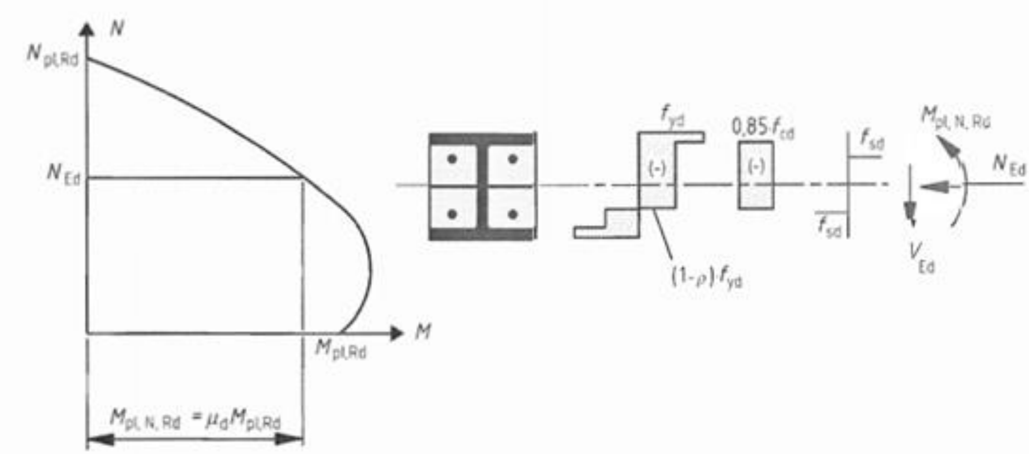

Figure 19 Compressive Strength calculation, Eurocode4 section 6.7

The following tables 5,6 and 7 show the values of compressive strength of all three specimen of conventional steel section W4x13, two angles 2L 3.5x3x5/16 and four angles 4L 2x2x1/4 using the Eurocode4 equation shown in Figure 18 and 19.

Table 5 compressive strength values of steel section W 4x13 using Eurocode4 section 6.7

Concrete	**fck (Ksi)**	**4.00**	**Steel Section**	**W4x13**	
	Ec (Ksi)	3606.00		Aa (in2)	3.83
	Ac (in2)	64.00		Fya (Ksi)	60.00
	Ic (in4)	238.93		Ea (Ksi)	29000.00
Section	bc (in)	8.00		Ia (in4)	3.86
	hc (in)	8.00			
			Strength Calculations	Npl,rd (Kips)	**258.27**
Steel Bars	Fy (Ksi)	60.00			
	# of Bars	4.00			
	Diameter (in)	0.50			
	As (in2)	0.80			
	Es (Ksi)	29000.00			
	Is (in4)	0.01			

Table 6 compressive strength values of steel section 4L 2x2x1/4 using Eurocode4 section 6.7

Concrete	**fck (Ksi)**	**4.00**	**Steel Section**	**4L2x2x1/4**	
	Ec (Ksi)	3606.00		Aa (in2)	3.76
	Ac (in2)	64.00		Fya (Ksi)	60.00
	Ic (in4)	238.93		Ea (Ksi)	29000.00
Section	bc (in)	8.00		Ia (in4)	1.40
	hc (in)	8.00			
			Strength Calculations	Npl,rd (Kips)	**256.19**
Steel Bars	Fy (Ksi)	60.00			
	# of Bars	4.00			
	Diameter (in)	0.50			
	As (in2)	0.79			
	Es (Ksi)	29000.00			
	Is (in4)	0.15			

Table 7 compressive strength values of steel section 2L 3.5x3x5/16 using Eurocode4 section 6.7

Concrete	**fck (Ksi)**	**4.00**	**Steel Section**	**2L3.5x3x5/16**	
	Ec (Ksi)	6000.00		Aa (in2)	3.86
	Ac (in2)	64.00		Fya (Ksi)	60.00
	Ic (in4)	238.93		Ea (Ksi)	29000.00
Section	bc (in)	8.00		Ia (in4)	4.66
	hc (in)	8.00			
			Strength Calculations	Npl,rd (Kips)	**258.55**
Steel Bars	Fy (Ksi)	60.00			
	# of Bars	4.00			
	Diameter (in)	0.50			
	As (in2)	0.79			
	Es (Ksi)	29000.00			
	Is (in4)	0.15			

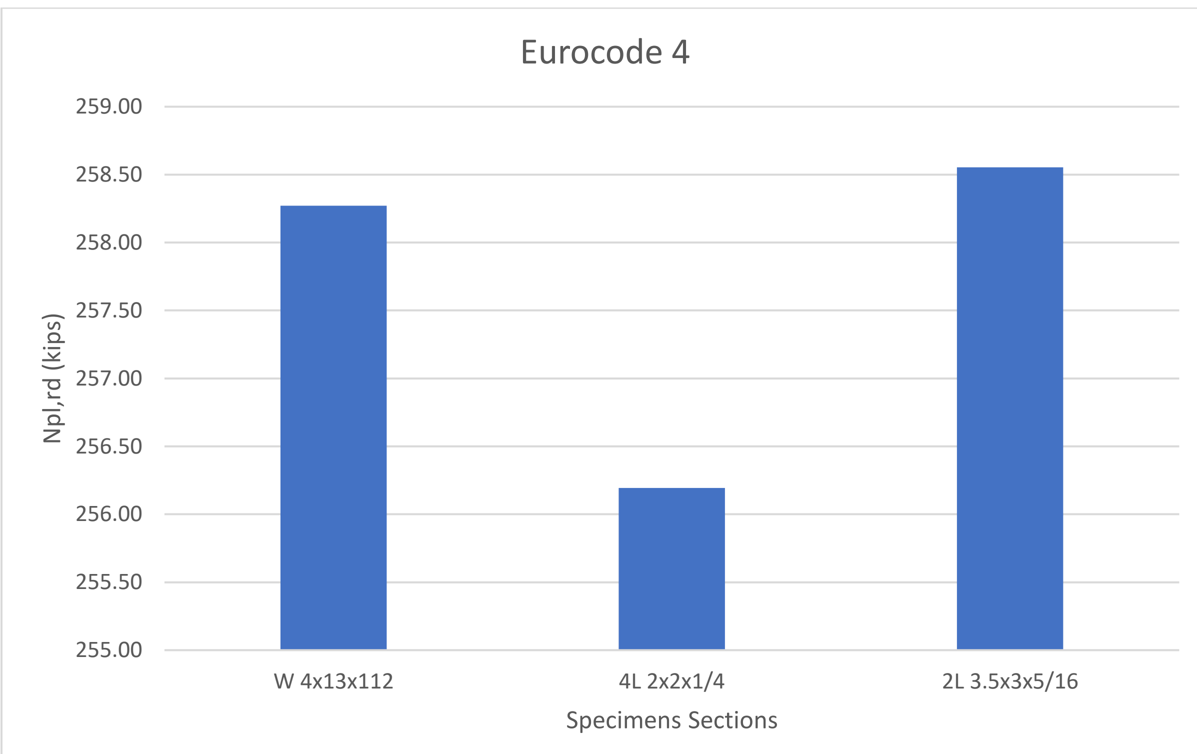

Figure 20 Eurocode 4 Compressive Strength Values

Figure 21 shows that 2L and W section have the same compressive strength and larger with 1 kips difference than 4L section

5.a.3 Stress-Strain Curve:

Kent and Park (2011) model for confined and unconfied concrete was used to draw the stress strain diagram and figure out the concrete damage behavior and input the results in ABAQUS.

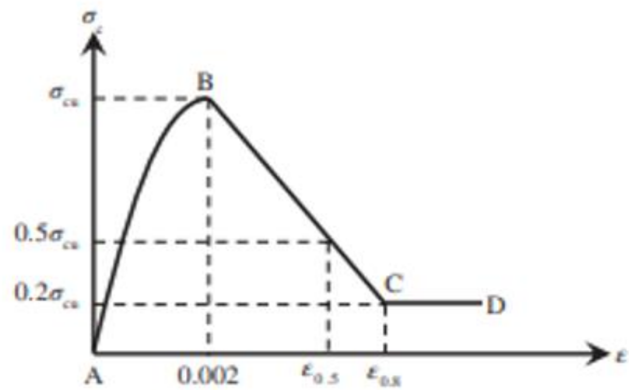

Figure 21 Kent and Park model for confined and unconfined concrete

Applying Kent and Park model equations gives the following tables, then graphs were drawn to show stress-strain diagram for both compressive and tensile. Same values were input in the ABAQUS material properties for concrete.

Table 8 Compressive stress and strain values as per Kent and Park model

Stress (Ksi)	Strain
0	0
1200	0.00033287
3102.49308	0.001
3722.99169	0.0014
3988.91967	0.0018
4000	0.0019
800	0.005

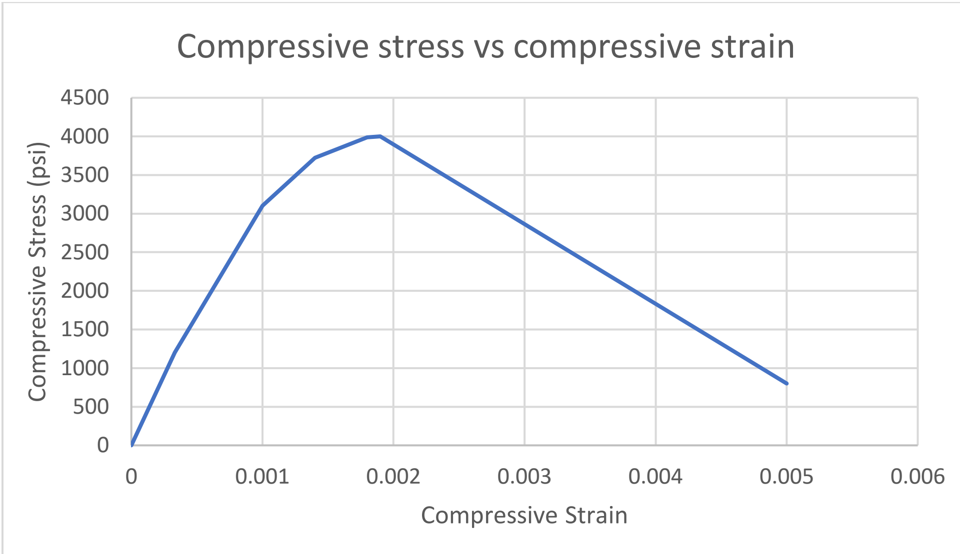

Figure 22 Stress and Strain values as per Kent and Park model

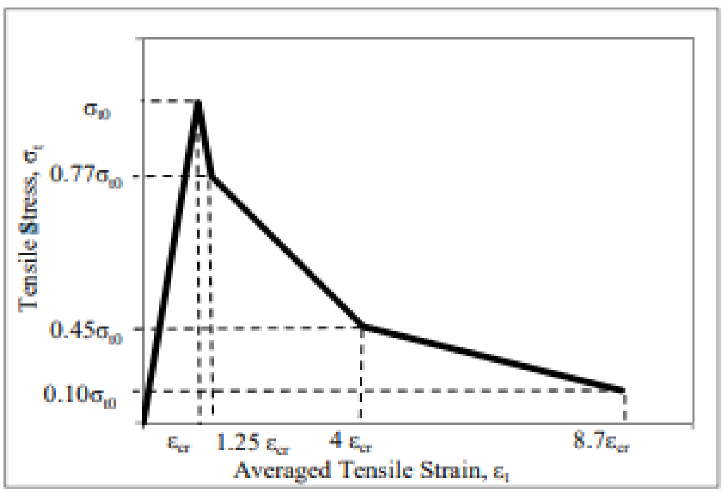

Figure 23 Tensile stress vs tensile strain

Table 9 Tensile stress and strain values as per Kent and Park model

Stress (Kips)	Strain
0	0
474.341649	0.00013158
365.24307	0.00016447
213.453742	0.00052632
47.4341649	0.00114474

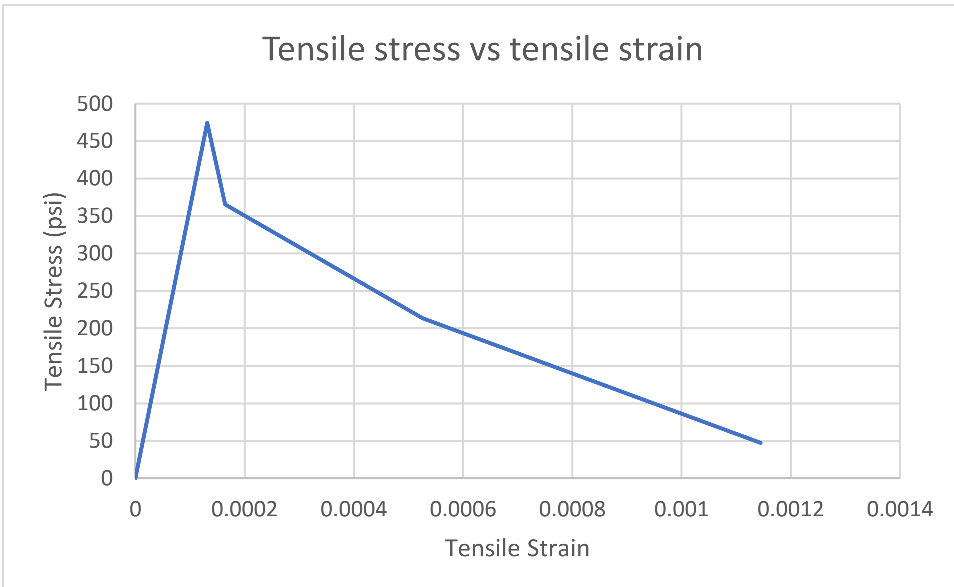

Figure 24 Tensile stress vs tensile strain

From above graphs, maximum compressive stress is 4 Ksi, and maximum tensile stress is 0.47 Ksi. Concrete will fail under compression of 4 Ksi and it will fracture under 0.47 Ksi tension stress.

5.b Software Analysis (Finite Element Analysis):

Finite element analysis was conducted using ABAQUS on the three specimens that were used in theoretical analysis. The main goal here is to determine the column compressive strength of the three specimens and make a comparison between them.

Two boundary conditions were assumed in ABAQUS for all specimens, one end is fixed and the other end is hinge at the loading side. Displacement control approach applied to force the column to have displacement of one inch and calculate the reaction forces after. Displacement approach was used due to difficulties of running the simulation after applying the load, because the concrete from the load side will fail and cause disturbance to the meshes which will affect the end results.

Reaction forces (they represent the compressive strength) of the three specimens after reaching the one-inch deflection are shown in the following table:

Table 10 Forces at failure of all specimens

Specimens	Force at failure	Displacement
W 4x13	**550 Ib**	**1 inch**
2L 3.5x3x5/16	**580 Ib**	**1 inch**
4L 2x2x1/4	**545 Ib**	**1 inch**

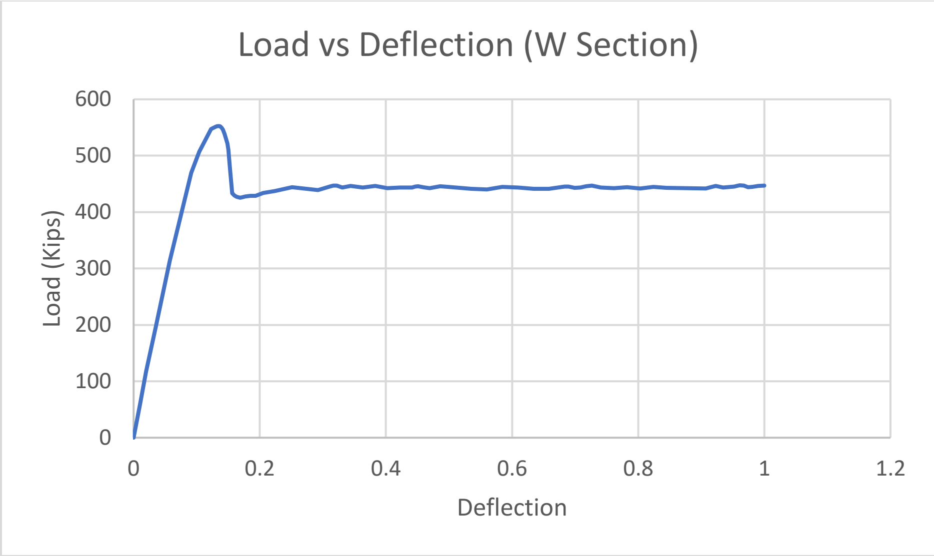

Figure 25 Force vs Strain for steel W section column

The reaction force of steel 4L section column at failure is 550 Ib

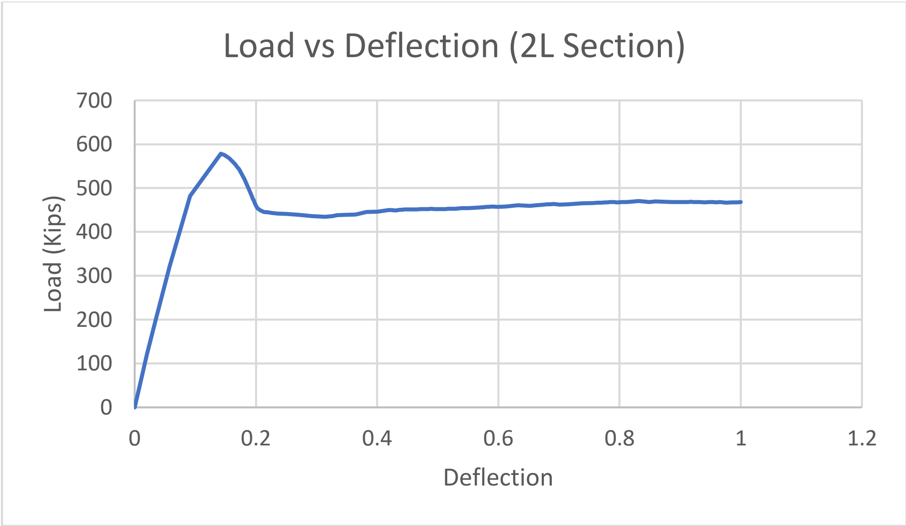

Figure 26 Force vs Strain for steel 2L section column

The reaction force of steel 4L section column at failure is 580 Ib

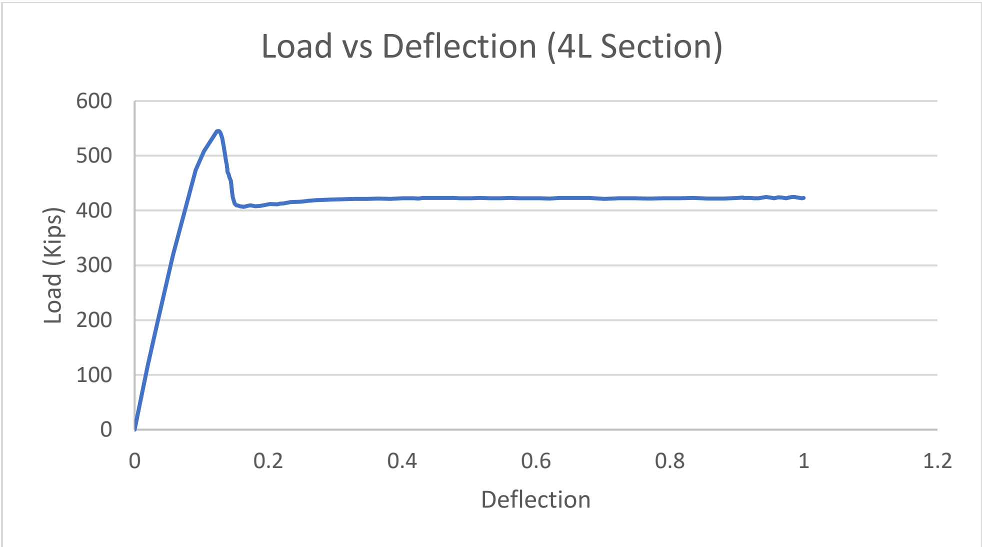

Figure 27 Force vs Strain for steel 4L section column

The reaction force of steel 4L section column at failure is 545 lb

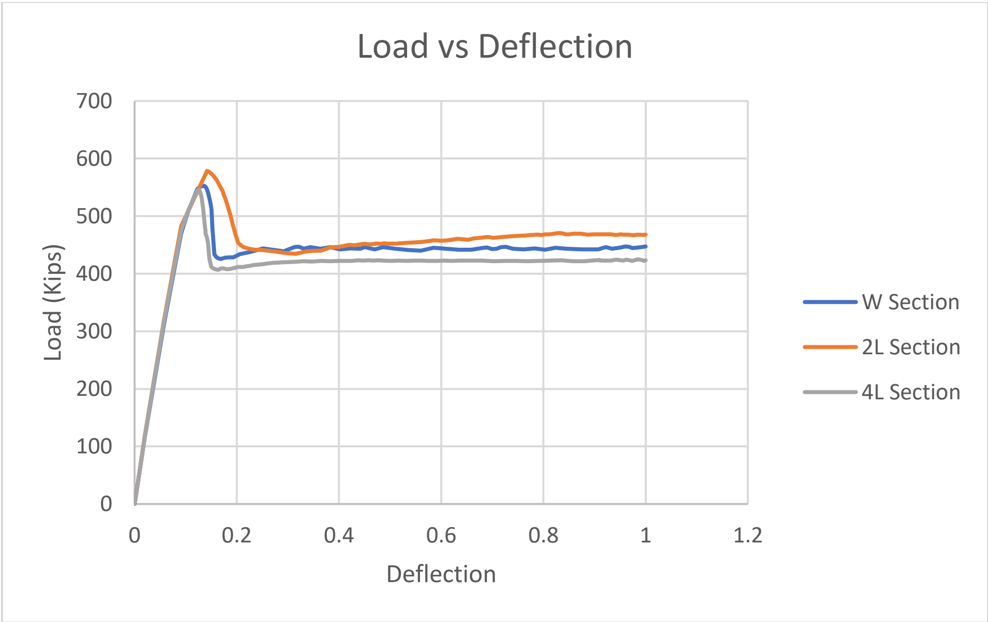

Figure 28 Comparison of load vs deflection of all specimens tested at the lab

All three speciments do not show that the section will fail because, these forces are applied to reach a diplacement of 1 inch, due to displacement control approach that was used. The goal of the simulation is to find the load which cause a drop of force like the lab testing experiment without proceeding to the full failure of the column. Four angles show similar or less compressive strength than the conventional “W” seciton, while the two angles shows greater compressive strength than conventional “W” sectiona and 4L section. Using two angles is better based on the software analysis but it is used with care, because using 2L section require larger sectional depth and create limitation on the size for the column, for example, the 2L specimen section used is 6 inches depth and width while the “W” and 4L sections are 4 inches depth and width.

Steps of using ABAQUS are explained in detail with figures in Appendix C: ABAQUS Steps.

5.c Cost Analysis

To make a practical comparison between the proposed steel section columns and the conventional steel concrete column, the following approaches were used:

- Excel sheet with over 100 W steel sections, over 50 of 2L and 50 of 4L sections were included with all details of sections dimensions, steel sections strength and composite column strength.
- Because sections will vary in depth so the concrete column cross section will vary too, for this reason 7 columns were identified as a base for the comparison (9”x9”, 10”x10”, 11’’x11’’, 13’’x13’’, 15’’x15’’, 20’’x20’’ and 25’’x25’’), and all steel section that will fit in with the cover of 1.5’’ were compared using each concrete cross section.
- Columns with similar composite compressive strength were separated to be compared with price.
- Price based on several resources in Oklahoma from steel manufacturer, steel sections cost $1.2 per pound per feet, so the cost of each section is calculated based on the length and weight (Price = $1.2 x length (ft) x Weight (Ib/ft)).
-

The following figures show comparison between the φcPn composite compressive strength, sections dimensions, weight and cost for different sections, divided based on concrete sectional area:

5.c.2 Column 9”x9”:

Figure 29 shows values for compressive strength of sections that could fit in columns with 9” by 9” cross section. Next, a comparison between sections that fall in 300-450 kips of compressive strength and its cost was conducted.

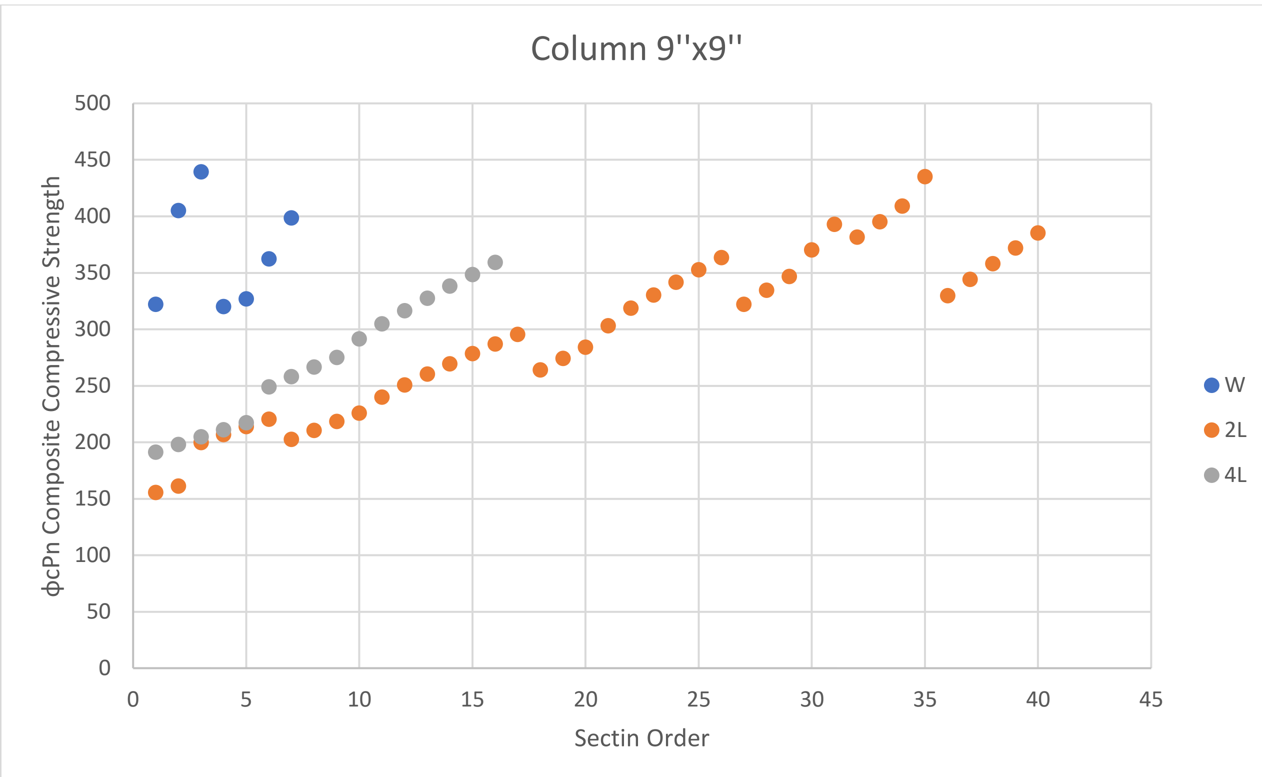

Figure 29 Column 9"x9" Strength vs Sections in ascending order per AISC

Following table 11 shows steel sections with similar compressive strength period (300-450) Kips and its cost. Price of steel section is based on its length, weight and cost per pound and length – for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 11 Column 9"x9" Strength and cost comparison for (300-450) Kips period

AISC_Manual_Label	W	A		ϕcPn	L (ft)	$/lb/ft	Total $
W4X13	13.0			322	6	1.2	94
W5X16	16.0			405	6	1.2	115
W5X19	19.0			439	6	1.2	137
W6X8.5	8.50			320	6	1.2	61
W6X9	9.00			327	6	1.2	65
W6X12	12.0			362	6	1.2	86
W6X15	15.0			399	6	1.2	108
L3X3X3/16	3.71			305	6	1.2	107
L3X3X1/4	4.90			316	6	1.2	141
L3X3X5/16	6.10			327	6	1.2	176
L3X3X3/8	7.20			338	6	1.2	207
L3X3X7/16	8.30			348	6	1.2	239
L3X3X1/2	9.40			359	6	1.2	271
L3-1/2X2-1/2X1/2	9.40			303	6	1.2	135
L3-1/2X3X1/4	5.40			319	6	1.2	78
L3-1/2X3X5/16	6.60			330	6	1.2	95
L3-1/2X3X3/8	7.90			342	6	1.2	114
L3-1/2X3X7/16	9.10			353	6	1.2	131
L3-1/2X3X1/2	10.2			363	6	1.2	147
L4X3X1/4	5.80			322	6	1.2	84
L4X3X5/16	7.20			335	6	1.2	104
L4X3X3/8	8.50			347	6	1.2	122
L4X3X1/2	11.1			370	6	1.2	160
L4X3X5/8	13.6			393	6	1.2	196
L4X3-1/2X1/4	6.20			382	6	1.2	89
L4X3-1/2X5/16	7.70			395	6	1.2	111
L4X3-1/2X3/8	9.10			409	6	1.2	131
L4X3-1/2X1/2	11.9			435	6	1.2	171
L5X3X1/4	6.60			330	6	1.2	95
L5X3X5/16	8.20			344	6	1.2	118
L5X3X3/8	9.80			358	6	1.2	141
L5X3X7/16	11.3			372	6	1.2	163
L5X3X1/2	12.8			385	6	1.2	184

Figure 30 shows comparison between cost of sections from the above table and compressive strength in range (300-450) Kips. Some sections of 2L and 4L have comparable compressive strength to the W sections and less cost.

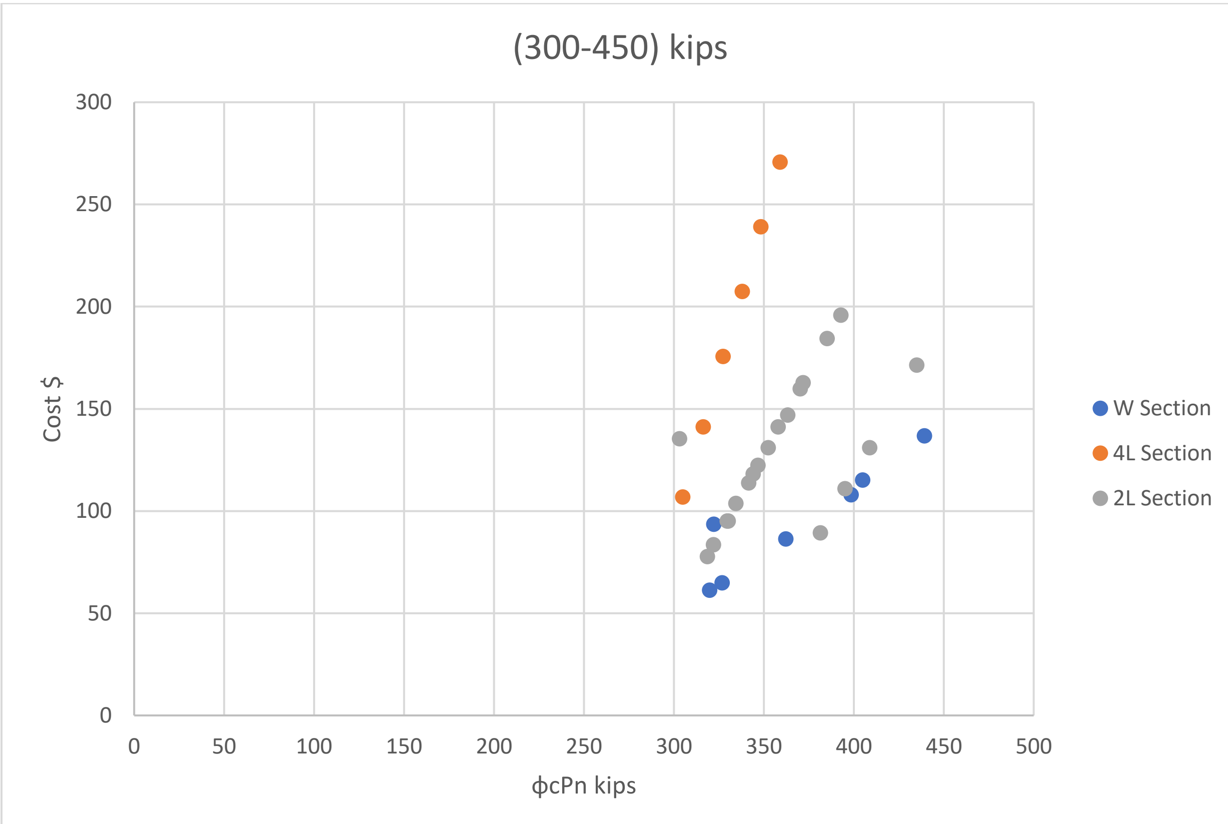

Figure 30 Column 9”x9” Strength and cost comparison for (300-350) Kips period

5.c.3 Column 10”x10”:

Figure 31 shows values for compressive strength of sections that could fit in columns with 10” by 10” cross section. Next, a comparison between sections that fall in 350-500 kips of compressive strength and its cost was conducted.

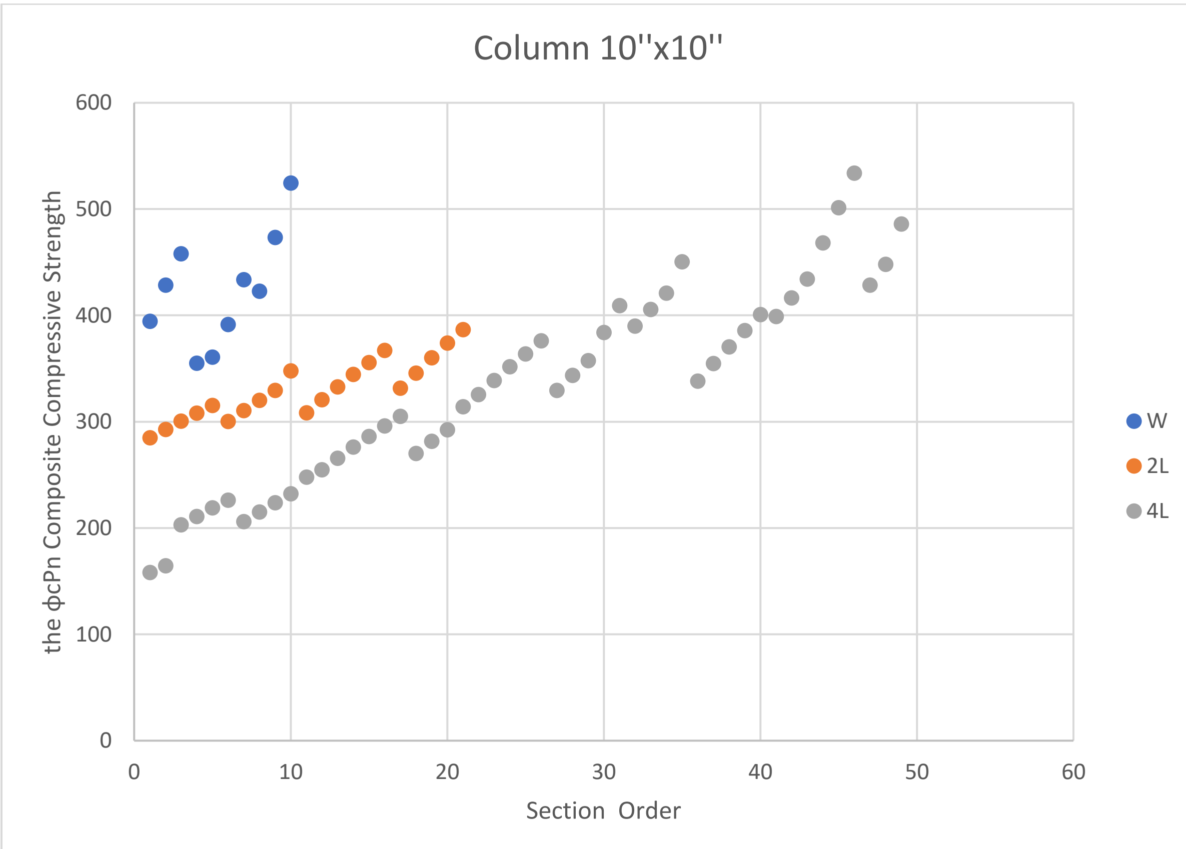

Figure 31 Column 10"x10" Strength vs Sections in ascending order per AISC

Following table 12 shows steel sections with similar compressive strength period (350-500) kips and its cost. Price of steel section is based on its length, weight and cost per pound and length – for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 12 Column 10"x10" Strength and cost comparison for (350-500) Kips period

AISC_Manual_Label	W	ϕcPn	L (ft)	$/lb/ft	Total $
W4X13	13.0	395	6	1.2	94
W5X16	16.0	428	6	1.2	115
W5X19	19.0	458	6	1.2	137
W6X8.5	8.50	355	6	1.2	61
W6X9	9.00	361	6	1.2	65
W6X12	12.0	391	6	1.2	86
W6X16	16.0	434	6	1.2	115
W6X15	15.0	423	6	1.2	108
W6X20	20.0	473	6	1.2	144
L3X3X7/16	8.30	356	6	1.2	239
L3X3X1/2	9.40	367	6	1.2	271
L3-1/2X3-1/2X3/8	8.50	360	6	1.2	245
L3-1/2X3-1/2X7/16	9.80	374	6	1.2	282
L3-1/2X3-1/2X1/2	11.1	387	6	1.2	320
L4X3X3/8	8.50	358	6	1.2	122
L4X3X1/2	11.1	384	6	1.2	160
L4X3X5/8	13.6	409	6	1.2	196
L4X3-1/2X1/4	6.20	390	6	1.2	89
L4X3-1/2X5/16	7.70	405	6	1.2	111
L4X3-1/2X3/8	9.10	421	6	1.2	131
L4X3-1/2X1/2	11.9	451	6	1.2	171
L5X3X5/16	8.20	355	6	1.2	118
L5X3X3/8	9.80	370	6	1.2	141
L5X3X7/16	11.3	386	6	1.2	163
L5X3X1/2	12.8	401	6	1.2	184
L5X3-1/2X1/4	7.00	399	6	1.2	101
L5X3-1/2X5/16	8.70	417	6	1.2	125
L5X3-1/2X3/8	10.4	434	6	1.2	150
L5X3-1/2X1/2	13.6	468	6	1.2	196
L5X3-1/2X5/8	16.8	501	6	1.2	242
L5X3-1/2X3/4	19.8	534	6	1.2	285
L6X3-1/2X5/16	9.80	428	6	1.2	141
L6X3-1/2X3/8	11.7	448	6	1.2	168
L6X3-1/2X1/2	15.3	486	6	1.2	220

Following figure 32 shows comparison between cost of sections from the above table and compressive strength in range (350-500) kips. Some sections of 2L and 4L have comparable compressive strength to the W sections and less cost.

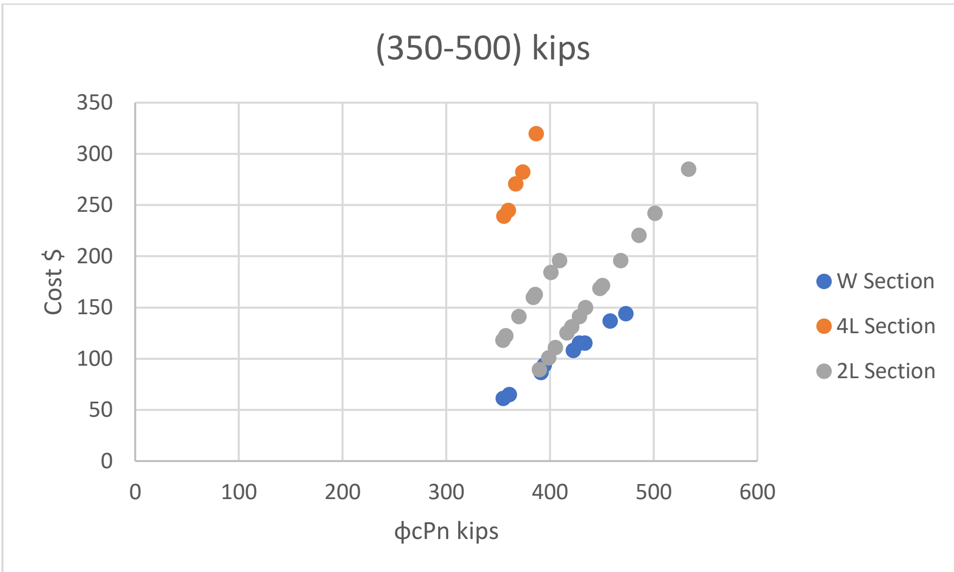

Figure 32 Column 10"x10" Strength and cost comparison for (350-400) Kips period

5.c.4 Column 11”x11”:

Figure 33 shows values for compressive strength of sections that could fit in columns with 11” by 11” cross section. Next, a comparison between sections that fall in 300-500 kips of compressive strength and its cost was conducted.

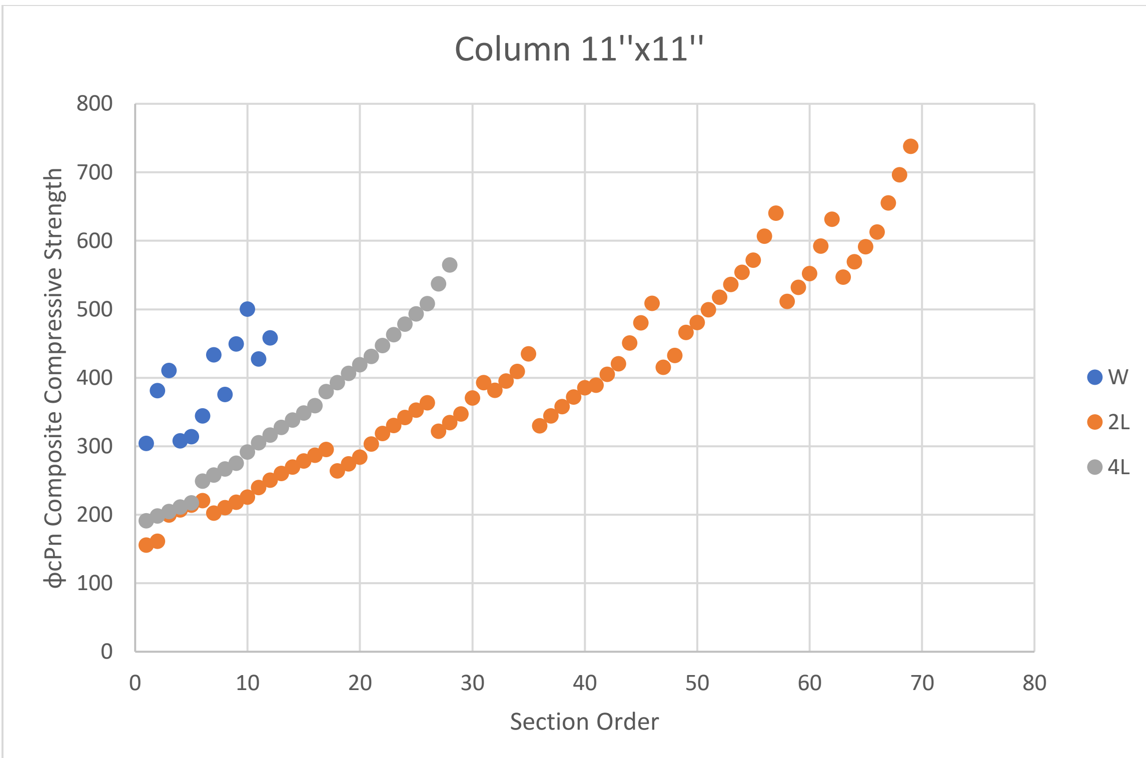

Figure 33 Column 11"x11" Strength vs Sections in ascending order per AISC

Following table 13 shows steel sections with similar compressive strength period (300-500) kips and its cost. Price of steel section is based on its length, weight and cost per pound and length – for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 13 Column 11"x11" Strength and cost comparison for (300-500) Kips period

AISC_Manual_Label	W		ϕcPn	L (ft)	$/lb/ft	Total $
W4X13	13.0		304	6	1.2	94
W5X16	16.0		381	6	1.2	115
W5X19	19.0		411	6	1.2	137
W6X8.5	8.50		308	6	1.2	61
W6X9	9.00		314	6	1.2	65
W6X12	12.0		345	6	1.2	86
W6X16	16.0		434	6	1.2	115
W6X15	15.0		376	6	1.2	108
W6X20	20.0		449	6	1.2	144
W6X25	25.0		500	6	1.2	180
W8X10	10.0		427	6	1.2	72
W8X13	13.0		458	6	1.2	94
L3X3X3/16	3.71		305	6	1.2	107
L3X3X1/4	4.90		316	6	1.2	141
L3X3X5/16	6.10		327	6	1.2	176
L3X3X3/8	7.20		338	6	1.2	207
L3X3X7/16	8.30		348	6	1.2	239
L3X3X1/2	9.40		359	6	1.2	271
L3-1/2X3-1/2X1/4	5.80		380	6	1.2	167
L3-1/2X3-1/2X5/16	7.20		393	6	1.2	207
L3-1/2X3-1/2X3/8	8.50		406	6	1.2	245
L3-1/2X3-1/2X7/16	9.80		419	6	1.2	282
L3-1/2X3-1/2X1/2	11.1		431	6	1.2	320
L4X4X1/4	6.60		447	6	1.2	190
L4X4X5/16	8.20		463	6	1.2	236
L4X4X3/8	9.80		478	6	1.2	282
L4X4X7/16	11.3		493	6	1.2	325
L4X4X1/2	12.8		508	6	1.2	369
L3-1/2X2-1/2X1/2	9.40		303	6	1.2	135
L3-1/2X3X1/4	5.40		319	6	1.2	78
L3-1/2X3X5/16	6.60		330	6	1.2	95
L3-1/2X3X3/8	7.90		342	6	1.2	114
L3-1/2X3X7/16	9.10		353	6	1.2	131
L3-1/2X3X1/2	10.2		363	6	1.2	147
L4X3X1/4	5.80		322	6	1.2	84
L4X3X5/16	7.20		335	6	1.2	104
L4X3X3/8	8.50		347	6	1.2	122
L4X3X1/2	11.1		370	6	1.2	160

L4X3X5/8	13.6		393	6	1.2	196
L4X3-1/2X1/4	6.20		382	6	1.2	89
L4X3-1/2X5/16	7.70		395	6	1.2	111
L4X3-1/2X3/8	9.10		409	6	1.2	131
L4X3-1/2X1/2	11.9		435	6	1.2	171
L5X3X1/4	6.60		330	6	1.2	95
L5X3X5/16	8.20		344	6	1.2	118
L5X3X3/8	9.80		358	6	1.2	141
L5X3X7/16	11.3		372	6	1.2	163
L5X3X1/2	12.8		385	6	1.2	184
L5X3-1/2X1/4	7.00		389	6	1.2	101
L5X3-1/2X5/16	8.70		405	6	1.2	125
L5X3-1/2X3/8	10.4		421	6	1.2	150
L5X3-1/2X1/2	13.6		451	6	1.2	196
L5X3-1/2X5/8	16.8		480	6	1.2	242
L5X3-1/2X3/4	19.8		509	6	1.2	285
L6X3-1/2X5/16	9.80		415	6	1.2	141
L6X3-1/2X3/8	11.7		433	6	1.2	168
L6X3-1/2X1/2	15.3		466	6	1.2	220
L6X4X5/16	10.3		480	6	1.2	148
L6X4X3/8	12.3		499	6	1.2	177
L6X4X7/16	14.3		518	6	1.2	206

Following figure 34 shows comparison between cost of sections from the above table and compressive strength in range (300-500) kips. Some sections of 2L and 4L have comparable compressive strength to the W sections and less cost.

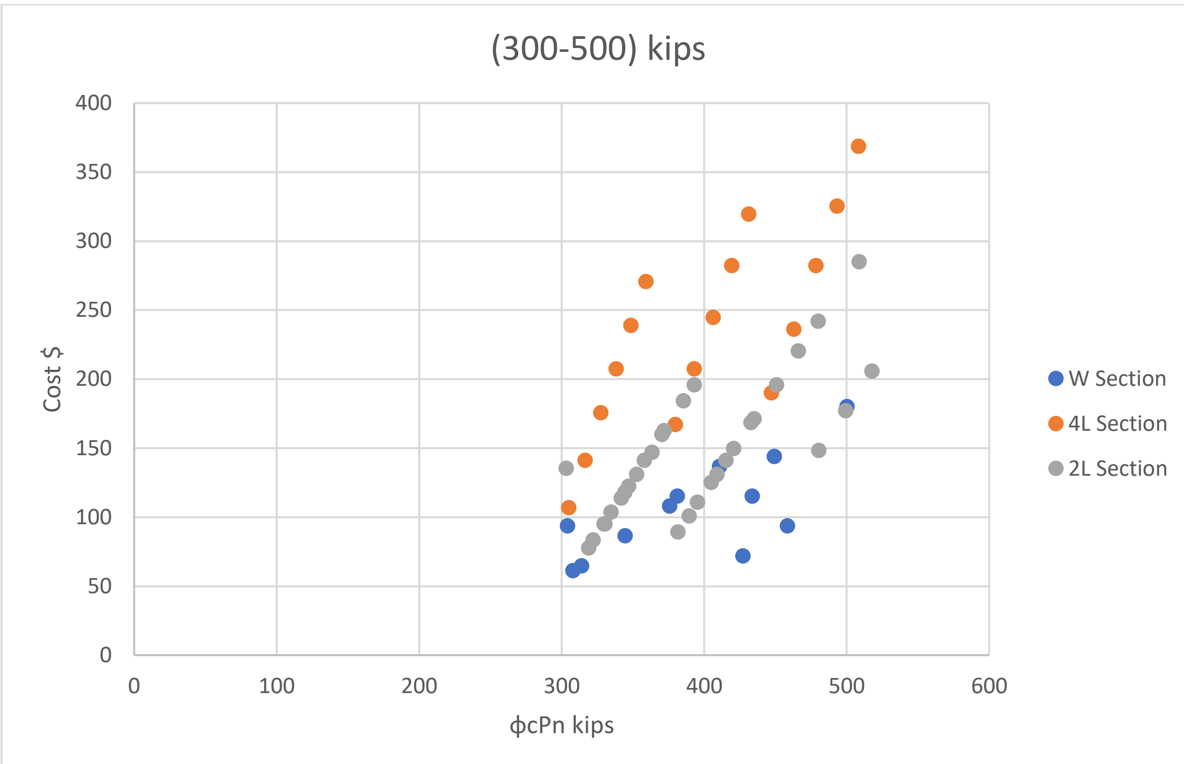

Figure 34 Column 11"x11" Strength and cost comparison for (300-500) Kips period

5.c.5 Column 13"x13":

Figure 35 shows values for compressive strength of sections that could fit in columns with 13" by 13" cross section. Next, a comparison between sections that fall in 450-650 kips of compressive strength and its cost was conducted.

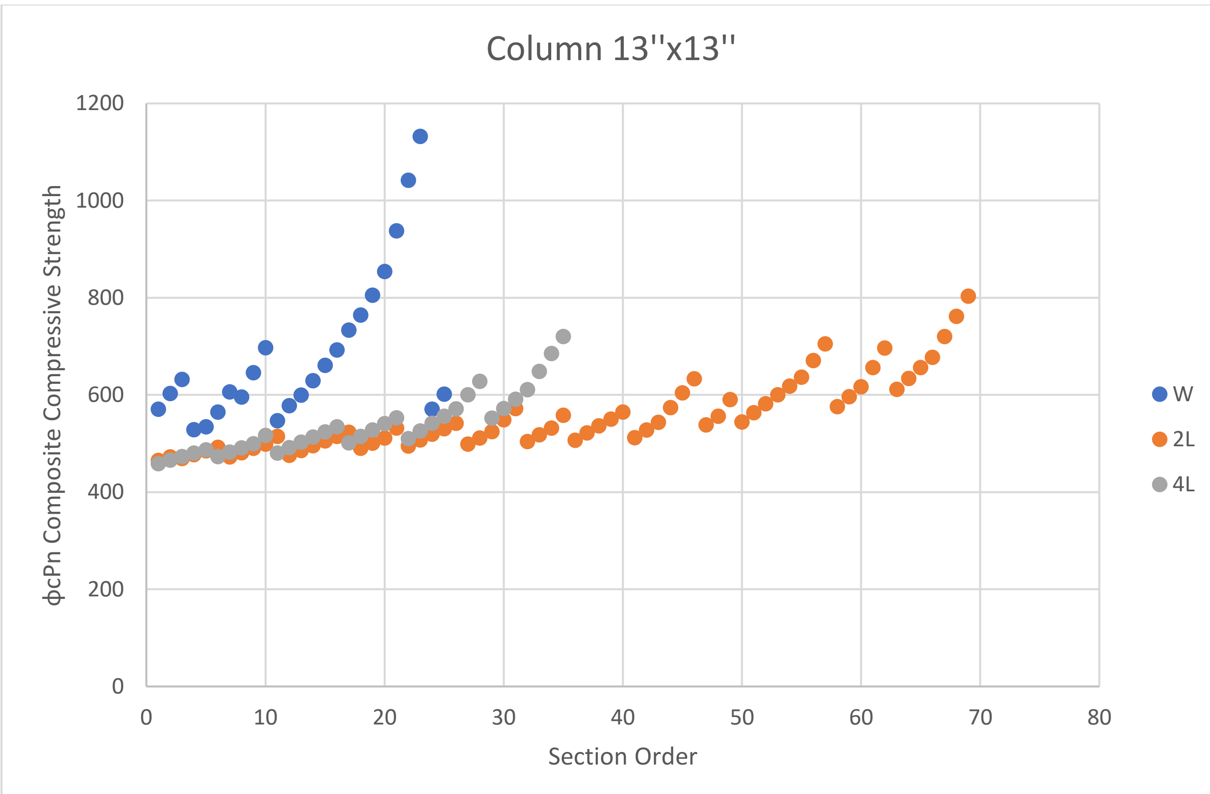

Figure 35 Column 13"x13" Strength vs Sections in ascending order per AISC

Following table 14 shows steel sections with similar compressive strength period (450-650) kips and its cost. Price of steel section is based on its length, weight and cost per pound and length – for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 14 Column 13"x13" Strength and cost comparison for (450-650) Kips period

AISC_Manual_Label	W		ϕcPn	L (ft)	$/lb/ft	Total $
W4X13	13.0		571	6	1.2	94
W5X16	16.0		603	6	1.2	115
W5X19	19.0		632	6	1.2	137
W6X8.5	8.50		528	6	1.2	61
W6X9	9.00		534	6	1.2	65
W6X12	12.0		565	6	1.2	86
W6X16	16.0		606	6	1.2	115
W6X15	15.0		595	6	1.2	108
W6X20	20.0		646	6	1.2	144
W8X10	10.0		547	6	1.2	72
W8X13	13.0		578	6	1.2	94
W8X15	15.0		600	6	1.2	108
W8X18	18.0		629	6	1.2	130
W10X12	12.0		570	6	1.2	86
W10X15	15.0		602	6	1.2	108
L2X2X1/8	1.65		459	6	1.2	48
L2X2X3/16	2.44		466	6	1.2	70
L2X2X1/4	3.19		473	6	1.2	92
L2X2X5/16	3.92		480	6	1.2	113
L2X2X3/8	4.70		487	6	1.2	135
L2-1/2X2-1/2X3/16	3.07		473	6	1.2	88
L2-1/2X2-1/2X1/4	4.10		482	6	1.2	118
L2-1/2X2-1/2X5/16	5.00		491	6	1.2	144
L2-1/2X2-1/2X3/8	5.90		500	6	1.2	170
L2-1/2X2-1/2X1/2	7.70		517	6	1.2	222
L3X3X3/16	3.71		480	6	1.2	107
L3X3X1/4	4.90		492	6	1.2	141
L3X3X5/16	6.10		503	6	1.2	176
L3X3X3/8	7.20		513	6	1.2	207
L3X3X7/16	8.30		524	6	1.2	239
L3X3X1/2	9.40		535	6	1.2	271
L3-1/2X3-1/2X1/4	5.80		501	6	1.2	167
L3-1/2X3-1/2X5/16	7.20		515	6	1.2	207
L3-1/2X3-1/2X3/8	8.50		528	6	1.2	245
L3-1/2X3-1/2X7/16	9.80		541	6	1.2	282
L3-1/2X3-1/2X1/2	11.1		553	6	1.2	320
L4X4X1/4	6.60		510	6	1.2	190
L4X4X5/16	8.20		526	6	1.2	236
L4X4X3/8	9.80		542	6	1.2	282

L4X4X7/16	11.3		556	6	1.2	325
L4X4X1/2	12.8		571	6	1.2	369
L4X4X5/8	15.7		600	6	1.2	452
L4X4X3/4	18.5		628	6	1.2	533
L5X5X5/16	10.3		552	6	1.2	297
L5X5X3/8	12.3		572	6	1.2	354
L5X5X7/16	14.3		591	6	1.2	412
L5X5X1/2	16.2		611	6	1.2	467
L5X5X5/8	20.0		649	6	1.2	576
L2-1/2X1-1/2X3/16	2.44		465	6	1.2	35
L2-1/2X1-1/2X1/4	3.19		472	6	1.2	46
L2-1/2X2X3/16	2.75		469	6	1.2	40
L2-1/2X2X1/4	3.62		477	6	1.2	52
L2-1/2X2X5/16	4.50		485	6	1.2	65
L2-1/2X2X3/8	5.30		492	6	1.2	76
L3X2X3/16	3.07		472	6	1.2	44
L3X2X1/4	4.10		481	6	1.2	59
L3X2X5/16	5.00		490	6	1.2	72
L3X2X3/8	5.90		498	6	1.2	85
L3X2X1/2	7.70		515	6	1.2	111
L3X2-1/2X3/16	3.39		476	6	1.2	49
L3X2-1/2X1/4	4.50		486	6	1.2	65
L3X2-1/2X5/16	5.60		496	6	1.2	81
L3X2-1/2X3/8	6.60		505	6	1.2	95
L3X2-1/2X7/16	7.60		515	6	1.2	109
L3X2-1/2X1/2	8.50		523	6	1.2	122
L3-1/2X2-1/2X1/4	4.90		490	6	1.2	71
L3-1/2X2-1/2X5/16	6.10		501	6	1.2	88
L3-1/2X2-1/2X3/8	7.20		511	6	1.2	104
L3-1/2X2-1/2X1/2	9.40		532	6	1.2	135
L3-1/2X3X1/4	5.40		495	6	1.2	78
L3-1/2X3X5/16	6.60		507	6	1.2	95
L3-1/2X3X3/8	7.90		519	6	1.2	114
L3-1/2X3X7/16	9.10		530	6	1.2	131
L3-1/2X3X1/2	10.2		541	6	1.2	147
L4X3X1/4	5.80		499	6	1.2	84
L4X3X5/16	7.20		511	6	1.2	104
L4X3X3/8	8.50		524	6	1.2	122
L4X3X1/2	11.1		549	6	1.2	160
L4X3X5/8	13.6		572	6	1.2	196
L4X3-1/2X1/4	6.20		504	6	1.2	89
L4X3-1/2X5/16	7.70		518	6	1.2	111

L4X3-1/2X3/8	9.10		532	6	1.2	131
L4X3-1/2X1/2	11.9		558	6	1.2	171
L5X3X1/4	6.60		507	6	1.2	95
L5X3X5/16	8.20		522	6	1.2	118
L5X3X3/8	9.80		536	6	1.2	141
L5X3X7/16	11.3		550	6	1.2	163
L5X3X1/2	12.8		564	6	1.2	184
L5X3-1/2X1/4	7.00		512	6	1.2	101
L5X3-1/2X5/16	8.70		528	6	1.2	125
L5X3-1/2X3/8	10.4		544	6	1.2	150
L5X3-1/2X1/2	13.6		574	6	1.2	196
L5X3-1/2X5/8	16.8		604	6	1.2	242
L5X3-1/2X3/4	19.8		634	6	1.2	285
L6X3-1/2X5/16	9.80		538	6	1.2	141
L6X3-1/2X3/8	11.7		556	6	1.2	168
L6X3-1/2X1/2	15.3		590	6	1.2	220
L6X4X5/16	10.3		544	6	1.2	148
L6X4X3/8	12.3		563	6	1.2	177
L6X4X7/16	14.3		582	6	1.2	206
L6X4X1/2	16.2		600	6	1.2	233
L6X4X9/16	18.1		618	6	1.2	261
L6X4X5/8	20.0		636	6	1.2	288
L7X4X3/8	13.6		576	6	1.2	196
L7X4X7/16	15.7		596	6	1.2	226
L7X4X1/2	17.9		617	6	1.2	258
L7X4X5/8	22.1		657	6	1.2	318
L8X4X7/16	17.2		611	6	1.2	248
L8X4X1/2	19.6		634	6	1.2	282
L8X4X9/16	21.9		656	6	1.2	315

Figure 36 shows comparison between cost of sections from the above table and compressive strength in range (450-650) kips. Some sections of 2L and 4L have comparable compressive strength to the W sections and less cost.

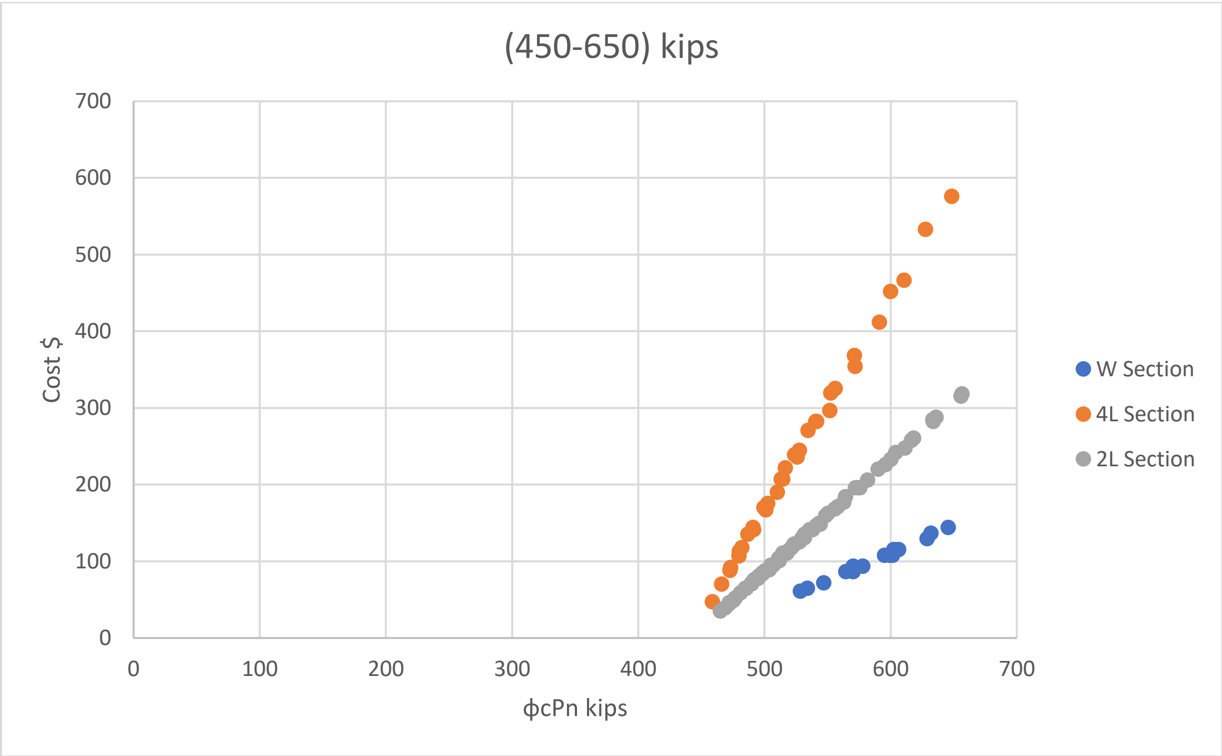

Figure 36 Column 13"x13" Strength and cost comparison for (450-650) Kips period

5.c.6 Column 15”x15”:

Following figure 37 shows values for compressive strength of sections that could fit in columns with 15” by 15” cross section. Next, a comparison between sections that fall in 600-800 kips of compressive strength and its cost was conducted.

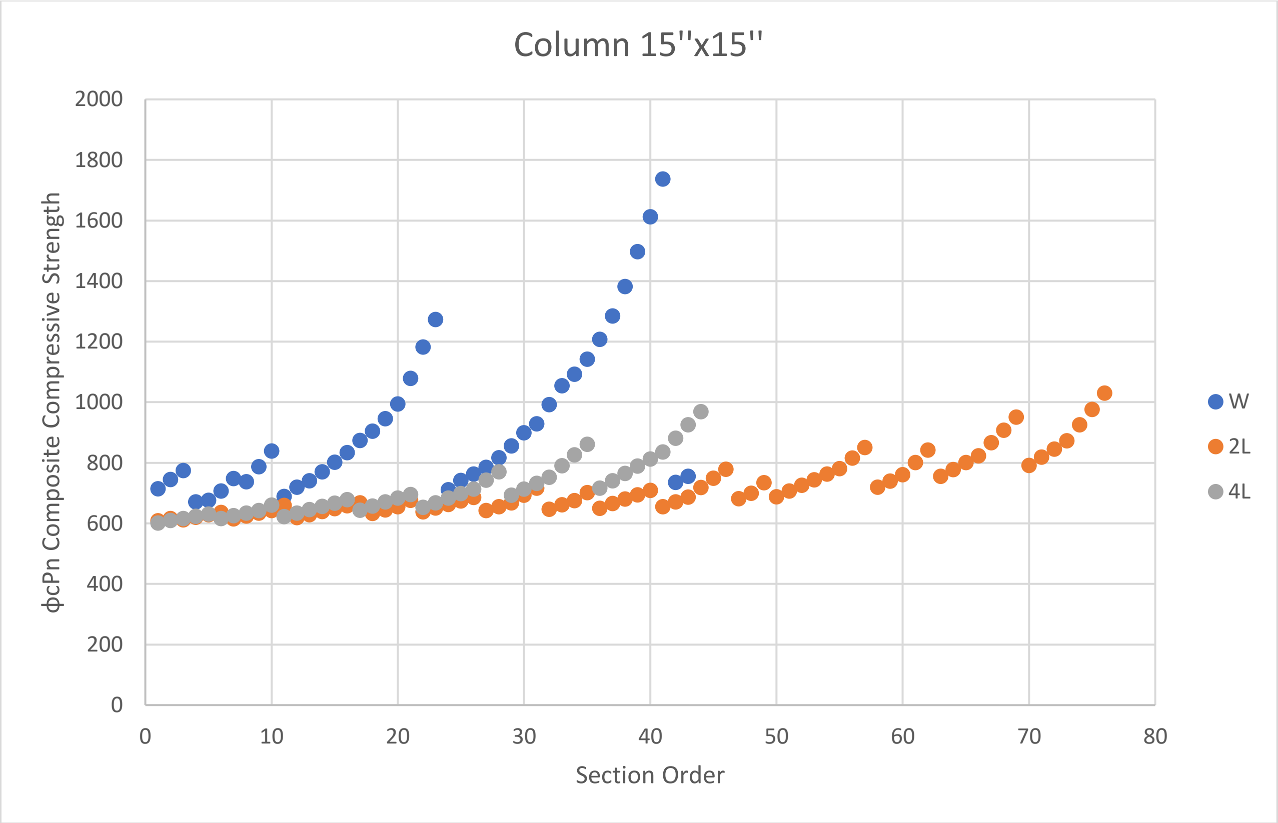

Figure 37 Column 15"x15" Strength vs Sections in ascending order per AISC

Following table 15 shows steel sections with similar compressive strength period (600-800) Kips and its cost. Price of steel section is based on its length, weight and cost per pound and length – for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 15 Column 15"x15" Strength and cost comparison for (600-800) Kips period

AISC_Manual_Label	W			ϕcPn	L (ft)	$/lb/ft	Total $
W4X13	13.0			714	6	1.2	28
W5X16	16.0			745	6	1.2	34
W5X19	19.0			775	6	1.2	40
W6X8.5	8.50			671	6	1.2	18
W6X9	9.00			676	6	1.2	19
W6X12	12.0			707	6	1.2	26
W6X16	16.0			748	6	1.2	34
W6X15	15.0			737	6	1.2	32
W6X20	20.0			787	6	1.2	42
W8X10	10.0			688	6	1.2	21
W8X13	13.0			719	6	1.2	28
W8X15	15.0			740	6	1.2	32
W8X18	18.0			770	6	1.2	38
W8X21	21.0			802	6	1.2	44
W10X12	12.0			711	6	1.2	25
W10X15	15.0			742	6	1.2	32
W10X17	17.0			763	6	1.2	36
W10X19	19.0			785	6	1.2	40
W10X22	22.0			816	6	1.2	47
W12X14	14.0			735	6	1.2	30
W12X16	16.0			755	6	1.2	34
L2X2X1/8	1.65			602	6	1.2	14
L2X2X3/16	2.44			609	6	1.2	21
L2X2X1/4	3.19			616	6	1.2	27
L2X2X5/16	3.92			623	6	1.2	33
L2X2X3/8	4.70			630	6	1.2	39
L2-1/2X2-1/2X3/16	3.07			616	6	1.2	26
L2-1/2X2-1/2X1/4	4.10			625	6	1.2	34
L2-1/2X2-1/2X5/16	5.00			634	6	1.2	42
L2-1/2X2-1/2X3/8	5.90			643	6	1.2	50
L2-1/2X2-1/2X1/2	7.70			660	6	1.2	65
L3X3X3/16	3.71			623	6	1.2	31
L3X3X1/4	4.90			634	6	1.2	41
L3X3X5/16	6.10			645	6	1.2	51
L3X3X3/8	7.20			656	6	1.2	61
L3X3X7/16	8.30			667	6	1.2	70
L3X3X1/2	9.40			678	6	1.2	79
L3-1/2X3-1/2X1/4	5.80			644	6	1.2	49
L3-1/2X3-1/2X5/16	7.20			657	6	1.2	60

L3-1/2X3-1/2X3/8	8.50			670	6	1.2	72
L3-1/2X3-1/2X7/16	9.80			683	6	1.2	83
L3-1/2X3-1/2X1/2	11.1			695	6	1.2	94
L4X4X1/4	6.60			652	6	1.2	56
L4X4X5/16	8.20			668	6	1.2	69
L4X4X3/8	9.80			684	6	1.2	82
L4X4X7/16	11.3			698	6	1.2	95
L4X4X1/2	12.8			714	6	1.2	108
L4X4X5/8	15.7			742	6	1.2	133
L4X4X3/4	18.5			770	6	1.2	157
L5X5X5/16	10.3			693	6	1.2	88
L5X5X3/8	12.3			713	6	1.2	105
L5X5X7/16	14.3			733	6	1.2	122
L5X5X1/2	16.2			752	6	1.2	138
L5X5X5/8	20.0			790	6	1.2	170
L6X6X5/16	12.4			716	6	1.2	106
L6X6X3/8	14.9			741	6	1.2	126
L6X6X7/16	17.2			765	6	1.2	146
L6X6X1/2	19.6			789	6	1.2	166
L6X6X9/16	21.9			812	6	1.2	186
L2-1/2X1-1/2X3/16	2.44			608	6	1.2	10
L2-1/2X1-1/2X1/4	3.19			616	6	1.2	14
L2-1/2X2X3/16	2.75			612	6	1.2	12
L2-1/2X2X1/4	3.62			620	6	1.2	15
L2-1/2X2X5/16	4.50			628	6	1.2	19
L2-1/2X2X3/8	5.30			636	6	1.2	22
L3X2X3/16	3.07			615	6	1.2	13
L3X2X1/4	4.10			624	6	1.2	17
L3X2X5/16	5.00			634	6	1.2	21
L3X2X3/8	5.90			642	6	1.2	25
L3X2X1/2	7.70			659	6	1.2	33
L3X2-1/2X3/16	3.39			619	6	1.2	14
L3X2-1/2X1/4	4.50			629	6	1.2	19
L3X2-1/2X5/16	5.60			639	6	1.2	23
L3X2-1/2X3/8	6.60			649	6	1.2	28
L3X2-1/2X7/16	7.60			658	6	1.2	32
L3X2-1/2X1/2	8.50			667	6	1.2	36
L3-1/2X2-1/2X1/4	4.90			633	6	1.2	21
L3-1/2X2-1/2X5/16	6.10			644	6	1.2	26
L3-1/2X2-1/2X3/8	7.20			655	6	1.2	31
L3-1/2X2-1/2X1/2	9.40			676	6	1.2	40
L3-1/2X3X1/4	5.40			638	6	1.2	23

L3-1/2X3X5/16	6.60			650	6	1.2	28
L3-1/2X3X3/8	7.90			662	6	1.2	33
L3-1/2X3X7/16	9.10			674	6	1.2	38
L3-1/2X3X1/2	10.2			685	6	1.2	43
L4X3X1/4	5.80			642	6	1.2	24
L4X3X5/16	7.20			655	6	1.2	30
L4X3X3/8	8.50			668	6	1.2	36
L4X3X1/2	11.1			693	6	1.2	47
L4X3X5/8	13.6			717	6	1.2	57
L4X3-1/2X1/4	6.20			647	6	1.2	26
L4X3-1/2X5/16	7.70			661	6	1.2	32
L4X3-1/2X3/8	9.10			675	6	1.2	39
L4X3-1/2X1/2	11.9			702	6	1.2	50
L5X3X1/4	6.60			650	6	1.2	28
L5X3X5/16	8.20			665	6	1.2	35
L5X3X3/8	9.80			680	6	1.2	41
L5X3X7/16	11.3			695	6	1.2	48
L5X3X1/2	12.8			709	6	1.2	54
L5X3-1/2X1/4	7.00			655	6	1.2	30
L5X3-1/2X5/16	8.70			671	6	1.2	37
L5X3-1/2X3/8	10.4			687	6	1.2	44
L5X3-1/2X1/2	13.6			718	6	1.2	58
L5X3-1/2X5/8	16.8			749	6	1.2	71
L5X3-1/2X3/4	19.8			778	6	1.2	84
L6X3-1/2X5/16	9.80			682	6	1.2	42
L6X3-1/2X3/8	11.7			700	6	1.2	50
L6X3-1/2X1/2	15.3			734	6	1.2	65
L6X4X5/16	10.3			687	6	1.2	44
L6X4X3/8	12.3			707	6	1.2	52
L6X4X7/16	14.3			725	6	1.2	60
L6X4X1/2	16.2			744	6	1.2	68
L6X4X9/16	18.1			762	6	1.2	76
L6X4X5/8	20.0			780	6	1.2	84
L7X4X3/8	13.6			719	6	1.2	58
L7X4X7/16	15.7			740	6	1.2	67
L7X4X1/2	17.9			761	6	1.2	76
L7X4X5/8	22.1			801	6	1.2	94
L8X4X7/16	17.2			756	6	1.2	74
L8X4X1/2	19.6			778	6	1.2	84
L8X4X9/16	21.9			801	6	1.2	93
L8X6X7/16	20.2			791	6	1.2	86

Figure 38 shows comparison between cost of sections from the above table and compressive strength in range (600-800) Kips. Some sections of 2L and 4L have comparable compressive strength to the W sections and less cost.

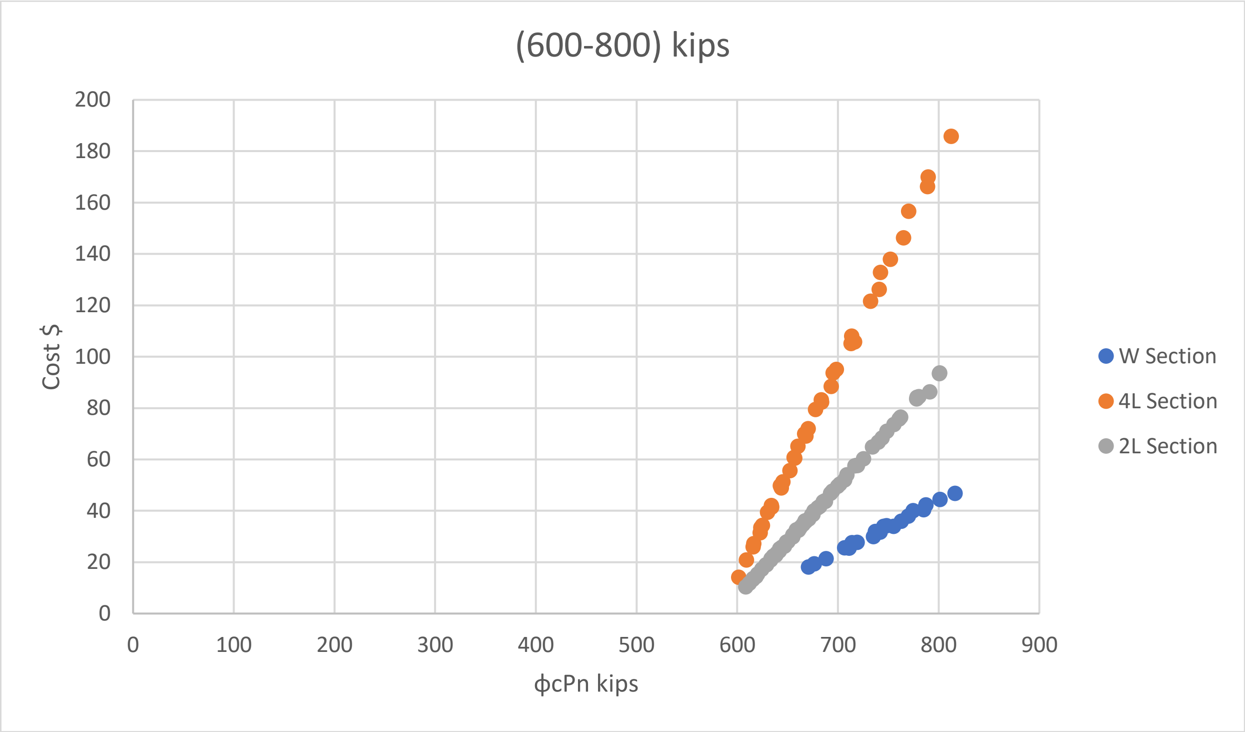

Figure 38 Column 15"x15" Strength and cost comparison for (600-800) Kips period

5.c.7 Column 20”x20”:

Following figure 39 shows values for compressive strength of sections that could fit in columns with 20” by 20” cross section. Next, a comparison between sections that fall in 1000-1500 kips of compressive strength and its cost was conducted.

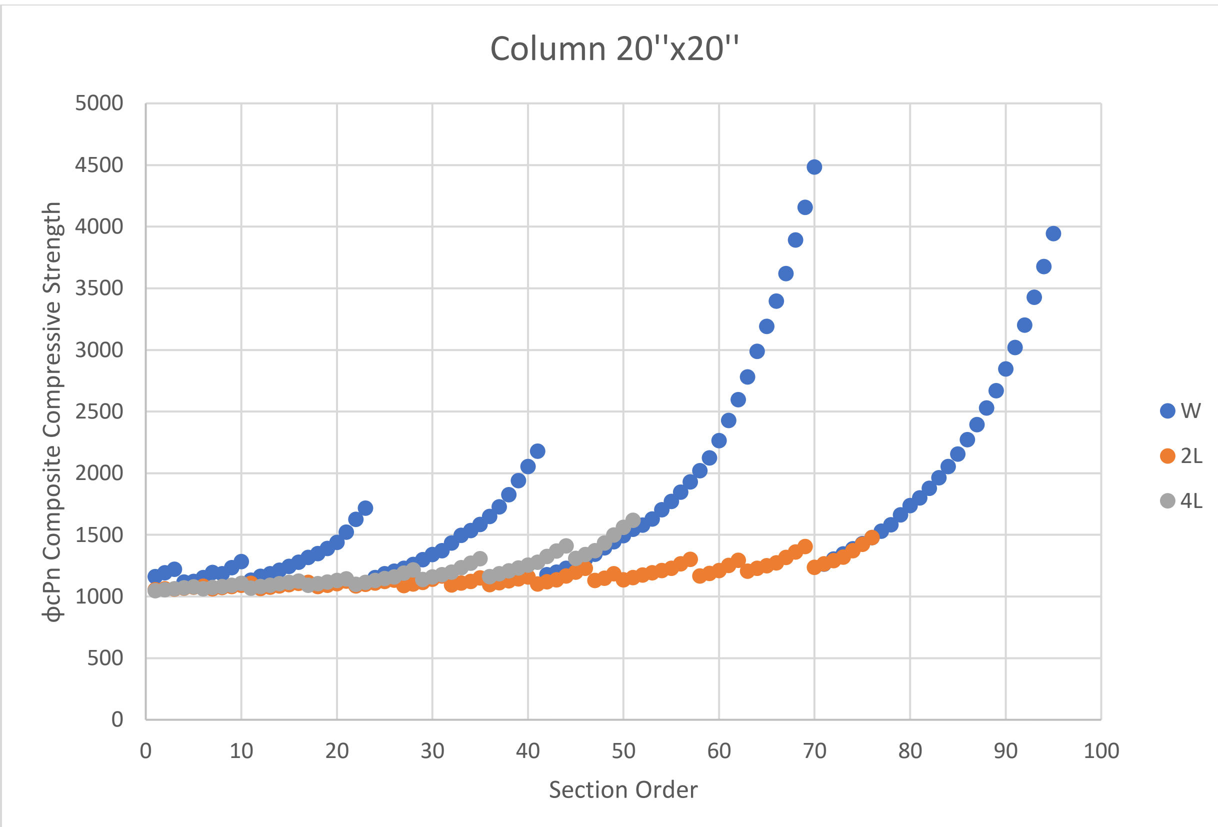

Figure 39 Column 20"x20" Strength vs Sections in ascending order per AISC

Following table 16 shows steel sections with similar compressive strength period (1000-1500) Kips and its cost. Price of steel section is based on its length, weight and cost per pound and length – for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 16 Column 20"x20" Strength and cost comparison for (1000-1500) Kips period

AISC_Manual_Label	W		ϕcPn	L (ft)	$/lb/ft	Total $
W4X13	13.0		1161	6	1.2	94
W5X16	16.0		1192	6	1.2	115
W5X19	19.0		1221	6	1.2	137
W6X8.5	8.50		1117	6	1.2	61
W6X9	9.00		1123	6	1.2	65
W6X12	12.0		1153	6	1.2	86
W6X16	16.0		1194	6	1.2	115
W6X15	15.0		1183	6	1.2	108
W6X20	20.0		1233	6	1.2	144
W6X25	25.0		1284	6	1.2	180
W8X10	10.0		1133	6	1.2	72
W8X13	13.0		1164	6	1.2	94
W8X15	15.0		1185	6	1.2	108
W8X18	18.0		1214	6	1.2	130
W8X21	21.0		1245	6	1.2	151
W8X24	24.0		1277	6	1.2	173
W8X28	28.0		1318	6	1.2	202
W8X31	31.0		1348	6	1.2	223
W8X35	35.0		1389	6	1.2	252
W8X40	40.0		1438	6	1.2	288
W8X48	48.0		1521	6	1.2	346
W10X12	12.0		1154	6	1.2	86
W10X15	15.0		1185	6	1.2	108
W10X17	17.0		1205	6	1.2	122
W10X19	19.0		1228	6	1.2	137
W10X22	22.0		1258	6	1.2	158
W10X26	26.0		1298	6	1.2	187
W10X30	30.0		1341	6	1.2	216
W10X33	33.0		1371	6	1.2	238
W10X39	39.0		1433	6	1.2	281
W10X45	45.0		1496	6	1.2	324
W10X49	49.0		1535	6	1.2	353
W12X14	14.0		1177	6	1.2	101
W12X16	16.0		1197	6	1.2	115
W12X19	19.0		1228	6	1.2	137
W12X22	22.0		1260	6	1.2	158
W12X26	26.0		1302	6	1.2	187
W12X30	30.0		1342	6	1.2	216
W12X35	35.0		1395	6	1.2	252
W12X40	40.0		1443	6	1.2	288

W12X45	45.0		1492	6	1.2	324
W12X50	50.0		1545	6	1.2	360
W14X22	22.0		1262	6	1.2	158
W14X26	26.0		1304	6	1.2	187
W14X30	30.0		1345	6	1.2	216
W14X34	34.0		1386	6	1.2	245
W14X38	38.0		1428	6	1.2	274
W14X43	43.0		1477	6	1.2	310
W14X48	48.0		1530	6	1.2	346
L2X2X1/8	1.65		1048	6	1.2	48
L2X2X3/16	2.44		1056	6	1.2	70
L2X2X1/4	3.19		1063	6	1.2	92
L2X2X5/16	3.92		1070	6	1.2	113
L2X2X3/8	4.70		1077	6	1.2	135
L2-1/2X2-1/2X3/16	3.07		1062	6	1.2	88
L2-1/2X2-1/2X1/4	4.10		1072	6	1.2	118
L2-1/2X2-1/2X5/16	5.00		1081	6	1.2	144
L2-1/2X2-1/2X3/8	5.90		1090	6	1.2	170
L2-1/2X2-1/2X1/2	7.70		1108	6	1.2	222
L3X3X3/16	3.71		1069	6	1.2	107
L3X3X1/4	4.90		1081	6	1.2	141
L3X3X5/16	6.10		1092	6	1.2	176
L3X3X3/8	7.20		1103	6	1.2	207
L3X3X7/16	8.30		1114	6	1.2	239
L3X3X1/2	9.40		1125	6	1.2	271
L3-1/2X3-1/2X1/4	5.80		1090	6	1.2	167
L3-1/2X3-1/2X5/16	7.20		1103	6	1.2	207
L3-1/2X3-1/2X3/8	8.50		1117	6	1.2	245
L3-1/2X3-1/2X7/16	9.80		1130	6	1.2	282
L3-1/2X3-1/2X1/2	11.1		1142	6	1.2	320
L4X4X1/4	6.60		1098	6	1.2	190
L4X4X5/16	8.20		1114	6	1.2	236
L4X4X3/8	9.80		1130	6	1.2	282
L4X4X7/16	11.3		1144	6	1.2	325
L4X4X1/2	12.8		1160	6	1.2	369
L4X4X5/8	15.7		1189	6	1.2	452
L4X4X3/4	18.5		1217	6	1.2	533
L5X5X5/16	10.3		1138	6	1.2	297
L5X5X3/8	12.3		1158	6	1.2	354
L5X5X7/16	14.3		1177	6	1.2	412
L5X5X1/2	16.2		1197	6	1.2	467
L5X5X5/8	20.0		1234	6	1.2	576

L5X5X3/4	23.6		1271	6	1.2	680
L5X5X7/8	27.2		1306	6	1.2	783
L6X6X5/16	12.4		1160	6	1.2	357
L6X6X3/8	14.9		1184	6	1.2	429
L6X6X7/16	17.2		1208	6	1.2	495
L6X6X1/2	19.6		1232	6	1.2	564
L6X6X9/16	21.9		1255	6	1.2	631
L6X6X5/8	24.2		1279	6	1.2	697
L6X6X3/4	28.7		1324	6	1.2	827
L6X6X7/8	33.1		1369	6	1.2	953
L6X6X1	37.4		1411	6	1.2	1077
L8X8X1/2	26.4		1308	6	1.2	760
L8X8X9/16	29.6		1340	6	1.2	852
L8X8X5/8	32.7		1372	6	1.2	942
L8X8X3/4	38.9		1435	6	1.2	1120
L8X8X7/8	45.0		1497	6	1.2	1296
L8X8X1	51.0		1559	6	1.2	1469
L2-1/2X1-1/2X3/16	2.44		1055	6	1.2	35
L2-1/2X1-1/2X1/4	3.19		1063	6	1.2	46
L2-1/2X2X3/16	2.75		1059	6	1.2	40
L2-1/2X2X1/4	3.62		1067	6	1.2	52
L2-1/2X2X5/16	4.50		1076	6	1.2	65
L2-1/2X2X3/8	5.30		1083	6	1.2	76
L3X2X3/16	3.07		1062	6	1.2	44
L3X2X1/4	4.10		1072	6	1.2	59
L3X2X5/16	5.00		1081	6	1.2	72
L3X2X3/8	5.90		1090	6	1.2	85
L3X2X1/2	7.70		1107	6	1.2	111
L3X2-1/2X3/16	3.39		1065	6	1.2	49
L3X2-1/2X1/4	4.50		1076	6	1.2	65
L3X2-1/2X5/16	5.60		1086	6	1.2	81
L3X2-1/2X3/8	6.60		1096	6	1.2	95
L3X2-1/2X7/16	7.60		1106	6	1.2	109
L3X2-1/2X1/2	8.50		1115	6	1.2	122
L3-1/2X2-1/2X1/4	4.90		1080	6	1.2	71
L3-1/2X2-1/2X5/16	6.10		1092	6	1.2	88
L3-1/2X2-1/2X3/8	7.20		1103	6	1.2	104
L3-1/2X2-1/2X1/2	9.40		1124	6	1.2	135
L3-1/2X3X1/4	5.40		1085	6	1.2	78
L3-1/2X3X5/16	6.60		1097	6	1.2	95
L3-1/2X3X3/8	7.90		1110	6	1.2	114
L3-1/2X3X7/16	9.10		1122	6	1.2	131

L3-1/2X3X1/2	10.2		1133	6	1.2	147
L4X3X1/4	5.80		1089	6	1.2	84
L4X3X5/16	7.20		1102	6	1.2	104
L4X3X3/8	8.50		1116	6	1.2	122
L4X3X1/2	11.1		1141	6	1.2	160
L4X3X5/8	13.6		1166	6	1.2	196
L4X3-1/2X1/4	6.20		1093	6	1.2	89
L4X3-1/2X5/16	7.70		1108	6	1.2	111
L4X3-1/2X3/8	9.10		1122	6	1.2	131
L4X3-1/2X1/2	11.9		1150	6	1.2	171
L5X3X1/4	6.60		1097	6	1.2	95
L5X3X5/16	8.20		1113	6	1.2	118
L5X3X3/8	9.80		1128	6	1.2	141
L5X3X7/16	11.3		1143	6	1.2	163
L5X3X1/2	12.8		1158	6	1.2	184
L5X3-1/2X1/4	7.00		1102	6	1.2	101
L5X3-1/2X5/16	8.70		1118	6	1.2	125
L5X3-1/2X3/8	10.4		1135	6	1.2	150
L5X3-1/2X1/2	13.6		1167	6	1.2	196
L5X3-1/2X5/8	16.8		1198	6	1.2	242
L5X3-1/2X3/4	19.8		1229	6	1.2	285
L6X3-1/2X5/16	9.80		1129	6	1.2	141
L6X3-1/2X3/8	11.7		1148	6	1.2	168
L6X3-1/2X1/2	15.3		1183	6	1.2	220
L6X4X5/16	10.3		1135	6	1.2	148
L6X4X3/8	12.3		1154	6	1.2	177
L6X4X7/16	14.3		1173	6	1.2	206
L6X4X1/2	16.2		1192	6	1.2	233
L6X4X9/16	18.1		1211	6	1.2	261
L6X4X5/8	20.0		1230	6	1.2	288
L6X4X3/4	23.6		1266	6	1.2	340
L6X4X7/8	27.2		1301	6	1.2	392
L7X4X3/8	13.6		1167	6	1.2	196
L7X4X7/16	15.7		1188	6	1.2	226
L7X4X1/2	17.9		1209	6	1.2	258
L7X4X5/8	22.1		1251	6	1.2	318
L7X4X3/4	26.2		1292	6	1.2	377
L8X4X7/16	17.2		1204	6	1.2	248
L8X4X1/2	19.6		1227	6	1.2	282
L8X4X9/16	21.9		1251	6	1.2	315
L8X4X5/8	24.2		1273	6	1.2	348
L8X4X3/4	28.7		1317	6	1.2	413
L8X4X7/8	33.1		1361	6	1.2	477

L8X4X1	37.4		1405	6	1.2	539
L8X6X7/16	20.2		1237	6	1.2	291
L8X6X1/2	23.0		1264	6	1.2	331
L8X6X9/16	25.7		1292	6	1.2	370
L8X6X5/8	28.5		1319	6	1.2	410
L8X6X3/4	33.8		1372	6	1.2	487
L8X6X7/8	39.1		1424	6	1.2	563
L8X6X1	44.2		1478	6	1.2	636

Figure 40 shows comparison between cost of sections from the above table and compressive strength in range (1000-1500) Kips. Some sections of 2L and 4L have comparable compressive strength to the W sections and less cost.

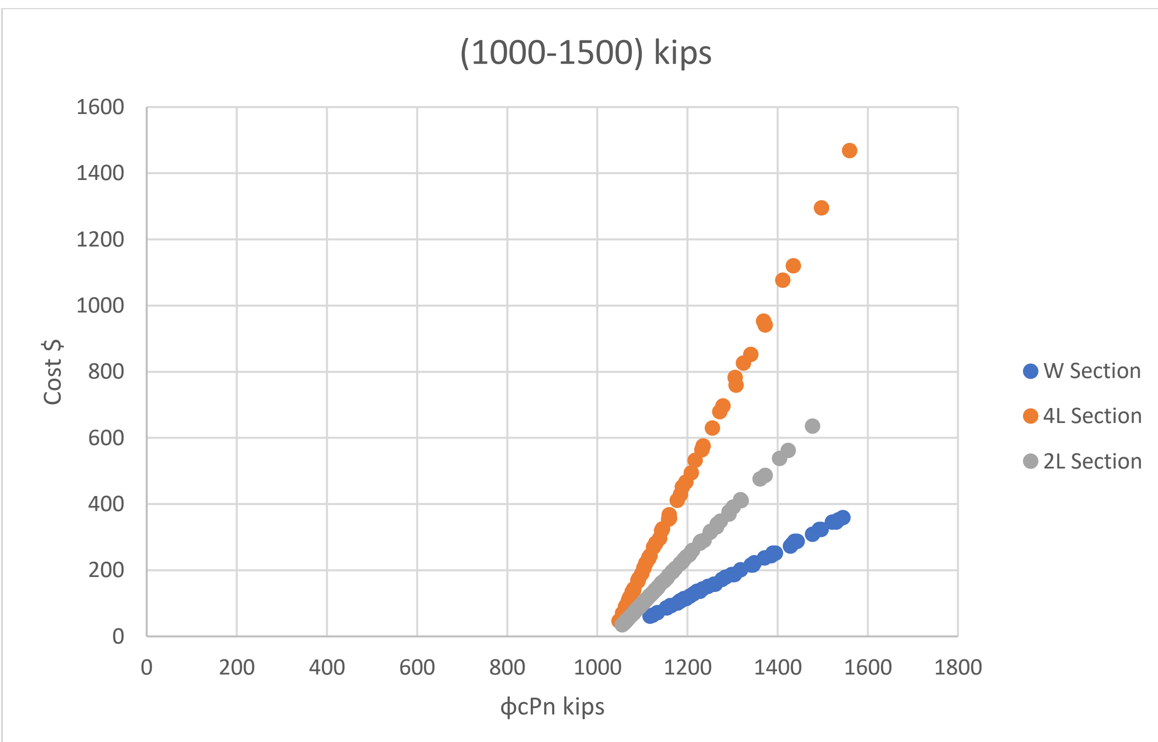

Figure 40 Column 20”x20” Strength and cost comparison for (1000-1500) Kips period

7.c.8 Column 25"x25":

Following figure 41 shows values for compressive strength of sections that could fit in columns with 25" by 25" cross section. Next, a comparison between sections that fall in 1500-2000 kips of compressive strength and its cost was conducted.

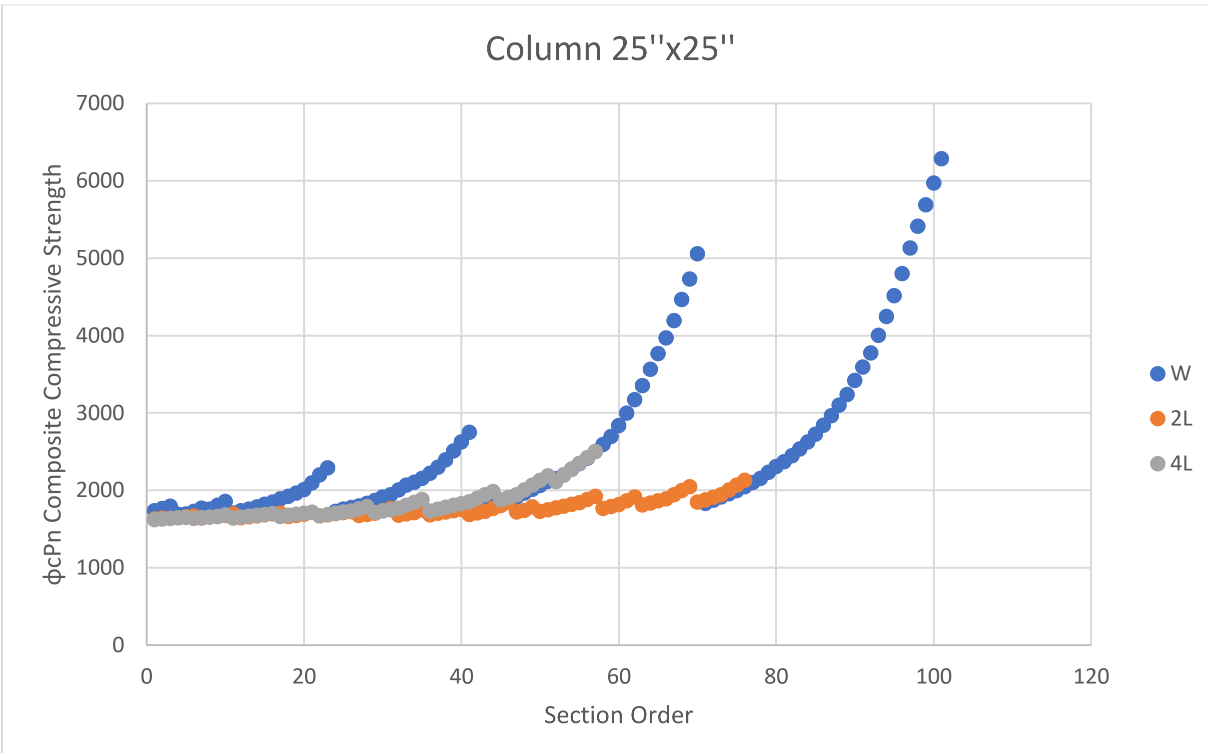

Figure 41 Column 25"x25" Strength vs Sections in ascending order per AISC

Following table 17 shows steel sections with similar compressive strength period (1500-2000) Kips and its cost. Price of steel section is based on its length, weight and cost per pound and length – for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 17 Column 25”x25” Strength and cost comparison for (1500-2000) Kips period

AISC_Manual_Label	W		ϕcPn	L (ft)	$/lb/ft	Total $
W4X13	13.0		1736	6	1.2	94
W5X16	16.0		1767	6	1.2	115
W5X19	19.0		1796	6	1.2	137
W6X8.5	8.50		1691	6	1.2	61
W6X9	9.00		1697	6	1.2	65
W6X12	12.0		1727	6	1.2	86
W6X16	16.0		1768	6	1.2	115
W6X15	15.0		1757	6	1.2	108
W6X20	20.0		1807	6	1.2	144
W6X25	25.0		1858	6	1.2	180
W8X10	10.0		1707	6	1.2	72
W8X13	13.0		1737	6	1.2	94
W8X15	15.0		1758	6	1.2	108
W8X18	18.0		1787	6	1.2	130
W8X21	21.0		1818	6	1.2	151
W8X24	24.0		1850	6	1.2	173
W8X28	28.0		1891	6	1.2	202
W8X31	31.0		1921	6	1.2	223
W8X35	35.0		1962	6	1.2	252
W8X40	40.0		2011	6	1.2	288
W10X12	12.0		1727	6	1.2	86
W10X15	15.0		1758	6	1.2	108
W10X17	17.0		1778	6	1.2	122
W10X19	19.0		1800	6	1.2	137
W10X22	22.0		1831	6	1.2	158
W10X26	26.0		1870	6	1.2	187
W10X30	30.0		1913	6	1.2	216
W10X33	33.0		1943	6	1.2	238
W10X39	39.0		2005	6	1.2	281
W12X14	14.0		1750	6	1.2	101
W12X16	16.0		1769	6	1.2	115
W12X19	19.0		1799	6	1.2	137
W12X22	22.0		1831	6	1.2	158
W12X26	26.0		1873	6	1.2	187
W12X30	30.0		1913	6	1.2	216
W12X35	35.0		1965	6	1.2	252
W12X40	40.0		2014	6	1.2	288
W14X22	22.0		1833	6	1.2	158
W14X26	26.0		1875	6	1.2	187
W14X30	30.0		1916	6	1.2	216

W14X34	34.0		1956	6	1.2	245
W14X38	38.0		1998	6	1.2	274
W14X43	43.0		2047	6	1.2	310
L2X2X1/8	1.65		1622	6	1.2	48
L2X2X3/16	2.44		1629	6	1.2	70
L2X2X1/4	3.19		1637	6	1.2	92
L2X2X5/16	3.92		1644	6	1.2	113
L2X2X3/8	4.70		1651	6	1.2	135
L2-1/2X2-1/2X3/16	3.07		1636	6	1.2	88
L2-1/2X2-1/2X1/4	4.10		1646	6	1.2	118
L2-1/2X2-1/2X5/16	5.00		1655	6	1.2	144
L2-1/2X2-1/2X3/8	5.90		1664	6	1.2	170
L2-1/2X2-1/2X1/2	7.70		1682	6	1.2	222
L3X3X3/16	3.71		1642	6	1.2	107
L3X3X1/4	4.90		1654	6	1.2	141
L3X3X5/16	6.10		1666	6	1.2	176
L3X3X3/8	7.20		1677	6	1.2	207
L3X3X7/16	8.30		1688	6	1.2	239
L3X3X1/2	9.40		1699	6	1.2	271
L3-1/2X3-1/2X1/4	5.80		1664	6	1.2	167
L3-1/2X3-1/2X5/16	7.20		1677	6	1.2	207
L3-1/2X3-1/2X3/8	8.50		1691	6	1.2	245
L3-1/2X3-1/2X7/16	9.80		1704	6	1.2	282
L3-1/2X3-1/2X1/2	11.1		1716	6	1.2	320
L4X4X1/4	6.60		1672	6	1.2	190
L4X4X5/16	8.20		1688	6	1.2	236
L4X4X3/8	9.80		1703	6	1.2	282
L4X4X7/16	11.3		1718	6	1.2	325
L4X4X1/2	12.8		1734	6	1.2	369
L4X4X5/8	15.7		1763	6	1.2	452
L4X4X3/4	18.5		1791	6	1.2	533
L5X5X5/16	10.3		1711	6	1.2	297
L5X5X3/8	12.3		1731	6	1.2	354
L5X5X7/16	14.3		1751	6	1.2	412
L5X5X1/2	16.2		1770	6	1.2	467
L5X5X5/8	20.0		1808	6	1.2	576
L5X5X3/4	23.6		1845	6	1.2	680
L5X5X7/8	27.2		1880	6	1.2	783
L6X6X5/16	12.4		1733	6	1.2	357
L6X6X3/8	14.9		1757	6	1.2	429
L6X6X7/16	17.2		1781	6	1.2	495
L6X6X1/2	19.6		1805	6	1.2	564

L6X6X9/16	21.9		1828	6	1.2	631
L6X6X5/8	24.2		1852	6	1.2	697
L6X6X3/4	28.7		1897	6	1.2	827
L6X6X7/8	33.1		1942	6	1.2	953
L6X6X1	37.4		1985	6	1.2	1077
L8X8X1/2	26.4		1879	6	1.2	760
L8X8X9/16	29.6		1911	6	1.2	852
L8X8X5/8	32.7		1943	6	1.2	942
L8X8X3/4	38.9		2006	6	1.2	1120
L8X8X7/8	45.0		2068	6	1.2	1296
L2-1/2X1-1/2X3/16	2.44		1629	6	1.2	35
L2-1/2X1-1/2X1/4	3.19		1642	6	1.2	46
L2-1/2X2X3/16	2.75		1637	6	1.2	40
L2-1/2X2X1/4	3.62		1648	6	1.2	52
L2-1/2X2X5/16	4.50		1657	6	1.2	65
L2-1/2X2X3/8	5.30		1667	6	1.2	76
L3X2X3/16	3.07		1641	6	1.2	44
L3X2X1/4	4.10		1653	6	1.2	59
L3X2X5/16	5.00		1664	6	1.2	72
L3X2X3/8	5.90		1675	6	1.2	85
L3X2X1/2	7.70		1695	6	1.2	111
L3X2-1/2X3/16	3.39		1645	6	1.2	49
L3X2-1/2X1/4	4.50		1658	6	1.2	65
L3X2-1/2X5/16	5.60		1670	6	1.2	81
L3X2-1/2X3/8	6.60		1682	6	1.2	95
L3X2-1/2X7/16	7.60		1694	6	1.2	109
L3X2-1/2X1/2	8.50		1705	6	1.2	122
L3-1/2X2-1/2X1/4	4.90		1663	6	1.2	71
L3-1/2X2-1/2X5/16	6.10		1676	6	1.2	88
L3-1/2X2-1/2X3/8	7.20		1690	6	1.2	104
L3-1/2X2-1/2X1/2	9.40		1715	6	1.2	135
L3-1/2X3X1/4	5.40		1668	6	1.2	78
L3-1/2X3X5/16	6.60		1683	6	1.2	95
L3-1/2X3X3/8	7.90		1698	6	1.2	114
L3-1/2X3X7/16	9.10		1712	6	1.2	131
L3-1/2X3X1/2	10.2		1726	6	1.2	147
L4X3X1/4	5.80		1673	6	1.2	84
L4X3X5/16	7.20		1689	6	1.2	104
L4X3X3/8	8.50		1705	6	1.2	122
L4X3X1/2	11.1		1735	6	1.2	160
L4X3X5/8	13.6		1764	6	1.2	196
L4X3-1/2X1/4	6.20		1678	6	1.2	89

L4X3-1/2X5/16	7.70		1695	6	1.2	111
L4X3-1/2X3/8	9.10		1712	6	1.2	131
L4X3-1/2X1/2	11.9		1745	6	1.2	171
L5X3X1/4	6.60		1683	6	1.2	95
L5X3X5/16	8.20		1701	6	1.2	118
L5X3X3/8	9.80		1719	6	1.2	141
L5X3X7/16	11.3		1737	6	1.2	163
L5X3X1/2	12.8		1755	6	1.2	184
L5X3-1/2X1/4	7.00		1688	6	1.2	101
L5X3-1/2X5/16	8.70		1708	6	1.2	125
L5X3-1/2X3/8	10.4		1727	6	1.2	150
L5X3-1/2X1/2	13.6		1765	6	1.2	196
L5X3-1/2X5/8	16.8		1802	6	1.2	242
L5X3-1/2X3/4	19.8		1838	6	1.2	285
L6X3-1/2X5/16	9.80		1721	6	1.2	141
L6X3-1/2X3/8	11.7		1743	6	1.2	168
L6X3-1/2X1/2	15.3		1785	6	1.2	220
L6X4X5/16	10.3		1727	6	1.2	148
L6X4X3/8	12.3		1750	6	1.2	177
L6X4X7/16	14.3		1772	6	1.2	206
L6X4X1/2	16.2		1795	6	1.2	233
L6X4X9/16	18.1		1817	6	1.2	261
L6X4X5/8	20.0		1839	6	1.2	288
L6X4X3/4	23.6		1882	6	1.2	340
L6X4X7/8	27.2		1924	6	1.2	392
L7X4X3/8	13.6		1765	6	1.2	196
L7X4X7/16	15.7		1790	6	1.2	226
L7X4X1/2	17.9		1815	6	1.2	258
L7X4X5/8	22.1		1865	6	1.2	318
L7X4X3/4	26.2		1914	6	1.2	377
L8X4X7/16	17.2		1809	6	1.2	248
L8X4X1/2	19.6		1837	6	1.2	282
L8X4X9/16	21.9		1864	6	1.2	315
L8X4X5/8	24.2		1891	6	1.2	348
L8X4X3/4	28.7		1944	6	1.2	413
L8X4X7/8	33.1		1995	6	1.2	477
L8X4X1	37.4		2047	6	1.2	539
L8X6X7/16	20.2		1846	6	1.2	291
L8X6X1/2	23.0		1879	6	1.2	331
L8X6X9/16	25.7		1911	6	1.2	370
L8X6X5/8	28.5		1943	6	1.2	410
L8X6X3/4	33.8		2006	6	1.2	487
L8X6X7/8	39.1		2066	6	1.2	563

Figure 42 shows comparison between cost of sections from the above table and compressive strength in range (1500-2000) Kips Some sections of 2L and 4L have comparable compressive strength to the W sections and less cost.

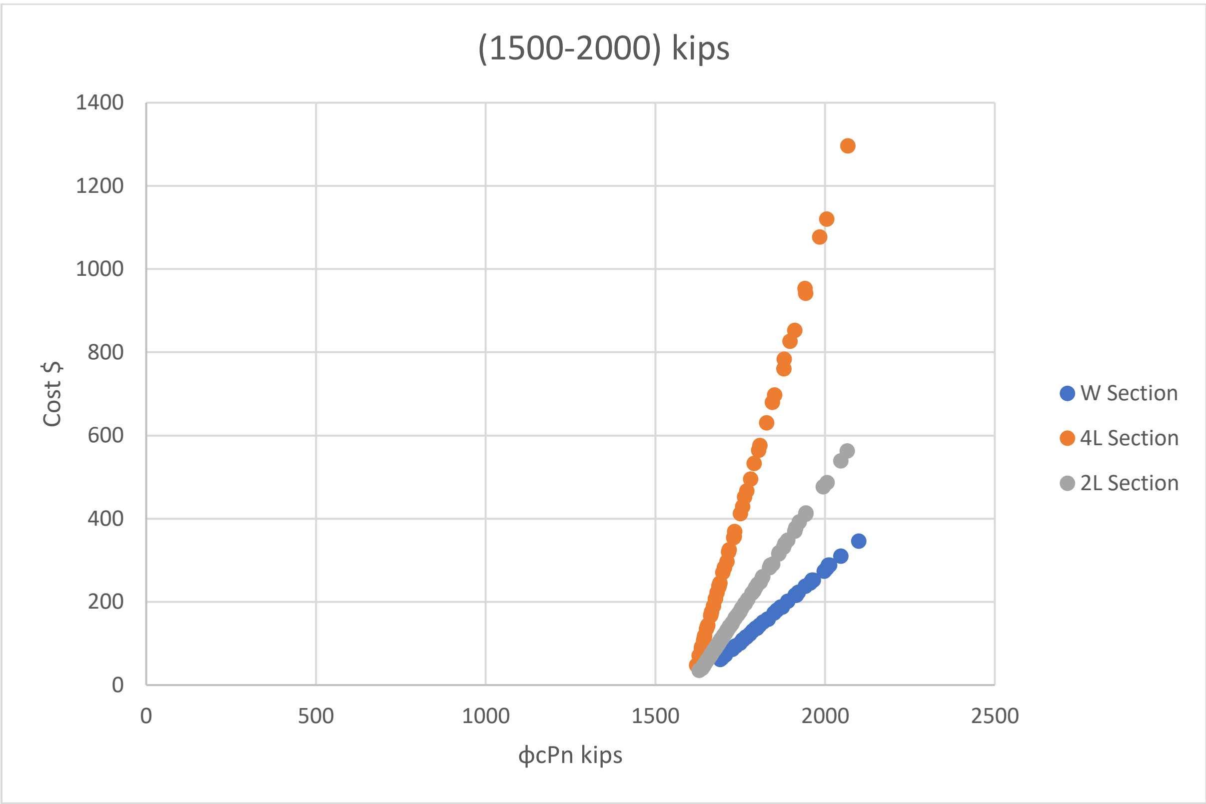

Figure 42 Column 25"x25" Strength and cost comparison for (1700-1800) Kips period

6. Conclusion

In this thesis, a new “X” shape steel construction was introduced. Using steel angles of shape “L” to represent the geometry of the proposed section. Theoretical analysis using universal codes (AISC and Eurocode 4) was conducted, and finite element analysis using ABAQUS software on three specimens (W4x13, 2L 3.5x3.5/16 and 4L 2x2x1/4). In addition, cost analysis on large sample of 100 W sections, 50 equal legs “4L” and 50 unequal legs “2L” from AISC steel sections was conducted.

- The axial load carrying capacity of composite concrete-steel column using the proposed “X” shape section (represented by four angles or two) are comparable to those of conventional composite concrete-steel “W” section. Compressive strength values of “X” shape can be enhanced to be better than conventional “W” section if the shape “X” is modified to have bigger cross-sectional area.
- Compressive strength values from AISC and Eurocode 4 equations are comparable, both indicated the “W” section is slightly higher than “X” shape. This can be modified by studying more sections than the chosen three samples in this thesis.
- Finite element analysis showed that “W” section and “X” section have comparable failure load.
- The proposed “X” shape if represented by steel angles (four or two angles), gives lower cost than conventional “W” shape in concrete cross sectional area of 15”x15” and less, and for compressive strength value of 1000 Kips and less. Increasing the

concrete cross section and the compressive strength make the conventional “W” section have better results.

- The limitation of using steel angles to represent the “X” shape affected the results, because the dimensions of the shape “X” were limited to the predefined dimensions of steel angles.
- Two angles were used to represent the shape of “X” in addition to the four angles. The use of two steel angles will require to have bigger concrete cross-sectional area of the column. Increasing the depth and width of the two angles used is required to have comparable results.

8. Appendices

In this chapter, references, general description on the universal codes used in this thesis (AISC and Eurocode 4), detailed steps of using ABAQUS software and list of tables and figures for reference.

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8.b Appendix A: AISC

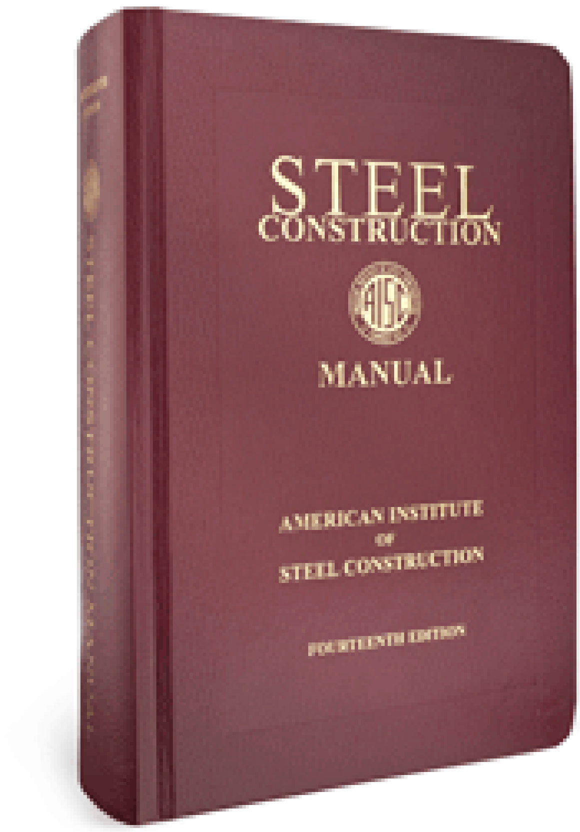


Figure 43 AISC Construction Manual

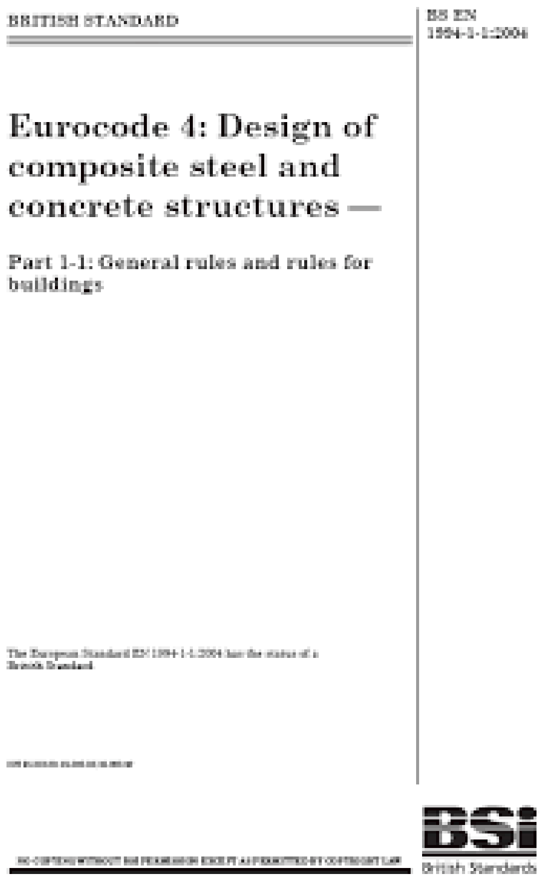
The *Specification* (AISC, 2016) provides the generally applicable requirements for the design and construction of structural steel buildings and other structures. Both LRFD and ASD methods of design are incorporated. Dual-units format provides for both U.S. customary and S.I. units. The latest version of this standard was revised June 2019.

The equations used in theoretical analysis for this paper mainly were token from chapter I.

16.1-x TABLE OF CONTENTS

Figure 44 Chapter I from AISC manual

8.c Appendix B: Eurocode 4


BRITISH STANDARD

BS EN 1994-1-1:2004

Eurocode 4: Design of composite steel and concrete structures —

Part 1-1: General rules and rules for buildings

BSi British Standards

Figure 45 Eurocode 4

In the Eurocode series of European standards (EN) related to construction, Eurocode 4: Design of composite steel and concrete structures (abbreviated EN 1994 or, informally, EC 4) describes how to design of composite structures, using the limit state design philosophy. It was approved by the European Committee for Standardization (CEN) on 4 November 2004. Eurocode 4 is divided in two parts EN 1994-1 and EN 1994-2.

The equations used in theoretical analysis for this paper mainly were token from section 6.7.

BS EN 1994-1-1:2004
EN 1994-1-1:2004 (E)

Figure 46 Section 6.7 form Eurocode4

8.d Appendix C: ABAQUS Steps

This section describe in details the steps used in ABAQUS:

- Define the parts (Concrete, Steel Rebars and Steel Section “W, 2L & 4L), including the dimensions.
- Define the parts materials including elastic and plastic properties.
- Create section for each part and assign it material.
- Assemble all parts together and define the boundary region (concrete).
- Identify the boundary conditions (fixed at one end and hinge at the other end).
- Create seeds and mesh the parts (1 inch each).
- Check the data and run the analysis.
- Export the results in excel.

8.d.1 Creating the Model:

Following figures shows in detail each step.

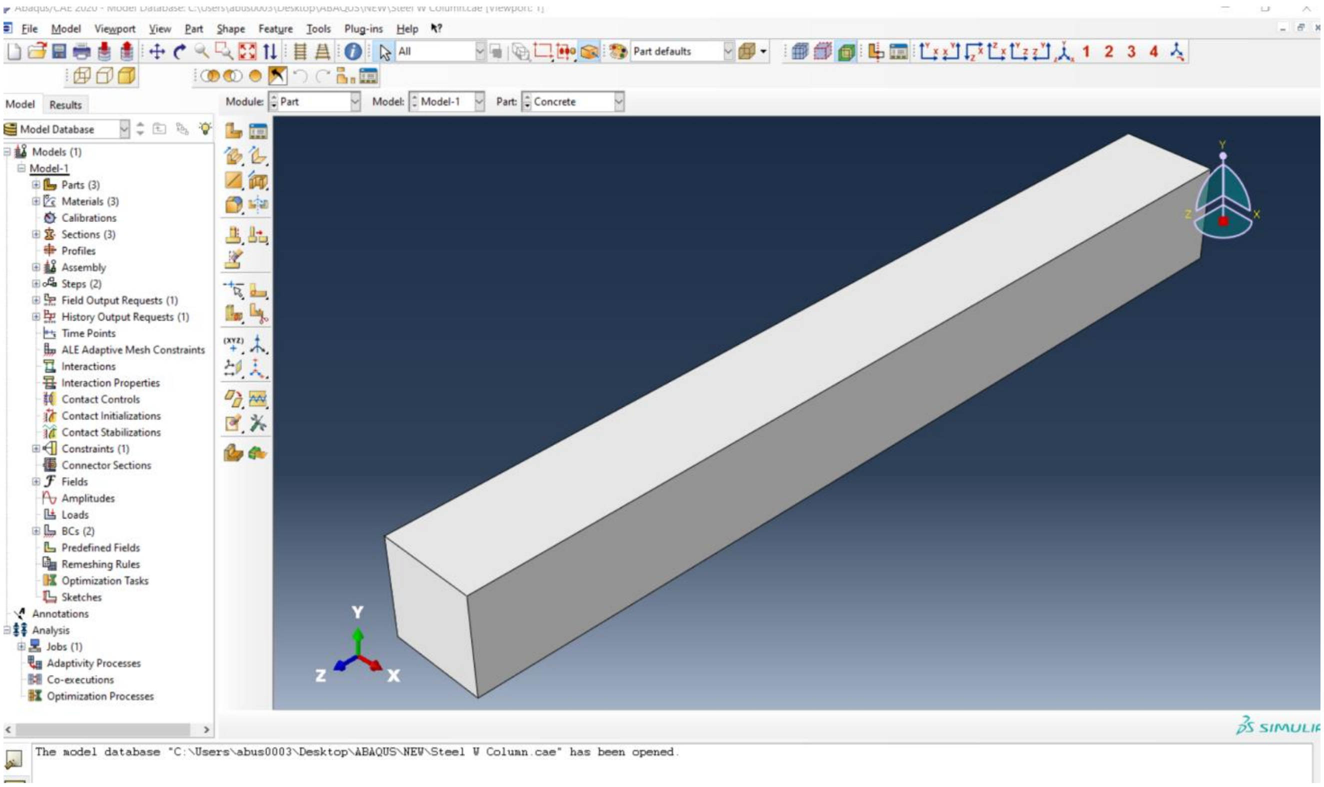


Figure 47 Concrete Part

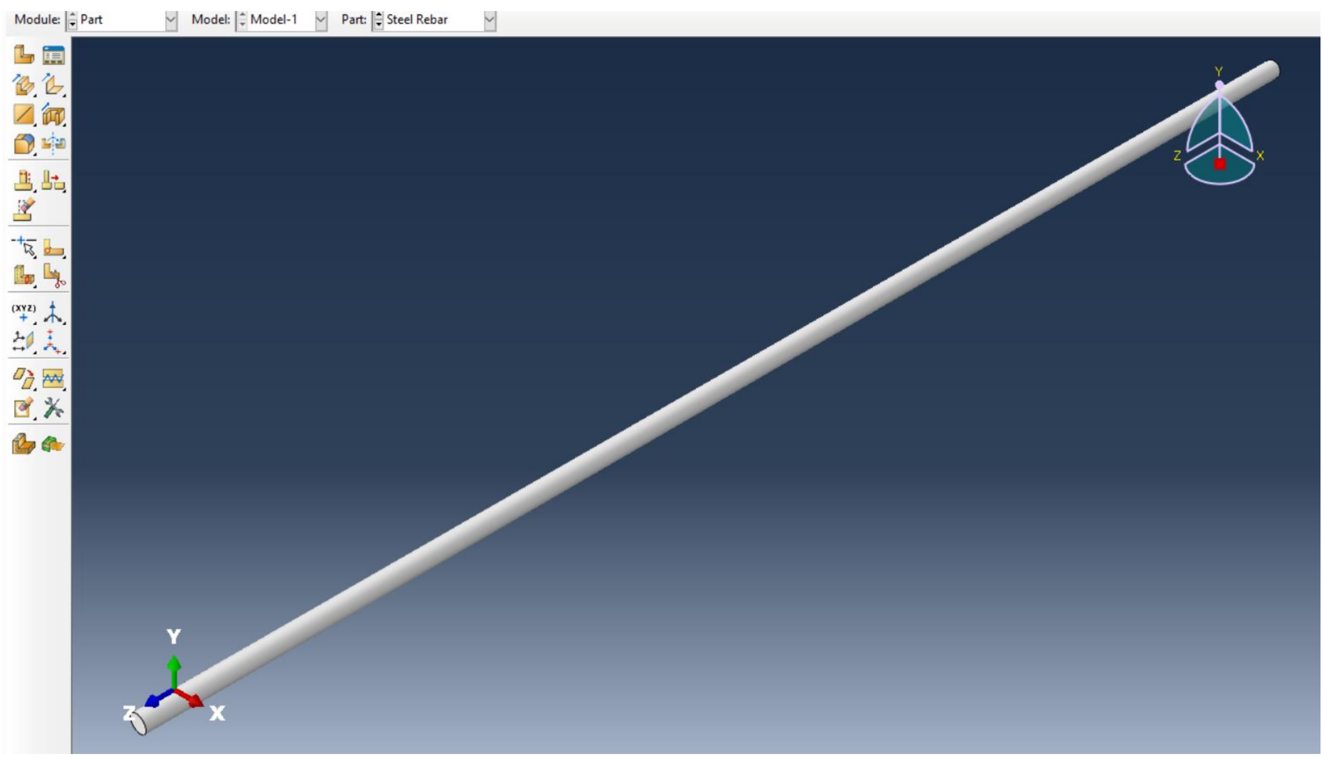


Figure 48 Steel Rebars part

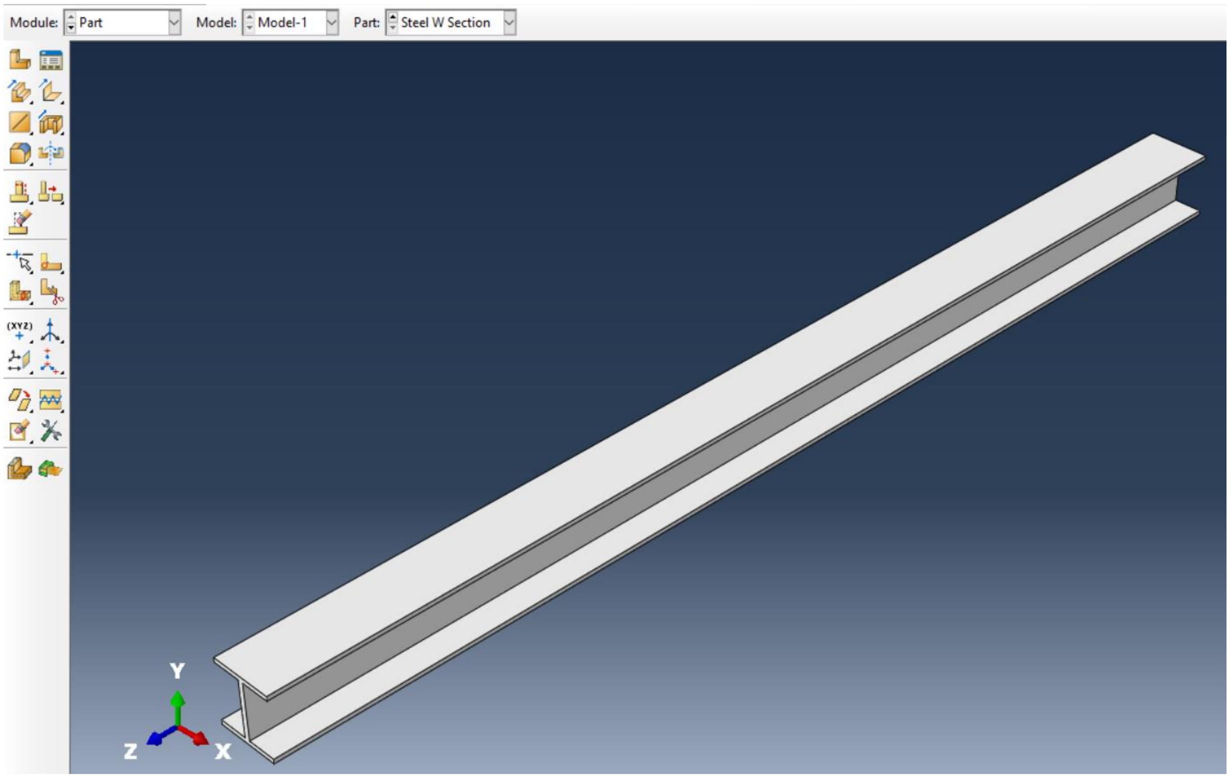


Figure 49 Steel W Section part

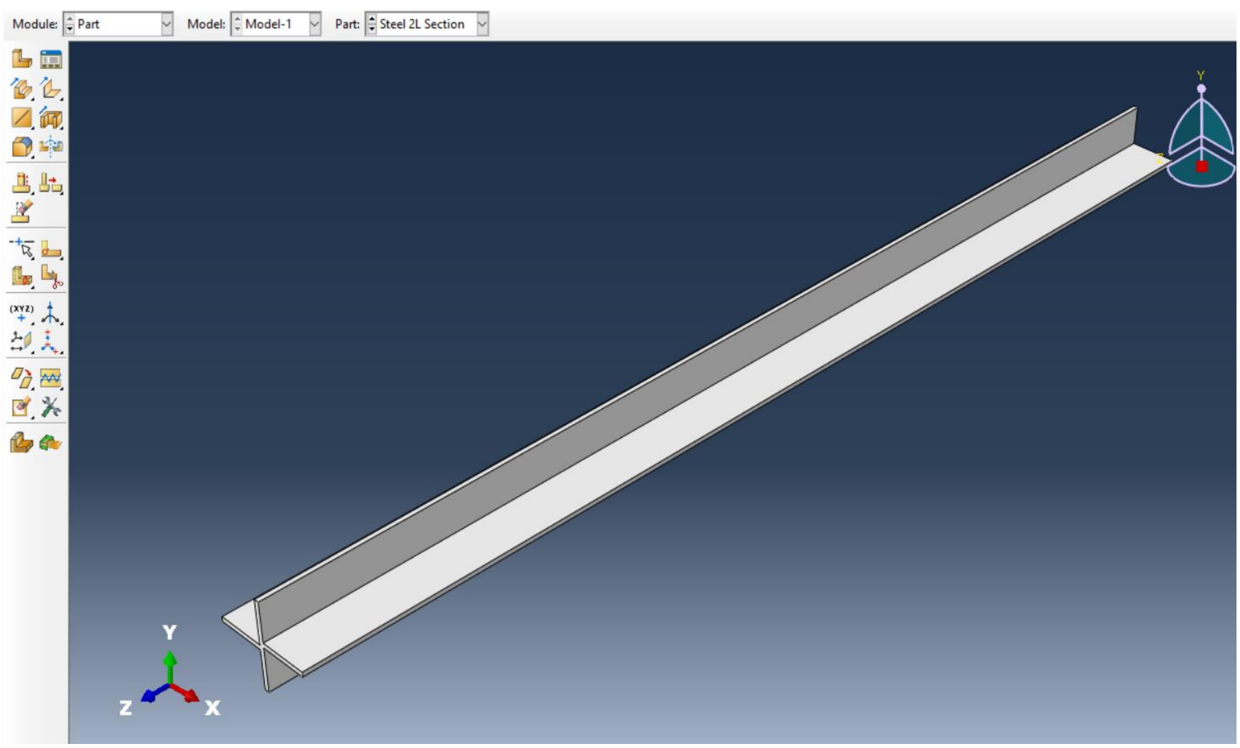


Figure 50 Steel 2L Section part

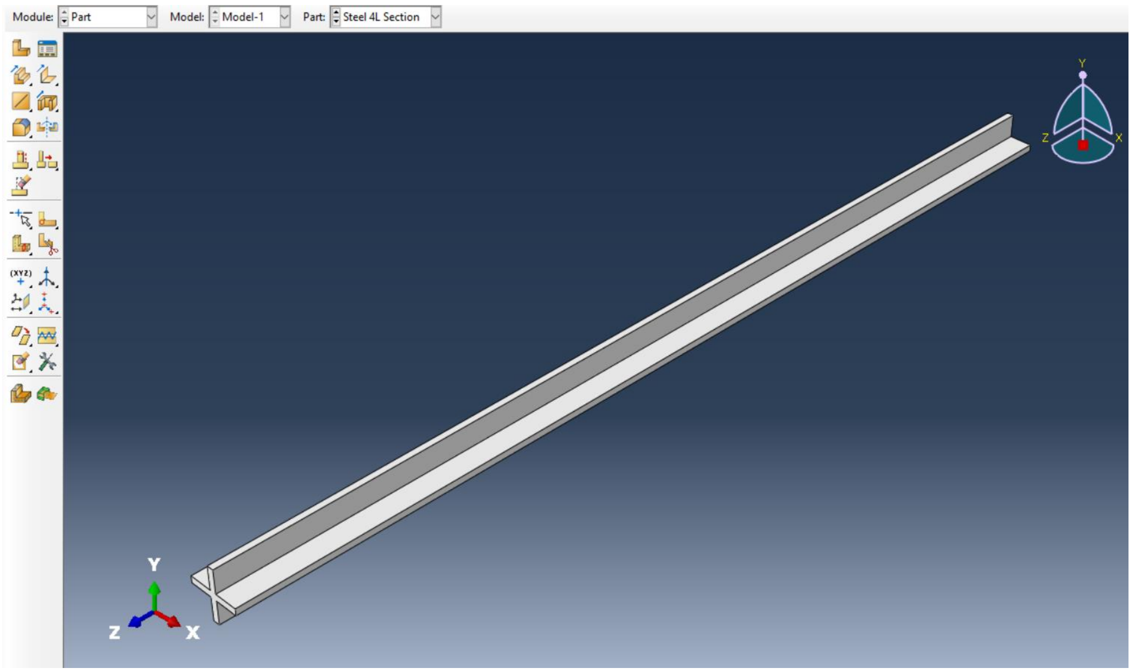


Figure 51 Steel 4L section part

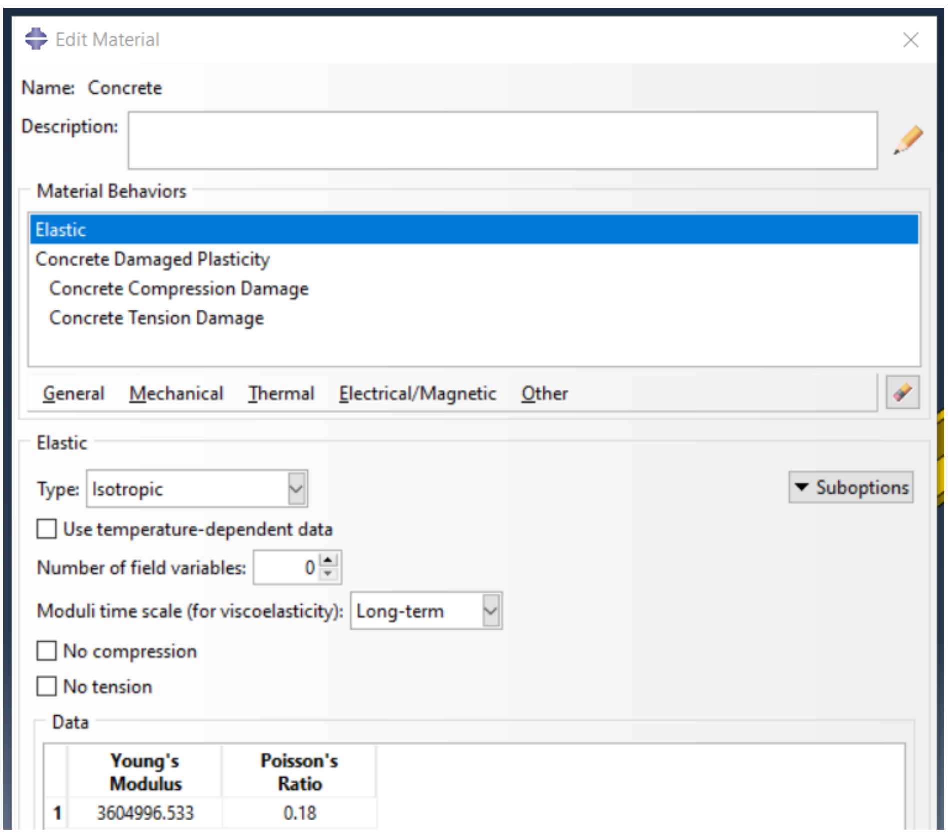


Figure 52 Concrete material elastic properties

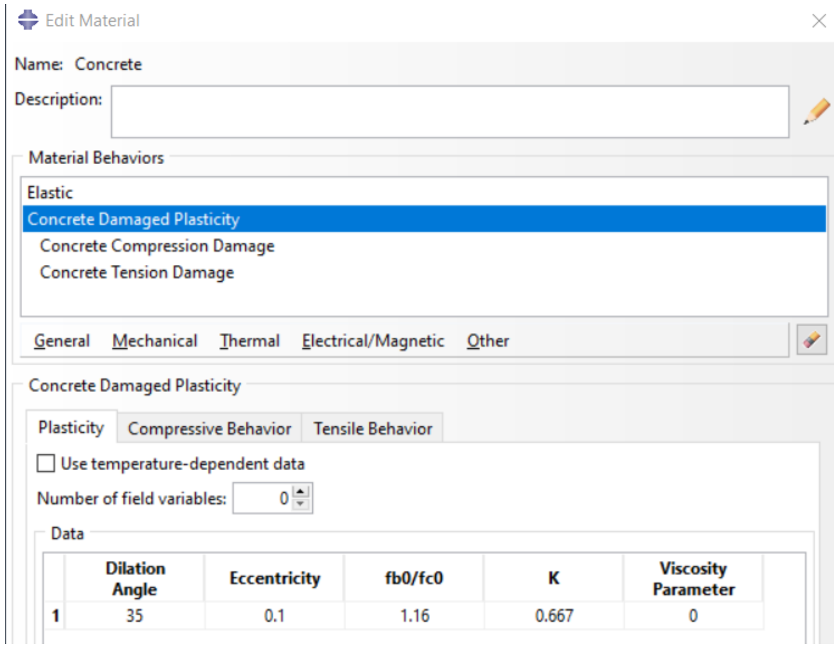


Figure 53 Concrete material plastic properties

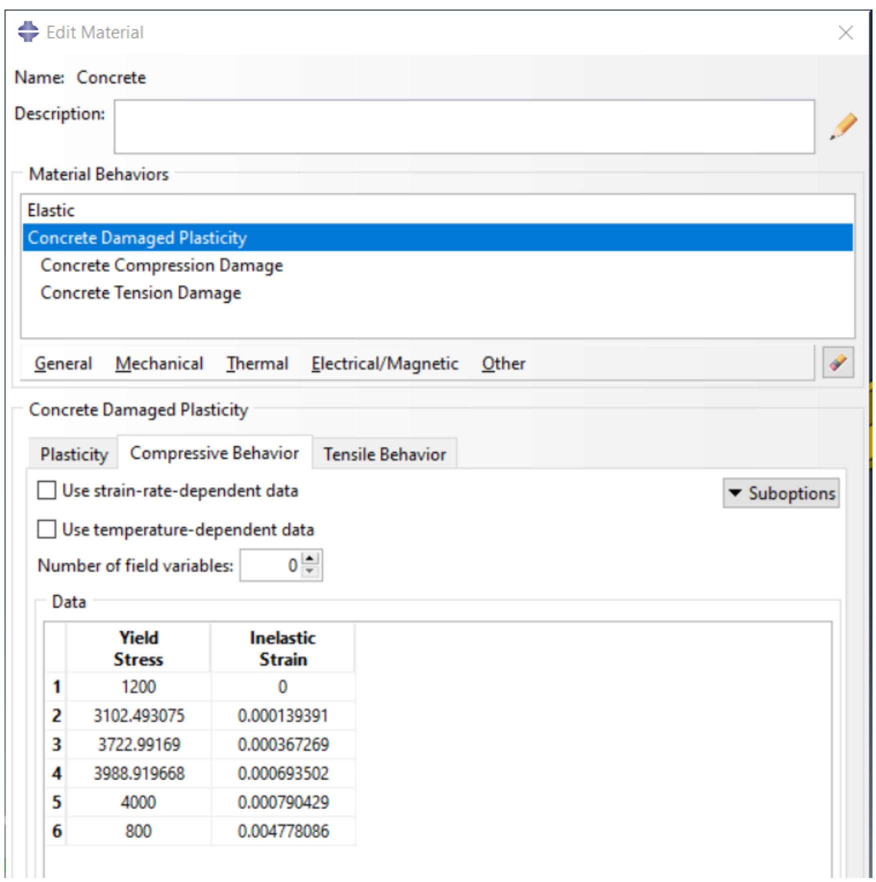


Figure 54 Concrete material compressive behavior

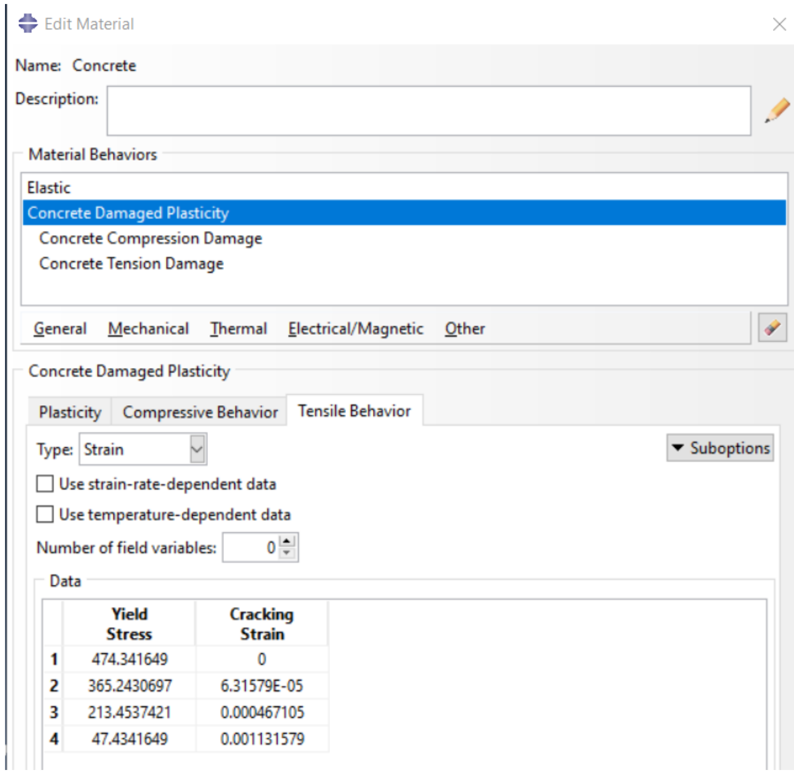


Figure 55 Concrete material tensile behavior

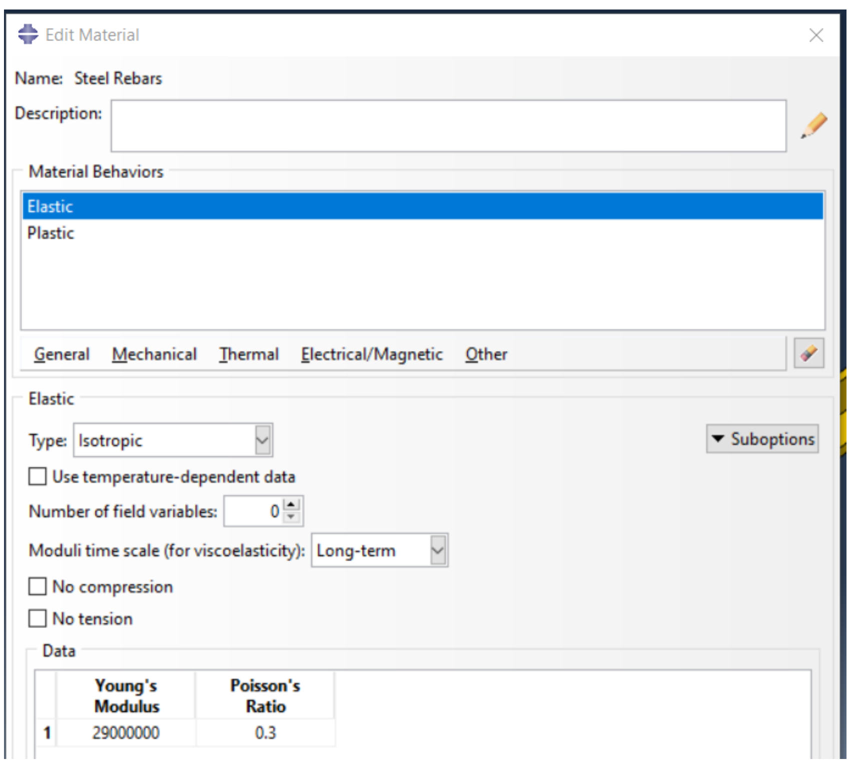


Figure 56 Steel rebars material elastic properties

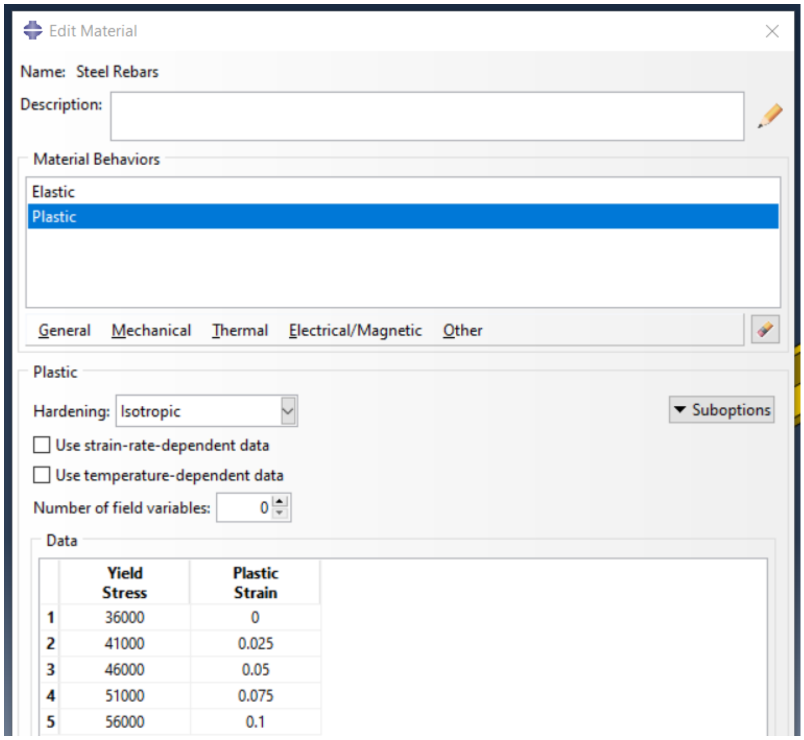


Figure 57 Steel rebars material plastic properties

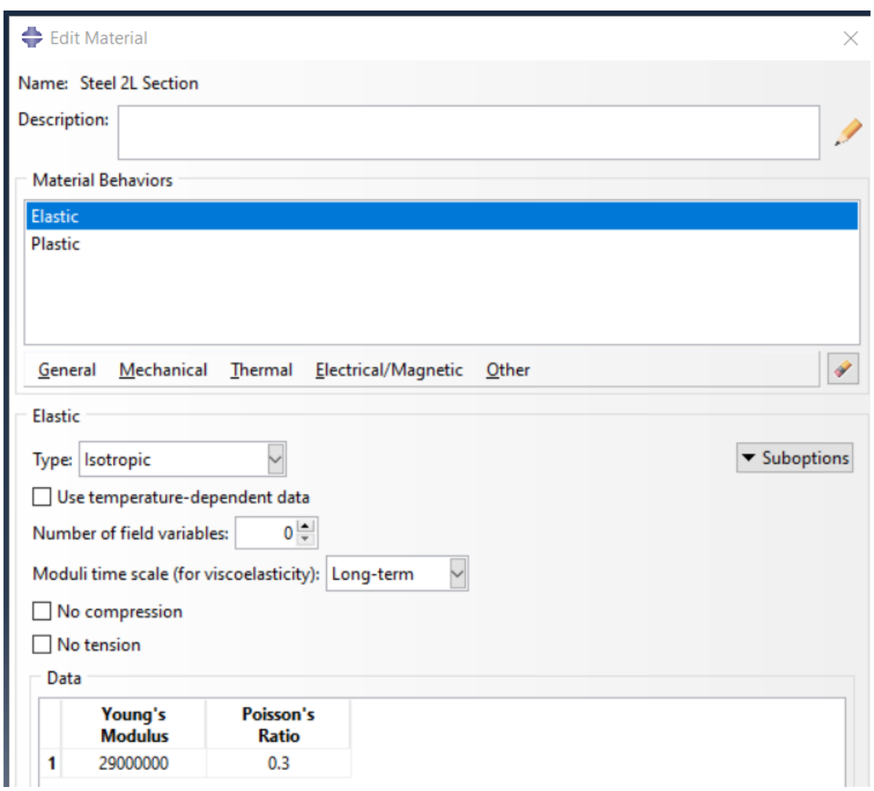


Figure 58 Steel sections (W, 2L, 4L) material elastic properties

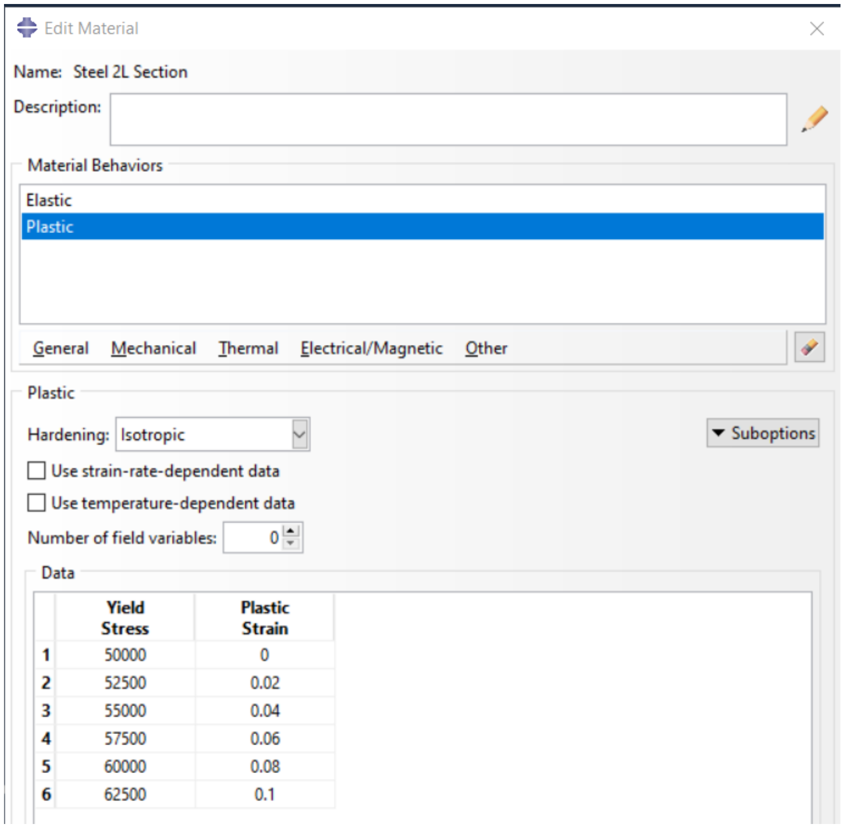


Figure 59 Steel section (W, 2L, 4L) material plastic properties

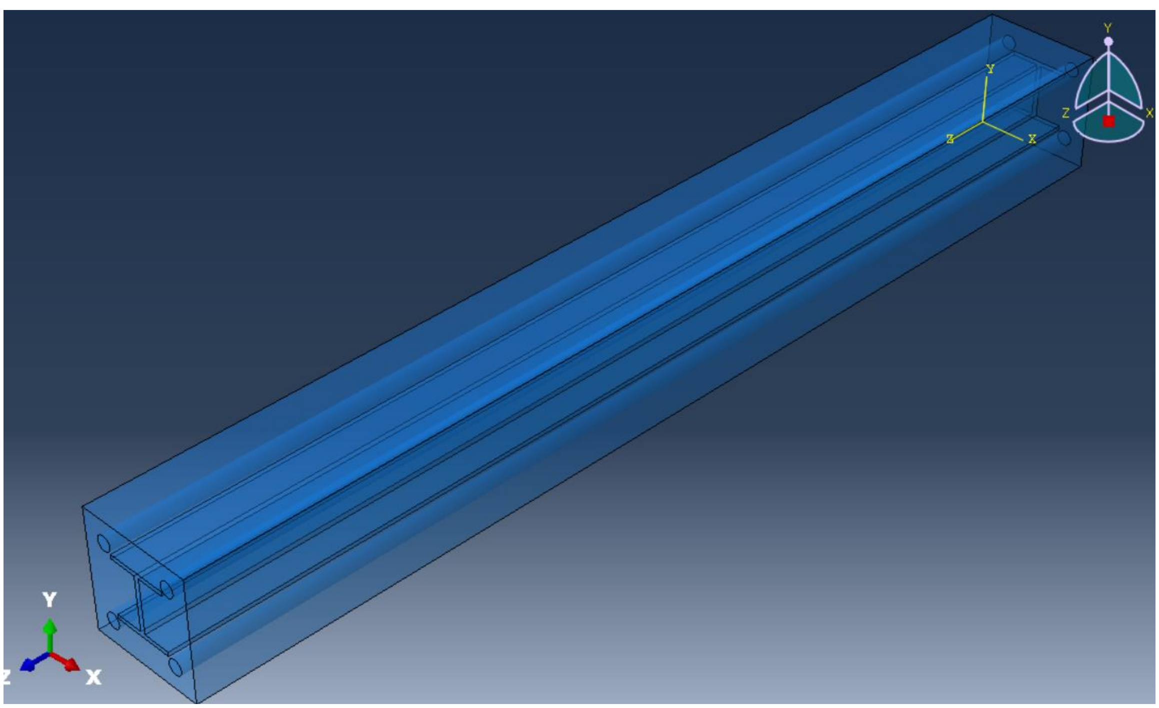


Figure 60 Steel W section column assembly

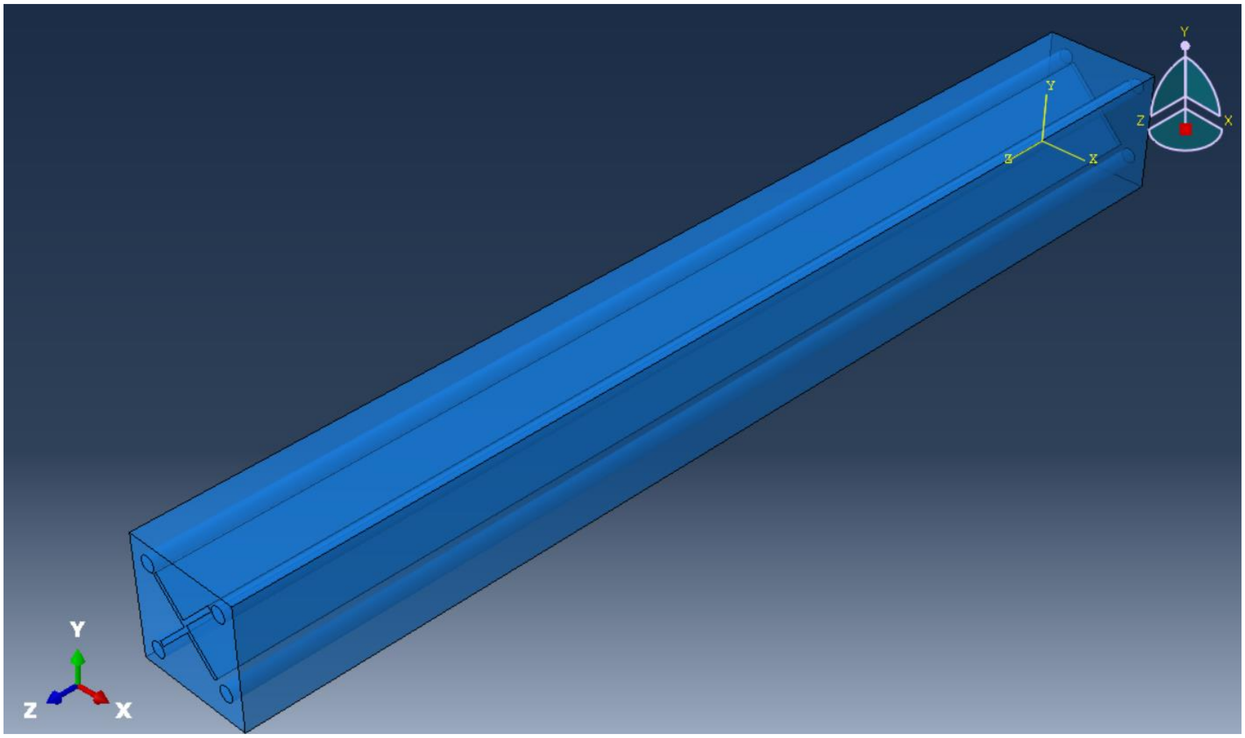


Figure 61 Steel 2L section column assembly

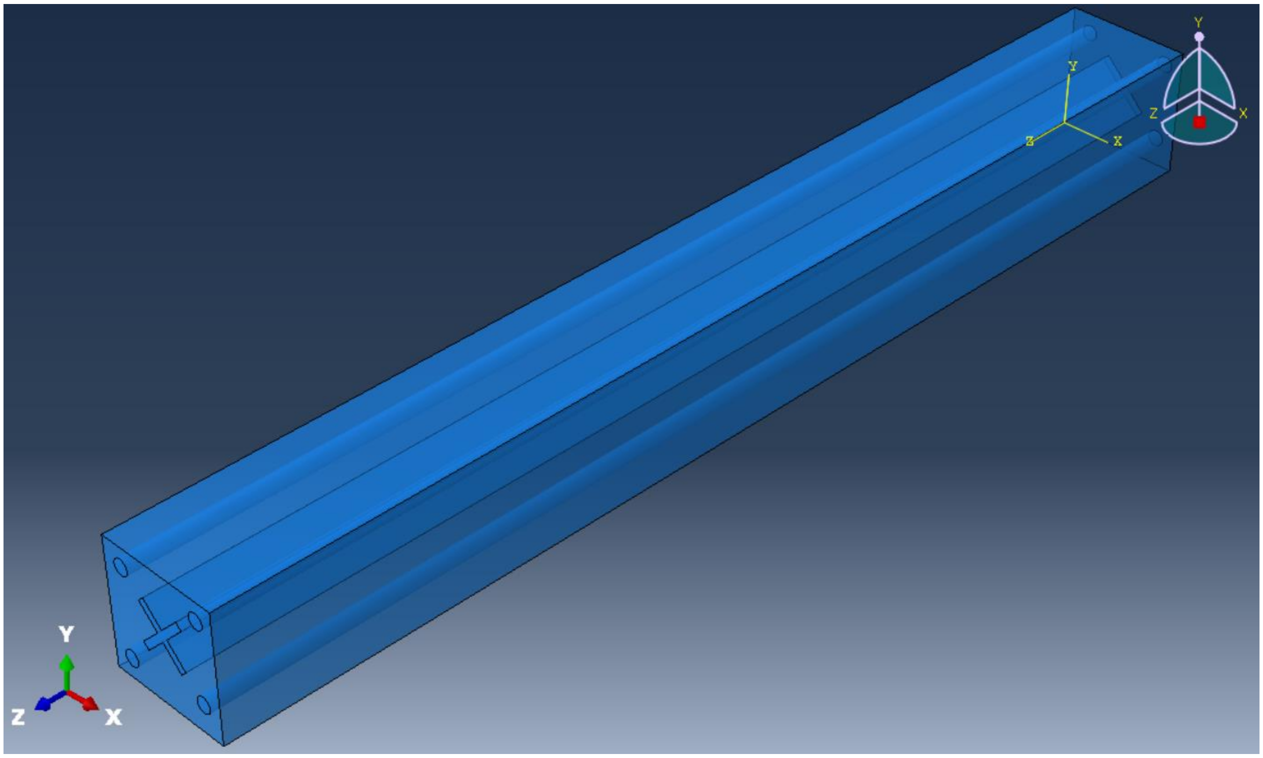


Figure 62 Steel 4L section column assembly

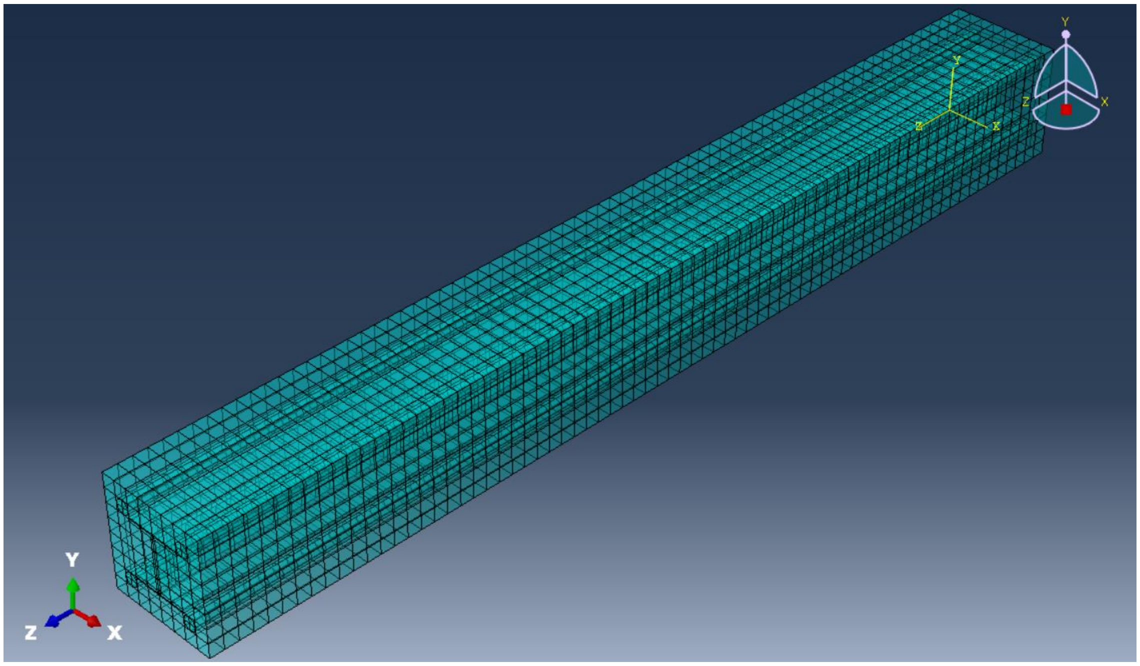


Figure 63 Meshing all parts

8.d.2 Simulation Results:

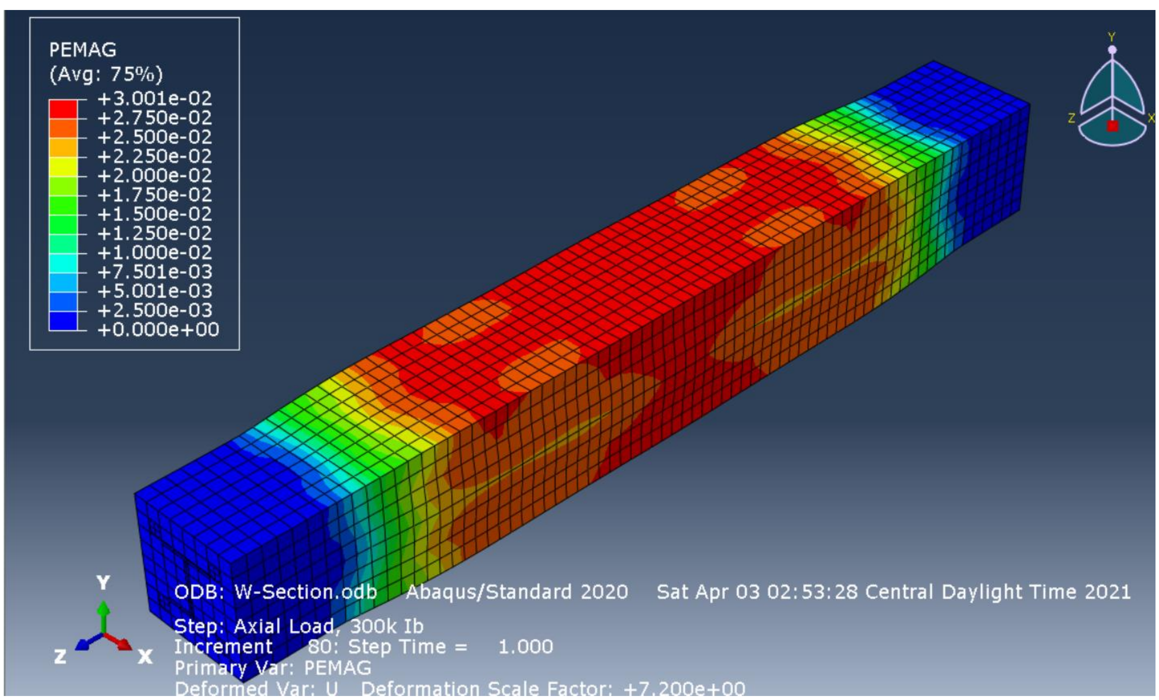


Figure 64 Plastic strain of steel W section column

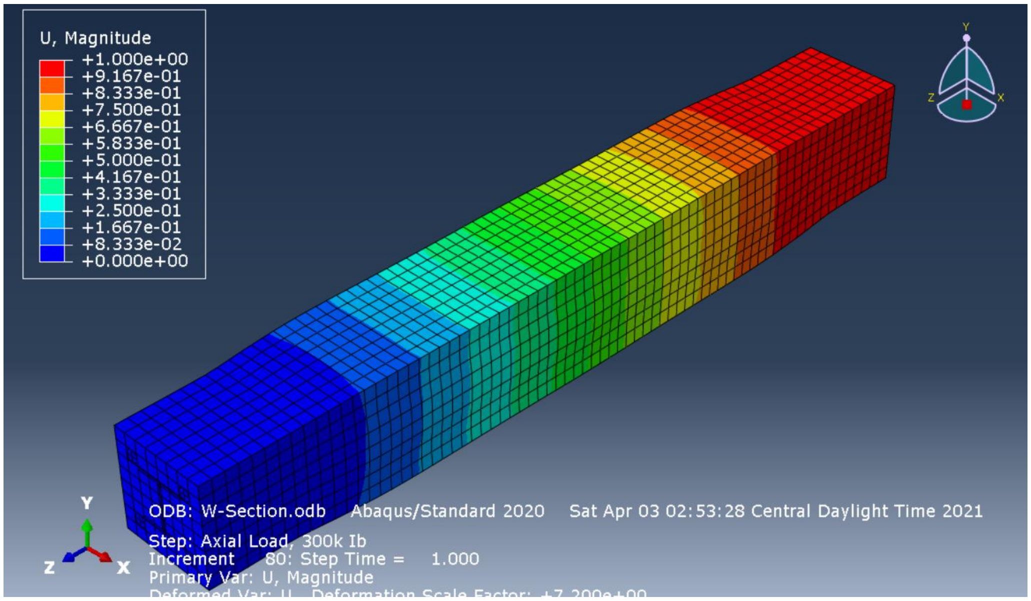


Figure 65 Displacement of Steel W section column

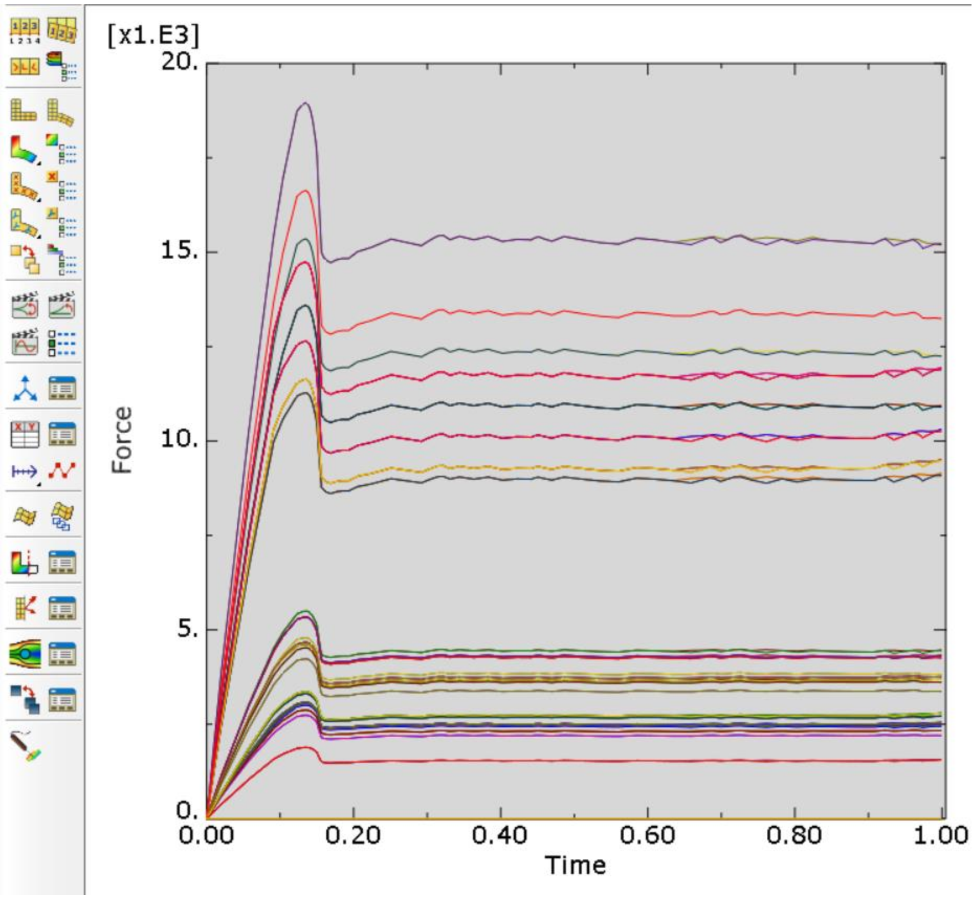


Figure 66 Reaction forces of steel W section column of different nodes at the hinge end

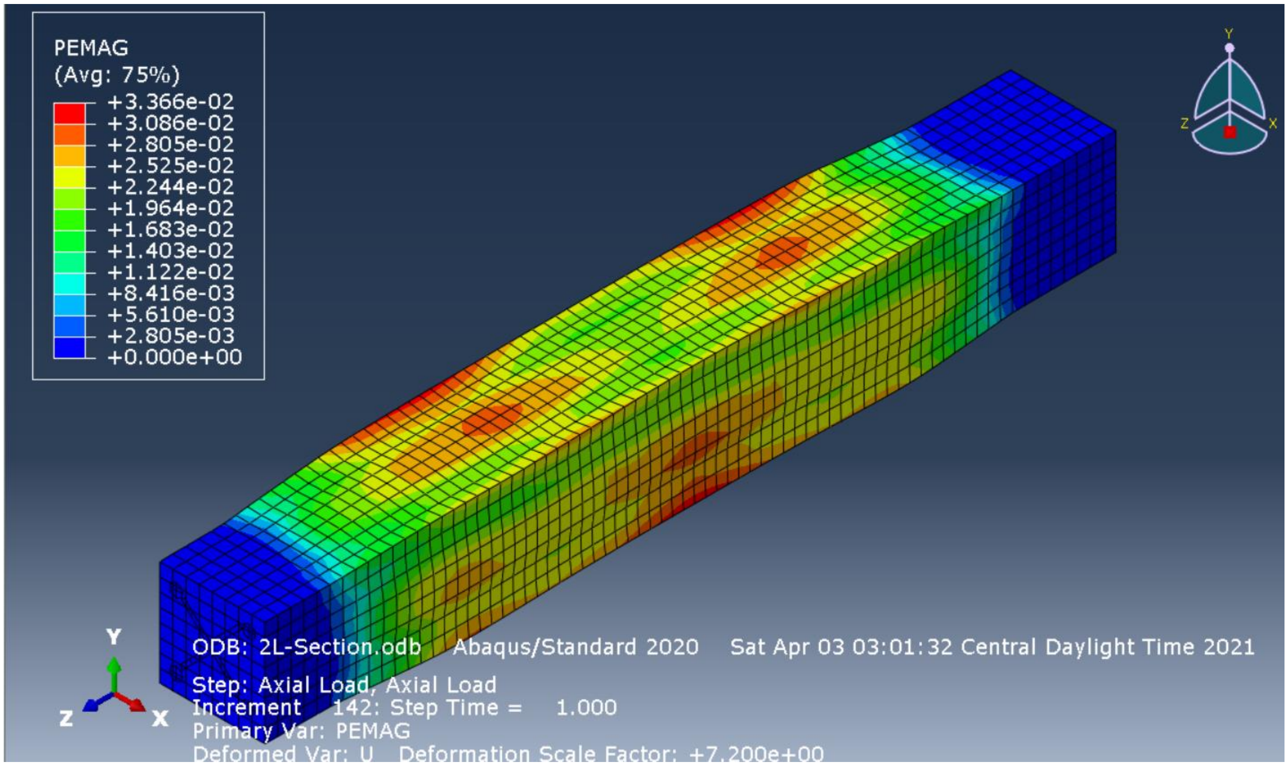


Figure 67 Plastic strain of steel 2L section column

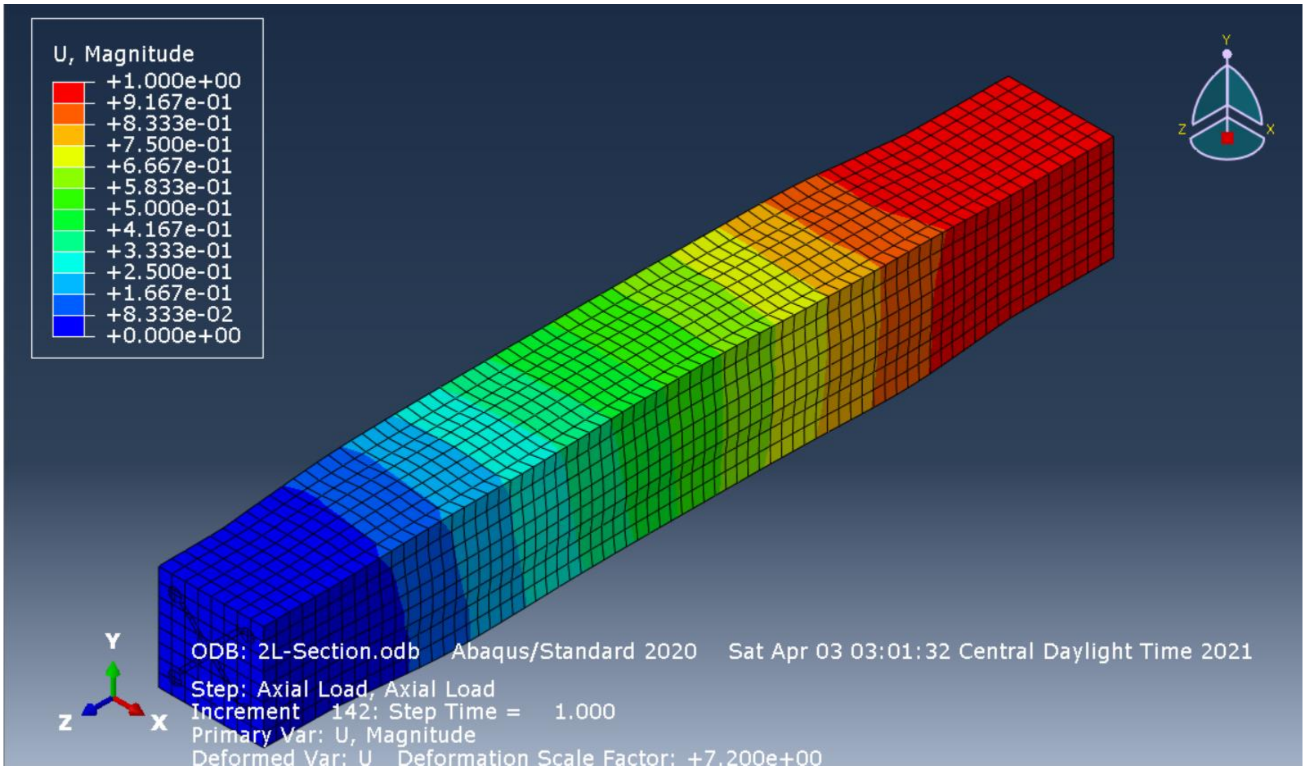


Figure 68 Displacement of steel 2L section column

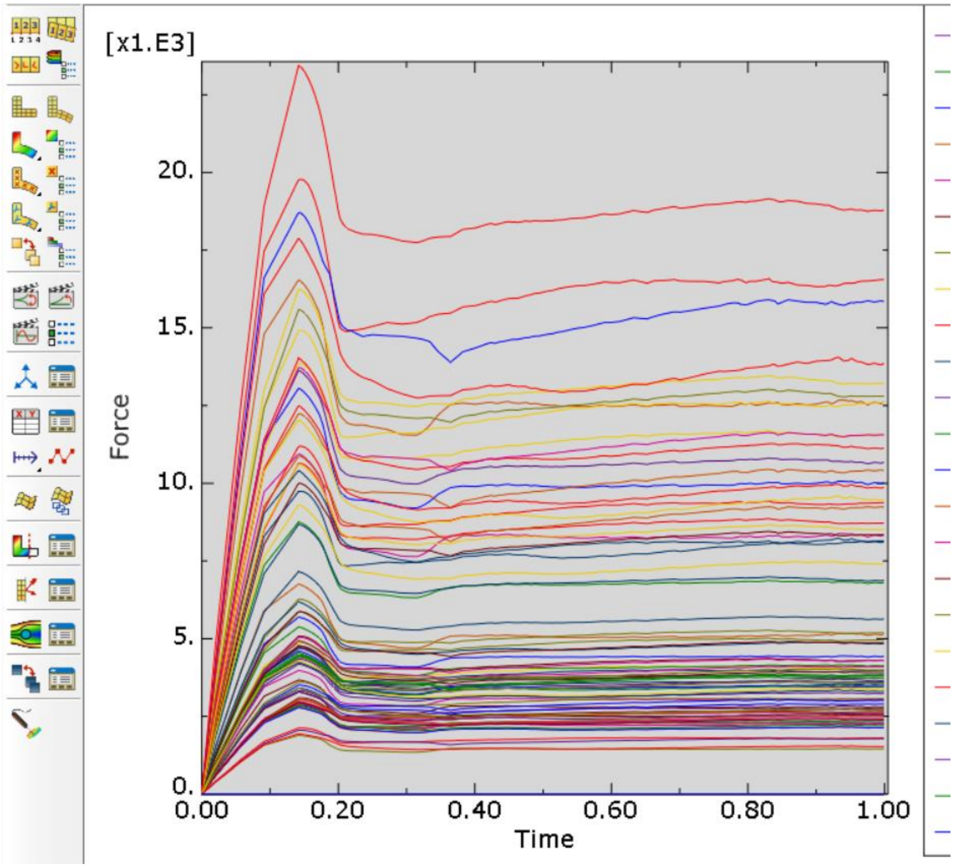


Figure 69 Reaction forces of steel 2L column at the hinge end

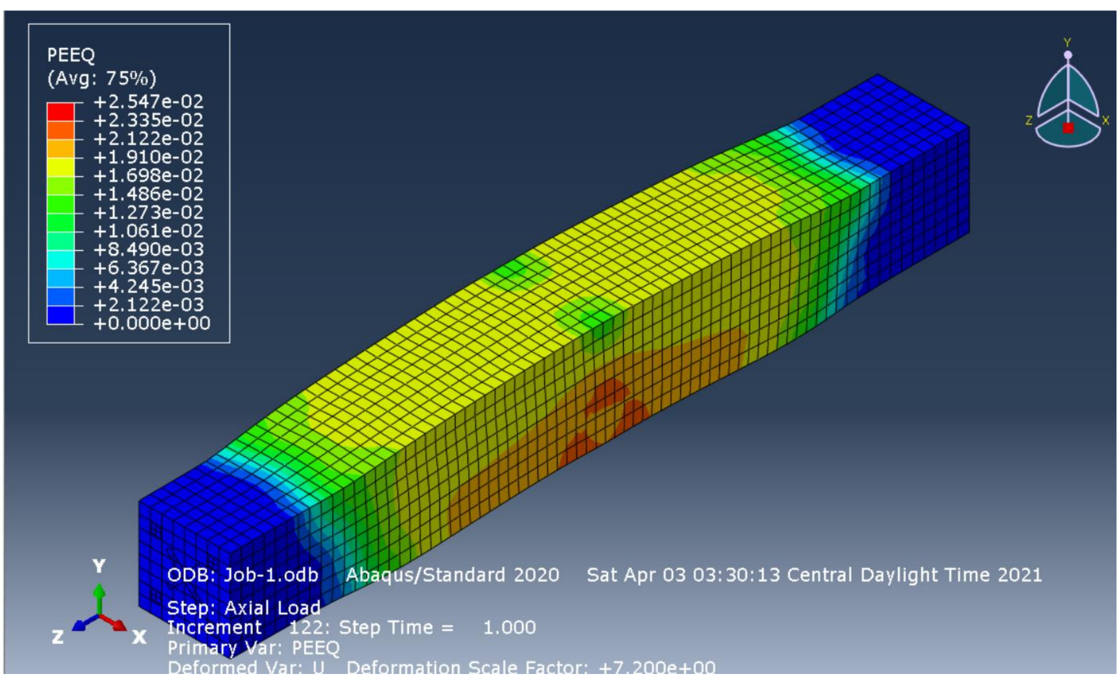


Figure 70 Plastic strain of steel 4L section column

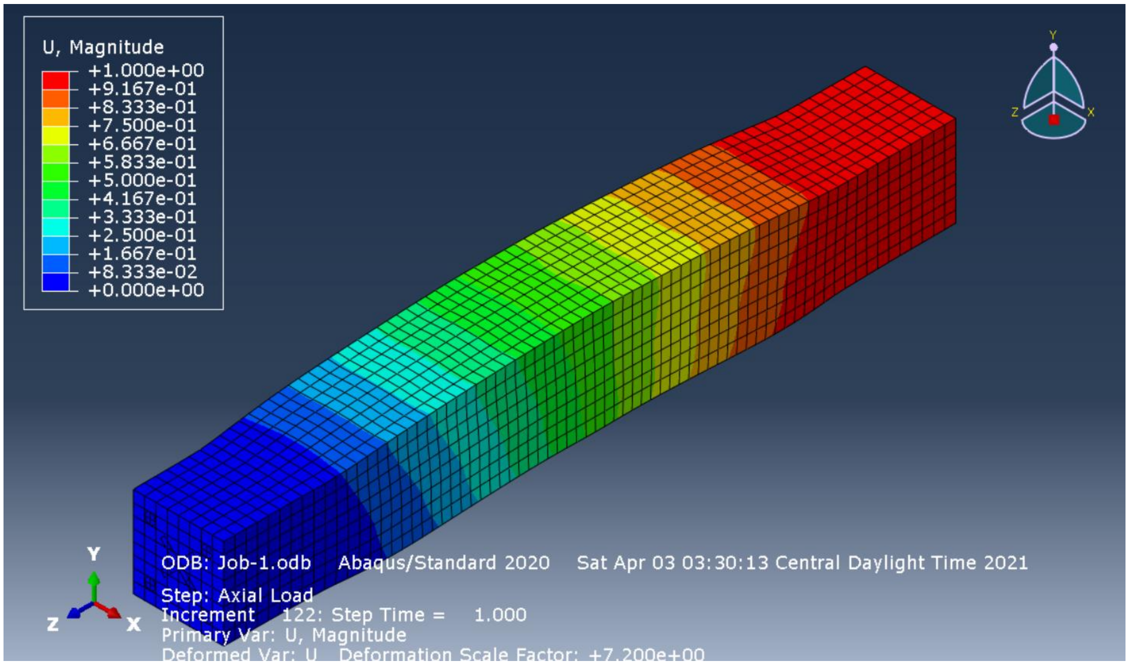


Figure 71 Displacement of steel 4L section column

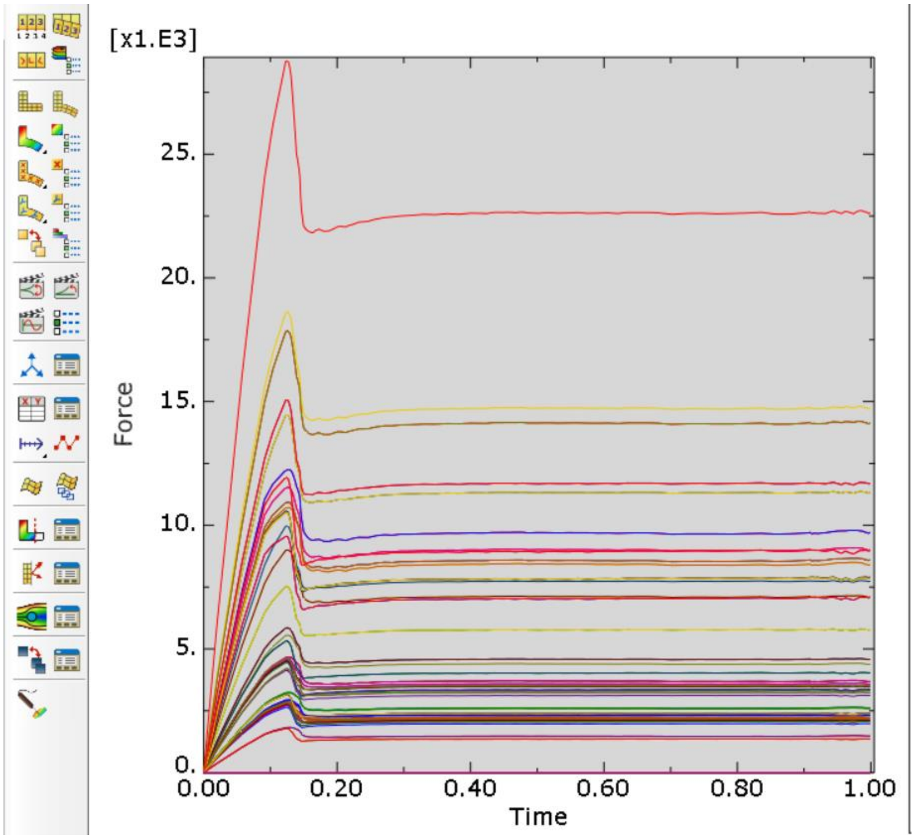


Figure 72 Reaction forces of steel 4L section at the hinge end

8.e Appendix D: List of Tables

Table 18 general description of specimens tested in the lab

	Specimen 1	Specimen 2	Specimen 3
Concrete	8x8x72 (inches)	8x8x72 (inches)	8x8x72 (inches)
Steel Sections	W4x13	2L3.5x3x5/16	4L2x2x1/4
Rebars	4#4	4#4	4#4
Failure Load	≤300 Kips	≤300 Kips	≤300 Kips

Table 19 compressive strength values of steel section W4x13 using AISC Chapter I Section 12

Concrete	**fc' (Ksi)**	**4.00**	**Steel Section**	**W 4x13x112**	
	Ec (Ksi)	3606.00		As (in2)	3.55
	Ac (in2)	60.01		Fy (Ksi)	36.00
	Ic (in4)	238.93		Es (Ksi)	29000.00
Section	b (in)	8.00		Is (in4)	11.30
	h (in)	8.00		Ig (in4)	341.33
	Ag (in2)	64.00	Strength Calculations	EI effective	708639.94
Steel Bars	Fysr (Ksi)	36.00		Pe (Kips)	2108.05
	# of Bars	4.00		Pno (Kips)	347.73
	Diameter (in)	0.38		Pno/Pe	0.16
	Asr (in2)	3.55		Pn (Kips)	324.53
	Esr (Ksi)	29000.00			
	Isr (in4)	0.15			

Table 20 compressive strength values of steel section 4L2x2x1/4 using AISC Chapter I Section 12

Concrete	**fc' (Ksi)**	**4.00**	**Steel Section**	**4L 2x2x1/4**	
	Ec (Ksi)	3606.00		As (in2)	3.76
	Ac (in2)	60.01		Fy (Ksi)	36.00

	Ic (in4)	238.93		Es (Ksi)	29000.00
Section	b (in)	8.00		Is (in4)	1.40
	h (in)	8.00		EI effective	430021.26
	Ag (in2)	64.00	Strength Calculations	Pe (Kips)	1279.22
Steel Bars	Fysr (Ksi)	36.00		Pno (Kips)	354.58
	# of Bars	4.00		Pno/Pe	0.28
	Diameter (in)	0.38		Pn (Kips)	315.74
	Asr (in2)	3.55			
	Esr (Ksi)	29000.00			
	Isr (in4)	0.15			

Table 21 compressive strength values of steel section 2L3.5x3x5/16 using AISC Chapter (I) Section 12

Concrete	**fc' (Ksi)**	**4.00**	**Steel Section**	**2L 3.5x3x5/16**	
	Ec (Ksi)	3606.00		As (in2)	3.24
	Ac (in2)	60.01		Fy (Ksi)	36.00
	Ic (in4)	238.93		Es (Ksi)	29000.00
Section	b (in)	8.00		Is (in4)	1.80
	h (in)	8.00		EI effective	441621.26
	Ag (in2)	64.00	Strength Calculations	Pe (Kips)	1313.73
Steel Bars	Fysr (Ksi)	36.00		Pno (Kips)	356.35
	# of Bars	4.00		Pno/Pe	0.27
	Diameter (in)	0.38		Pn (Kips)	318.10
	Asr (in2)	3.55			
	Esr (Ksi)	29000.00			
	Isr (in4)	0.15			

Table 22 compressive strength values of steel section W 4x13 using Eurocode4 section 6.7

Concrete	**fck (Ksi)**	**4.00**	**Steel Section**	**W4x13**	
	Ec (Ksi)	3606.00		Aa (in2)	3.83
	Ac (in2)	64.00		Fya (Ksi)	36.00
	Ic (in4)	238.93		Ea (Ksi)	29000.00
Section	bc (in)	8.00		Ia (in4)	11.30

	hc (in)	8.00			
			Strength Calculations	Npl,rd (Kips)	290.10
Steel Bars	Fy (Ksi)	36.00			
	# of Bars	4.00			
	Diameter (in)	0.50			
	As (in2)	0.80			
	Es (Ksi)	29000.00			
	Is (in4)	0.01			

Table 23 compressive strength values of steel section 4L 2x2x1/4 using Eurocode4 section 6.7

Concrete	fck (Ksi)	4.00	Steel Section	4L2x2x1/4	
	Ec (Ksi)	3606.00		Aa (in2)	0.94
	Ac (in2)	64.00		Fya (Ksi)	36.00
	Ic (in4)	238.93		Ea (Ksi)	29000.00
Section	bc (in)	8.00		Ia (in4)	0.35
	hc (in)	8.00			
			Strength Calculations	Npl,rd (Kips)	267.35
Steel Bars	Fy (Ksi)	36.00			
	# of Bars	4.00			
	Diameter (in)	0.38			
	As (in2)	0.44			
	Es (Ksi)	29000.00			
	Is (in4)	0.15			

Table 24 compressive strength values of steel section 2L 3.5x3x5/16 using Eurocode4 section 6.7

Concrete	fck (Ksi)	4.00	Steel Section	2L3.5x3x5/16	
	Ec (Ksi)	3606.00		Aa (in2)	1.93
	Ac (in2)	64.00		Fya (Ksi)	36.00
	Ic (in4)	238.93		Ea (Ksi)	29000.00
Section	bc (in)	8.00		Ia (in4)	2.30
	hc (in)	8.00			
			Strength Calculations	Npl,rd (Kips)	302.99
Steel Bars	Fy (Ksi)	36.00			
	# of Bars	4.00			
	Diameter (in)	0.38			
	As (in2)	0.44			

	Es (Ksi)	29000.00			
	Is (in4)	0.15			

Table 25 Compressive stress and strain values as per Kent and Park mode

Stress (Ksi)	Strain
0	0
1200	0.00033287
3102.49308	0.001
3722.99169	0.0014
3988.91967	0.0018
4000	0.0019
800	0.005

Table 26 Tensile stress and strain values as per Kent and Park model

Stress (Kips)	Strain
0	0
474.341649	0.00013158
365.24307	0.00016447
213.453742	0.00052632
47.4341649	0.00114474

Table 27 Forces at failure of all specimens

Specimens	Force at failure	Displacement
W 4x13	**550 lb**	**1 inch**
2L 3.5x3x5/16	**580 lb**	**1 inch**
4L 2x2x1/4	**545 lb**	**1 inch**

Table 28 Column 8"x8" Strength and cost comparison for (250-350) Kips period

	AISC_Manual_Label	W	φcPn	L (ft)	$/lb/ft	Total $
	W-Section Specimen					
1	W4X13	13	322.233	6	1.2	93.6
2	W5X16	16	362.947	6	1.2	115.2
	4L-Section Specimen					
1	L2X2X1/8	1.7	239.075	6	1.2	47.52
2	L2X2X3/16	2.4	239.051	6	1.2	70.272
3	L2X2X1/4	3.2	239.03	6	1.2	91.872
4	L2X2X5/16	3.9	239.009	6	1.2	112.9
5	L2X2X3/8	4.7	238.988	6	1.2	135.36
6	L2-1/2X2-1/2X3/16	3.1	256.59	6	1.2	88.416
7	L2-1/2X2-1/2X1/4	4.1	256.569	6	1.2	118.08
8	L2-1/2X2-1/2X5/16	5	256.545	6	1.2	144
9	L2-1/2X2-1/2X3/8	5.9	256.524	6	1.2	169.92
10	L2-1/2X2-1/2X1/2	7.7	256.481	6	1.2	221.76
	2L-Section Specimen					
1	L2-1/2X1-1/2X3/16	2.4	222.526	6	1.2	35.136
2	L2-1/2X1-1/2X1/4	3.2	222.5	6	1.2	45.936
3	L2-1/2X2X3/16	2.8	239.58	6	1.2	39.6
4	L2-1/2X2X1/4	3.6	239.556	6	1.2	52.128
5	L2-1/2X2X5/16	4.5	239.533	6	1.2	64.8
6	L2-1/2X2X3/8	5.3	239.509	6	1.2	76.32
7	L3X2X3/16	3.1	240.074	6	1.2	44.208
8	L3X2X1/4	4.1	240.051	6	1.2	59.04
9	L3X2X5/16	5	240.028	6	1.2	72
10	L3X2X3/8	5.9	240.006	6	1.2	84.96
11	L3X2X1/2	7.7	239.963	6	1.2	110.88
12	L3X2-1/2X3/16	3.4	257.115	6	1.2	48.816
13	L3X2-1/2X1/4	4.5	257.095	6	1.2	64.8
14	L3X2-1/2X5/16	5.6	257.071	6	1.2	80.64

15	L3X2-1/2X3/8	6.6	257.048	6	1.2	95.04
16	L3X2-1/2X7/16	7.6	257.027	6	1.2	109.44
17	L3X2-1/2X1/2	8.5	257.006	6	1.2	122.4
18	L3-1/2X2-1/2X1/4	4.9	257.619	6	1.2	70.56
19	L3-1/2X2-1/2X5/16	6.1	257.59	6	1.2	87.84
20	L3-1/2X2-1/2X3/8	7.2	257.561	6	1.2	103.68
21	L3-1/2X2-1/2X1/2	9.4	257.503	6	1.2	135.36

Table 29 Column 9"x9" Strength and cost comparison for (300-350) Kips period

	AISC_Manual_Label	W	φcPn	L (ft)	$/Ib/ft	Total $
	W-Section Specimen					
1	W4X13	13.0	322.2329	6	1.2	93.6
4	W6X8.5	8.50	320.037	6	1.2	61.2
5	W6X9	9.00	326.9037	6	1.2	64.8
	4L-Section Specimen					
6	L2-1/2X2-1/2X3/16	3.07	303.1907	6	1.2	88.416
7	L2-1/2X2-1/2X1/4	4.10	303.1769	6	1.2	118.08
8	L2-1/2X2-1/2X5/16	5.00	303.1613	6	1.2	144
9	L2-1/2X2-1/2X3/8	5.90	303.1475	6	1.2	169.92
10	L2-1/2X2-1/2X1/2	7.70	303.12	6	1.2	221.76
	2L-Section Specimen					
12	L3X2-1/2X3/16	3.39	303.5325	6	1.2	48.816
13	L3X2-1/2X1/4	4.50	303.519	6	1.2	64.8
14	L3X2-1/2X5/16	5.60	303.5036	6	1.2	80.64
15	L3X2-1/2X3/8	6.60	303.4882	6	1.2	95.04

16	L3X2-1/2X7/16	7.60	303.4747	6	1.2	109.44
17	L3X2-1/2X1/2	8.50	303.4612	6	1.2	122.4
18	L3-1/2X2-1/2X1/4	4.90	303.8627	6	1.2	70.56
19	L3-1/2X2-1/2X5/16	6.10	303.8438	6	1.2	87.84
20	L3-1/2X2-1/2X3/8	7.20	303.8248	6	1.2	103.68
21	L3-1/2X2-1/2X1/2	9.40	303.7869	6	1.2	135.36

Table 30 Column 9"x9" Strength and cost comparison for (350-400) Kips period

	AISC_Manual_Label	W	φcPn	L (ft)	$/lb/ft	Total $
	W-Section Specimen					
6	W6X12	12.0	362.383	6	1.2	86.4
7	W6X15	15.0	398.526	6	1.2	108
	4L-Section Specimen					
11	L3X3X3/16	3.71	372.5945	6	1.2	106.848
12	L3X3X1/4	4.90	372.5852	6	1.2	141.12
13	L3X3X5/16	6.10	372.5746	6	1.2	175.68
14	L3X3X3/8	7.20	372.564	6	1.2	207.36
15	L3X3X7/16	8.30	372.5547	6	1.2	239.04
16	L3X3X1/2	9.40	372.5441	6	1.2	270.72
	2L-Section Specimen					
22	L3-1/2X3X1/4	5.40	372.8143	6	1.2	77.76

23	L3-1/2X3X5/16	6.60	372.8012	6	1.2	95.04
24	L3-1/2X3X3/8	7.90	372.8012	6	1.2	113.76
25	L3-1/2X3X7/16	9.10	372.7881	6	1.2	131.04
26	L3-1/2X3X1/2	10.2	372.775	6	1.2	146.88
27	L4X3X1/4	5.80	373.0355	6	1.2	83.52
28	L4X3X5/16	7.20	373.0355	6	1.2	103.68
29	L4X3X3/8	8.50	373.0226	6	1.2	122.4
30	L4X3X1/2	11.1	372.9967	6	1.2	159.84
31	L4X3X5/8	13.6	372.9837	6	1.2	195.84
36	L5X3X1/4	6.60	373.4828	6	1.2	95.04
37	L5X3X5/16	8.20	373.4702	6	1.2	118.08
38	L5X3X3/8	9.80	373.4576	6	1.2	141.12
39	L5X3X7/16	11.3	373.4449	6	1.2	162.72
40	L5X3X1/2	12.8	373.4323	6	1.2	184.32

Table 31 Column 9”x9” Strength and cost comparison for (400-450) Kips period

	AISC_Manual_Label	W	φcPn	L (ft)	$/lb/ft	Total $
	W-Section Specimen					
2	W5X16	16.0	404.988	6	1.2	115.2
3	W5X19	19.0	439.297	6	1.2	136.8
	2L-Section Specimen					
32	L4X3-1/2X1/4	6.20	447.323	6	1.2	89.28

33	L4X3-1/2X5/16	7.70	447.314	6	1.2	110.88
34	L4X3-1/2X3/8	9.10	447.314	6	1.2	131.04
35	L4X3-1/2X1/2	11.9	447.296	6	1.2	171.36

Table 32 Column 10”x10” Strength and cost comparison for (350-400) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
4	W6X8.5	8.50	367.1453	6	1.2	61.2
5	W6X9	9.00	373.9593	6	1.2	64.8
	4L-Section Specimen					
6	L2-1/2X2-1/2X3/16	3.07	354.1649	6	1.2	88.416
7	L2-1/2X2-1/2X1/4	4.10	354.1557	6	1.2	118.08
8	L2-1/2X2-1/2X5/16	5.00	354.1452	6	1.2	144
9	L2-1/2X2-1/2X3/8	5.90	354.136	6	1.2	169.92
10	L2-1/2X2-1/2X1/2	7.70	354.1176	6	1.2	221.76
11	L3X3X3/16	3.71	372.5945	6	1.2	106.848
12	L3X3X1/4	4.90	372.5852	6	1.2	141.12
13	L3X3X5/16	6.10	372.5746	6	1.2	175.68
14	L3X3X3/8	7.20	372.564	6	1.2	207.36
15	L3X3X7/16	8.30	372.5547	6	1.2	239.04
16	L3X3X1/2	9.40	372.5441	6	1.2	270.72
17	L3-1/2X3-1/2X1/4	5.80	391.0162	6	1.2	167.04
18	L3-1/2X3-1/2X5/16	7.20	391.0028	6	1.2	207.36

19	L3-1/2X3-1/2X3/8	8.50	390.9895	6	1.2	244.8
20	L3-1/2X3-1/2X7/16	9.80	390.9761	6	1.2	282.24
21	L3-1/2X3-1/2X1/2	11.1	390.9627	6	1.2	319.68
	2L-Section Specimen					
22	L3-1/2X3X1/4	5.40	372.8143	6	1.2	77.76
23	L3-1/2X3X5/16	6.60	372.8012	6	1.2	95.04
24	L3-1/2X3X3/8	7.90	372.8012	6	1.2	113.76
25	L3-1/2X3X7/16	9.10	372.7881	6	1.2	131.04
26	L3-1/2X3X1/2	10.2	372.775	6	1.2	146.88
27	L4X3X1/4	5.80	373.0355	6	1.2	83.52
28	L4X3X5/16	7.20	373.0355	6	1.2	103.68
29	L4X3X3/8	8.50	373.0226	6	1.2	122.4
30	L4X3X1/2	11.1	372.9967	6	1.2	159.84
31	L4X3X5/8	13.6	372.9837	6	1.2	195.84
36	L5X3X1/4	6.60	373.4828	6	1.2	95.04
37	L5X3X5/16	8.20	373.4702	6	1.2	118.08
38	L5X3X3/8	9.80	373.4576	6	1.2	141.12
39	L5X3X7/16	11.3	373.4449	6	1.2	162.72
40	L5X3X1/2	12.8	373.4323	6	1.2	184.32

Table 33 Column 10”x10” Strength and cost comparison for (400-500) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**

	W-Section Specimen					
1	W4X13	13.0	413.3867	6	1.2	93.6
2	W5X16	16.0	452.4904	6	1.2	115.2
3	W5X19	19.0	486.7782	6	1.2	136.8
6	W6X12	12.0	409.3914	6	1.2	86.4
7	W6X16	16.0	458.3438	6	1.2	115.2
8	W6X15	15.0	445.495	6	1.2	108
9	W6X20	20.0	504.3234	6	1.2	144
	2L-Section Specimen					
32	L4X3-1/2X1/4	6.20	447.3238	6	1.2	89.28
33	L4X3-1/2X5/16	7.70	447.3147	6	1.2	110.88
34	L4X3-1/2X3/8	9.10	447.3147	6	1.2	131.04
35	L4X3-1/2X1/2	11.9	447.2963	6	1.2	171.36
41	L5X3-1/2X1/4	7.00	447.6416	6	1.2	100.8
42	L5X3-1/2X5/16	8.70	447.6326	6	1.2	125.28
43	L5X3-1/2X3/8	10.4	447.6236	6	1.2	149.76
44	L5X3-1/2X1/2	13.6	447.6146	6	1.2	195.84
45	L5X3-1/2X5/8	16.8	447.5966	6	1.2	241.92
46	L5X3-1/2X3/4	19.8	447.5875	6	1.2	285.12
47	L6X3-1/2X5/16	9.80	447.9363	6	1.2	141.12
48	L6X3-1/2X3/8	11.7	447.9275	6	1.2	168.48
49	L6X3-1/2X1/2	15.3	447.9186	6	1.2	220.32

Table 34 Column 11”x11” Strength and cost comparison for (300-350) Kips period

	AISC_Manual_Label	W	φcPn	L (ft)	$/lb/ft	Total $
	WL-Section Specimen					
1	W4X13	13.0	322.2329	6	1.2	93.6
4	W6X8.5	8.50	320.037	6	1.2	61.2
5	W6X9	9.00	326.9037	6	1.2	64.8
	2L-Section Specimen					
12	L3X2-1/2X3/16	3.39	303.5325	6	1.2	48.816
13	L3X2-1/2X1/4	4.50	303.519	6	1.2	64.8
14	L3X2-1/2X5/16	5.60	303.5036	6	1.2	80.64
15	L3X2-1/2X3/8	6.60	303.4882	6	1.2	95.04
16	L3X2-1/2X7/16	7.60	303.4747	6	1.2	109.44
17	L3X2-1/2X1/2	8.50	303.4612	6	1.2	122.4
18	L3-1/2X2-1/2X1/4	4.90	303.8627	6	1.2	70.56
19	L3-1/2X2-1/2X5/16	6.10	303.8438	6	1.2	87.84
20	L3-1/2X2-1/2X3/8	7.20	303.8248	6	1.2	103.68
21	L3-1/2X2-1/2X1/2	9.40	303.7869	6	1.2	135.36
	4L-Section Specimen					
6	L2-1/2X2-1/2X3/16	3.07	303.1907	6	1.2	88.416
7	L2-1/2X2-1/2X1/4	4.10	303.1769	6	1.2	118.08
8	L2-1/2X2-1/2X5/16	5.00	303.1613	6	1.2	144
9	L2-1/2X2-1/2X3/8	5.90	303.1475	6	1.2	169.92
10	L2-1/2X2-1/2X1/2	7.70	303.12	6	1.2	221.76

Table 35 Column 11”x11” Strength and cost comparison for (350-400) Kips period

	AISC_Manual_Label	W	φcPn	L (ft)	$/lb/ft	Total $
	W-Section Specimen					
6	W6X12	12.0	362.383	6	1.2	86.4
8	W6X15	15.0	398.526	6	1.2	108
	2L-Section Specimen					
22	L3-1/2X3X1/4	5.40	372.8143	6	1.2	77.76
23	L3-1/2X3X5/16	6.60	372.8012	6	1.2	95.04
24	L3-1/2X3X3/8	7.90	372.8012	6	1.2	113.76
25	L3-1/2X3X7/16	9.10	372.7881	6	1.2	131.04
26	L3-1/2X3X1/2	10.2	372.775	6	1.2	146.88
27	L4X3X1/4	5.80	373.0355	6	1.2	83.52
28	L4X3X5/16	7.20	373.0355	6	1.2	103.68
29	L4X3X3/8	8.50	373.0226	6	1.2	122.4
30	L4X3X1/2	11.1	372.9967	6	1.2	159.84
31	L4X3X5/8	13.6	372.9837	6	1.2	195.84
36	L5X3X1/4	6.60	373.4828	6	1.2	95.04
37	L5X3X5/16	8.20	373.4702	6	1.2	118.08
38	L5X3X3/8	9.80	373.4576	6	1.2	141.12
39	L5X3X7/16	11.3	373.4449	6	1.2	162.72
40	L5X3X1/2	12.8	373.4323	6	1.2	184.32
	2L-Section Specimen					
11	L3X3X3/16	3.71	372.5945	6	1.2	106.848
12	L3X3X1/4	4.90	372.5852	6	1.2	141.12

13	L3X3X5/16	6.10	372.5746	6	1.2	175.68
14	L3X3X3/8	7.20	372.564	6	1.2	207.36
15	L3X3X7/16	8.30	372.5547	6	1.2	239.04
16	L3X3X1/2	9.40	372.5441	6	1.2	270.72

Table 36 Column 11”x11” Strength and cost comparison for (400-450) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
2	W5X16	16.0	404.9882	6	1.2	115.2
3	W5X19	19.0	439.2971	6	1.2	136.8
7	W6X16	16.0	458.3438	6	1.2	115.2
11	W8X10	10.0	442.3954	6	1.2	72
	2L-Section Specimen					
32	L4X3-1/2X1/4	6.20	447.3238	6	1.2	89.28
33	L4X3-1/2X5/16	7.70	447.3147	6	1.2	110.88
34	L4X3-1/2X3/8	9.10	447.3147	6	1.2	131.04
35	L4X3-1/2X1/2	11.9	447.2963	6	1.2	171.36
41	L5X3-1/2X1/4	7.00	447.6416	6	1.2	100.8
42	L5X3-1/2X5/16	8.70	447.6326	6	1.2	125.28
43	L5X3-1/2X3/8	10.4	447.6236	6	1.2	149.76
44	L5X3-1/2X1/2	13.6	447.6146	6	1.2	195.84
45	L5X3-1/2X5/8	16.8	447.5966	6	1.2	241.92

46	L5X3-1/2X3/4	19.8	447.5875	6	1.2	285.12
47	L6X3-1/2X5/16	9.80	447.9363	6	1.2	141.12
48	L6X3-1/2X3/8	11.7	447.9275	6	1.2	168.48
49	L6X3-1/2X1/2	15.3	447.9186	6	1.2	220.32
	4L-Section Specimen					
17	L3-1/2X3-1/2X1/4	5.80	447.1675	6	1.2	167.04
18	L3-1/2X3-1/2X5/16	7.20	447.1583	6	1.2	207.36
19	L3-1/2X3-1/2X3/8	8.50	447.149	6	1.2	244.8
20	L3-1/2X3-1/2X7/16	9.80	447.1398	6	1.2	282.24
21	L3-1/2X3-1/2X1/2	11.1	447.1305	6	1.2	319.68

for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 37 Column 11"x11" Strength and cost comparison for (450-500) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
7	W6X16	16.0	458.3438	6	1.2	115.2
9	W6X20	20.0	480.1688	6	1.2	144
12	W8X13	13.0	478.4569	6	1.2	93.6
	2L-Section Specimen					
32	L4X3-1/2X1/4	6.20	447.3238	6	1.2	89.28
33	L4X3-1/2X5/16	7.70	447.3147	6	1.2	110.88
34	L4X3-1/2X3/8	9.10	447.3147	6	1.2	131.04
35	L4X3-1/2X1/2	11.9	447.2963	6	1.2	171.36

41	L5X3-1/2X1/4	7.00	447.6416	6	1.2	100.8
42	L5X3-1/2X5/16	8.70	447.6326	6	1.2	125.28
43	L5X3-1/2X3/8	10.4	447.6236	6	1.2	149.76
44	L5X3-1/2X1/2	13.6	447.6146	6	1.2	195.84
45	L5X3-1/2X5/8	16.8	447.5966	6	1.2	241.92
46	L5X3-1/2X3/4	19.8	447.5875	6	1.2	285.12
47	L6X3-1/2X5/16	9.80	447.9363	6	1.2	141.12
48	L6X3-1/2X3/8	11.7	447.9275	6	1.2	168.48
49	L6X3-1/2X1/2	15.3	447.9186	6	1.2	220.32
	4L-Section Specimen					
17	L3-1/2X3-1/2X1/4	5.80	447.1675	6	1.2	167.04
18	L3-1/2X3-1/2X5/16	7.20	447.1583	6	1.2	207.36
19	L3-1/2X3-1/2X3/8	8.50	447.149	6	1.2	244.8
20	L3-1/2X3-1/2X7/16	9.80	447.1398	6	1.2	282.24
21	L3-1/2X3-1/2X1/2	11.1	447.1305	6	1.2	319.68

Table 38 Column 13"x13" Strength and cost comparison for (500-600) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
1	W4X13	13.0	590.2197	6	1.2	93.6
4	W6X8.5	8.50	541.1558	6	1.2	61.2
5	W6X9	9.00	547.7799	6	1.2	64.8
6	W6X12	12.0	582.9591	6	1.2	86.4
12	W8X13	13.0	598.3783	6	1.2	93.6

24	W10X12	12.0	589.2709	6	1.2	86.4
	2L-Section Specimen					
1	L2-1/2X1-1/2X3/16	2.44	496.7107	6	1.2	35.136
2	L2-1/2X1-1/2X1/4	3.19	496.7067	6	1.2	45.936
3	L2-1/2X2X3/16	2.75	515.825	6	1.2	39.6
4	L2-1/2X2X1/4	3.62	515.8213	6	1.2	52.128
5	L2-1/2X2X5/16	4.50	515.8176	6	1.2	64.8
6	L2-1/2X2X3/8	5.30	515.8139	6	1.2	76.32
7	L3X2X3/16	3.07	515.9035	6	1.2	44.208
8	L3X2X1/4	4.10	515.8999	6	1.2	59.04
9	L3X2X5/16	5.00	515.8962	6	1.2	72
10	L3X2X3/8	5.90	515.8925	6	1.2	84.96
11	L3X2X1/2	7.70	515.8856	6	1.2	110.88
12	L3X2-1/2X3/16	3.39	535.0136	6	1.2	48.816
13	L3X2-1/2X1/4	4.50	535.0103	6	1.2	64.8
14	L3X2-1/2X5/16	5.60	535.0066	6	1.2	80.64
15	L3X2-1/2X3/8	6.60	535.0029	6	1.2	95.04
16	L3X2-1/2X7/16	7.60	534.9996	6	1.2	109.44
17	L3X2-1/2X1/2	8.50	534.9963	6	1.2	122.4
18	L3-1/2X2-1/2X1/4	4.90	535.0939	6	1.2	70.56
19	L3-1/2X2-1/2X5/16	6.10	535.0893	6	1.2	87.84
20	L3-1/2X2-1/2X3/8	7.20	535.0847	6	1.2	103.68
21	L3-1/2X2-1/2X1/2	9.40	535.0754	6	1.2	135.36
22	L3-1/2X3X1/4	5.40	554.1986	6	1.2	77.76

23	L3-1/2X3X5/16	6.60	554.1939	6	1.2	95.04
24	L3-1/2X3X3/8	7.90	554.1939	6	1.2	113.76
25	L3-1/2X3X7/16	9.10	554.1892	6	1.2	131.04
26	L3-1/2X3X1/2	10.2	554.1845	6	1.2	146.88
27	L4X3X1/4	5.80	554.2784	6	1.2	83.52
28	L4X3X5/16	7.20	554.2784	6	1.2	103.68
29	L4X3X3/8	8.50	554.2737	6	1.2	122.4
30	L4X3X1/2	11.1	554.2643	6	1.2	159.84
31	L4X3X5/8	13.6	554.2596	6	1.2	195.84
32	L4X3-1/2X1/4	6.20	573.3853	6	1.2	89.28
33	L4X3-1/2X5/16	7.70	573.3806	6	1.2	110.88
34	L4X3-1/2X3/8	9.10	573.3806	6	1.2	131.04
35	L4X3-1/2X1/2	11.9	573.3711	6	1.2	171.36
36	L5X3X1/4	6.60	554.4414	6	1.2	95.04
37	L5X3X5/16	8.20	554.4367	6	1.2	118.08
38	L5X3X3/8	9.80	554.4321	6	1.2	141.12
39	L5X3X7/16	11.3	554.4275	6	1.2	162.72
40	L5X3X1/2	12.8	554.4228	6	1.2	184.32
41	L5X3-1/2X1/4	7.00	573.5507	6	1.2	100.8
42	L5X3-1/2X5/16	8.70	573.546	6	1.2	125.28
43	L5X3-1/2X3/8	10.4	573.5413	6	1.2	149.76
44	L5X3-1/2X1/2	13.6	573.5366	6	1.2	195.84
45	L5X3-1/2X5/8	16.8	573.5272	6	1.2	241.92
46	L5X3-1/2X3/4	19.8	573.5225	6	1.2	285.12

47	L6X3-1/2X5/16	9.80	573.7052	6	1.2	141.12
48	L6X3-1/2X3/8	11.7	573.7005	6	1.2	168.48
49	L6X3-1/2X1/2	15.3	573.6958	6	1.2	220.32
50	L6X4X5/16	10.3	592.818	6	1.2	148.32
51	L6X4X3/8	12.3	592.8133	6	1.2	177.12
52	L6X4X7/16	14.3	592.8086	6	1.2	205.92
53	L6X4X1/2	16.2	592.8038	6	1.2	233.28
54	L6X4X9/16	18.1	592.7991	6	1.2	260.64
55	L6X4X5/8	20.0	592.7944	6	1.2	288
56	L6X4X3/4	23.6	592.7896	6	1.2	339.84
57	L6X4X7/8	27.2	592.7802	6	1.2	391.68
58	L7X4X3/8	13.6	592.9732	6	1.2	195.84
59	L7X4X7/16	15.7	592.9685	6	1.2	226.08
60	L7X4X1/2	17.9	592.9638	6	1.2	257.76
61	L7X4X5/8	22.1	592.9545	6	1.2	318.24
62	L7X4X3/4	26.2	592.9451	6	1.2	377.28
63	L8X4X7/16	17.2	593.1223	6	1.2	247.68
64	L8X4X1/2	19.6	593.1177	6	1.2	282.24
65	L8X4X9/16	21.9	593.1131	6	1.2	315.36
66	L8X4X5/8	24.2	593.1084	6	1.2	348.48
67	L8X4X3/4	28.7	593.1038	6	1.2	413.28
68	L8X4X7/8	33.1	593.0945	6	1.2	476.64
69	L8X4X1	37.4	593.0852	6	1.2	538.56
	4L-Section Specimen					

1	L2X2X1/8	1.65	515.7465	6	1.2	47.52
2	L2X2X3/16	2.44	515.7428	6	1.2	70.272
3	L2X2X1/4	3.19	515.7395	6	1.2	91.872
4	L2X2X5/16	3.92	515.7363	6	1.2	112.896
5	L2X2X3/8	4.70	515.733	6	1.2	135.36
6	L2-1/2X2-1/2X3/16	3.07	534.9314	6	1.2	88.416
7	L2-1/2X2-1/2X1/4	4.10	534.9281	6	1.2	118.08
8	L2-1/2X2-1/2X5/16	5.00	534.9244	6	1.2	144
9	L2-1/2X2-1/2X3/8	5.90	534.9211	6	1.2	169.92
10	L2-1/2X2-1/2X1/2	7.70	534.9146	6	1.2	221.76
11	L3X3X3/16	3.71	554.1198	6	1.2	106.848
12	L3X3X1/4	4.90	554.1165	6	1.2	141.12
13	L3X3X5/16	6.10	554.1127	6	1.2	175.68
14	L3X3X3/8	7.20	554.109	6	1.2	207.36
15	L3X3X7/16	8.30	554.1057	6	1.2	239.04
16	L3X3X1/2	9.40	554.1019	6	1.2	270.72
17	L3-1/2X3-1/2X1/4	5.80	573.3044	6	1.2	167.04
18	L3-1/2X3-1/2X5/16	7.20	573.2996	6	1.2	207.36
19	L3-1/2X3-1/2X3/8	8.50	573.2948	6	1.2	244.8
20	L3-1/2X3-1/2X7/16	9.80	573.2901	6	1.2	282.24
21	L3-1/2X3-1/2X1/2	11.1	573.2853	6	1.2	319.68
22	L4X4X1/4	6.60	592.489	6	1.2	190.08
23	L4X4X5/16	8.20	592.4842	6	1.2	236.16
24	L4X4X3/8	9.80	592.4794	6	1.2	282.24

25	L4X4X7/16	11.3	592.4745	6	1.2	325.44
26	L4X4X1/2	12.8	592.4697	6	1.2	368.64
27	L4X4X5/8	15.7	592.4649	6	1.2	452.16
28	L4X4X3/4	18.5	592.4553	6	1.2	532.8

Table 39 Column 13”x13” Strength and cost comparison for (600-700) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
2	W5X16	16.0	627.409	6	1.2	115.2
3	W5X19	19.0	661.5793	6	1.2	136.8
7	W6X16	16.0	631.5042	6	1.2	115.2
8	W6X15	15.0	618.7804	6	1.2	108
9	W6X20	20.0	677.3631	6	1.2	144
12	W8X13	13.0	598.3783	6	1.2	93.6
13	W8X15	15.0	623.2782	6	1.2	108
14	W8X18	18.0	657.5159	6	1.2	129.6
15	W8X21	21.0	694.5692	6	1.2	151.2
24	W10X12	12.0	589.2709	6	1.2	86.4
25	W10X15	15.0	625.38	6	1.2	108
	2L-Section Specimen					
50	L6X4X5/16	10.3	592.818	6	1.2	148.32
51	L6X4X3/8	12.3	592.8133	6	1.2	177.12
52	L6X4X7/16	14.3	592.8086	6	1.2	205.92
53	L6X4X1/2	16.2	592.8038	6	1.2	233.28

54	L6X4X9/16	18.1	592.7991	6	1.2	260.64
55	L6X4X5/8	20.0	592.7944	6	1.2	288
56	L6X4X3/4	23.6	592.7896	6	1.2	339.84
57	L6X4X7/8	27.2	592.7802	6	1.2	391.68
58	L7X4X3/8	13.6	592.9732	6	1.2	195.84
59	L7X4X7/16	15.7	592.9685	6	1.2	226.08
60	L7X4X1/2	17.9	592.9638	6	1.2	257.76
61	L7X4X5/8	22.1	592.9545	6	1.2	318.24
62	L7X4X3/4	26.2	592.9451	6	1.2	377.28
63	L8X4X7/16	17.2	593.1223	6	1.2	247.68
64	L8X4X1/2	19.6	593.1177	6	1.2	282.24
65	L8X4X9/16	21.9	593.1131	6	1.2	315.36
66	L8X4X5/8	24.2	593.1084	6	1.2	348.48
67	L8X4X3/4	28.7	593.1038	6	1.2	413.28
68	L8X4X7/8	33.1	593.0945	6	1.2	476.64
69	L8X4X1	37.4	593.0852	6	1.2	538.56
	4L-Section Specimen					
22	L4X4X1/4	6.60	592.489	6	1.2	190.08
23	L4X4X5/16	8.20	592.4842	6	1.2	236.16
24	L4X4X3/8	9.80	592.4794	6	1.2	282.24
25	L4X4X7/16	11.3	592.4745	6	1.2	325.44
26	L4X4X1/2	12.8	592.4697	6	1.2	368.64
27	L4X4X5/8	15.7	592.4649	6	1.2	452.16
28	L4X4X3/4	18.5	592.4553	6	1.2	532.8

29	L5X5X5/16	10.3	630.8496	6	1.2	296.64
30	L5X5X3/8	12.3	630.8447	6	1.2	354.24
31	L5X5X7/16	14.3	630.8399	6	1.2	411.84
32	L5X5X1/2	16.2	630.835	6	1.2	466.56
33	L5X5X5/8	20.0	630.8301	6	1.2	576

Table 40 Column 15"x15" Strength and cost comparison for (600-700) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
4	W6X8.5	8.50	683.6895	6	1.2	61.2
5	W6X9	9.00	690.2376	6	1.2	64.8
	2L-Section Specimen					
1	L2-1/2X1-1/2X3/16	2.44	640.714	6	1.2	35.136
2	L2-1/2X1-1/2X1/4	3.19	640.7117	6	1.2	45.936
3	L2-1/2X2X3/16	2.75	660.1615	6	1.2	39.6
4	L2-1/2X2X1/4	3.62	660.1594	6	1.2	52.128
5	L2-1/2X2X5/16	4.50	660.1573	6	1.2	64.8
6	L2-1/2X2X3/8	5.30	660.1552	6	1.2	76.32
7	L3X2X3/16	3.07	660.2059	6	1.2	44.208
8	L3X2X1/4	4.10	660.2038	6	1.2	59.04
9	L3X2X5/16	5.00	660.2018	6	1.2	72
10	L3X2X3/8	5.90	660.1997	6	1.2	84.96
11	L3X2X1/2	7.70	660.1958	6	1.2	110.88
12	L3X2-1/2X3/16	3.39	679.6507	6	1.2	48.816

13	L3X2-1/2X1/4	4.50	679.6488	6	1.2	64.8
14	L3X2-1/2X5/16	5.60	679.6467	6	1.2	80.64
15	L3X2-1/2X3/8	6.60	679.6446	6	1.2	95.04
16	L3X2-1/2X7/16	7.60	679.6428	6	1.2	109.44
17	L3X2-1/2X1/2	8.50	679.6409	6	1.2	122.4
18	L3-1/2X2-1/2X1/4	4.90	679.6961	6	1.2	70.56
19	L3-1/2X2-1/2X5/16	6.10	679.6935	6	1.2	87.84
20	L3-1/2X2-1/2X3/8	7.20	679.6908	6	1.2	103.68
21	L3-1/2X2-1/2X1/2	9.40	679.6856	6	1.2	135.36
22	L3-1/2X3X1/4	5.40	699.1374	6	1.2	77.76
23	L3-1/2X3X5/16	6.60	699.1348	6	1.2	95.04
24	L3-1/2X3X3/8	7.90	699.1348	6	1.2	113.76
25	L3-1/2X3X7/16	9.10	699.1321	6	1.2	131.04
26	L3-1/2X3X1/2	10.2	699.1295	6	1.2	146.88
27	L4X3X1/4	5.80	699.1825	6	1.2	83.52
28	L4X3X5/16	7.20	699.1825	6	1.2	103.68
29	L4X3X3/8	8.50	699.1798	6	1.2	122.4
30	L4X3X1/2	11.1	699.1745	6	1.2	159.84
31	L4X3X5/8	13.6	699.1719	6	1.2	195.84
	4L-Section Specimen					
1	L2X2X1/8	1.65	660.1172	6	1.2	47.52
2	L2X2X3/16	2.44	660.1151	6	1.2	70.272
3	L2X2X1/4	3.19	660.1132	6	1.2	91.872
4	L2X2X5/16	3.92	660.1114	6	1.2	112.896

5	L2X2X3/8	4.70	660.1096	6	1.2	135.36
6	L2-1/2X2-1/2X3/16	3.07	679.6043	6	1.2	88.416
7	L2-1/2X2-1/2X1/4	4.10	679.6025	6	1.2	118.08
8	L2-1/2X2-1/2X5/16	5.00	679.6004	6	1.2	144
9	L2-1/2X2-1/2X3/8	5.90	679.5985	6	1.2	169.92
10	L2-1/2X2-1/2X1/2	7.70	679.5948	6	1.2	221.76
11	L3X3X3/16	3.71	699.093	6	1.2	106.848
12	L3X3X1/4	4.90	699.0912	6	1.2	141.12
13	L3X3X5/16	6.10	699.089	6	1.2	175.68
14	L3X3X3/8	7.20	699.0869	6	1.2	207.36
15	L3X3X7/16	8.30	699.085	6	1.2	239.04
16	L3X3X1/2	9.40	699.0829	6	1.2	270.72

Table 41 Column 15”x15” Strength and cost comparison for (700-800) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
1	W4X13	13.0	733.9538	6	1.2	93.6
2	W5X16	16.0	770.4284	6	1.2	115.2
3	W5X19	19.0	804.5632	6	1.2	136.8
6	W6X12	12.0	725.3101	6	1.2	86.4
7	W6X16	16.0	773.6194	6	1.2	115.2
8	W6X15	15.0	760.9745	6	1.2	108

11	W8X10	10.0	703.8252	6	1.2	72
12	W8X13	13.0	739.659	6	1.2	93.6
13	W8X15	15.0	764.3982	6	1.2	108
14	W8X18	18.0	798.4152	6	1.2	129.6
24	W10X12	12.0	729.892	6	1.2	86.4
25	W10X15	15.0	765.8664	6	1.2	108
26	W10X17	17.0	790.069	6	1.2	122.4
	2L-Section Specimen					
33	L4X3-1/2X5/16	7.70	718.6221	6	1.2	110.88
34	L4X3-1/2X3/8	9.10	718.6221	6	1.2	131.04
35	L4X3-1/2X1/2	11.9	718.6167	6	1.2	171.36
41	L5X3-1/2X1/4	7.00	718.7182	6	1.2	100.8
42	L5X3-1/2X5/16	8.70	718.7155	6	1.2	125.28
43	L5X3-1/2X3/8	10.4	718.7128	6	1.2	149.76
44	L5X3-1/2X1/2	13.6	718.7102	6	1.2	195.84
45	L5X3-1/2X5/8	16.8	718.7049	6	1.2	241.92
46	L5X3-1/2X3/4	19.8	718.7022	6	1.2	285.12
47	L6X3-1/2X5/16	9.80	718.8058	6	1.2	141.12
48	L6X3-1/2X3/8	11.7	718.8031	6	1.2	168.48
49	L6X3-1/2X1/2	15.3	718.8005	6	1.2	220.32
50	L6X4X5/16	10.3	738.2507	6	1.2	148.32
51	L6X4X3/8	12.3	738.248	6	1.2	177.12
52	L6X4X7/16	14.3	738.2453	6	1.2	205.92
53	L6X4X1/2	16.2	738.2426	6	1.2	233.28

54	L6X4X9/16	18.1	738.24	6	1.2	260.64
55	L6X4X5/8	20.0	738.2373	6	1.2	288
56	L6X4X3/4	23.6	738.2346	6	1.2	339.84
57	L6X4X7/8	27.2	738.2293	6	1.2	391.68
58	L7X4X3/8	13.6	738.3388	6	1.2	195.84
59	L7X4X7/16	15.7	738.3361	6	1.2	226.08
60	L7X4X1/2	17.9	738.3335	6	1.2	257.76
61	L7X4X5/8	22.1	738.3281	6	1.2	318.24
62	L7X4X3/4	26.2	738.3228	6	1.2	377.28
63	L8X4X7/16	17.2	738.4238	6	1.2	247.68
64	L8X4X1/2	19.6	738.4211	6	1.2	282.24
65	L8X4X9/16	21.9	738.4185	6	1.2	315.36
66	L8X4X5/8	24.2	738.4158	6	1.2	348.48
67	L8X4X3/4	28.7	738.4132	6	1.2	413.28
68	L8X4X7/8	33.1	738.4079	6	1.2	476.64
69	L8X4X1	37.4	738.4026	6	1.2	538.56
	4L-Section Specimen					
17	L3-1/2X3-1/2X1/4	5.80	718.5791	6	1.2	167.04
18	L3-1/2X3-1/2X5/16	7.20	718.5765	6	1.2	207.36
19	L3-1/2X3-1/2X3/8	8.50	718.5738	6	1.2	244.8
20	L3-1/2X3-1/2X7/16	9.80	718.5711	6	1.2	282.24
21	L3-1/2X3-1/2X1/2	11.1	718.5684	6	1.2	319.68
22	L4X4X1/4	6.60	738.0649	6	1.2	190.08
23	L4X4X5/16	8.20	738.0622	6	1.2	236.16

24	L4X4X3/8	9.80	738.0595	6	1.2	282.24
25	L4X4X7/16	11.3	738.0568	6	1.2	325.44
26	L4X4X1/2	12.8	738.0541	6	1.2	368.64
27	L4X4X5/8	15.7	738.0513	6	1.2	452.16
28	L4X4X3/4	18.5	738.0459	6	1.2	532.8
29	L5X5X5/16	10.3	777.0304	6	1.2	296.64
30	L5X5X3/8	12.3	777.0277	6	1.2	354.24
31	L5X5X7/16	14.3	777.0249	6	1.2	411.84
32	L5X5X1/2	16.2	777.0222	6	1.2	466.56
33	L5X5X5/8	20.0	777.0194	6	1.2	576
34	L5X5X3/4	23.6	777.0139	6	1.2	679.68
35	L5X5X7/8	27.2	777.0111	6	1.2	783.36

angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 42 Column 20”x20” Strength and cost comparison for (1100-1200) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
1	W4X13	13.0	1182.211	6	1.2	93.6
2	W5X16	16.0	1218.019	6	1.2	115.2
4	W6X8.5	8.50	1130.351	6	1.2	61.2
5	W6X9	9.00	1136.833	6	1.2	64.8
6	W6X12	12.0	1171.893	6	1.2	86.4
8	W6X15	15.0	1207.443	6	1.2	108

11	W8X10	10.0	1149.026	6	1.2	72
12	W8X13	13.0	1184.682	6	1.2	93.6
13	W8X15	15.0	1209.145	6	1.2	108
	2L-Section Specimen					
1	L2-1/2X1-1/2X3/16	2.44	1088.651	6	1.2	35.136
2	L2-1/2X1-1/2X1/4	3.19	1088.65	6	1.2	45.936
3	L2-1/2X2X3/16	2.75	1108.544	6	1.2	39.6
4	L2-1/2X2X1/4	3.62	1108.544	6	1.2	52.128
5	L2-1/2X2X5/16	4.50	1108.543	6	1.2	64.8
6	L2-1/2X2X3/8	5.30	1108.543	6	1.2	76.32
7	L3X2X3/16	3.07	1108.558	6	1.2	44.208
8	L3X2X1/4	4.10	1108.558	6	1.2	59.04
9	L3X2X5/16	5.00	1108.557	6	1.2	72
10	L3X2X3/8	5.90	1108.557	6	1.2	84.96
11	L3X2X1/2	7.70	1108.555	6	1.2	110.88
12	L3X2-1/2X3/16	3.39	1128.451	6	1.2	48.816
13	L3X2-1/2X1/4	4.50	1128.451	6	1.2	64.8
14	L3X2-1/2X5/16	5.60	1128.45	6	1.2	80.64
15	L3X2-1/2X3/8	6.60	1128.449	6	1.2	95.04
16	L3X2-1/2X7/16	7.60	1128.449	6	1.2	109.44
17	L3X2-1/2X1/2	8.50	1128.448	6	1.2	122.4
18	L3-1/2X2-1/2X1/4	4.90	1128.465	6	1.2	70.56
19	L3-1/2X2-1/2X5/16	6.10	1128.465	6	1.2	87.84
20	L3-1/2X2-1/2X3/8	7.20	1128.464	6	1.2	103.68

21	L3-1/2X2-1/2X1/2	9.40	1128.462	6	1.2	135.36
22	L3-1/2X3X1/4	5.40	1148.357	6	1.2	77.76
23	L3-1/2X3X5/16	6.60	1148.356	6	1.2	95.04
24	L3-1/2X3X3/8	7.90	1148.356	6	1.2	113.76
25	L3-1/2X3X7/16	9.10	1148.355	6	1.2	131.04
26	L3-1/2X3X1/2	10.2	1148.354	6	1.2	146.88
27	L4X3X1/4	5.80	1148.371	6	1.2	83.52
28	L4X3X5/16	7.20	1148.371	6	1.2	103.68
29	L4X3X3/8	8.50	1148.37	6	1.2	122.4
30	L4X3X1/2	11.1	1148.369	6	1.2	159.84
31	L4X3X5/8	13.6	1148.368	6	1.2	195.84
32	L4X3-1/2X1/4	6.20	1168.263	6	1.2	89.28
33	L4X3-1/2X5/16	7.70	1168.262	6	1.2	110.88
34	L4X3-1/2X3/8	9.10	1168.262	6	1.2	131.04
35	L4X3-1/2X1/2	11.9	1168.26	6	1.2	171.36
36	L5X3X1/4	6.60	1148.4	6	1.2	95.04
37	L5X3X5/16	8.20	1148.399	6	1.2	118.08
38	L5X3X3/8	9.80	1148.398	6	1.2	141.12
39	L5X3X7/16	11.3	1148.398	6	1.2	162.72
40	L5X3X1/2	12.8	1148.397	6	1.2	184.32
41	L5X3-1/2X1/4	7.00	1168.292	6	1.2	100.8
42	L5X3-1/2X5/16	8.70	1168.291	6	1.2	125.28
43	L5X3-1/2X3/8	10.4	1168.29	6	1.2	149.76
44	L5X3-1/2X1/2	13.6	1168.289	6	1.2	195.84

45	L5X3-1/2X5/8	16.8	1168.288	6	1.2	241.92
46	L5X3-1/2X3/4	19.8	1168.287	6	1.2	285.12
47	L6X3-1/2X5/16	9.80	1168.319	6	1.2	141.12
48	L6X3-1/2X3/8	11.7	1168.318	6	1.2	168.48
49	L6X3-1/2X1/2	15.3	1168.318	6	1.2	220.32
50	L6X4X5/16	10.3	1188.211	6	1.2	148.32
51	L6X4X3/8	12.3	1188.21	6	1.2	177.12
52	L6X4X7/16	14.3	1188.21	6	1.2	205.92
53	L6X4X1/2	16.2	1188.209	6	1.2	233.28
54	L6X4X9/16	18.1	1188.208	6	1.2	260.64
55	L6X4X5/8	20.0	1188.207	6	1.2	288
56	L6X4X3/4	23.6	1188.206	6	1.2	339.84
57	L6X4X7/8	27.2	1188.205	6	1.2	391.68
58	L7X4X3/8	13.6	1188.239	6	1.2	195.84
59	L7X4X7/16	15.7	1188.238	6	1.2	226.08
60	L7X4X1/2	17.9	1188.237	6	1.2	257.76
61	L7X4X5/8	22.1	1188.236	6	1.2	318.24
62	L7X4X3/4	26.2	1188.234	6	1.2	377.28
63	L8X4X7/16	17.2	1188.266	6	1.2	247.68
64	L8X4X1/2	19.6	1188.265	6	1.2	282.24
65	L8X4X9/16	21.9	1188.264	6	1.2	315.36
66	L8X4X5/8	24.2	1188.263	6	1.2	348.48
67	L8X4X3/4	28.7	1188.262	6	1.2	413.28
68	L8X4X7/8	33.1	1188.261	6	1.2	476.64

69	L8X4X1	37.4	1188.259	6	1.2	538.56
	4L-Section Specimen					
1	L2X2X1/8	1.65	1108.531	6	1.2	47.52
2	L2X2X3/16	2.44	1108.53	6	1.2	70.272
3	L2X2X1/4	3.19	1108.529	6	1.2	91.872
4	L2X2X5/16	3.92	1108.529	6	1.2	112.896
5	L2X2X3/8	4.70	1108.528	6	1.2	135.36
6	L2-1/2X2-1/2X3/16	3.07	1128.437	6	1.2	88.416
7	L2-1/2X2-1/2X1/4	4.10	1128.436	6	1.2	118.08
8	L2-1/2X2-1/2X5/16	5.00	1128.435	6	1.2	144
9	L2-1/2X2-1/2X3/8	5.90	1128.435	6	1.2	169.92
10	L2-1/2X2-1/2X1/2	7.70	1128.434	6	1.2	221.76
11	L3X3X3/16	3.71	1148.343	6	1.2	106.848
12	L3X3X1/4	4.90	1148.342	6	1.2	141.12
13	L3X3X5/16	6.10	1148.342	6	1.2	175.68
14	L3X3X3/8	7.20	1148.341	6	1.2	207.36
15	L3X3X7/16	8.30	1148.341	6	1.2	239.04
16	L3X3X1/2	9.40	1148.34	6	1.2	270.72
17	L3-1/2X3-1/2X1/4	5.80	1168.248	6	1.2	167.04
18	L3-1/2X3-1/2X5/16	7.20	1168.247	6	1.2	207.36
19	L3-1/2X3-1/2X3/8	8.50	1168.247	6	1.2	244.8
20	L3-1/2X3-1/2X7/16	9.80	1168.246	6	1.2	282.24
21	L3-1/2X3-1/2X1/2	11.1	1168.245	6	1.2	319.68
22	L4X4X1/4	6.60	1188.153	6	1.2	190.08

23	L4X4X5/16	8.20	1188.152	6	1.2	236.16
24	L4X4X3/8	9.80	1188.152	6	1.2	282.24
25	L4X4X7/16	11.3	1188.151	6	1.2	325.44
26	L4X4X1/2	12.8	1188.15	6	1.2	368.64
27	L4X4X5/8	15.7	1188.149	6	1.2	452.16
28	L4X4X3/4	18.5	1188.147	6	1.2	532.8

Figure

Table 43 Column 20”x20” Strength and cost comparison for (1200-1300) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
2	W5X16	16.0	1218.019	6	1.2	115.2
3	W5X19	19.0	1252.225	6	1.2	136.8
7	W6X16	16.0	1220.003	6	1.2	115.2
8	W6X15	15.0	1207.443	6	1.2	108
9	W6X20	20.0	1265.661	6	1.2	144
13	W8X15	15.0	1209.145	6	1.2	108
14	W8X18	18.0	1242.709	6	1.2	129.6
15	W8X21	21.0	1279.401	6	1.2	151.2
25	W10X15	15.0	1209.249	6	1.2	108
26	W10X17	17.0	1233.127	6	1.2	122.4
27	W10X19	19.0	1259.049	6	1.2	136.8
28	W10X22	22.0	1294.888	6	1.2	158.4

42	W12X14	14.0	1200.384	6	1.2	100.8
43	W12X16	16.0	1223.082	6	1.2	115.2
44	W12X19	19.0	1258.726	6	1.2	136.8
45	W12X22	22.0	1296.237	6	1.2	158.4
71	W14X22	22.0	1298.327	6	1.2	158.4
	2L-Section Specimen					
70	L8X6X7/16	20.2	1267.825	6	1.2	290.88
71	L8X6X1/2	23.0	1267.824	6	1.2	331.2
72	L8X6X9/16	25.7	1267.824	6	1.2	370.08
73	L8X6X5/8	28.5	1267.823	6	1.2	410.4
74	L8X6X3/4	33.8	1267.821	6	1.2	486.72
75	L8X6X7/8	39.1	1267.82	6	1.2	563.04
76	L8X6X1	44.2	1267.819	6	1.2	636.48
	4L-Section Specimen			6	1.2	0
29	L5X5X5/16	10.3	1227.96	6	1.2	296.64
30	L5X5X3/8	12.3	1227.96	6	1.2	354.24
31	L5X5X7/16	14.3	1227.959	6	1.2	411.84
32	L5X5X1/2	16.2	1227.958	6	1.2	466.56
33	L5X5X5/8	20.0	1227.957	6	1.2	576
34	L5X5X3/4	23.6	1227.955	6	1.2	679.68
35	L5X5X7/8	27.2	1227.954	6	1.2	783.36
36	L6X6X5/16	12.4	1267.766	6	1.2	357.12
37	L6X6X3/8	14.9	1267.765	6	1.2	429.12
38	L6X6X7/16	17.2	1267.765	6	1.2	495.36

39	L6X6X1/2	19.6	1267.765	6	1.2	564.48
40	L6X6X9/16	21.9	1267.764	6	1.2	630.72
41	L6X6X5/8	24.2	1267.763	6	1.2	696.96
42	L6X6X3/4	28.7	1267.761	6	1.2	826.56
43	L6X6X7/8	33.1	1267.76	6	1.2	953.28

Table 44 Column 20”x20” Strength and cost comparison for (1300-1400) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
10	W6X25	25.0	1325.036	6	1.2	180
16	W8X24	24.0	1316.52	6	1.2	172.8
17	W8X28	28.0	1364.057	6	1.2	201.6
18	W8X31	31.0	1399.824	6	1.2	223.2
29	W10X26	26.0	1340.854	6	1.2	187.2
30	W10X30	30.0	1391.154	6	1.2	216
46	W12X26	26.0	1344.925	6	1.2	187.2
47	W12X30	30.0	1391.755	6	1.2	216
72	W14X26	26.0	1347.938	6	1.2	187.2
73	W14X30	30.0	1395.82	6	1.2	216
	4L-Section Specimen					
45	L8X8X1/2	26.4	1347.369	6	1.2	380.16
46	L8X8X9/16	29.6	1347.369	6	1.2	426.24

47	L8X8X5/8	32.7	1347.368	6	1.2	470.88
48	L8X8X3/4	38.9	1347.367	6	1.2	560.16
49	L8X8X7/8	45.0	1347.366	6	1.2	648
50	L8X8X1	51.0	1347.364	6	1.2	734.4
51	L8X8X1-1/8	56.9	1347.362	6	1.2	819.36

for steel angles the cost multiplied by 4 for the 4L sections and 2 for 2L sections).

Table 45 Column 25"x25" Strength and cost comparison for (1700-1800) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
1	W4X13	13.0	1757.247	6	1.2	93.6
2	W5X16	16.0	1792.961	6	1.2	115.2
4	W6X8.5	8.50	1704.692	6	1.2	61.2
5	W6X9	9.00	1711.174	6	1.2	64.8
6	W6X12	12.0	1746.341	6	1.2	86.4
7	W6X16	16.0	1794.511	6	1.2	115.2
8	W6X15	15.0	1781.95	6	1.2	108
11	W8X10	10.0	1722.891	6	1.2	72
12	W8X13	13.0	1758.553	6	1.2	93.6
13	W8X15	15.0	1782.941	6	1.2	108
24	W10X12	12.0	1746.918	6	1.2	86.4
25	W10X15	15.0	1782.356	6	1.2	108
42	W12X14	14.0	1772.855	6	1.2	100.8

43	W12X16	16.0	1795.378	6	1.2	115.2
	2L-Section Specimen					
12	L3X2-1/2X3/16	3.39	1703.429	6	1.2	48.816
13	L3X2-1/2X1/4	4.50	1703.429	6	1.2	64.8
14	L3X2-1/2X5/16	5.60	1703.428	6	1.2	80.64
15	L3X2-1/2X3/8	6.60	1703.428	6	1.2	95.04
16	L3X2-1/2X7/16	7.60	1703.428	6	1.2	109.44
17	L3X2-1/2X1/2	8.50	1703.428	6	1.2	122.4
18	L3-1/2X2-1/2X1/4	4.90	1703.435	6	1.2	70.56
19	L3-1/2X2-1/2X5/16	6.10	1703.434	6	1.2	87.84
20	L3-1/2X2-1/2X3/8	7.20	1703.434	6	1.2	103.68
21	L3-1/2X2-1/2X1/2	9.40	1703.433	6	1.2	135.36
22	L3-1/2X3X1/4	5.40	1723.536	6	1.2	77.76
23	L3-1/2X3X5/16	6.60	1723.536	6	1.2	95.04
24	L3-1/2X3X3/8	7.90	1723.536	6	1.2	113.76
25	L3-1/2X3X7/16	9.10	1723.535	6	1.2	131.04
26	L3-1/2X3X1/2	10.2	1723.535	6	1.2	146.88
27	L4X3X1/4	5.80	1723.542	6	1.2	83.52
28	L4X3X5/16	7.20	1723.542	6	1.2	103.68
29	L4X3X3/8	8.50	1723.541	6	1.2	122.4
30	L4X3X1/2	11.1	1723.541	6	1.2	159.84
31	L4X3X5/8	13.6	1723.54	6	1.2	195.84
32	L4X3-1/2X1/4	6.20	1743.643	6	1.2	89.28
33	L4X3-1/2X5/16	7.70	1743.643	6	1.2	110.88

34	L4X3-1/2X3/8	9.10	1743.643	6	1.2	131.04
35	L4X3-1/2X1/2	11.9	1743.642	6	1.2	171.36
36	L5X3X1/4	6.60	1723.553	6	1.2	95.04
37	L5X3X5/16	8.20	1723.553	6	1.2	118.08
38	L5X3X3/8	9.80	1723.553	6	1.2	141.12
39	L5X3X7/16	11.3	1723.552	6	1.2	162.72
40	L5X3X1/2	12.8	1723.552	6	1.2	184.32
41	L5X3-1/2X1/4	7.00	1743.655	6	1.2	100.8
42	L5X3-1/2X5/16	8.70	1743.654	6	1.2	125.28
43	L5X3-1/2X3/8	10.4	1743.654	6	1.2	149.76
44	L5X3-1/2X1/2	13.6	1743.654	6	1.2	195.84
45	L5X3-1/2X5/8	16.8	1743.653	6	1.2	241.92
46	L5X3-1/2X3/4	19.8	1743.653	6	1.2	285.12
47	L6X3-1/2X5/16	9.80	1743.666	6	1.2	141.12
48	L6X3-1/2X3/8	11.7	1743.666	6	1.2	168.48
49	L6X3-1/2X1/2	15.3	1743.665	6	1.2	220.32
50	L6X4X5/16	10.3	1763.767	6	1.2	148.32
51	L6X4X3/8	12.3	1763.767	6	1.2	177.12
52	L6X4X7/16	14.3	1763.767	6	1.2	205.92
53	L6X4X1/2	16.2	1763.766	6	1.2	233.28
54	L6X4X9/16	18.1	1763.766	6	1.2	260.64
55	L6X4X5/8	20.0	1763.766	6	1.2	288
56	L6X4X3/4	23.6	1763.765	6	1.2	339.84
57	L6X4X7/8	27.2	1763.765	6	1.2	391.68

58	L7X4X3/8	13.6	1763.778	6	1.2	195.84
59	L7X4X7/16	15.7	1763.778	6	1.2	226.08
60	L7X4X1/2	17.9	1763.778	6	1.2	257.76
61	L7X4X5/8	22.1	1763.777	6	1.2	318.24
62	L7X4X3/4	26.2	1763.776	6	1.2	377.28
63	L8X4X7/16	17.2	1763.789	6	1.2	247.68
64	L8X4X1/2	19.6	1763.789	6	1.2	282.24
65	L8X4X9/16	21.9	1763.789	6	1.2	315.36
66	L8X4X5/8	24.2	1763.788	6	1.2	348.48
67	L8X4X3/4	28.7	1763.788	6	1.2	413.28
68	L8X4X7/8	33.1	1763.787	6	1.2	476.64
69	L8X4X1	37.4	1763.787	6	1.2	538.56
	4L-Section Specimen					
6	L2-1/2X2-1/2X3/16	3.07	1703.423	6	1.2	88.416
7	L2-1/2X2-1/2X1/4	4.10	1703.423	6	1.2	118.08
8	L2-1/2X2-1/2X5/16	5.00	1703.423	6	1.2	144
9	L2-1/2X2-1/2X3/8	5.90	1703.422	6	1.2	169.92
10	L2-1/2X2-1/2X1/2	7.70	1703.422	6	1.2	221.76
11	L3X3X3/16	3.71	1723.53	6	1.2	106.848
12	L3X3X1/4	4.90	1723.53	6	1.2	141.12
13	L3X3X5/16	6.10	1723.53	6	1.2	175.68
14	L3X3X3/8	7.20	1723.53	6	1.2	207.36
15	L3X3X7/16	8.30	1723.529	6	1.2	239.04
16	L3X3X1/2	9.40	1723.529	6	1.2	270.72

17	L3-1/2X3-1/2X1/4	5.80	1743.637	6	1.2	167.04
18	L3-1/2X3-1/2X5/16	7.20	1743.637	6	1.2	207.36
19	L3-1/2X3-1/2X3/8	8.50	1743.637	6	1.2	244.8
20	L3-1/2X3-1/2X7/16	9.80	1743.636	6	1.2	282.24
21	L3-1/2X3-1/2X1/2	11.1	1743.636	6	1.2	319.68
22	L4X4X1/4	6.60	1763.744	6	1.2	190.08
23	L4X4X5/16	8.20	1763.743	6	1.2	236.16
24	L4X4X3/8	9.80	1763.743	6	1.2	282.24
25	L4X4X7/16	11.3	1763.743	6	1.2	325.44
26	L4X4X1/2	12.8	1763.742	6	1.2	368.64
27	L4X4X5/8	15.7	1763.742	6	1.2	452.16
28	L4X4X3/4	18.5	1763.741	6	1.2	532.8

Table 46 Column 25”x25” Strength and cost comparison for (1800-1900) Kips period

	AISC_Manual_Label	**W**	**φcPn**	**L (ft)**	**$/lb/ft**	**Total $**
	W-Section Specimen					
3	W5X19	19.0	1827.297	6	1.2	136.8
9	W6X20	20.0	1840.246	6	1.2	144
10	W6X25	25.0	1899.737	6	1.2	180
14	W8X18	18.0	1816.341	6	1.2	129.6
15	W8X21	21.0	1852.937	6	1.2	151.2
16	W8X24	24.0	1890.16	6	1.2	172.8

26	W10X17	17.0	1806.061	6	1.2	122.4
27	W10X19	19.0	1831.81	6	1.2	136.8
28	W10X22	22.0	1867.406	6	1.2	158.4
44	W12X19	19.0	1830.697	6	1.2	136.8
45	W12X22	22.0	1867.979	6	1.2	158.4
71	W14X22	22.0	1869.396	6	1.2	158.4
	2L-Section Specimen					
70	L8X6X7/16	20.2	1844.19	6	1.2	290.88
71	L8X6X1/2	23.0	1844.19	6	1.2	331.2
72	L8X6X9/16	25.7	1844.19	6	1.2	370.08
73	L8X6X5/8	28.5	1844.19	6	1.2	410.4
74	L8X6X3/4	33.8	1844.189	6	1.2	486.72
75	L8X6X7/8	39.1	1844.188	6	1.2	563.04
76	L8X6X1	44.2	1844.188	6	1.2	636.48
	4L-Section Specimen					
29	L5X5X5/16	10.3	1803.956	6	1.2	296.64
30	L5X5X3/8	12.3	1803.955	6	1.2	354.24
31	L5X5X7/16	14.3	1803.955	6	1.2	411.84
32	L5X5X1/2	16.2	1803.955	6	1.2	466.56
33	L5X5X5/8	20.0	1803.954	6	1.2	576
34	L5X5X3/4	23.6	1803.954	6	1.2	679.68
35	L5X5X7/8	27.2	1803.953	6	1.2	783.36
36	L6X6X5/16	12.4	1844.167	6	1.2	357.12
37	L6X6X3/8	14.9	1844.166	6	1.2	429.12

38	L6X6X7/16	17.2	1844.166	6	1.2	495.36
39	L6X6X1/2	19.6	1844.166	6	1.2	564.48
40	L6X6X9/16	21.9	1844.166	6	1.2	630.72
41	L6X6X5/8	24.2	1844.165	6	1.2	696.96
42	L6X6X3/4	28.7	1844.165	6	1.2	826.56
43	L6X6X7/8	33.1	1844.164	6	1.2	953.28
44	L6X6X1	37.4	1844.164	6	1.2	1077.12

8.f Appendix E: List of Figures

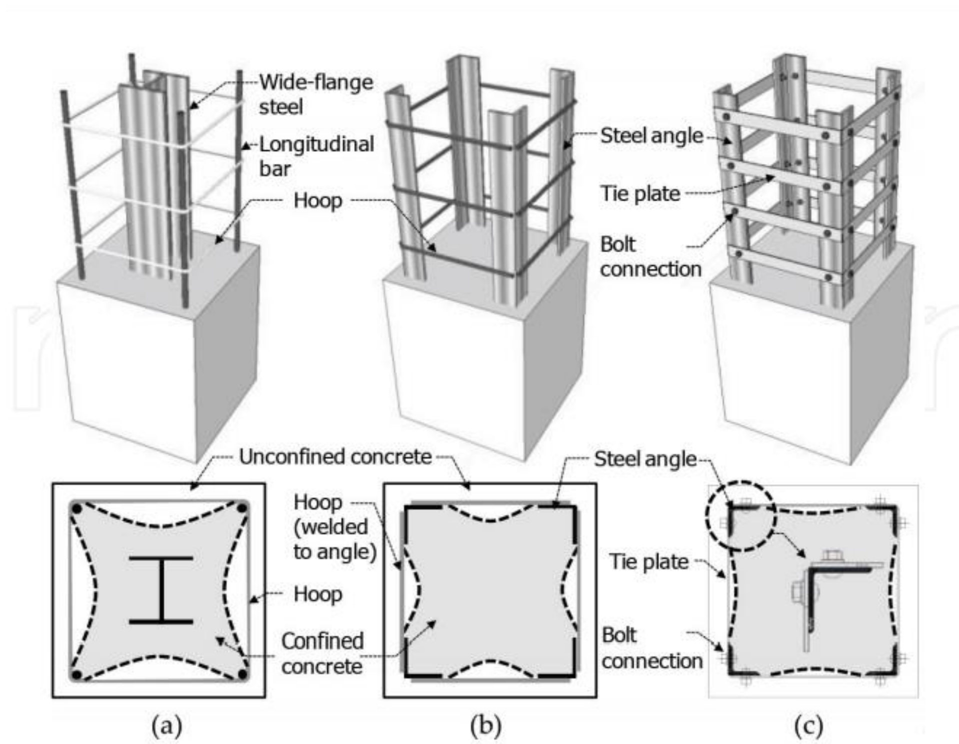


Figure 73 Comparison of CES column and PSRC columns. (a) CES composite column, (b) PSRC composite column (weld connection), (c) PSRC composite column (bolt connection). Hwang (2018)

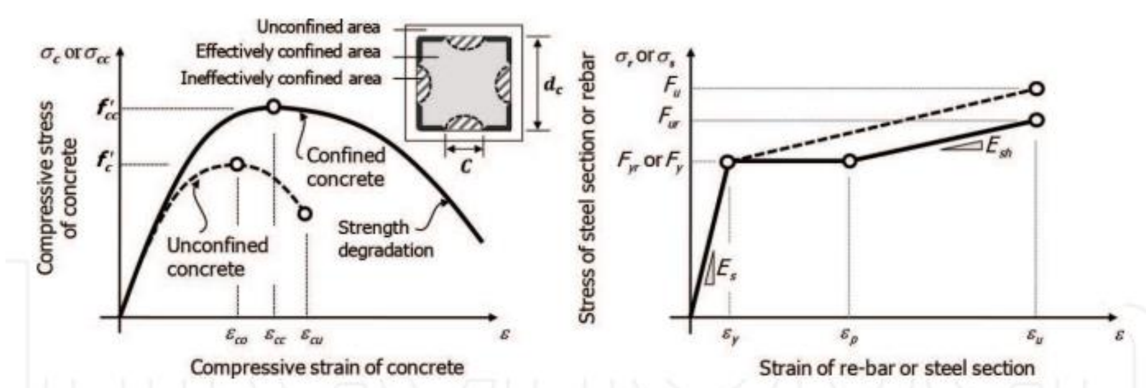


Figure 74 Stress-strain relationship of concrete and steel for numerical analysis (Hwang (2018))

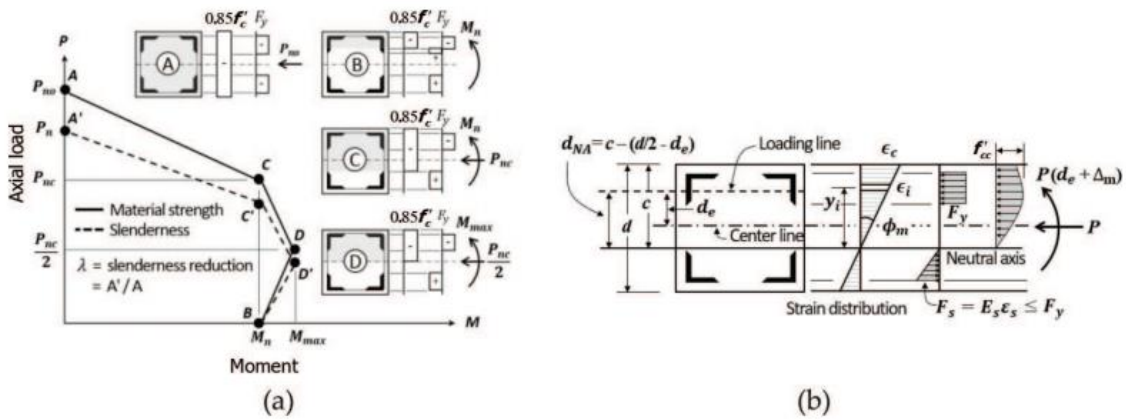


Figure 75 Section analysis methods of PSRC column under eccentric axial loading: (a) P-M interaction diagram and (b) strain-compatibility method. Hwang (2018)

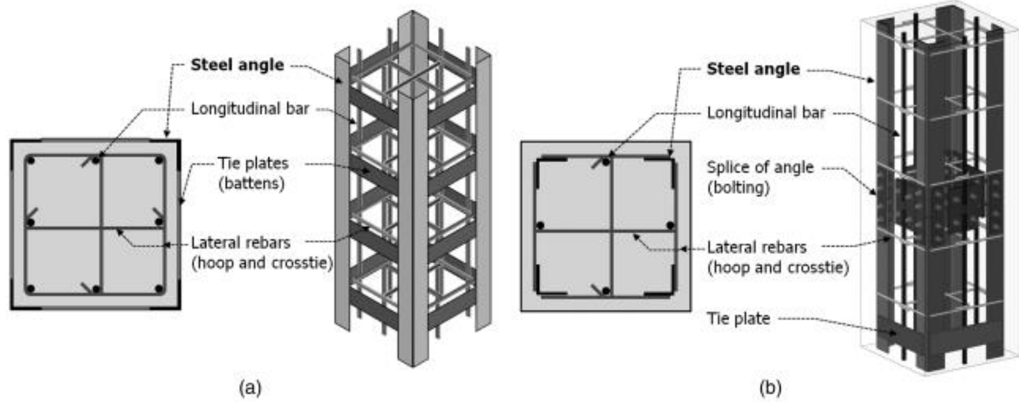


Figure 76 Composite columns using prefabricated steel angles: (a) existing method of retrofitting [data from Poon (1999), Montuori and Piluso (2009), and (Hwang, 2018)ione (2010)]; (b) proposed PSRC composite column (Eom et al. (2014))

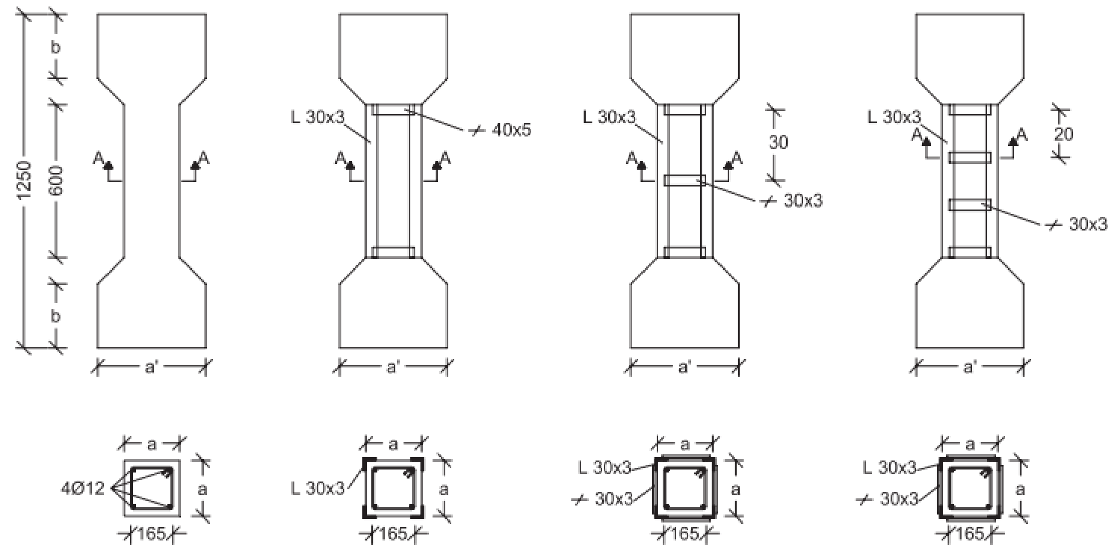


Figure 77 Strengthened specimens with steel angles and steel battens. Campione (2013)

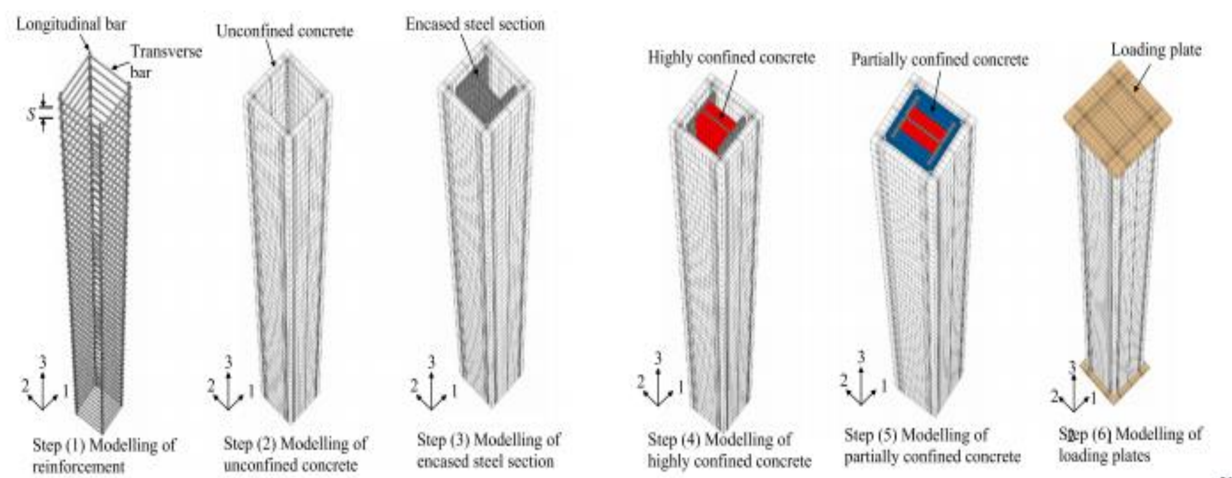


Figure 78 Modelling steps of concrete encased steel composite columns. Young and Ellobody (2010)

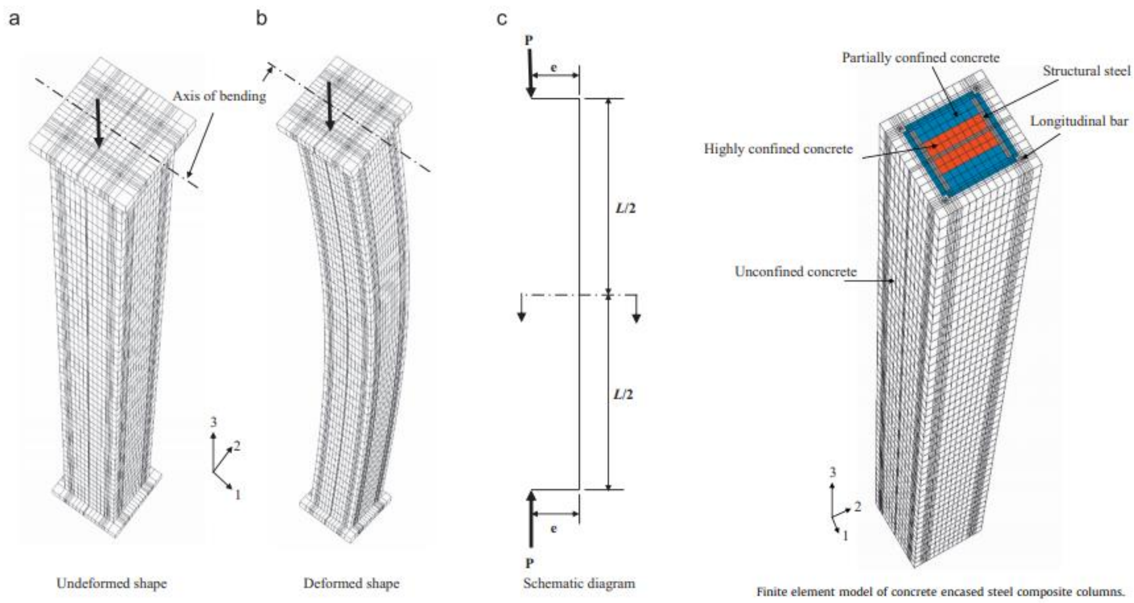


Figure 79 shows finite element model of concrete encased steel composite columns. Ellobody, Young and Lam (2010)

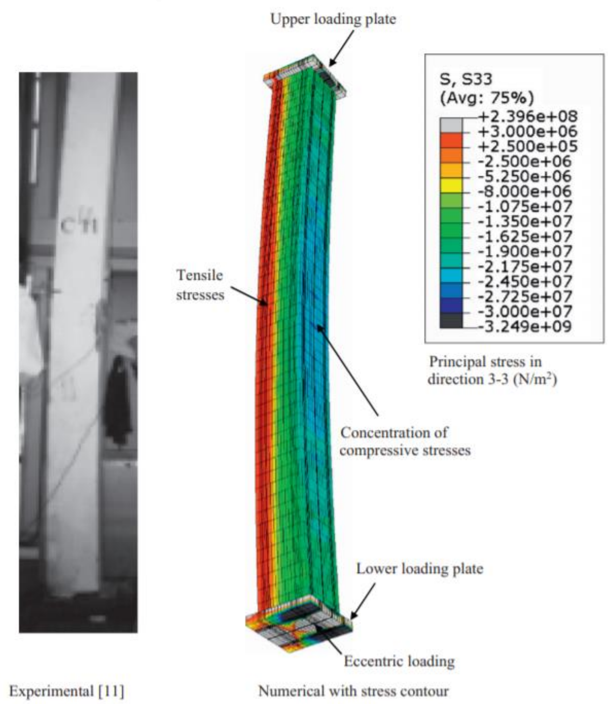


Figure 80 Comparison of deformed shapes at failure for eccentrically loaded concrete encased steel composite column BC5. Ellobody, Young and Lam (2010)

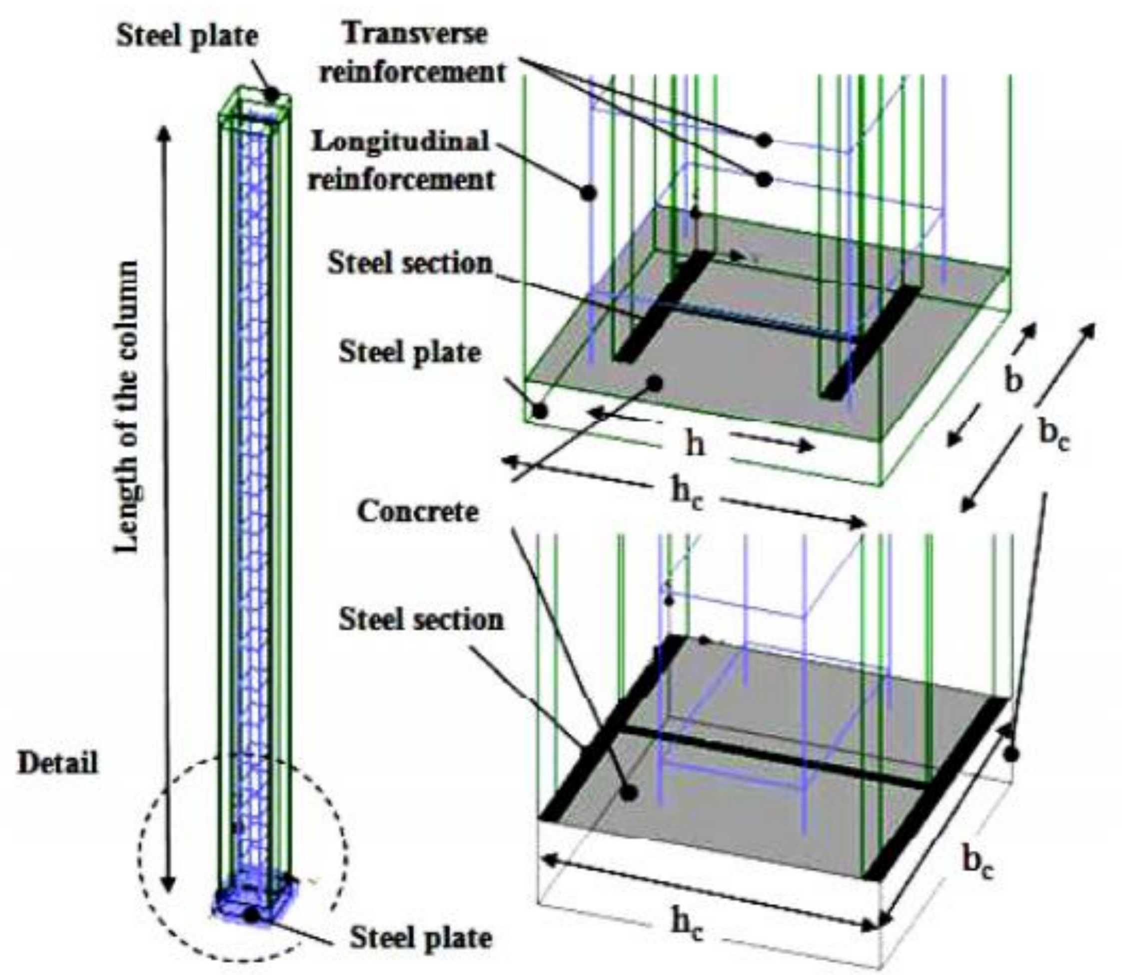


Figure 81 Model of the composite SC columns in software Atena 3D. Lelkes and Gramblicka (2013)

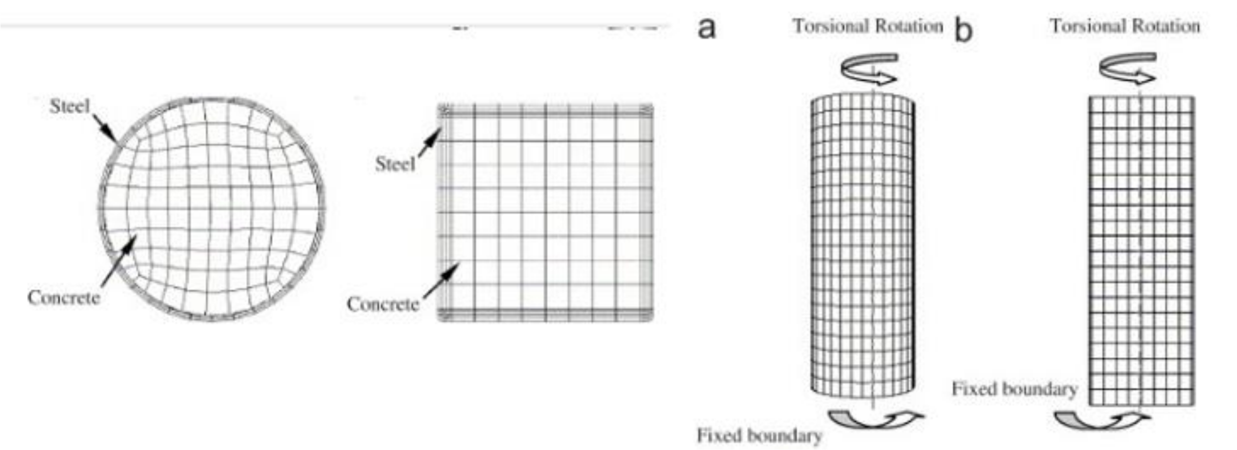


Figure 82 A schematic view of the element division (circular and square). Han, Yao and Tao (2007)

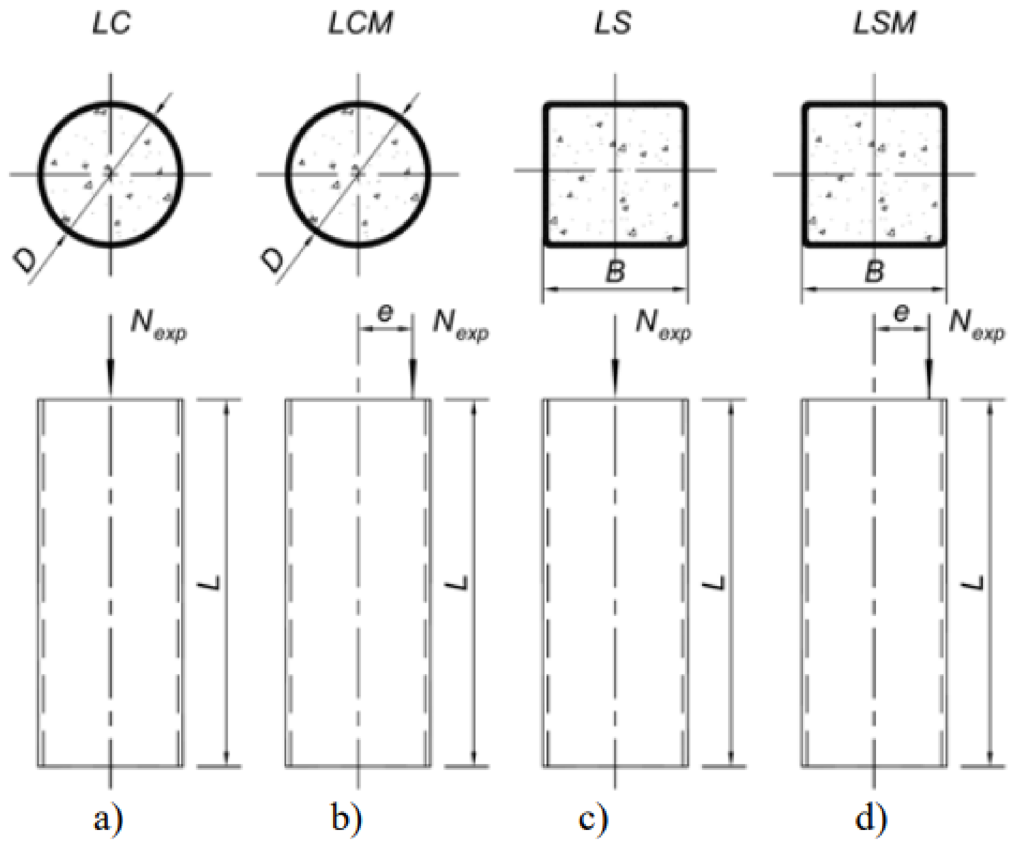


Figure 83 Sections used in Goode, Kuranovas and Kvedaras experiment (2010)

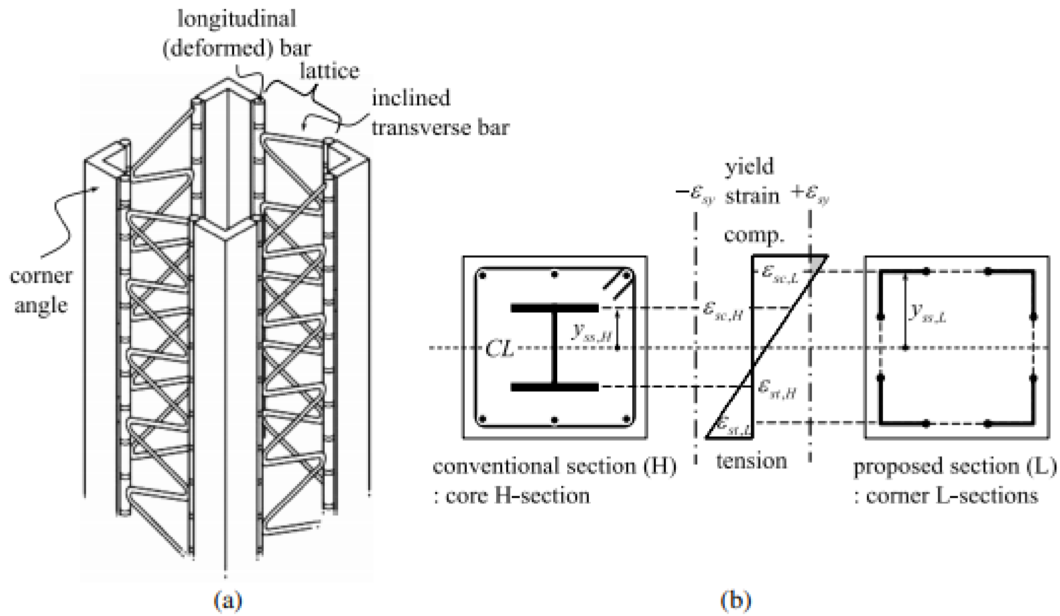


Figure 84 Concrete encased steel column with L corner sections: (a) prefabricated steel section with lattices, (b) strain distribution in steel sections. Kim et al. (2014)

1b. Compressive Strength

The design compressive strength, $\phi_c P_n$, and allowable compressive strength, P_n/Ω_c, of doubly symmetric axially loaded encased composite members shall be determined for the limit state of flexural buckling based on member slenderness as follows:

$$\phi_c = 0.75 \text{ (LRFD)} \qquad \Omega_c = 2.00 \text{ (ASD)}$$

(a) When $\dfrac{P_{no}}{P_e} \le 2.25$

$$P_n = P_{no}\left(0.658^{\frac{P_{no}}{P_e}}\right) \tag{I2-2}$$

(b) When $\dfrac{P_{no}}{P_e} > 2.25$

$$P_n = 0.877 P_e \tag{I2-3}$$

where

P_{no} $= F_y A_s + F_{ysr} A_{sr} + 0.85 f'_c A_c$ (I2-4)

P_e = elastic critical buckling load determined in accordance with Chapter C or Appendix 7, kips (N)

$= \pi^2 (EI_{eff}) / L_c^2$ (I2-5)

A_c = area of concrete, in.^{2} (mm^2)

A_s = cross-sectional area of steel section, in.^{2} (mm^2)

E_c = modulus of elasticity of concrete

$= w_c^{1.5}\sqrt{f'_c}$, ksi $\left(0.043 w_c^{1.5}\sqrt{f'_c}\text{, MPa}\right)$

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Figure 85 Compressive strengh equation, AISC Chapter I Section 12

16.1-92 AXIAL FORCE [Sect. I2.

EI_{eff} = effective stiffness of composite section, kip-in.^{2} (N-mm^2)

$= E_sI_s + E_sI_{sr} + C_1E_cI_c$ (I2-6)

C_1 = coefficient for calculation of effective rigidity of an encased composite compression member

$$= 0.25 + 3\left(\frac{A_s + A_{sr}}{A_g}\right) \leq 0.7 \quad \text{(I2-7)}$$

E_s = modulus of elasticity of steel

= 29,000 ksi (200 000 MPa)

F_y = specified minimum yield stress of steel section, ksi (MPa)

F_{ysr} = specified minimum yield stress of reinforcing bars, ksi (MPa)

I_c = moment of inertia of the concrete section about the elastic neutral axis of the composite section, in.^{4} (mm^4)

I_s = moment of inertia of steel shape about the elastic neutral axis of the composite section, in.^{4} (mm^4)

I_{sr} = moment of inertia of reinforcing bars about the elastic neutral axis of the composite section, in.^{4} (mm^4)

K = effective length factor

L = laterally unbraced length of the member, in. (mm)

L_c = KL = effective length of the member, in. (mm)

f_c' = specified compressive strength of concrete, ksi (MPa)

w_c = weight of concrete per unit volume ($90 \leq w_c \leq 155$ lb/ft^3 or $1500 \leq w_c \leq 2500$ kg/m^3)

The available compressive strength need not be less than that specified for the bare steel member, as required by Chapter E.

Figure 86 Compressive strength equation, AISC Chapter I Section 12

6.7.3.2 Resistance of cross sections

(1) The plastic resistance to compression $N_{pl,Rd}$ of a composite cross-section should be calculated by adding the plastic resistances of its components:

$$N_{pl,Rd} = A_a f_{yd} + 0{,}85 A_c f_{cd} + A_s f_{sd} \quad (6.30)$$

Expression (6.30) applies for concrete encased and partially concrete encased steel sections. For concrete filled sections the coefficient 0,85 may be replaced by 1,0.

(2) The resistance of a cross-section to combined compression and bending and the corresponding interaction curve may be calculated assuming rectangular stress blocks as shown in Figure 6.18, taking account of the design shear force V_{Ed} in accordance with (3). The tensile strength of the concrete should be neglected.

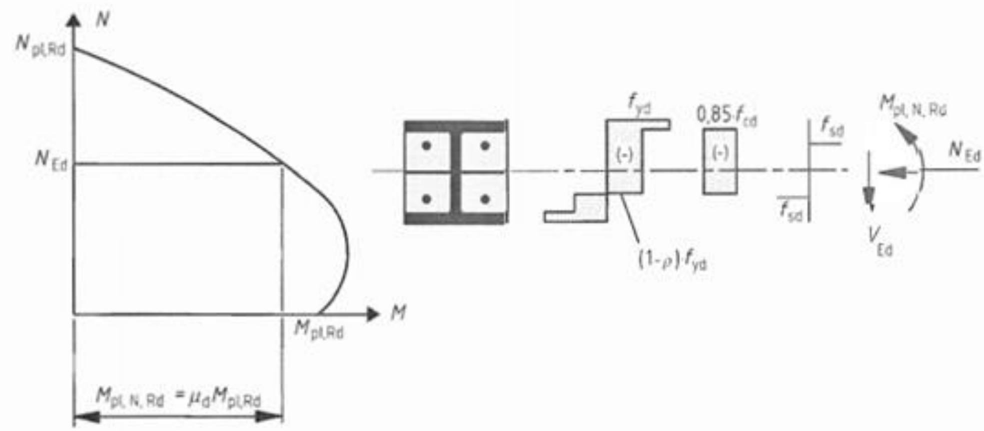

Figure 87 Compressive Strength calculation, Eurocode4 section 6.7

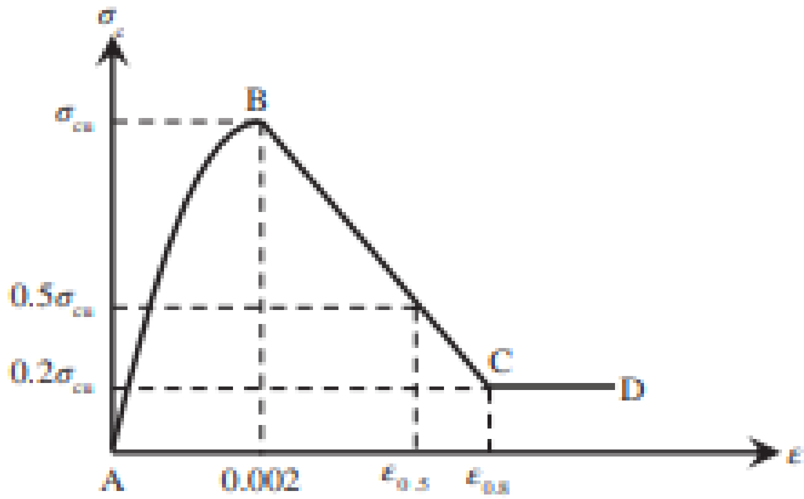

Fig. 2: Kent and Park model for confined and unconfined concrete.[29] *(Units: [–])*

Figure 88 Kent and Park model for confined and unconfined concrete

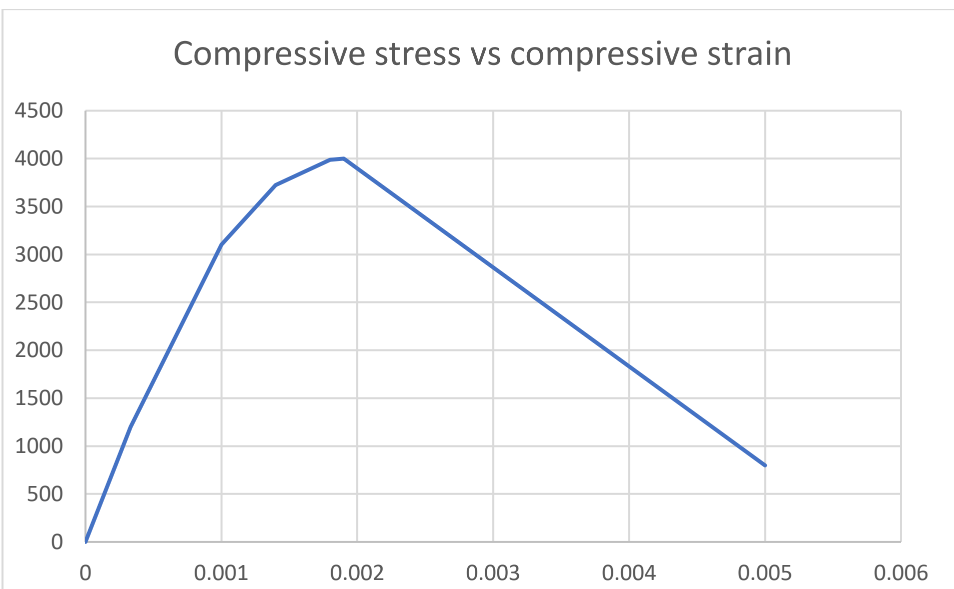

Figure 89 Stress and Strain values as per Kent and Park model

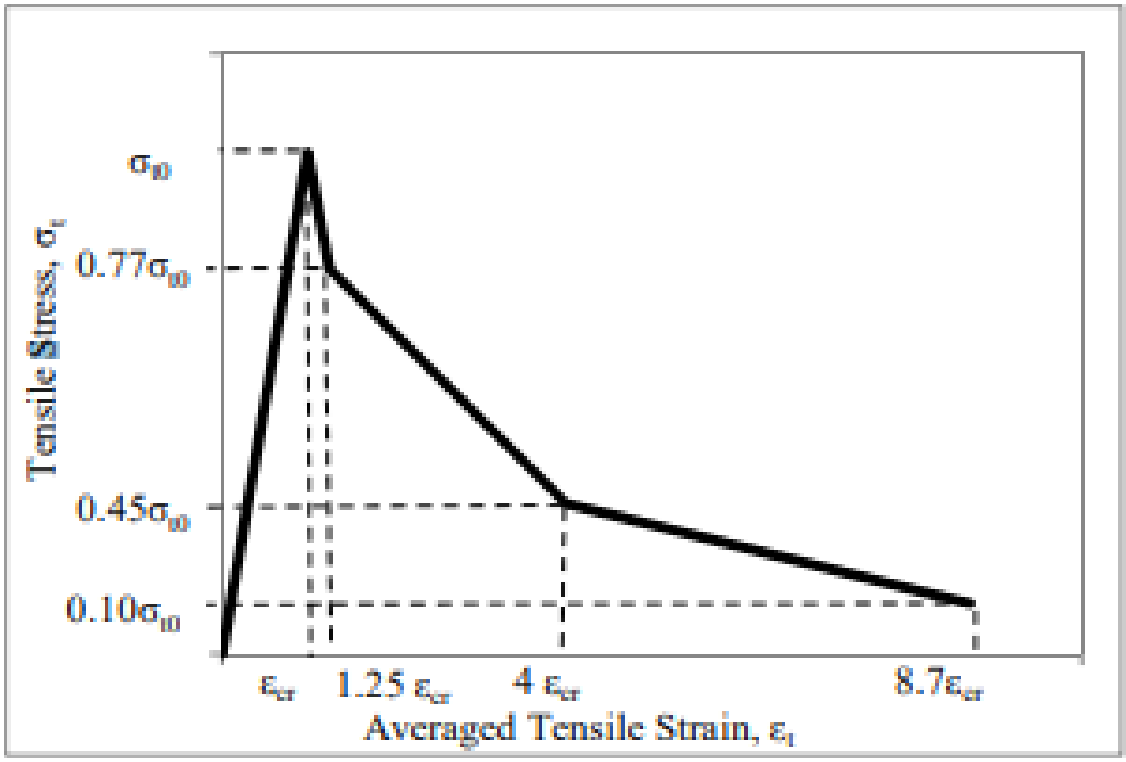

Figure 90 Tensile stress vs tensile strain

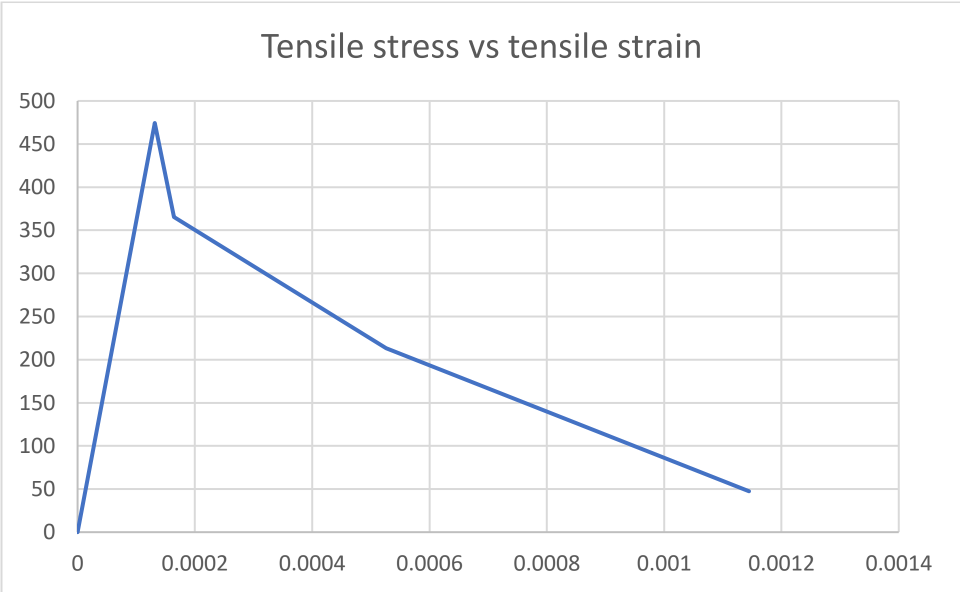

Figure 91 Tensile stress vs tensile strain

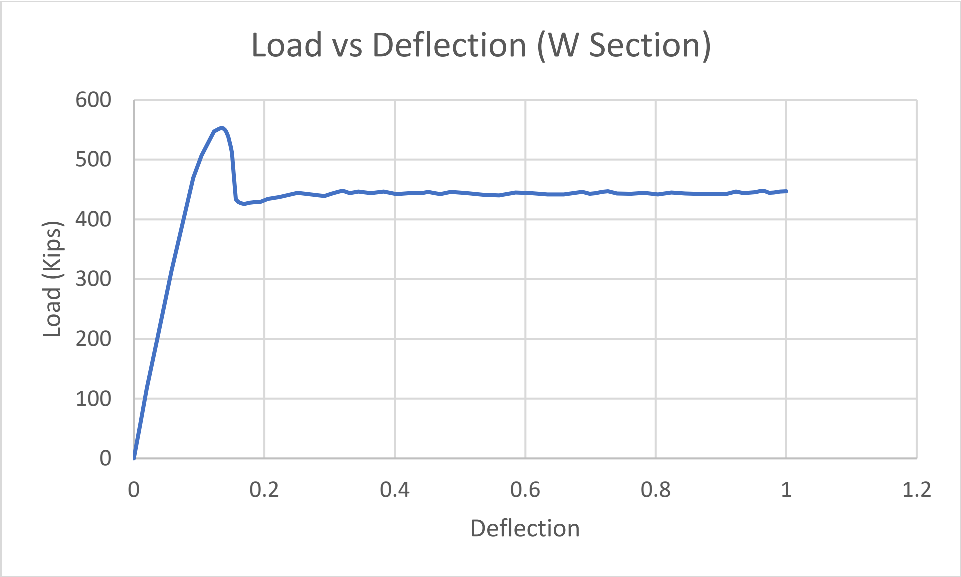

Figure 92 Force vs Strain for steel W section column

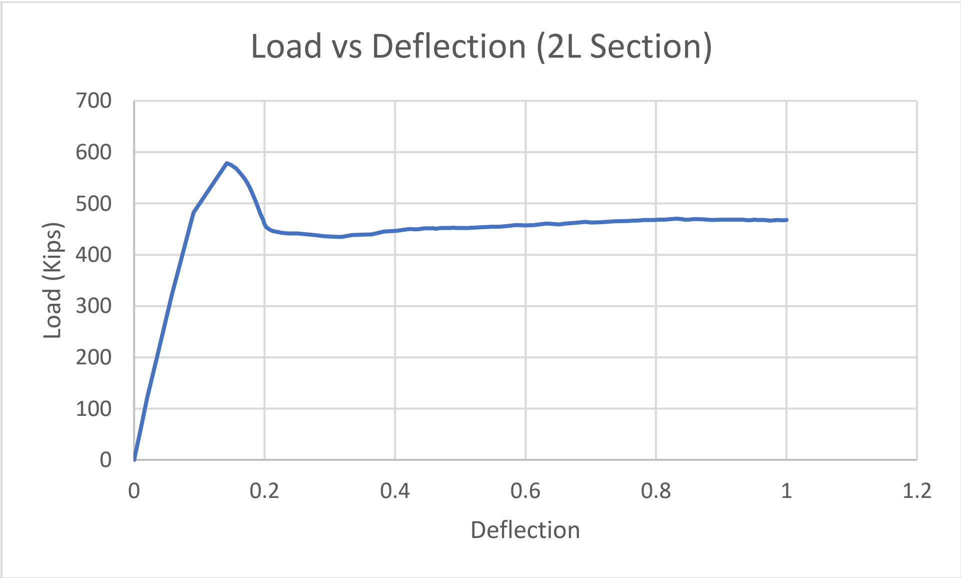

Figure 93 Force vs Strain for steel 2L section column

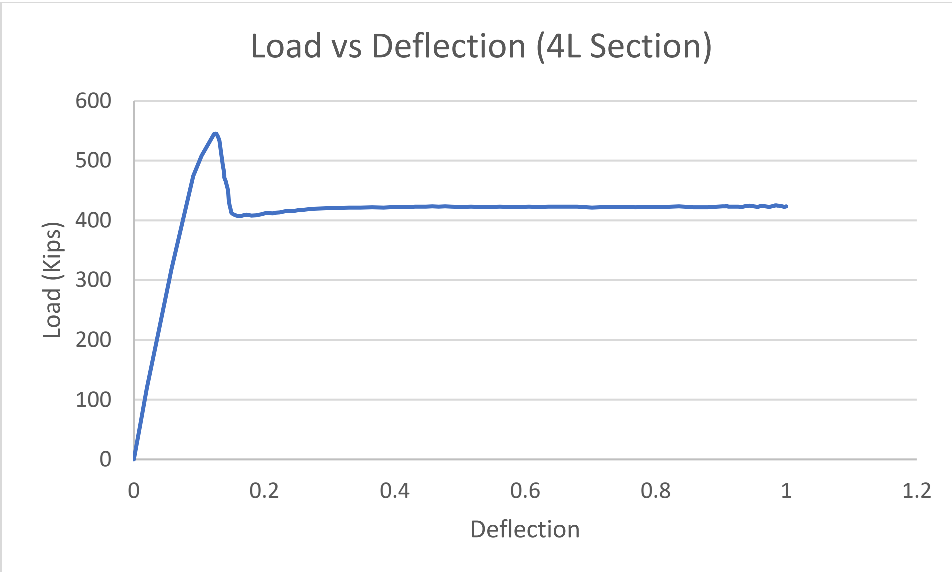

Figure 94 Force vs Strain for steel 4L section column

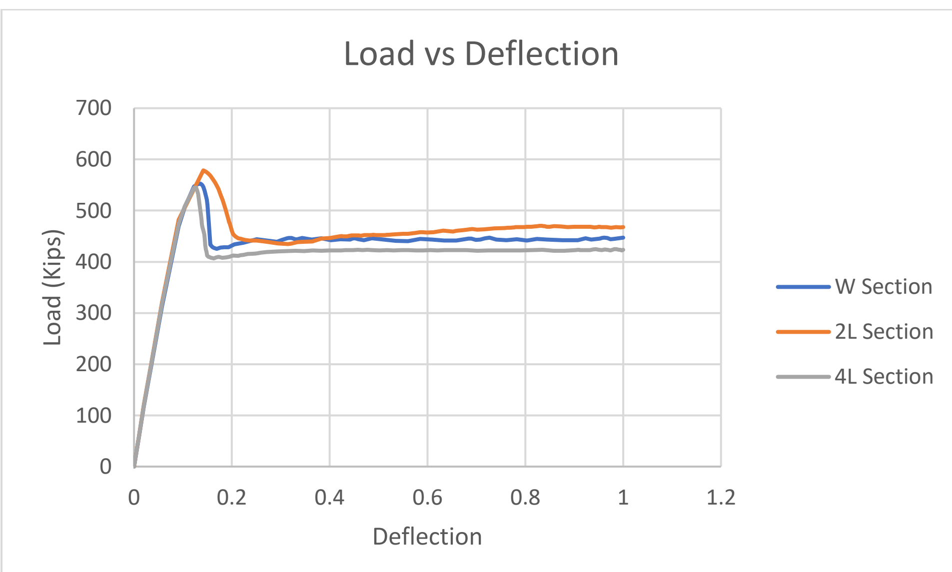

Figure 95 Comparison of load vs deflection of all specimens tested at the lab

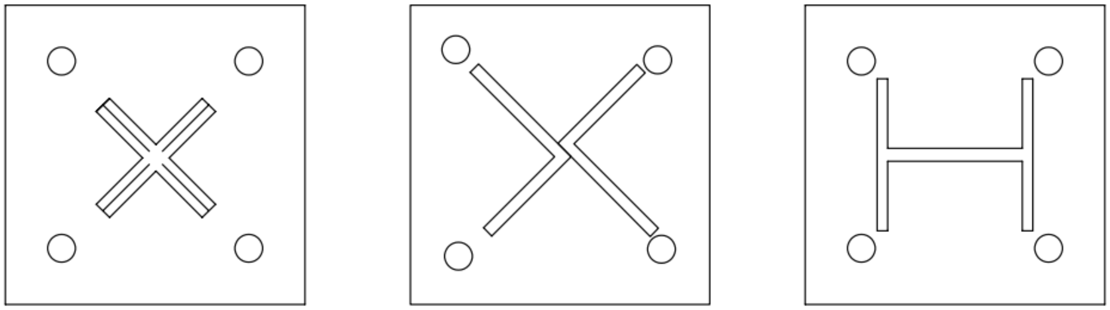

Figure 96 AutoCAD Sketches of the three specimens at the lab to be tested.

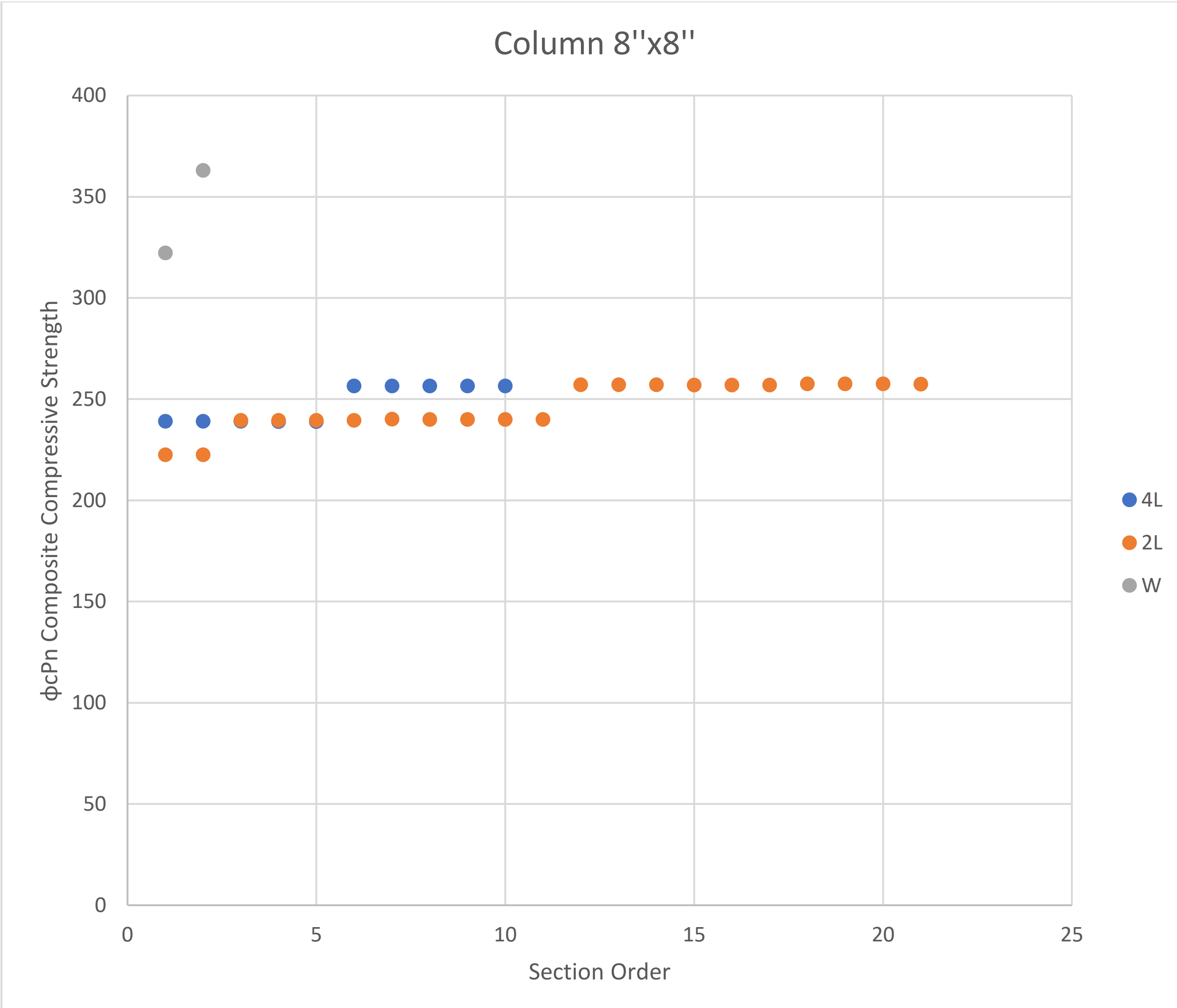

Figure 97 Column 8"x8" Strength vs Sections in ascending order per AISC

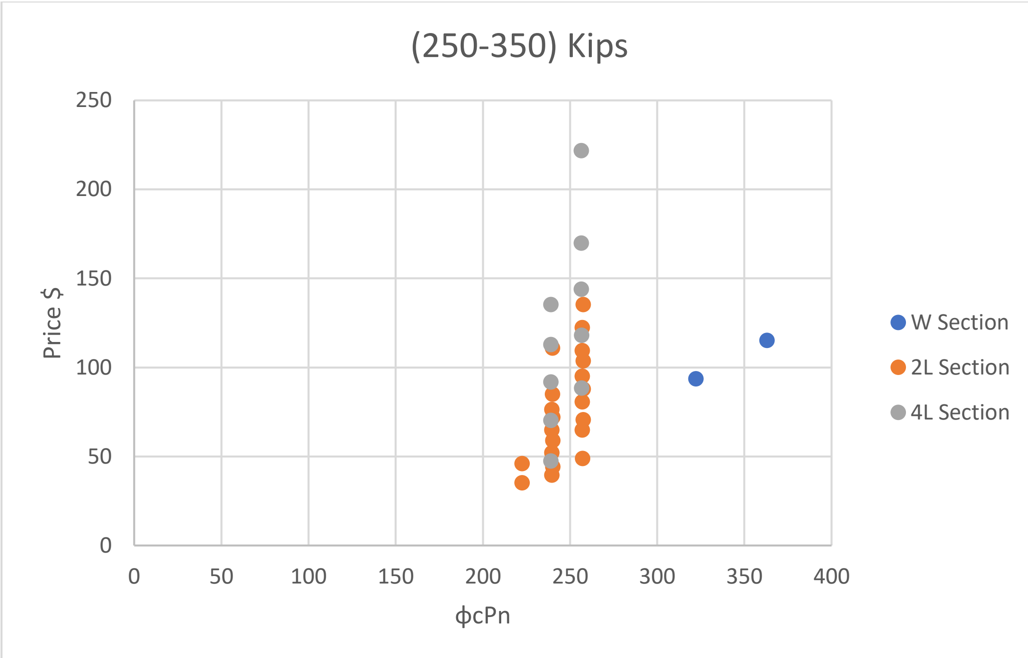

Figure 98 Column 8"x8" Strength and cost comparison for (250-350) Kips period

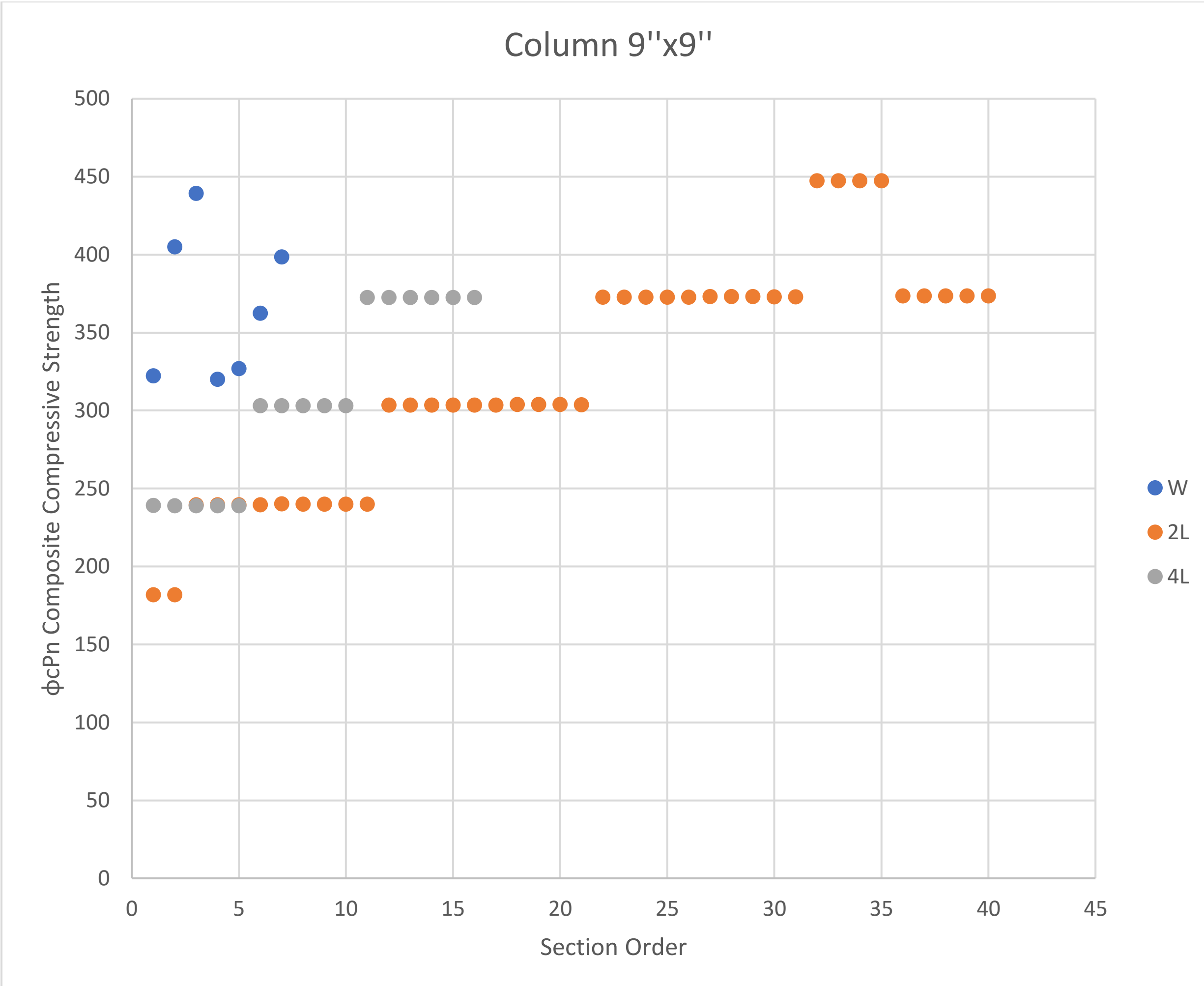

Figure 99 Column 9"x9" Strength vs Sections in ascending order per AISC

Figure 100 Column 9”x9” Strength and cost comparison for (300-350) Kips period

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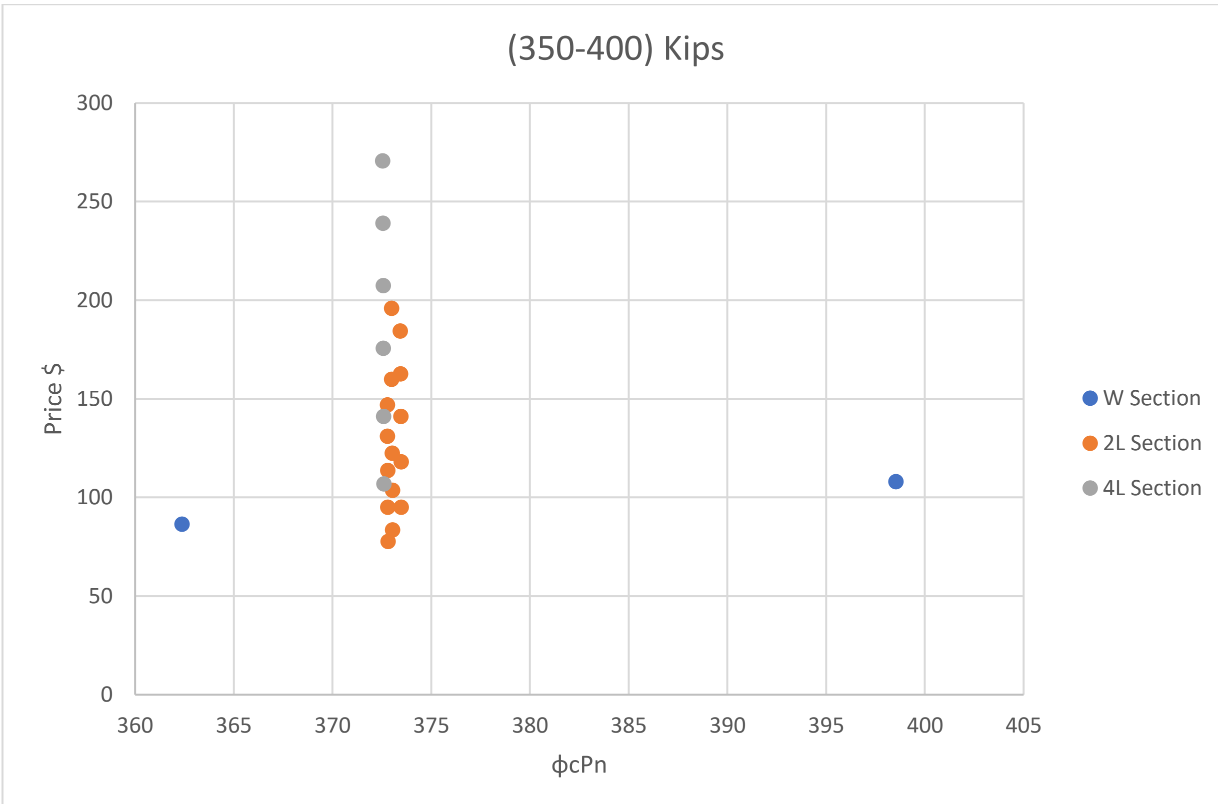


Figure 101 Column 9”x9” Strength and cost comparison for (350-400) Kips period

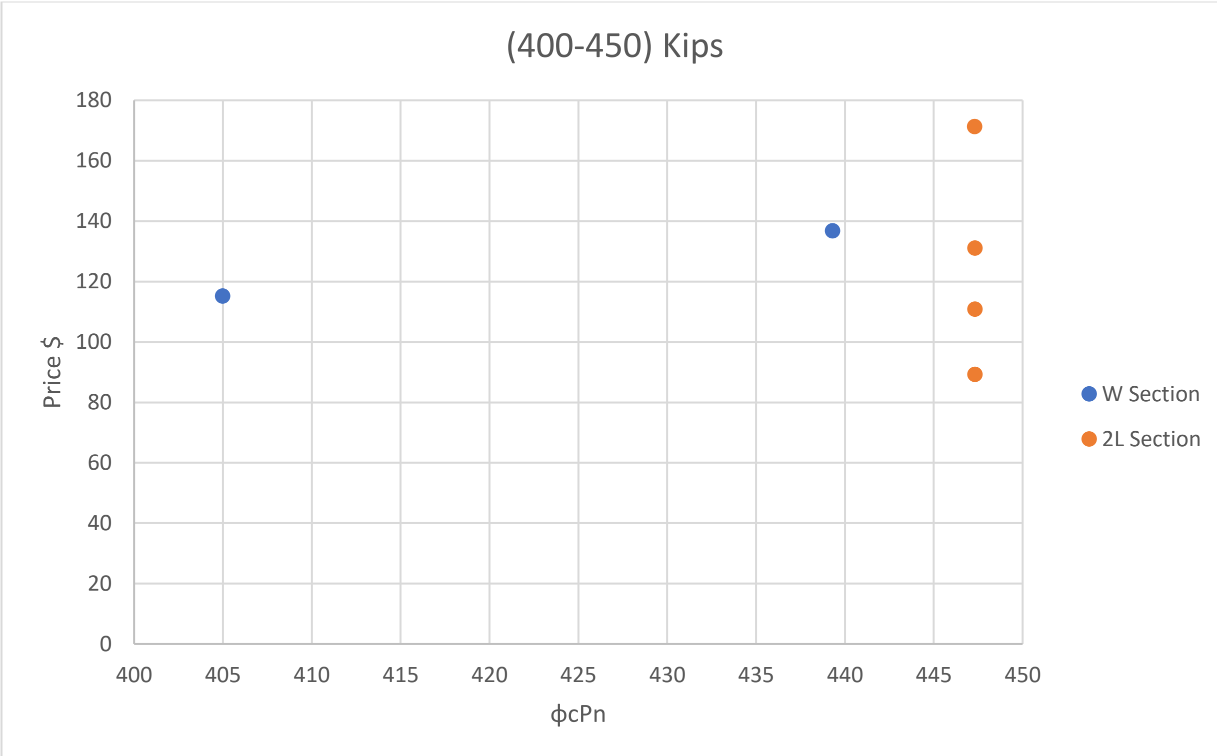


Figure 102 Column 9”x9” Strength and cost comparison for (400-450) Kips period

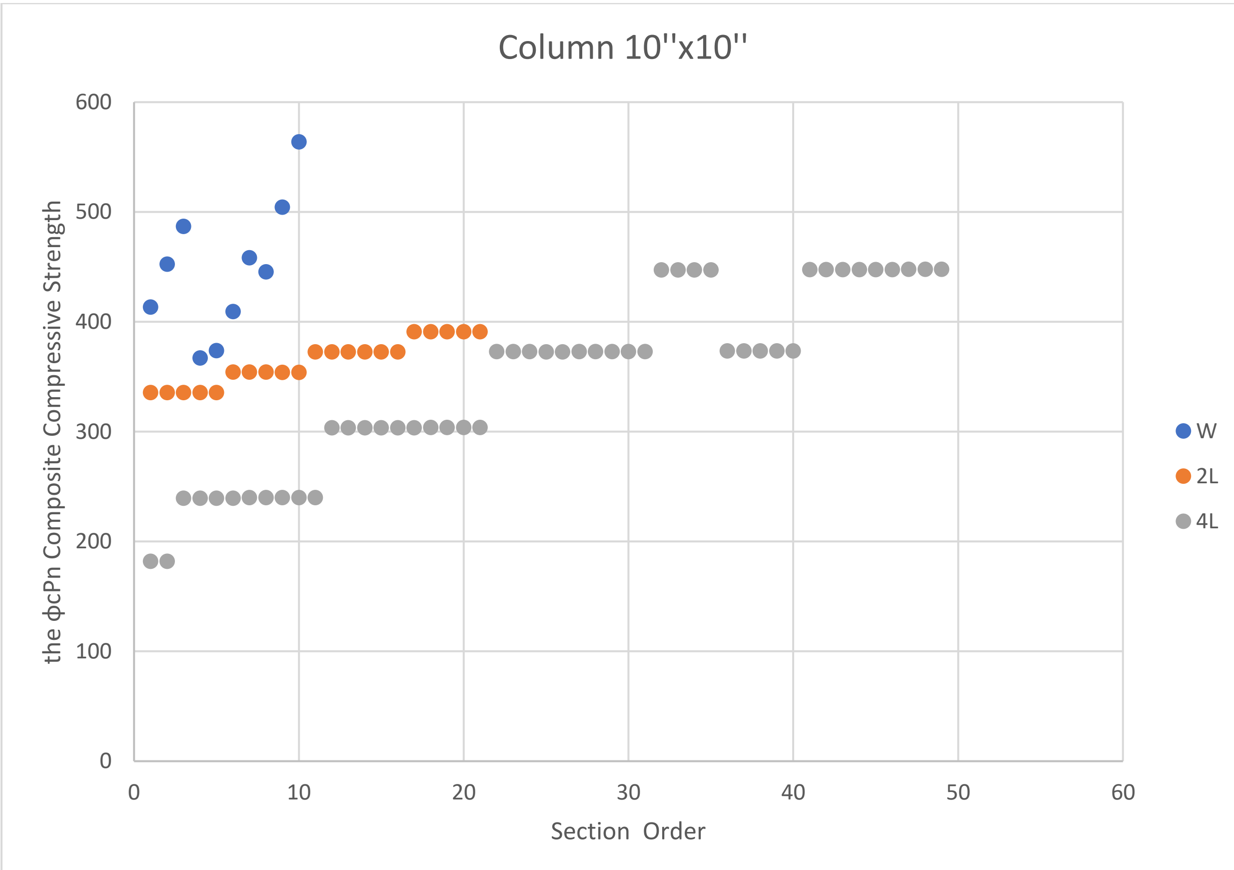


Figure 103 Column 10"x10" Strength vs Sections in ascending order per AISC

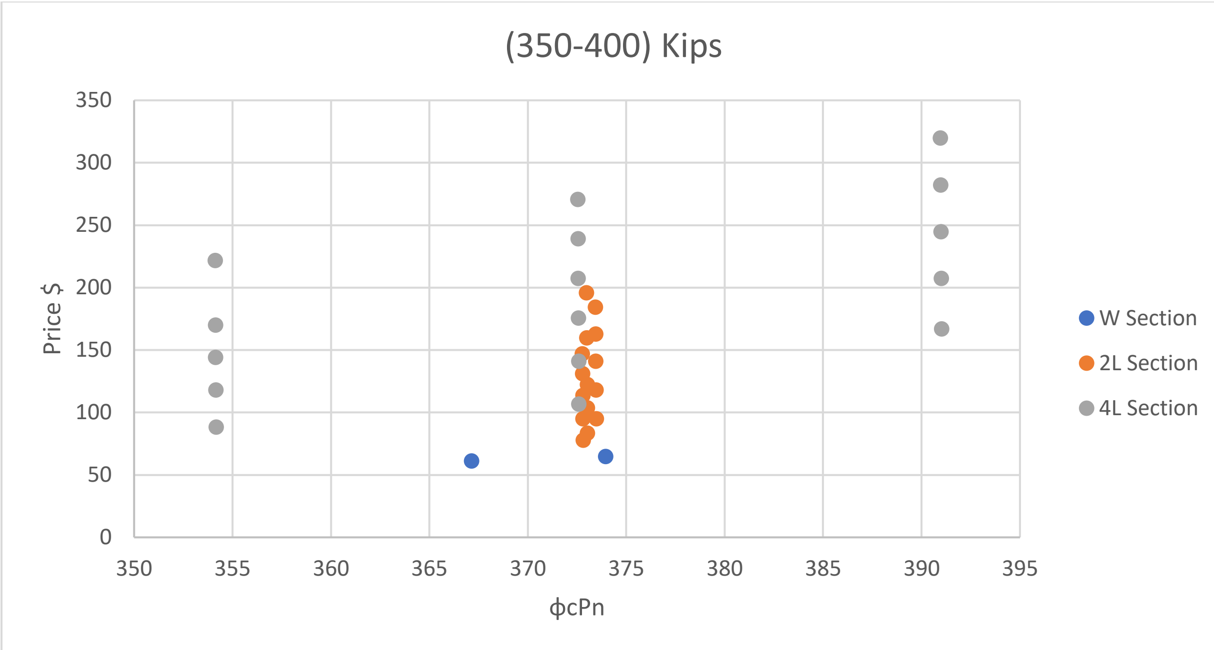


Figure 104 Column 10"x10" Strength and cost comparison for (350-400) Kips period

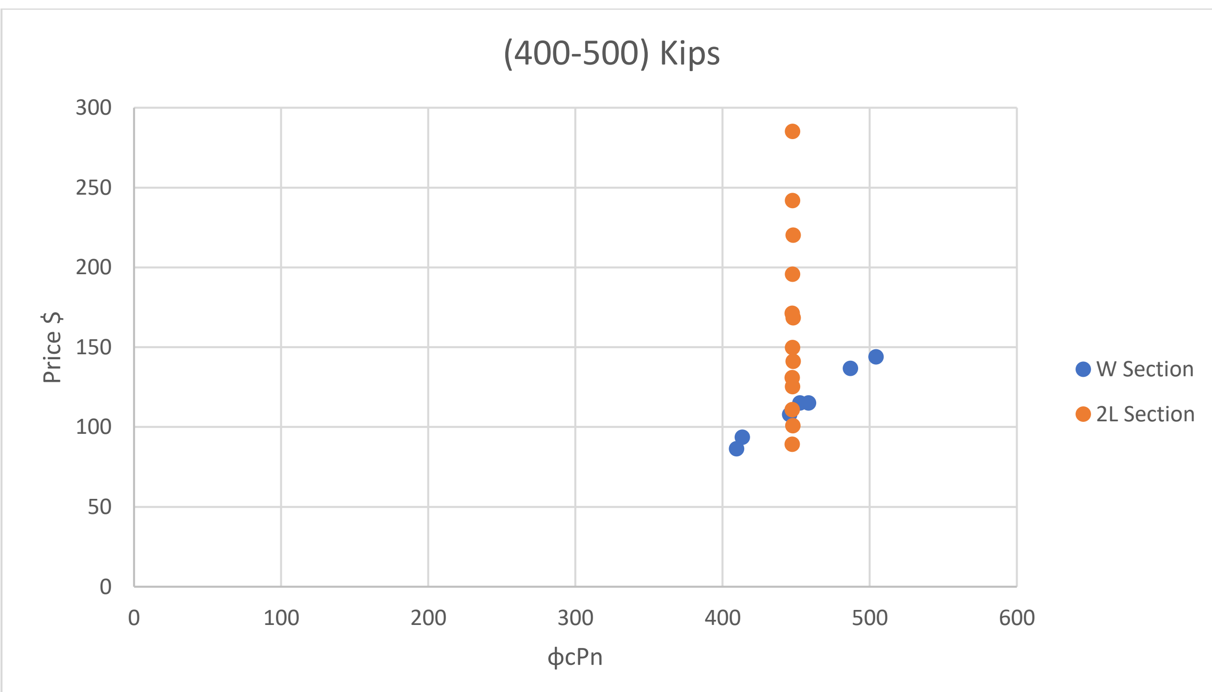


Figure 105 Column 10"x10" Strength and cost comparison for (400-500) Kips period

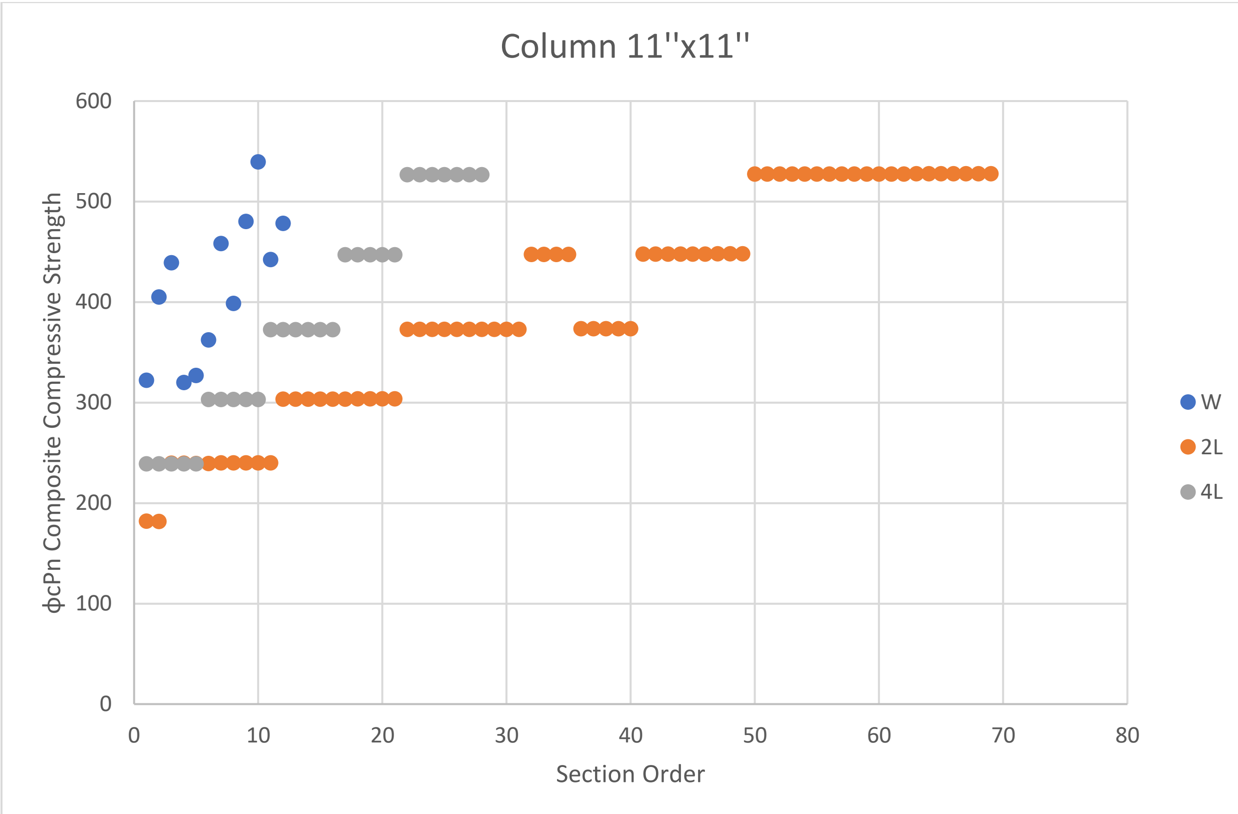


Figure 106 Column 11"x11" Strength vs Sections in ascending order per AISC

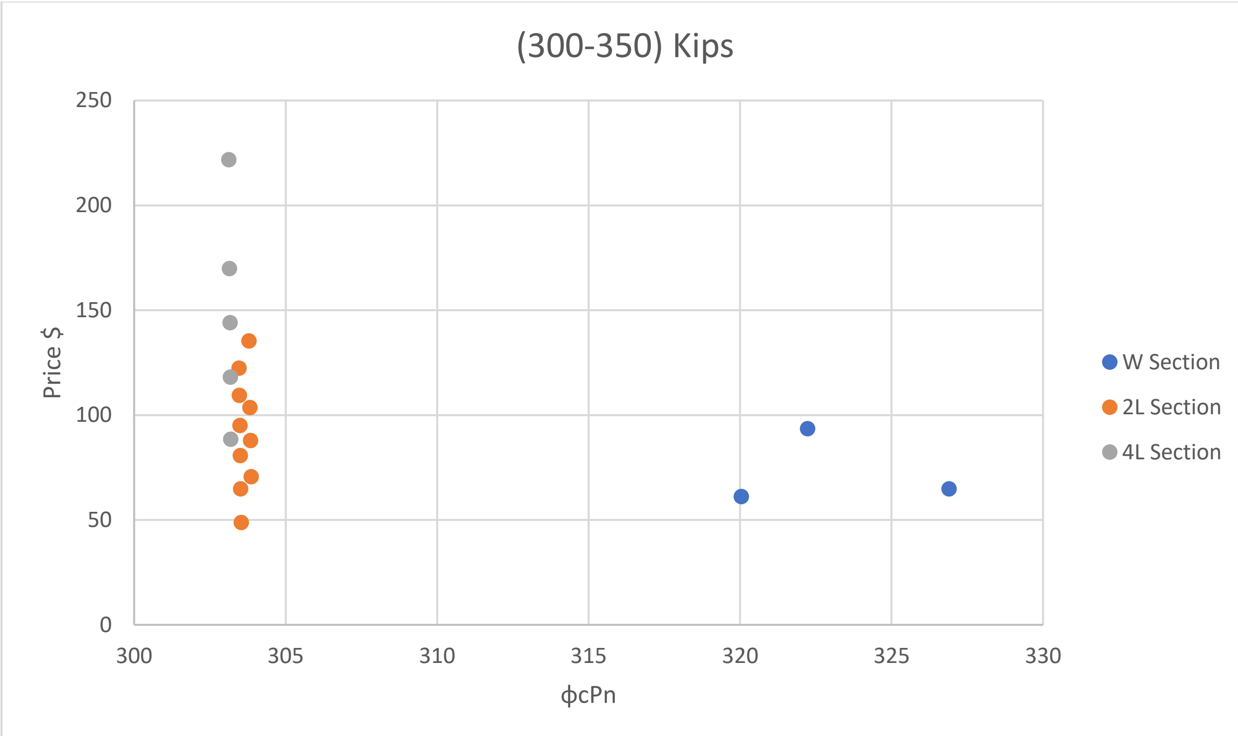


Figure 107 Column 11”x11” Strength and cost comparison for (300-350) Kips period

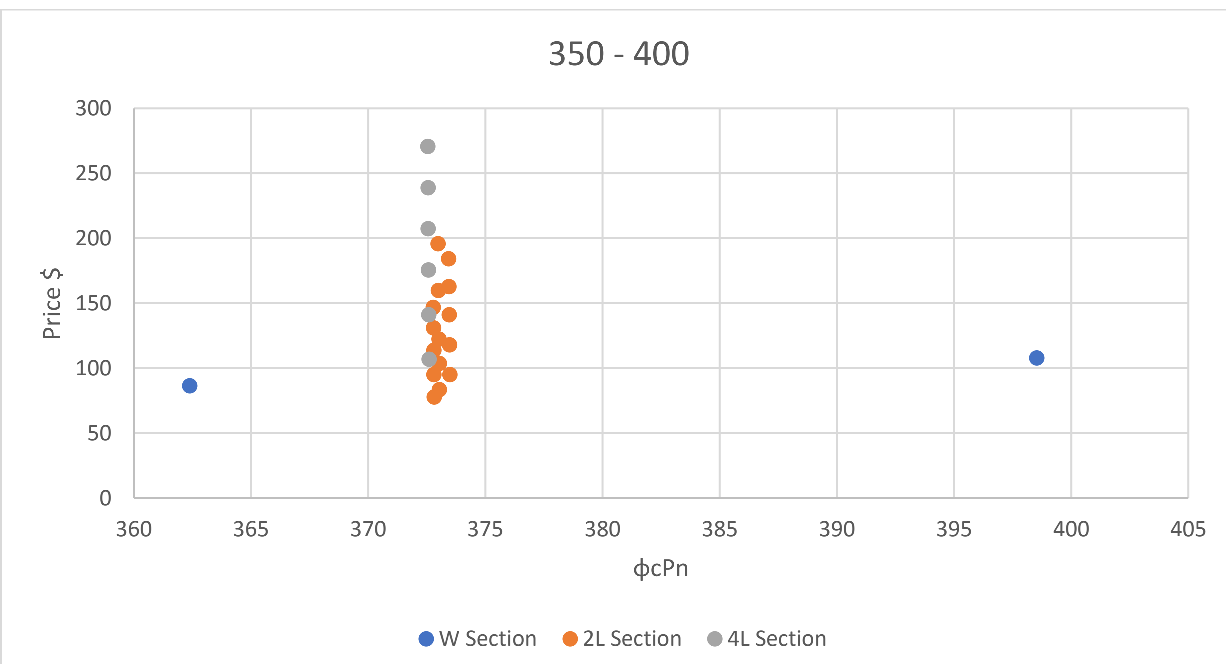


Figure 108 Column 11”x11” Strength and cost comparison for (350-400) Kips period

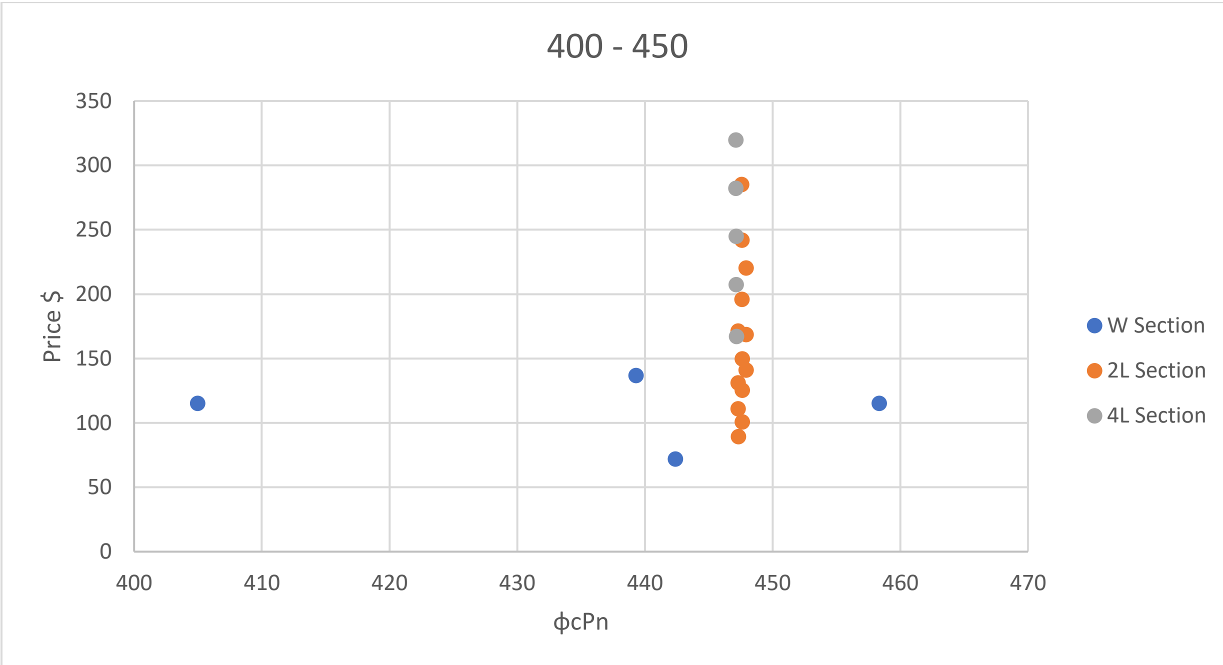


Figure 109 Column 11"x11" Strength and cost comparison for (400-450) Kips period

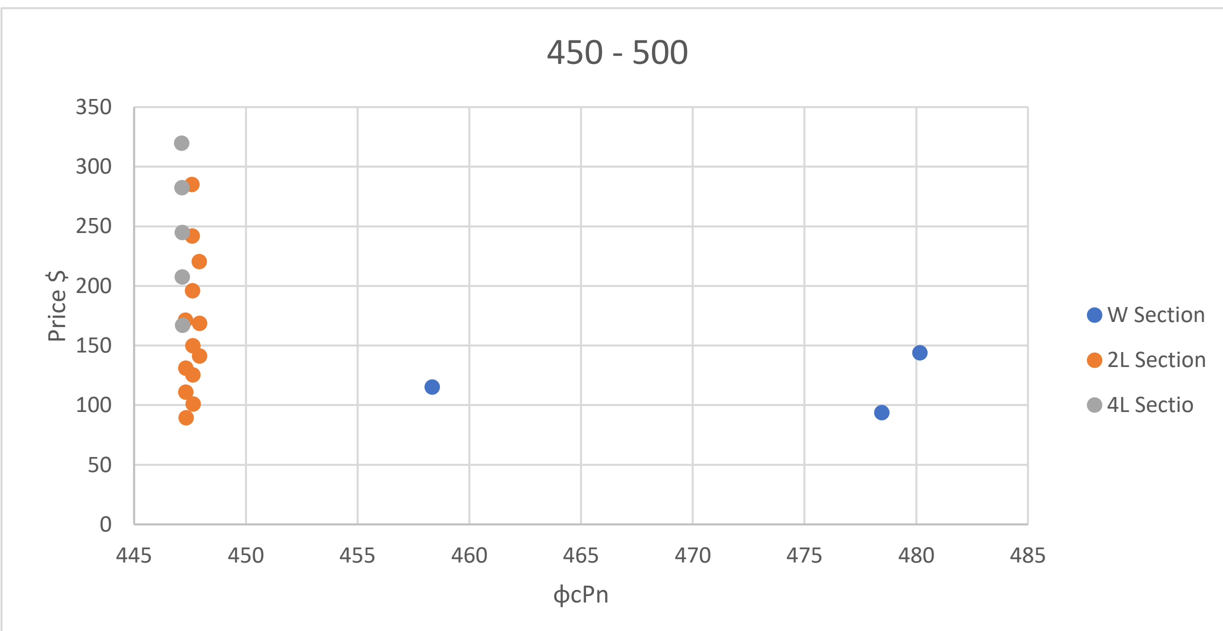


Figure 110 Column 11"x11" Strength and cost comparison for (450-500) Kips period

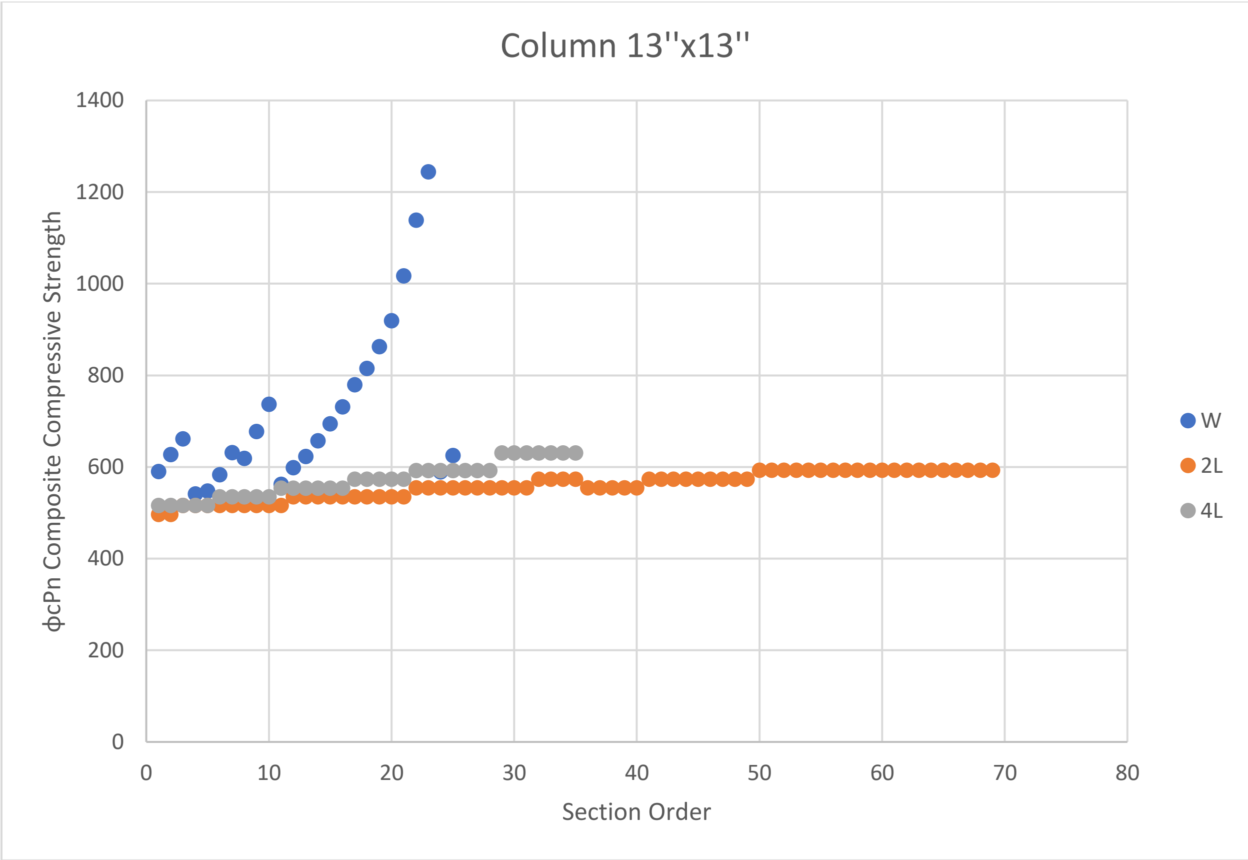


Figure 111 Column 13"x13" Strength vs Sections in ascending order per AISC

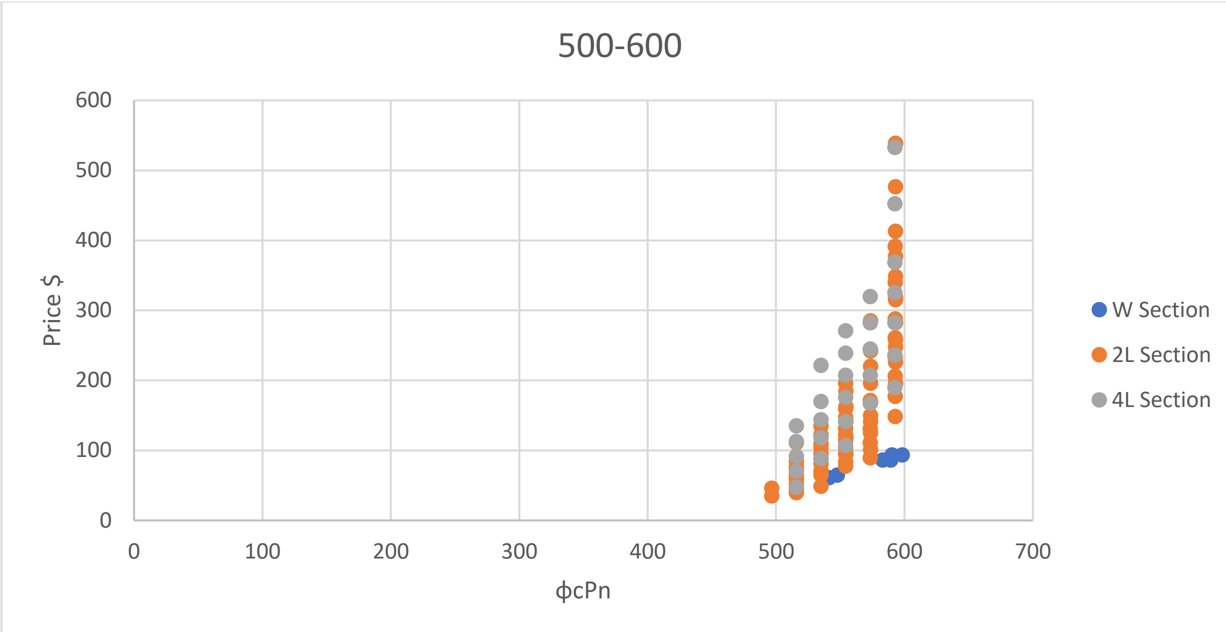


Figure 112 Column 13”x13” Strength and cost comparison for (500-600) Kips period

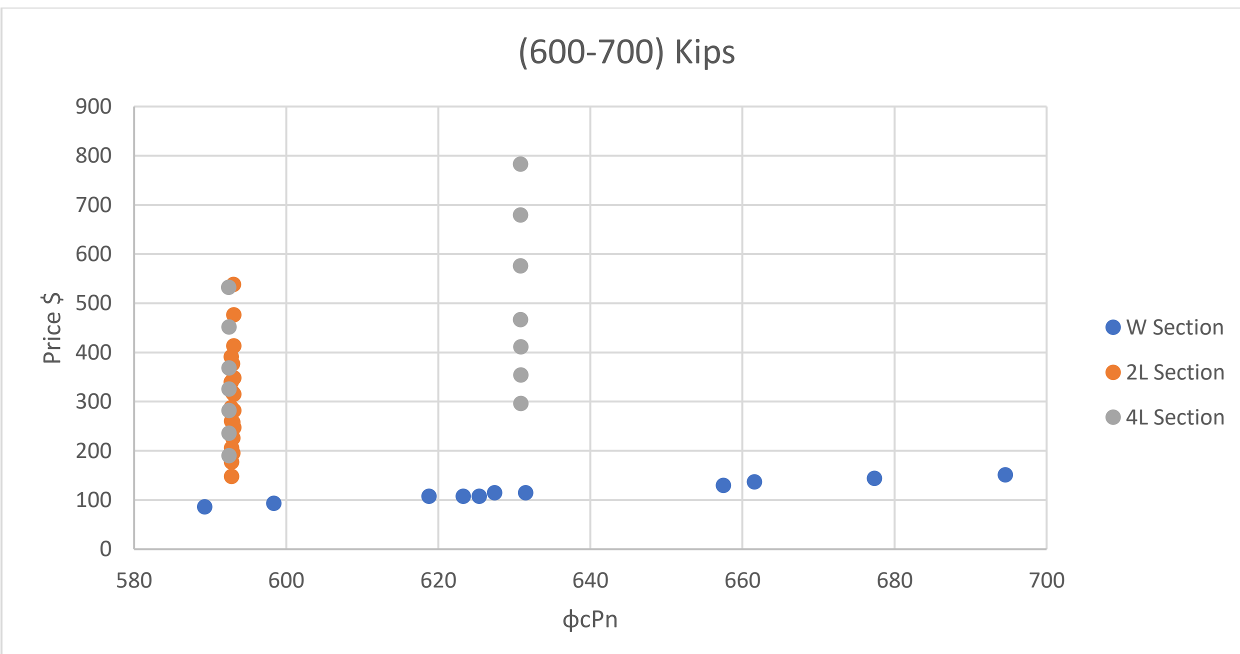


Figure 113 Column 13”x13” Strength and cost comparison for (600-700) Kips period

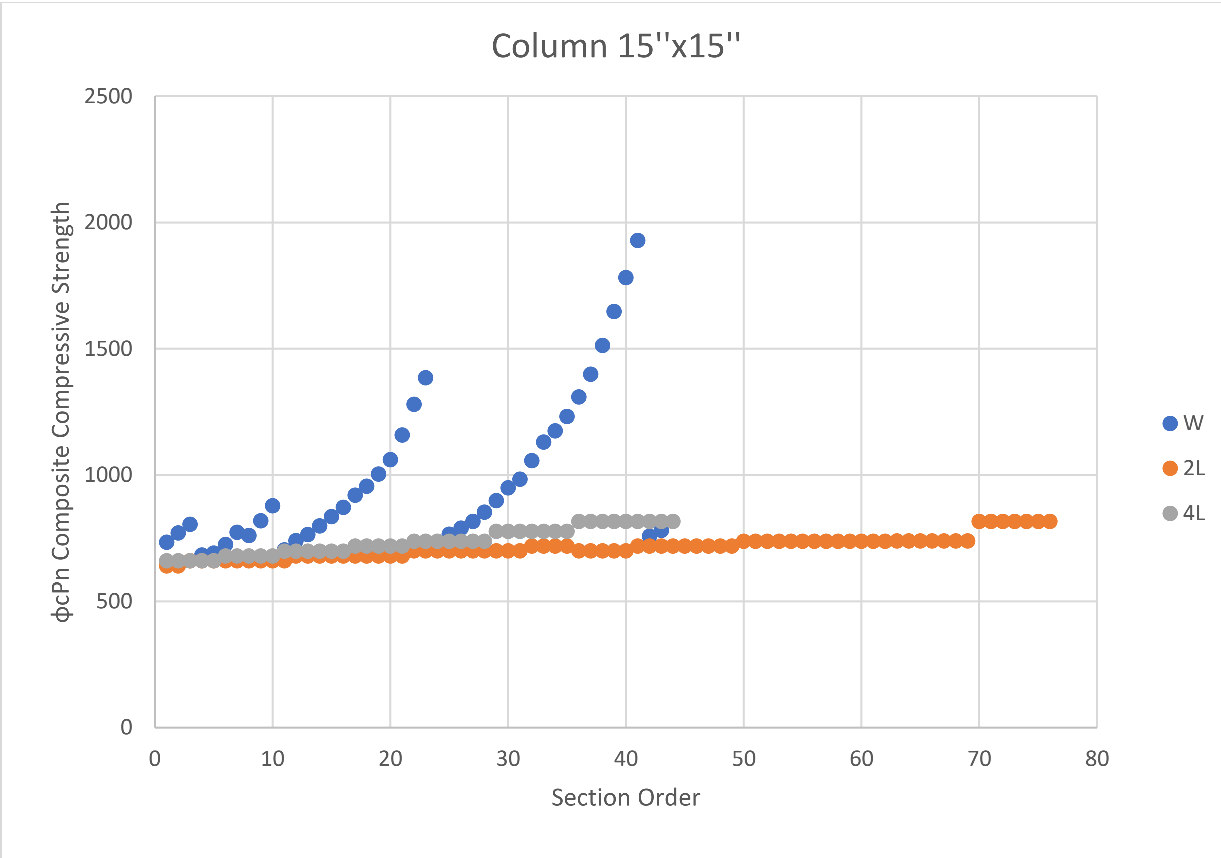
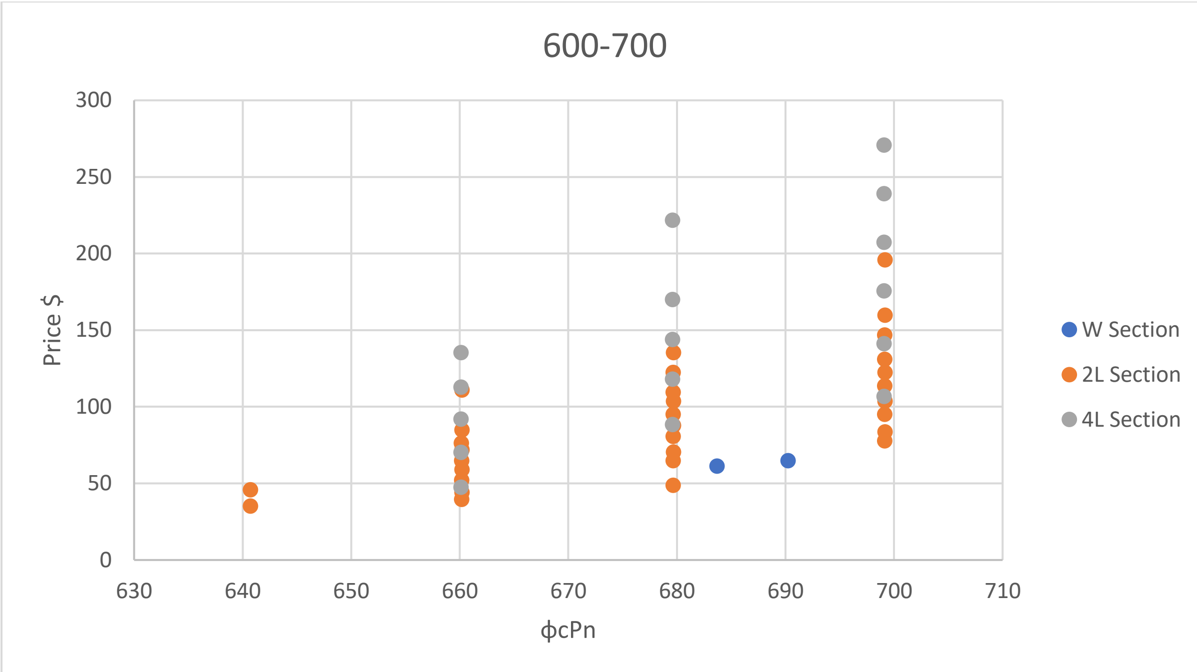


Figure 114 Column 15"x15" Strength vs Sections in ascending order per AISC



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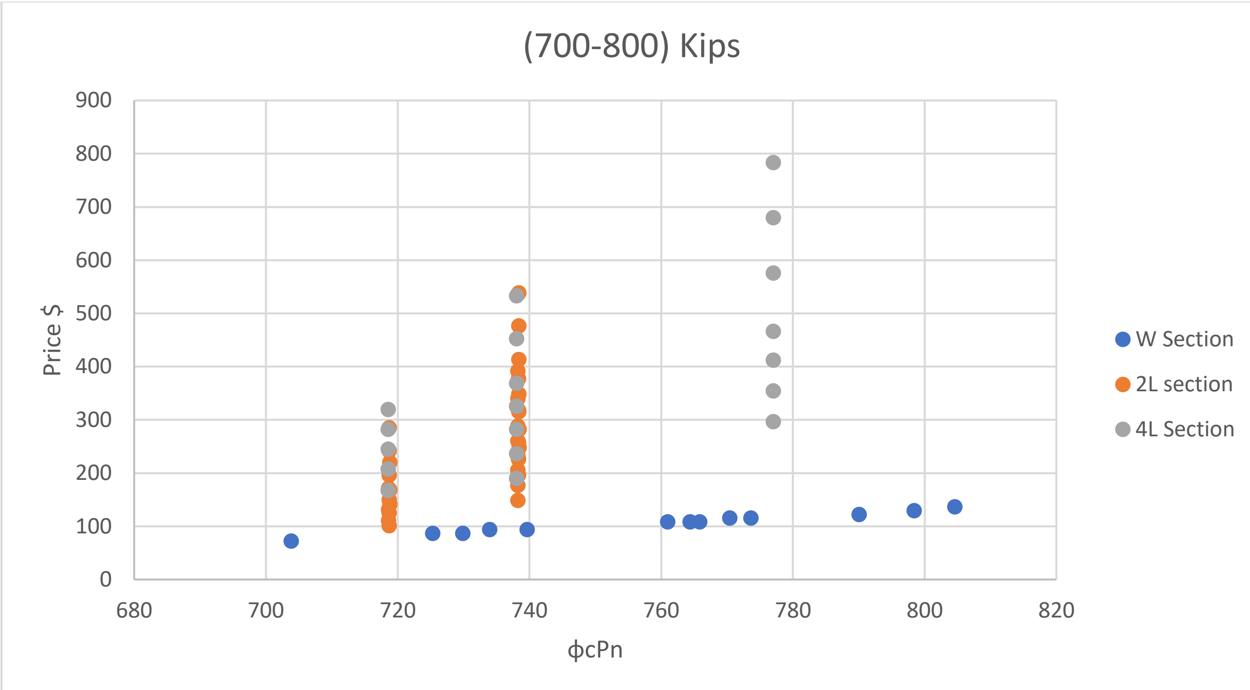

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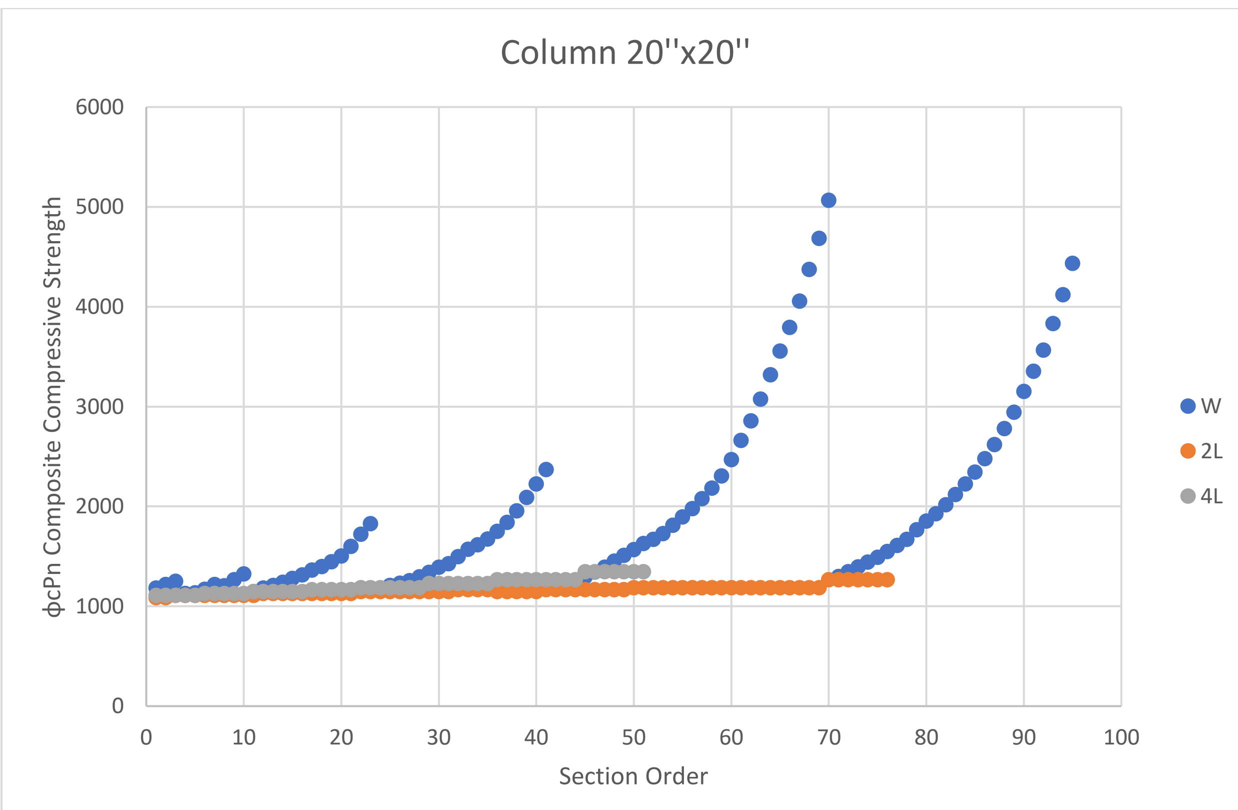

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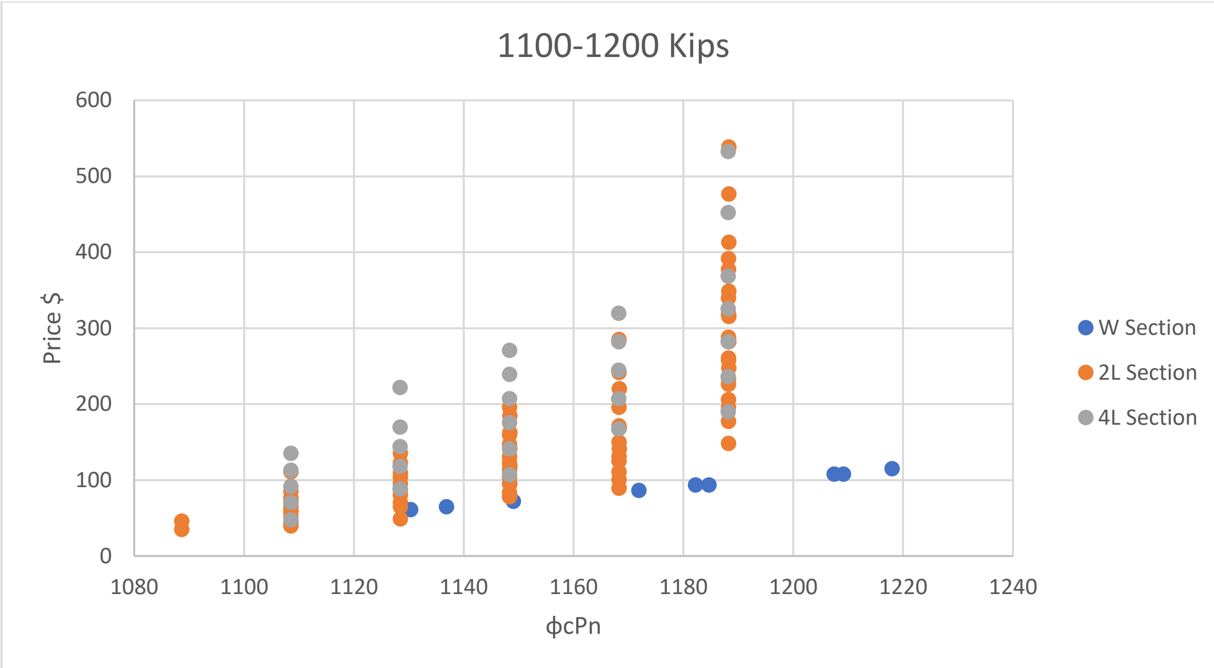

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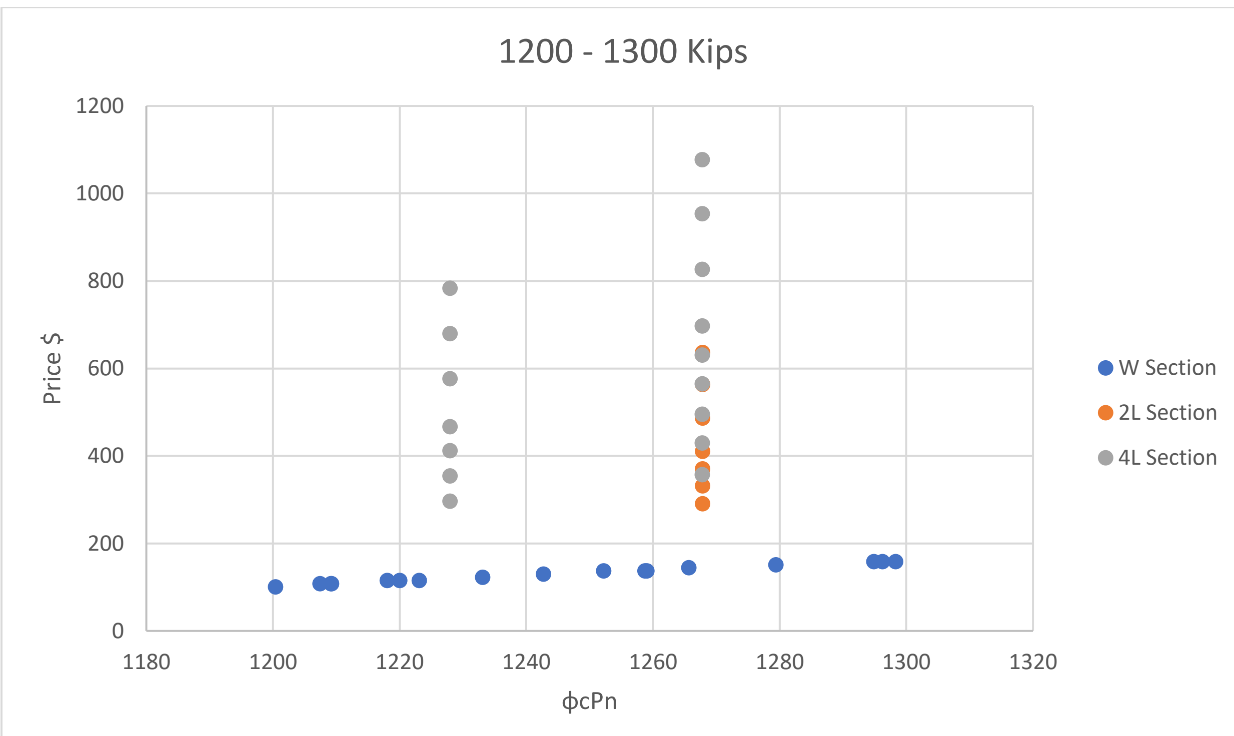

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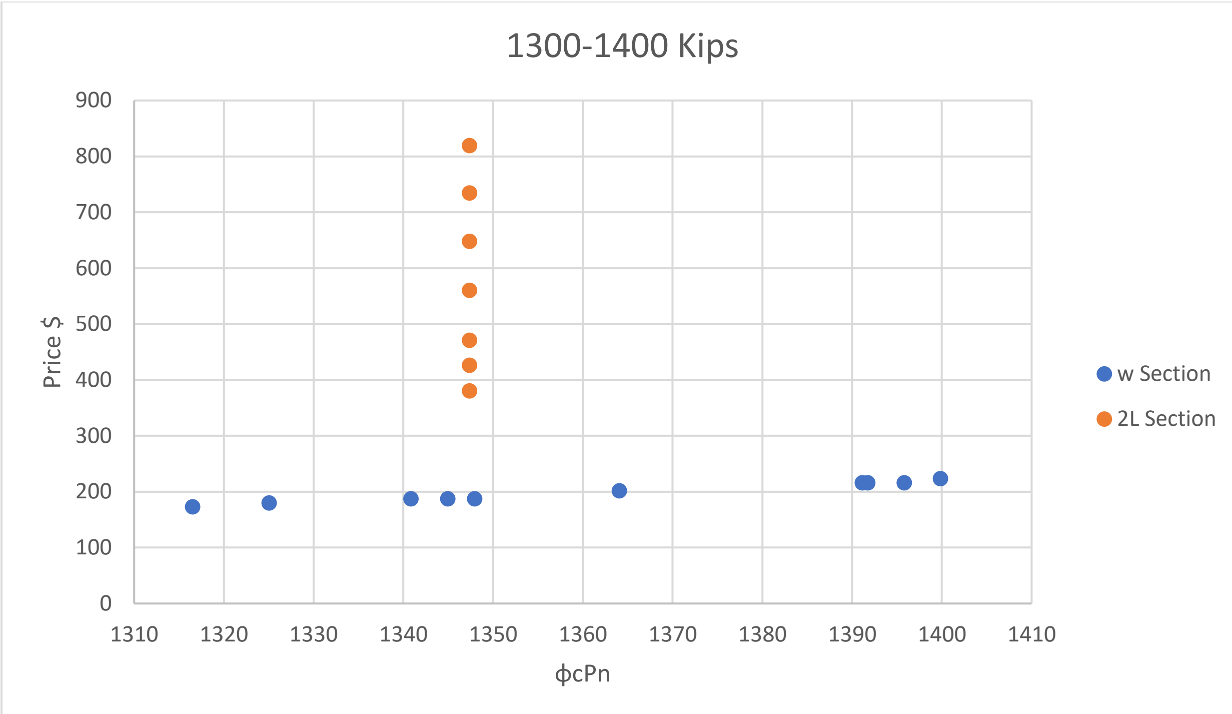

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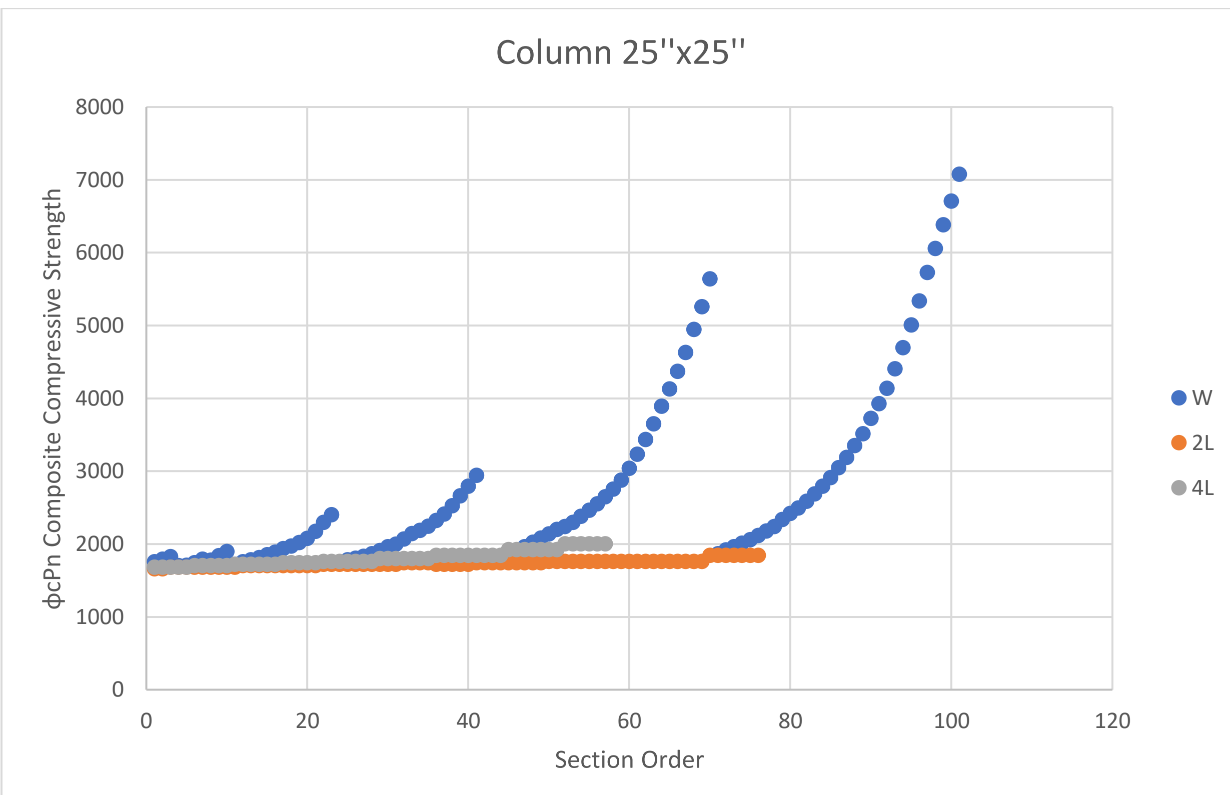

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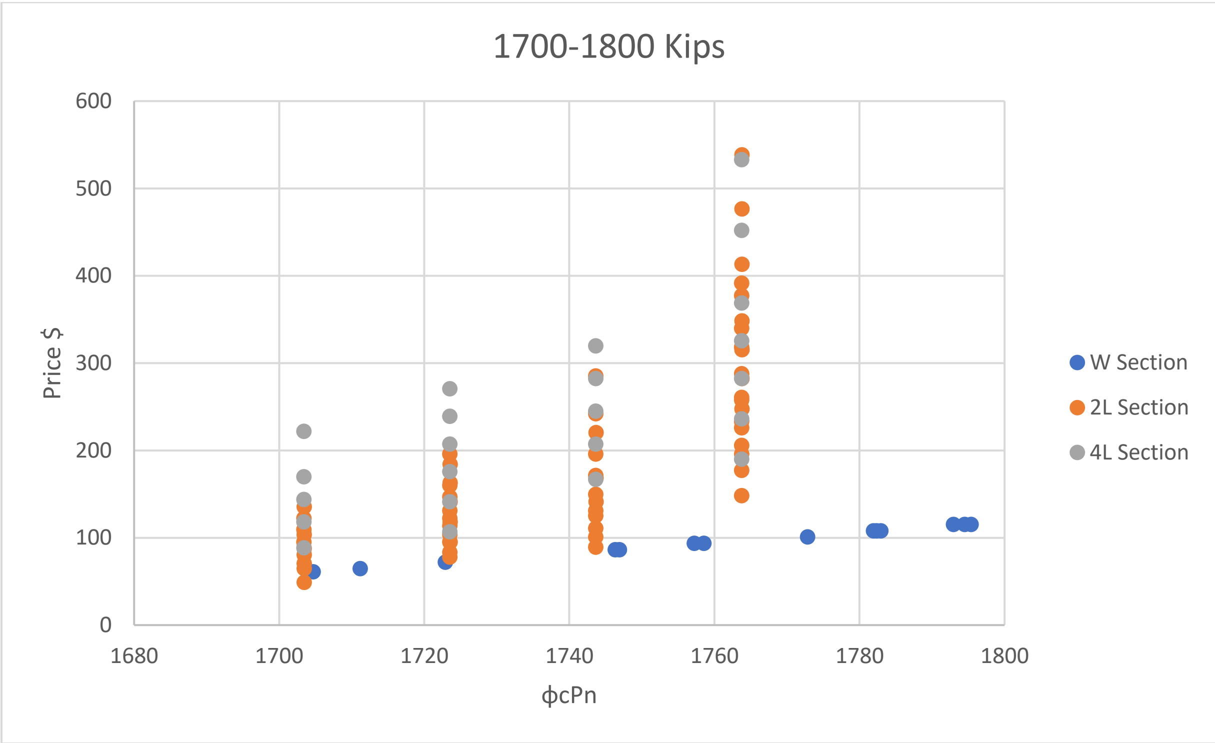

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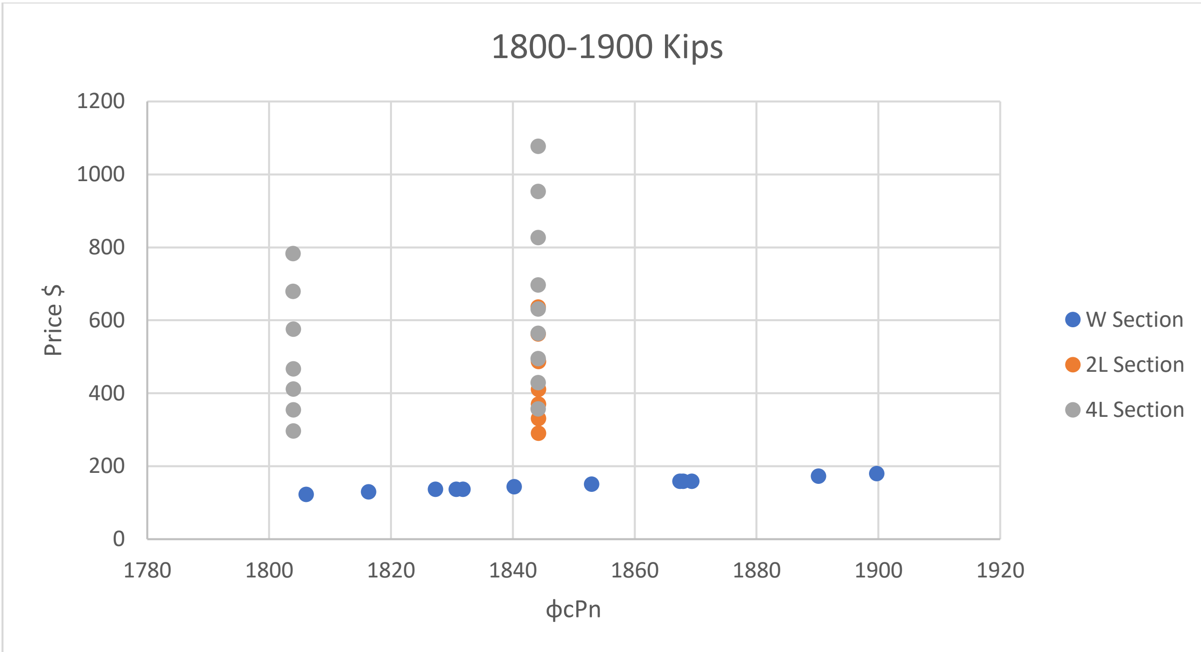

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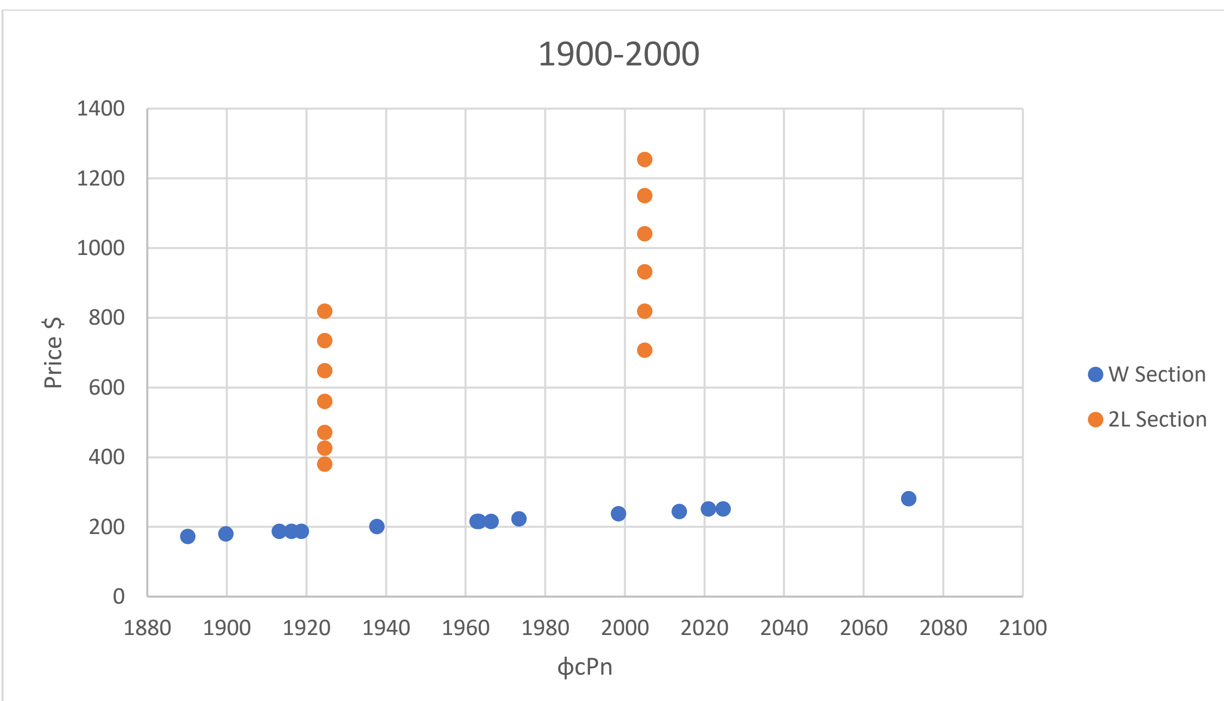

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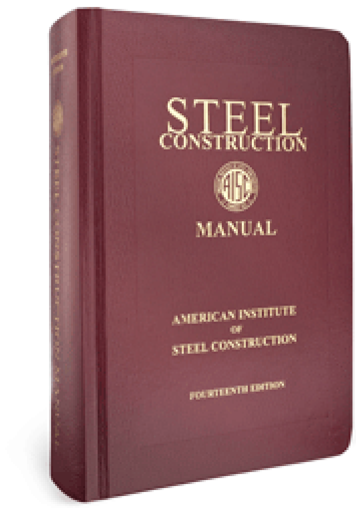

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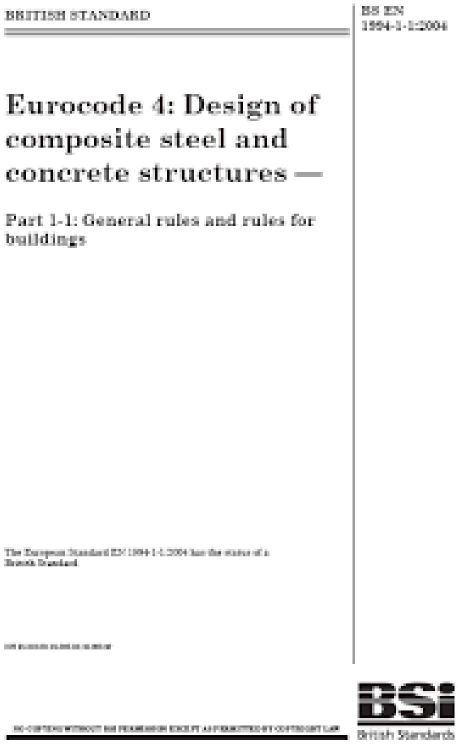
BRITISH STANDARD

BS EN 1994-1-1:2004

Eurocode 4: Design of composite steel and concrete structures —

Part 1-1: General rules and rules for buildings

The European Standard EN 1994-1-1:2004 has the status of a British Standard

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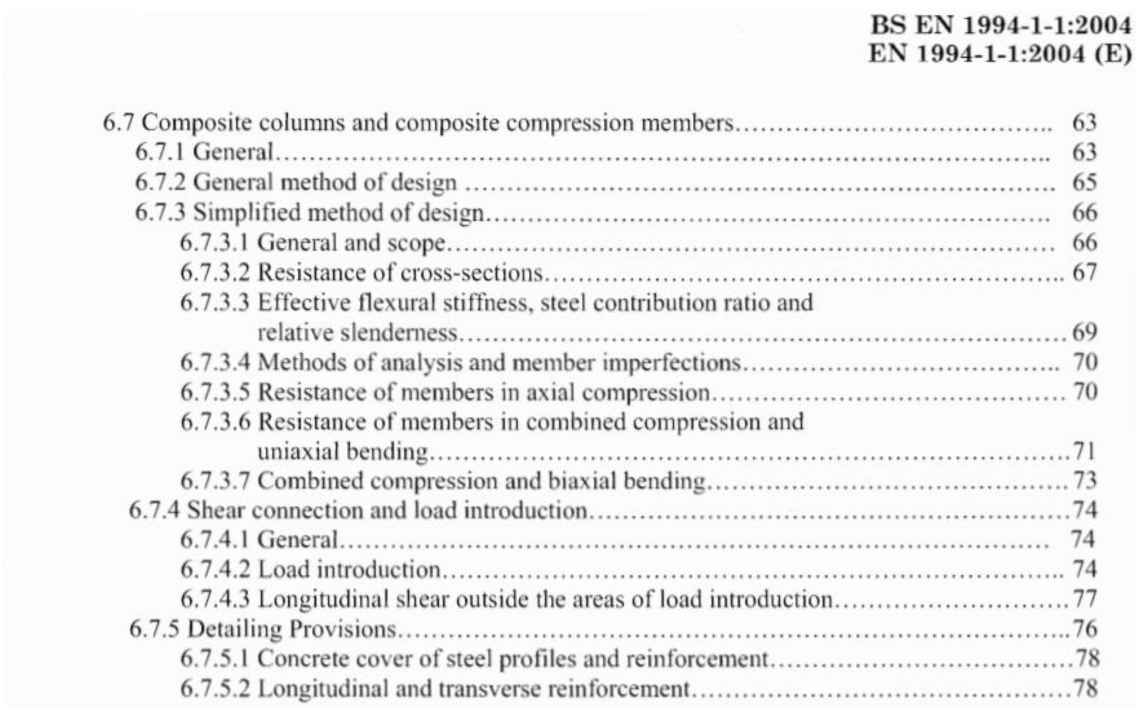
British Standards

Figure 127 Eurocode 4


BS EN 1994-1-1:2004
EN 1994-1-1:2004 (E)

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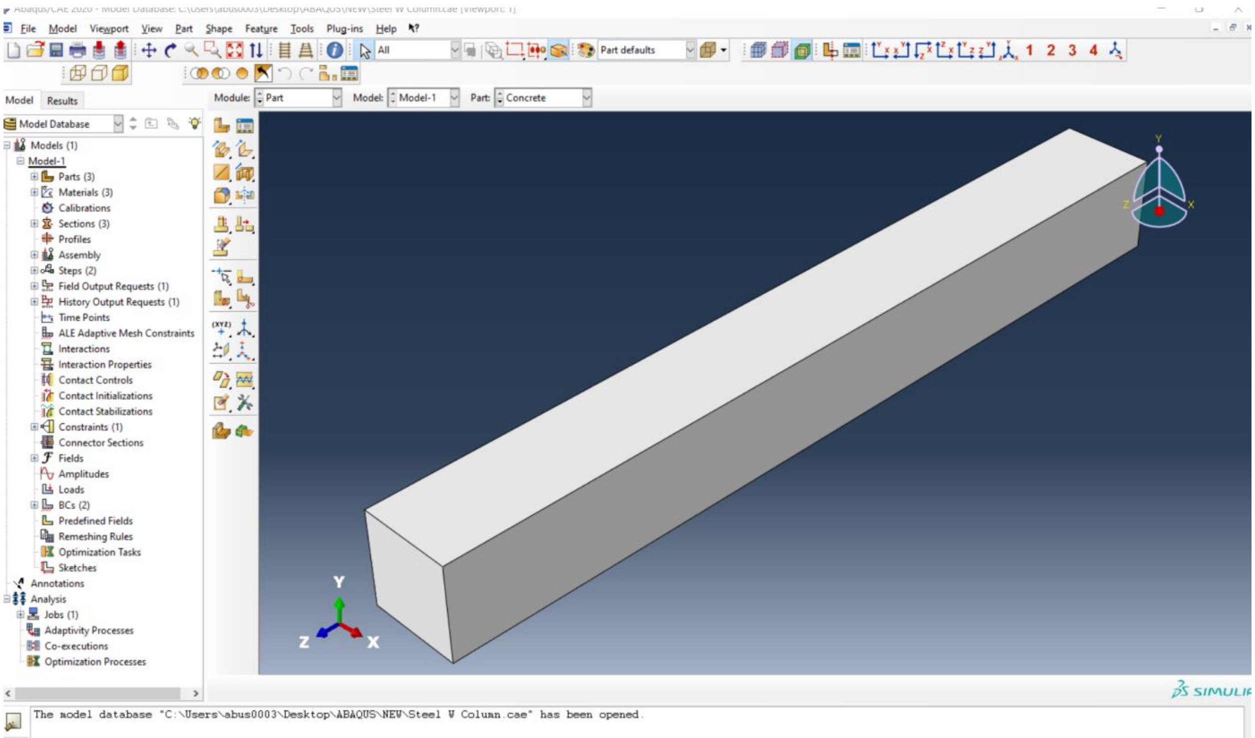


Figure 129 Concrete Part

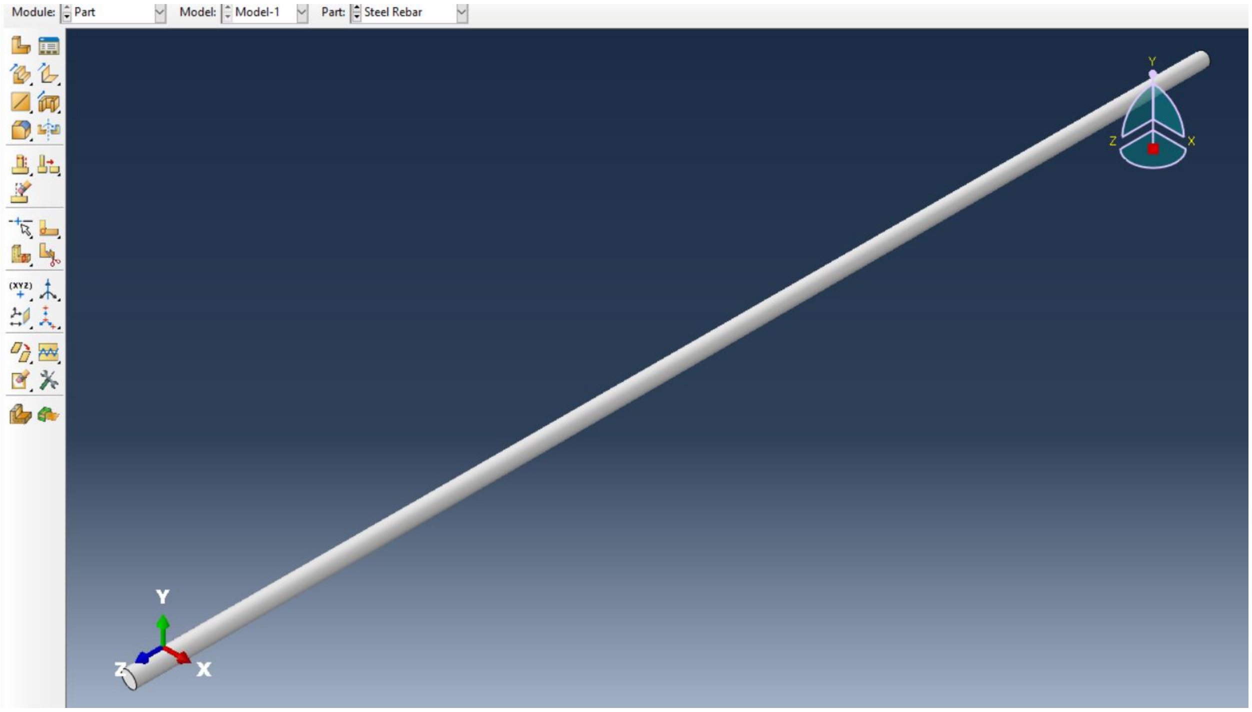


Figure 130 Steel Rebars part

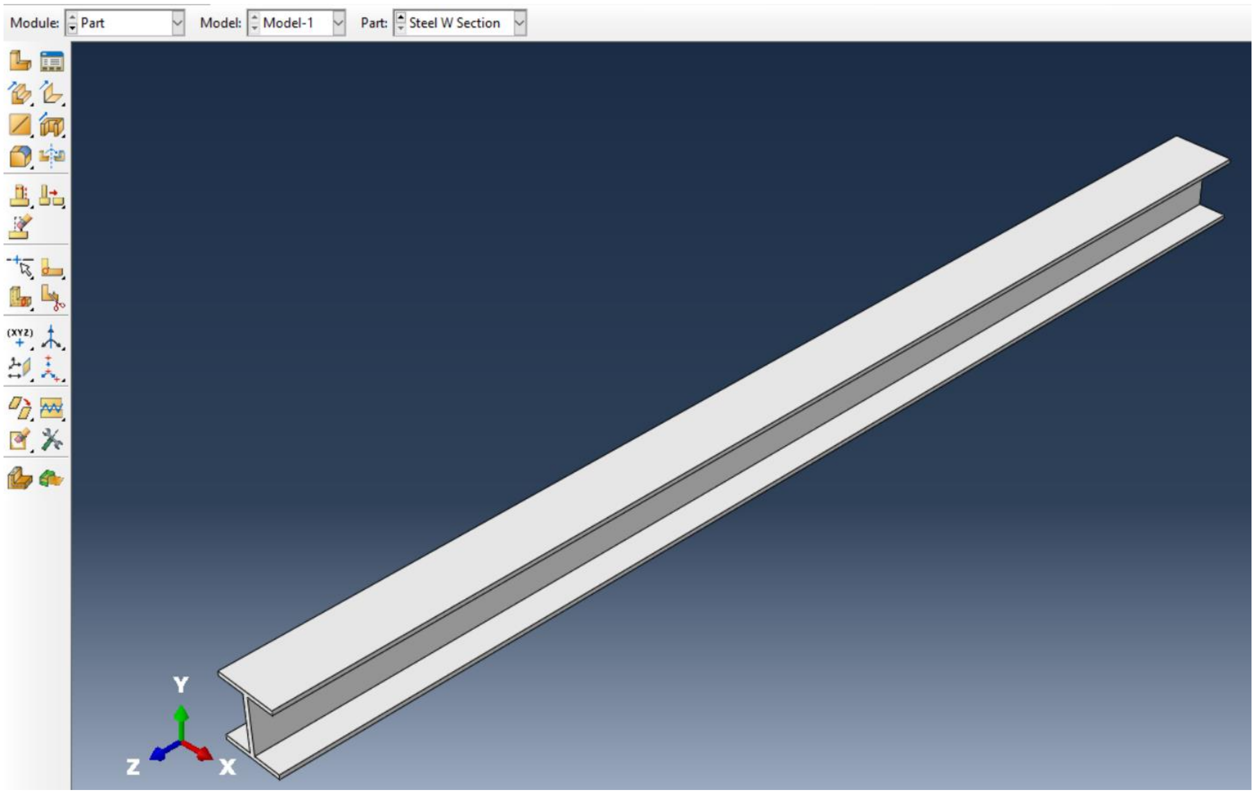


Figure 131 Steel W Section part

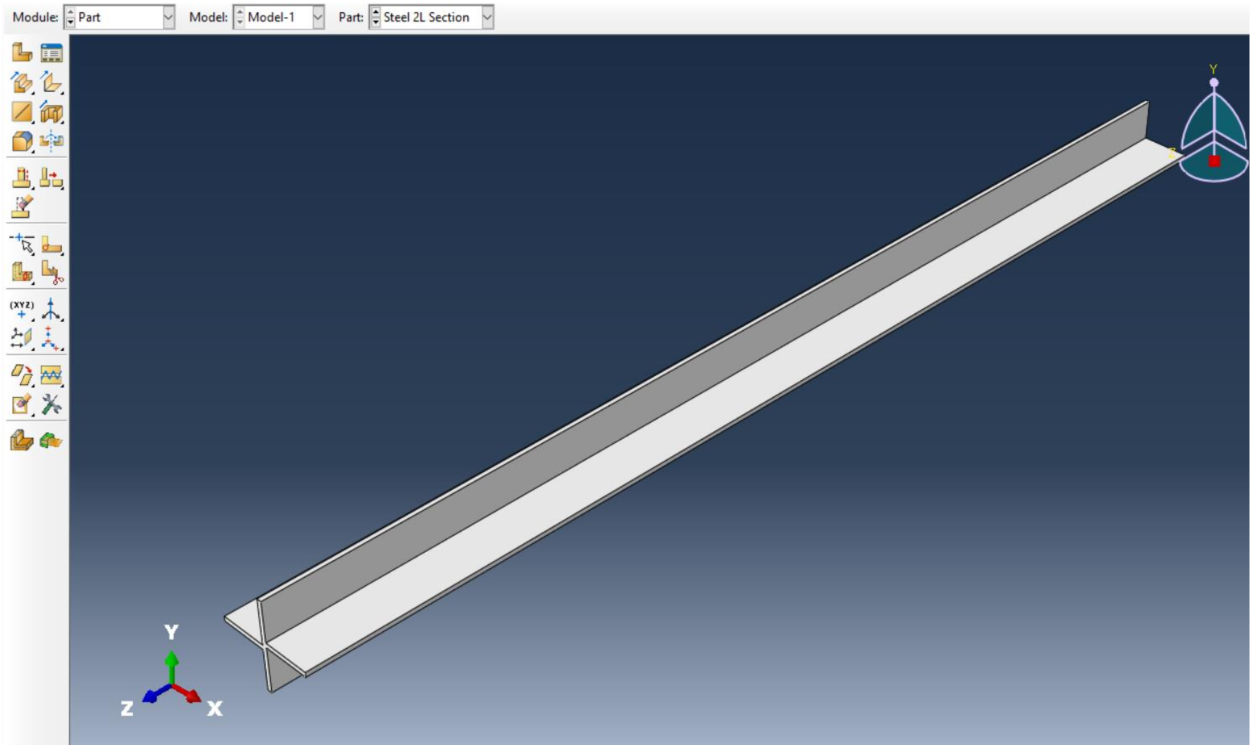
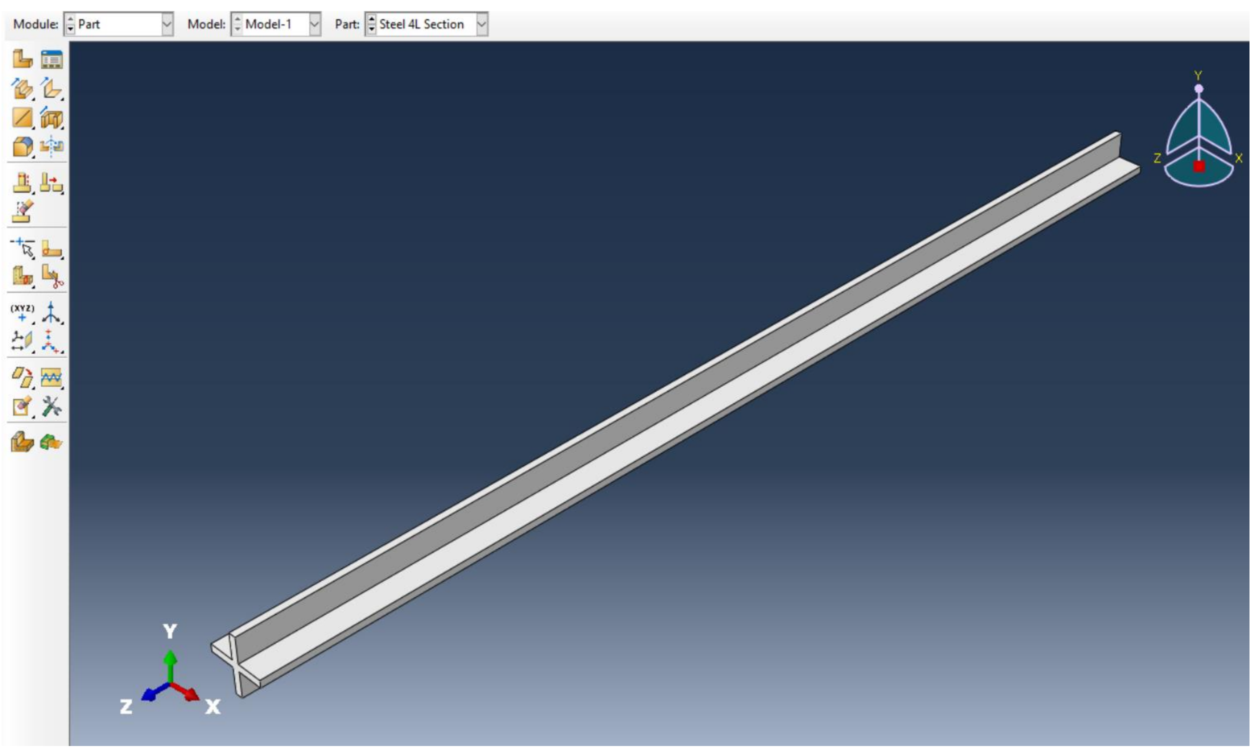


Figure 132 Steel 2L Section part



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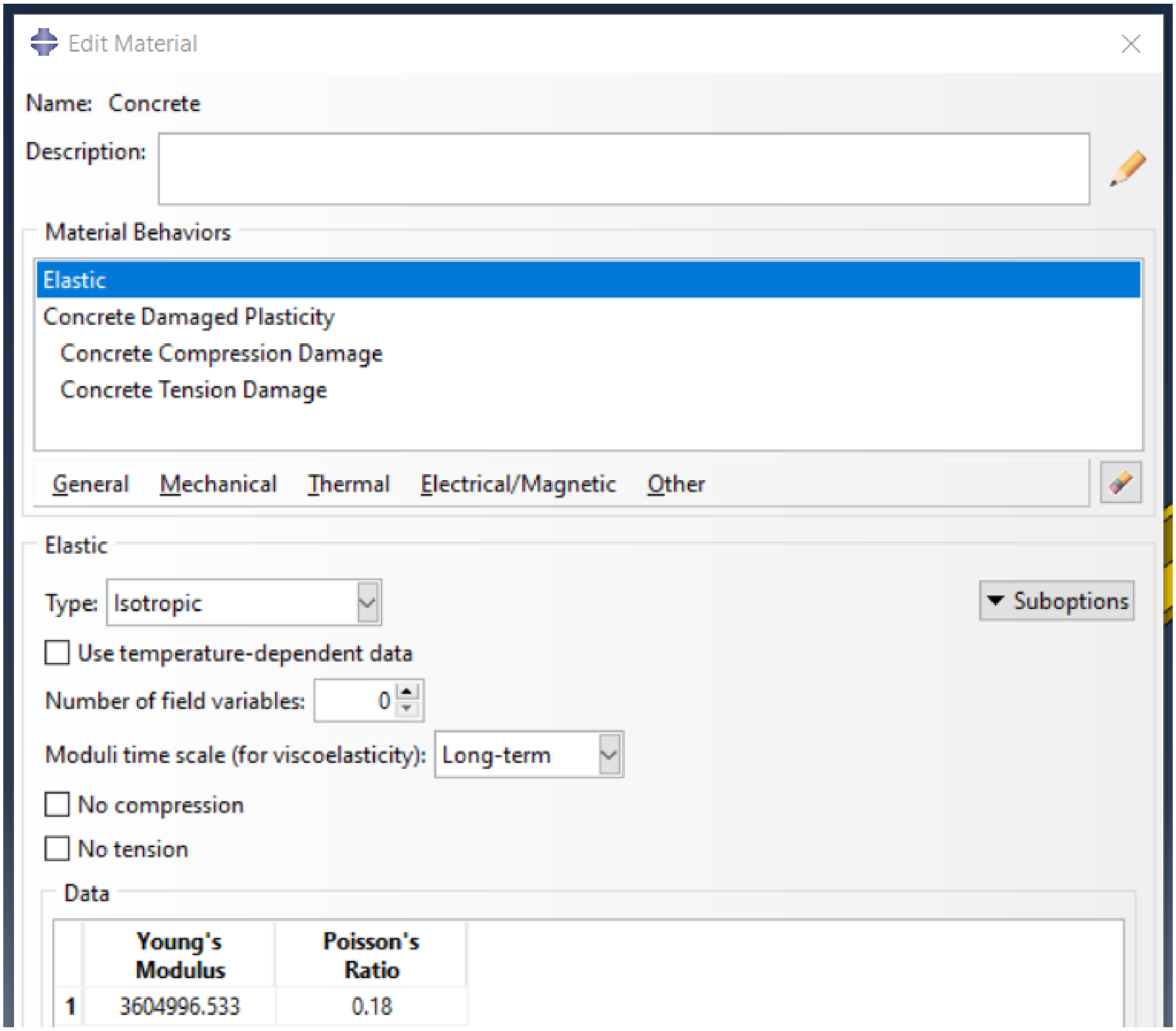


Figure 134 Concrete material elastic properties

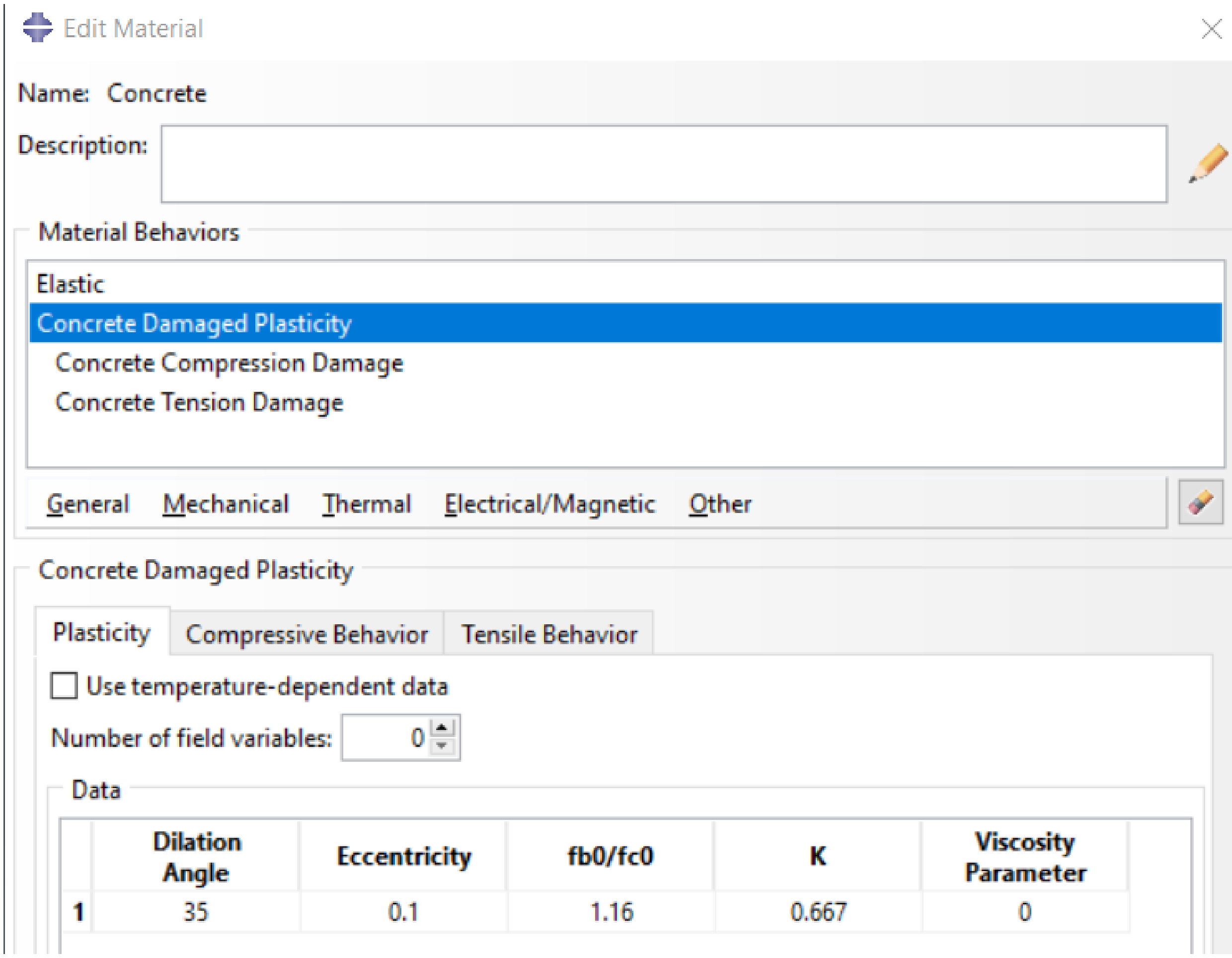
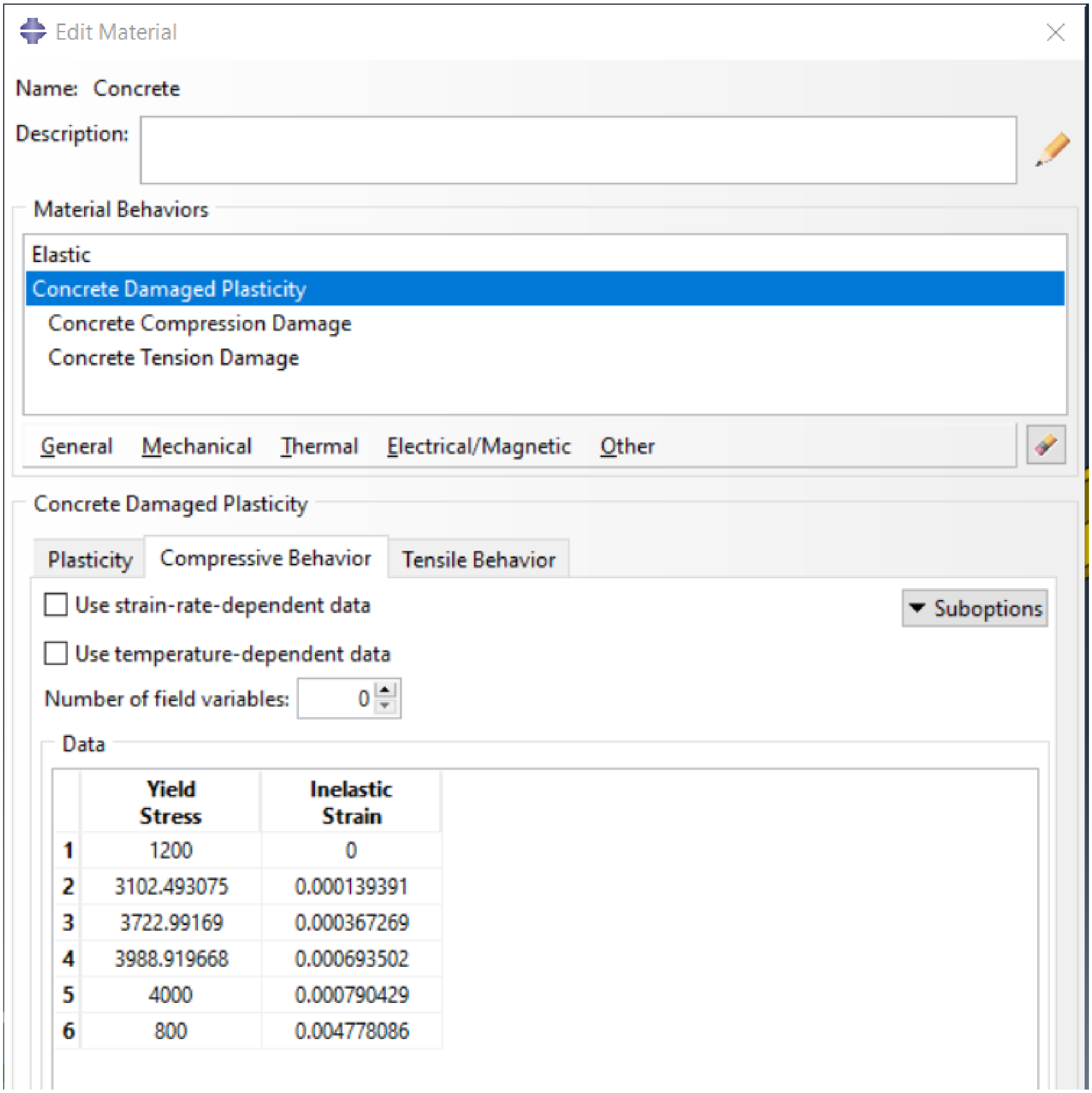


Figure 135 Concrete material plastic properties



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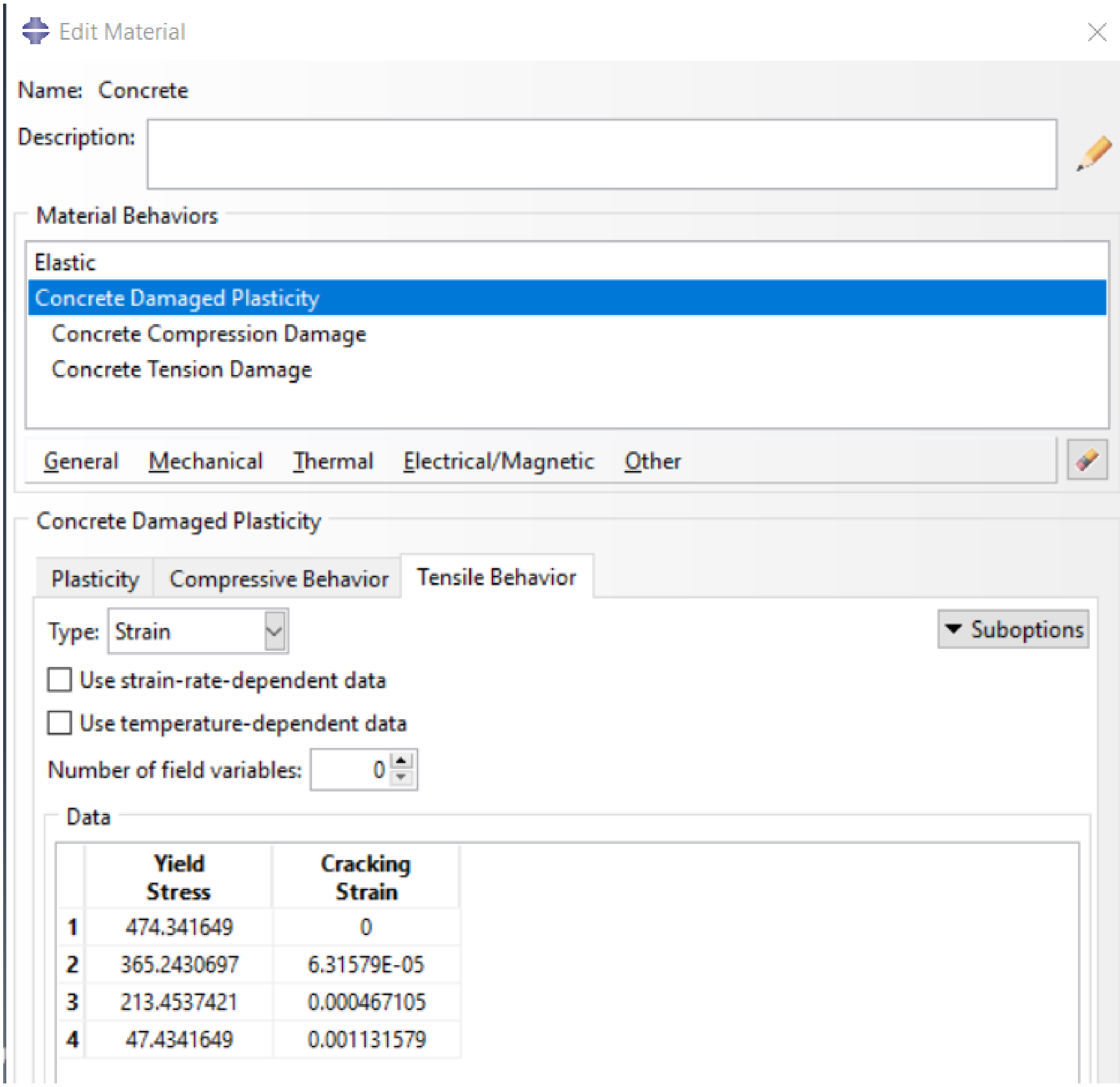

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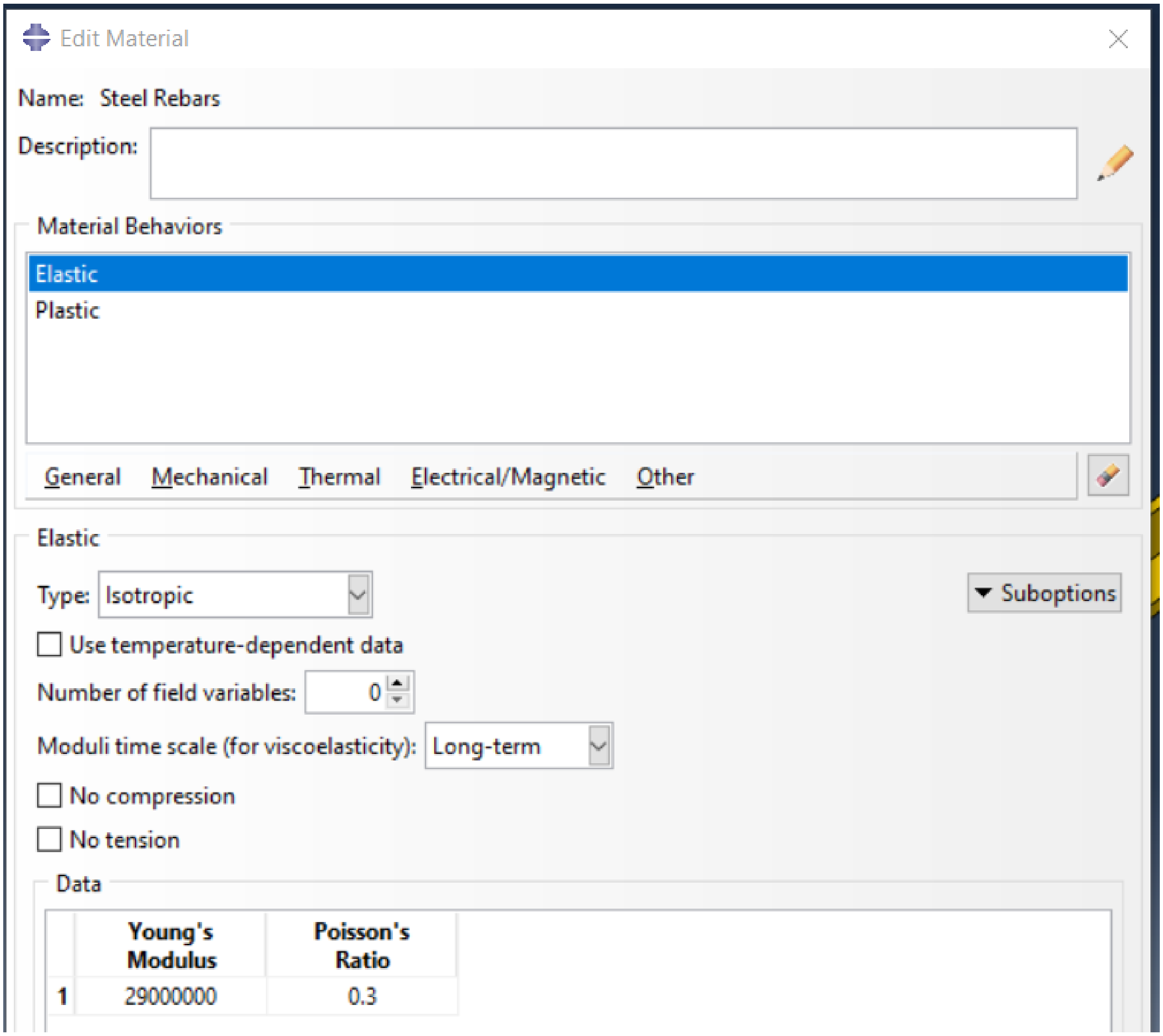

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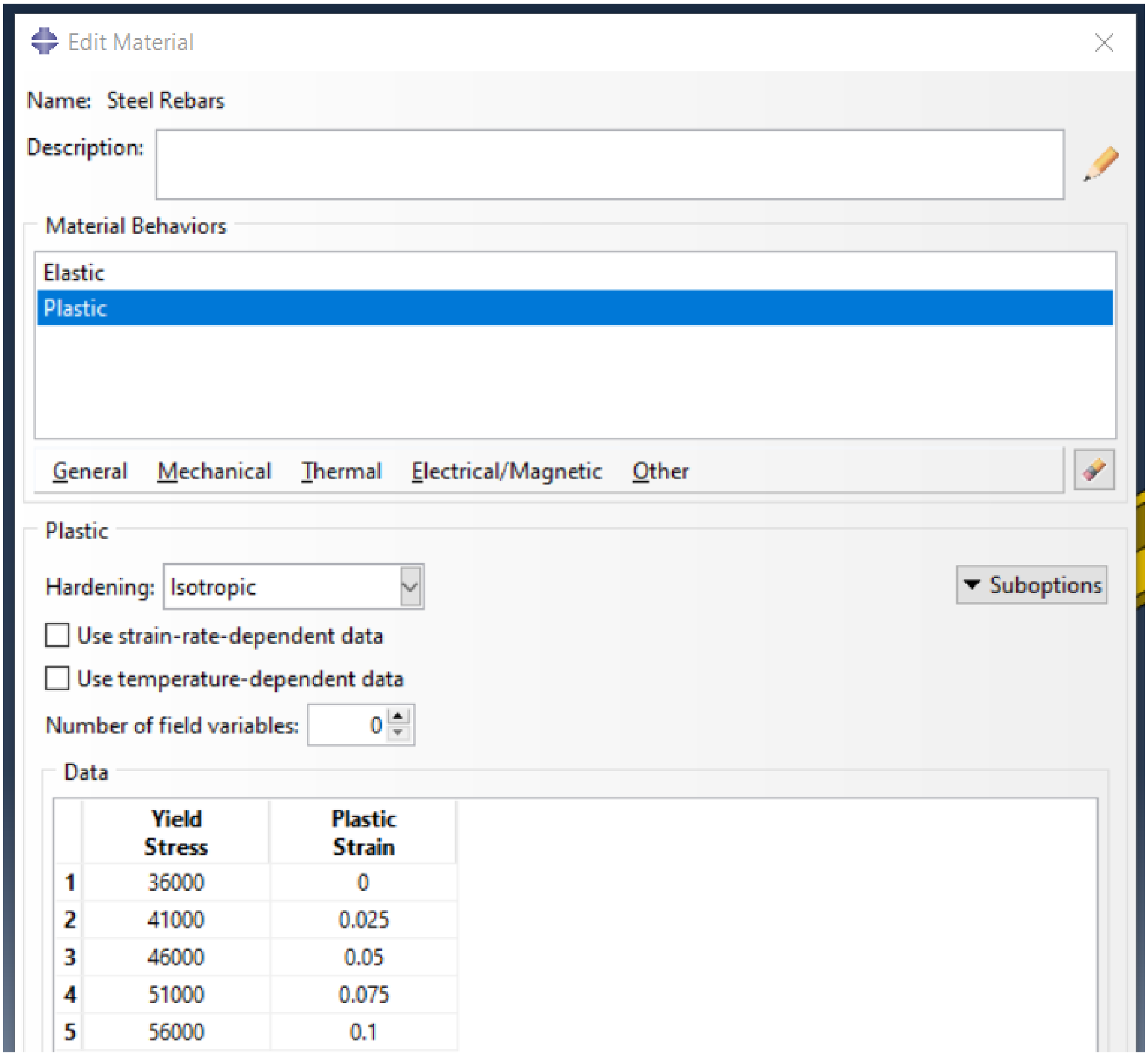
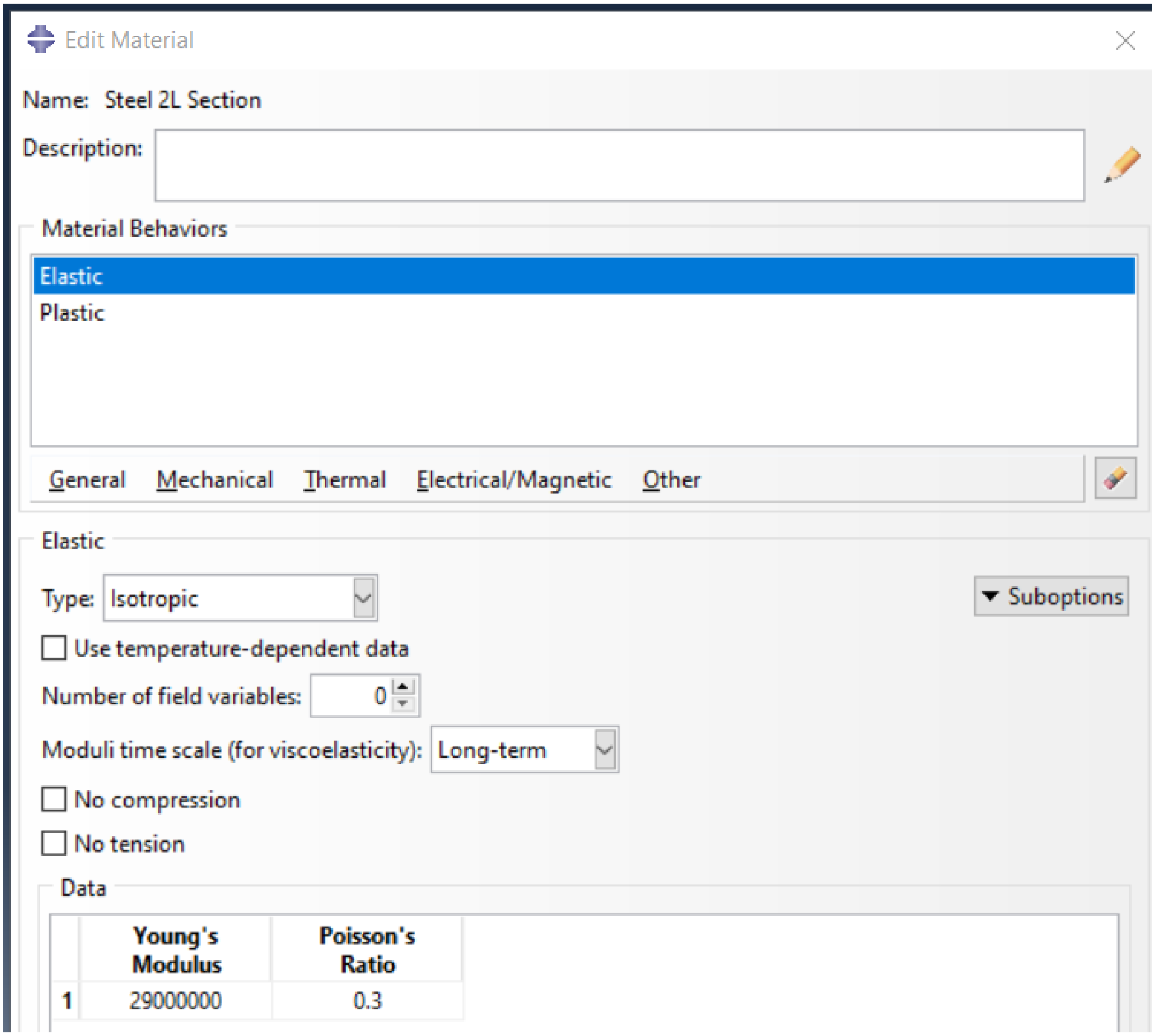


Figure 139 Steel rebars material plastic properties



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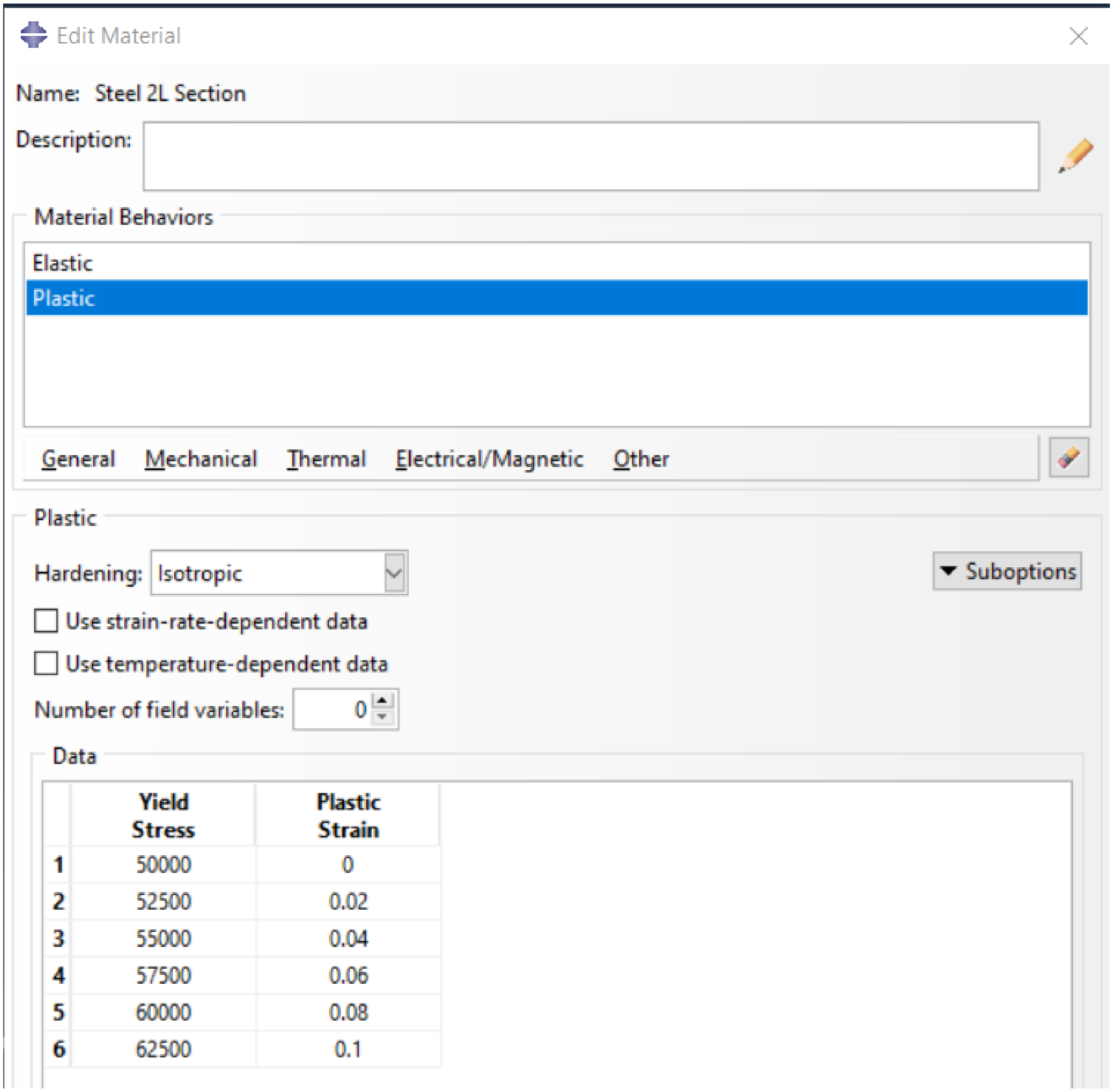
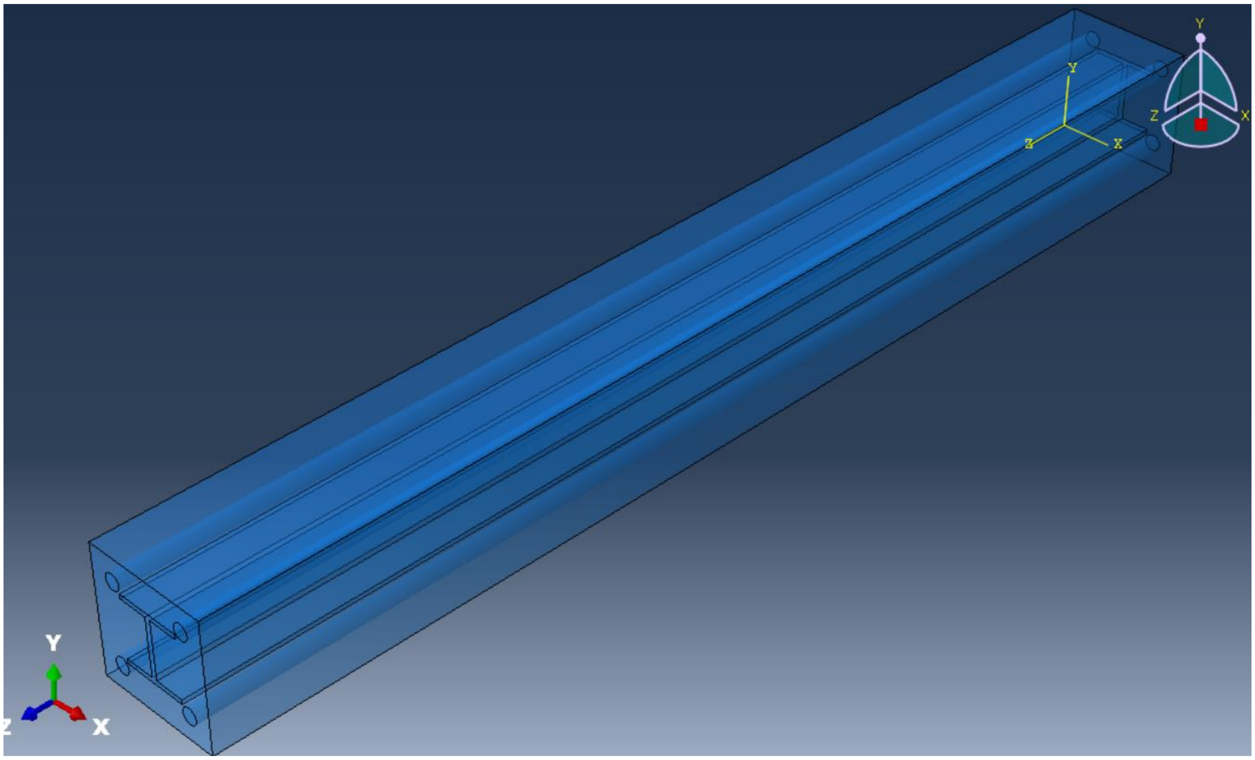


Figure 141 Steel section (W, 2L, 4L) material plastic properties



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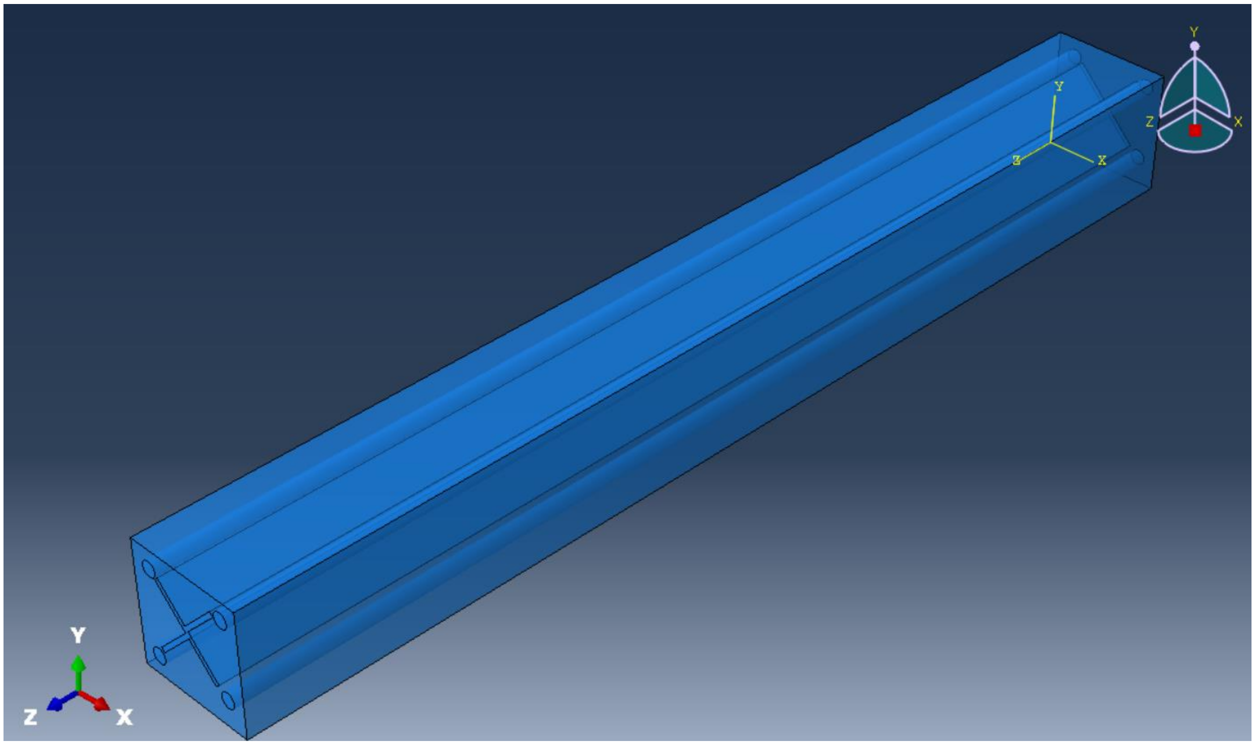

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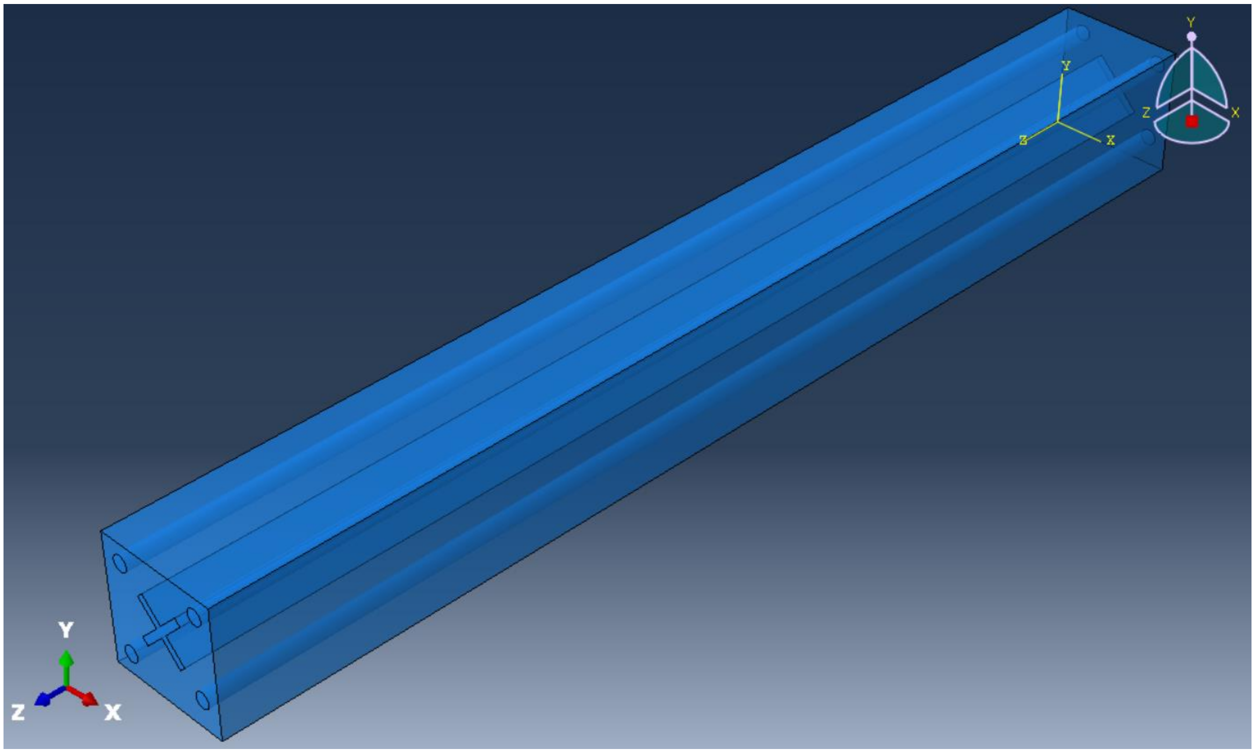

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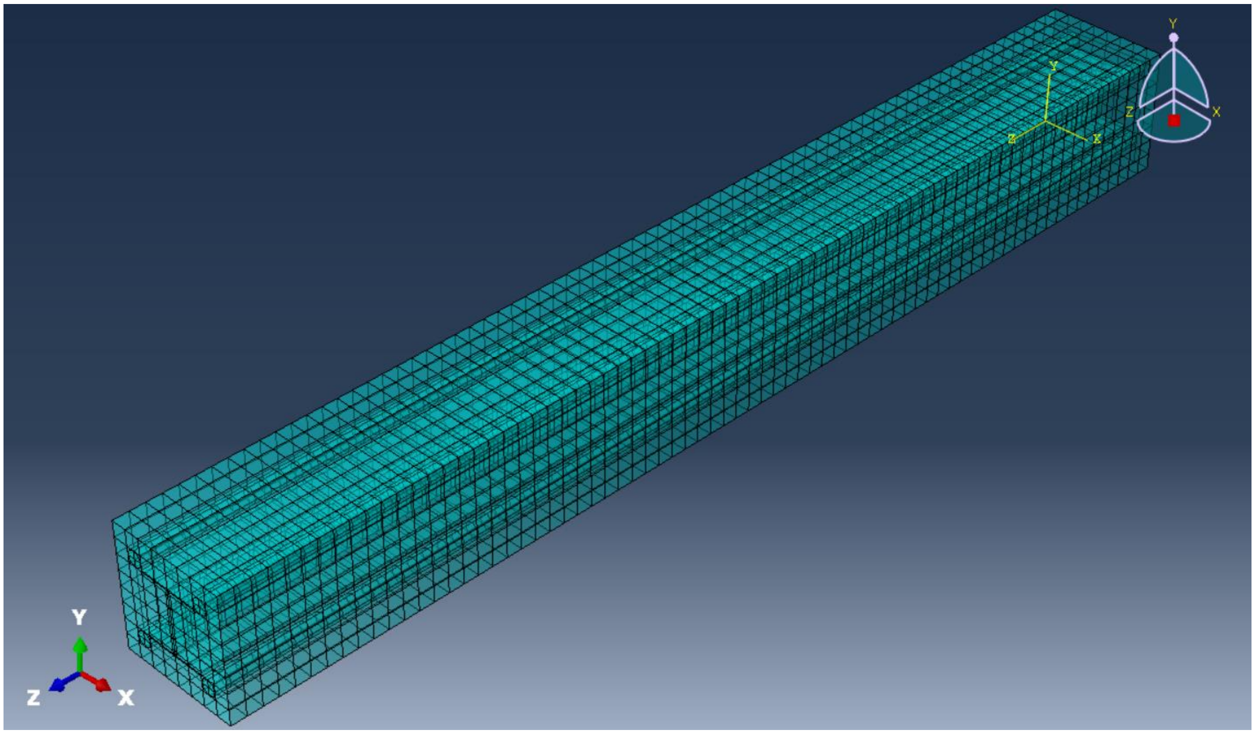

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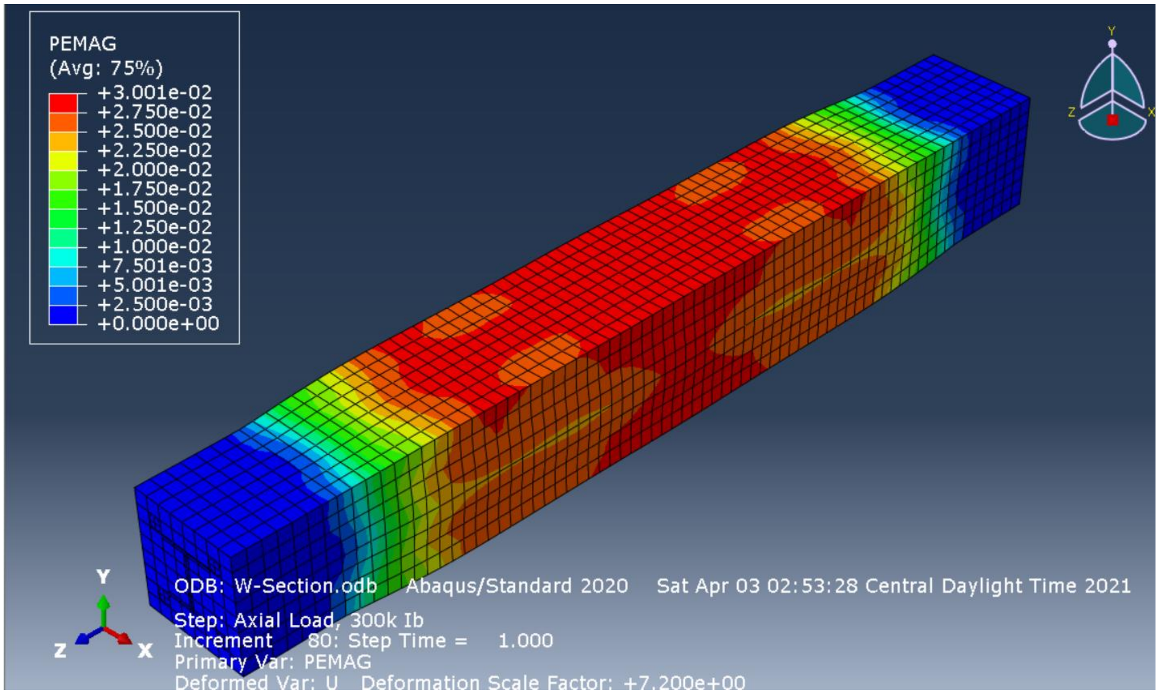

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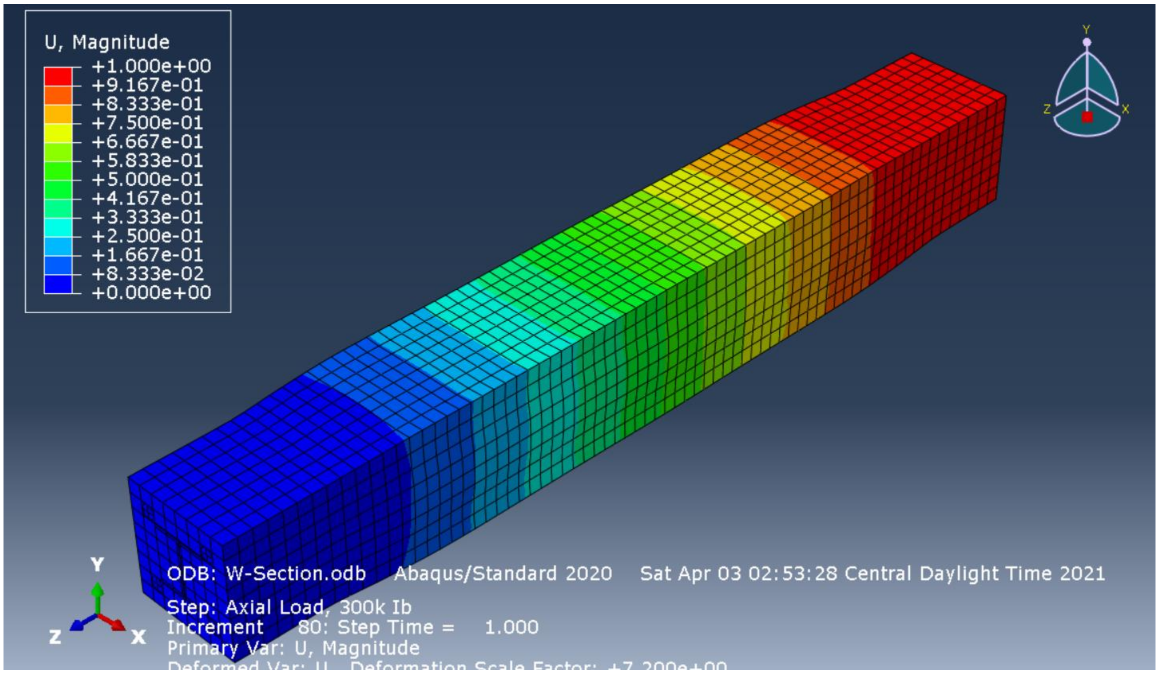

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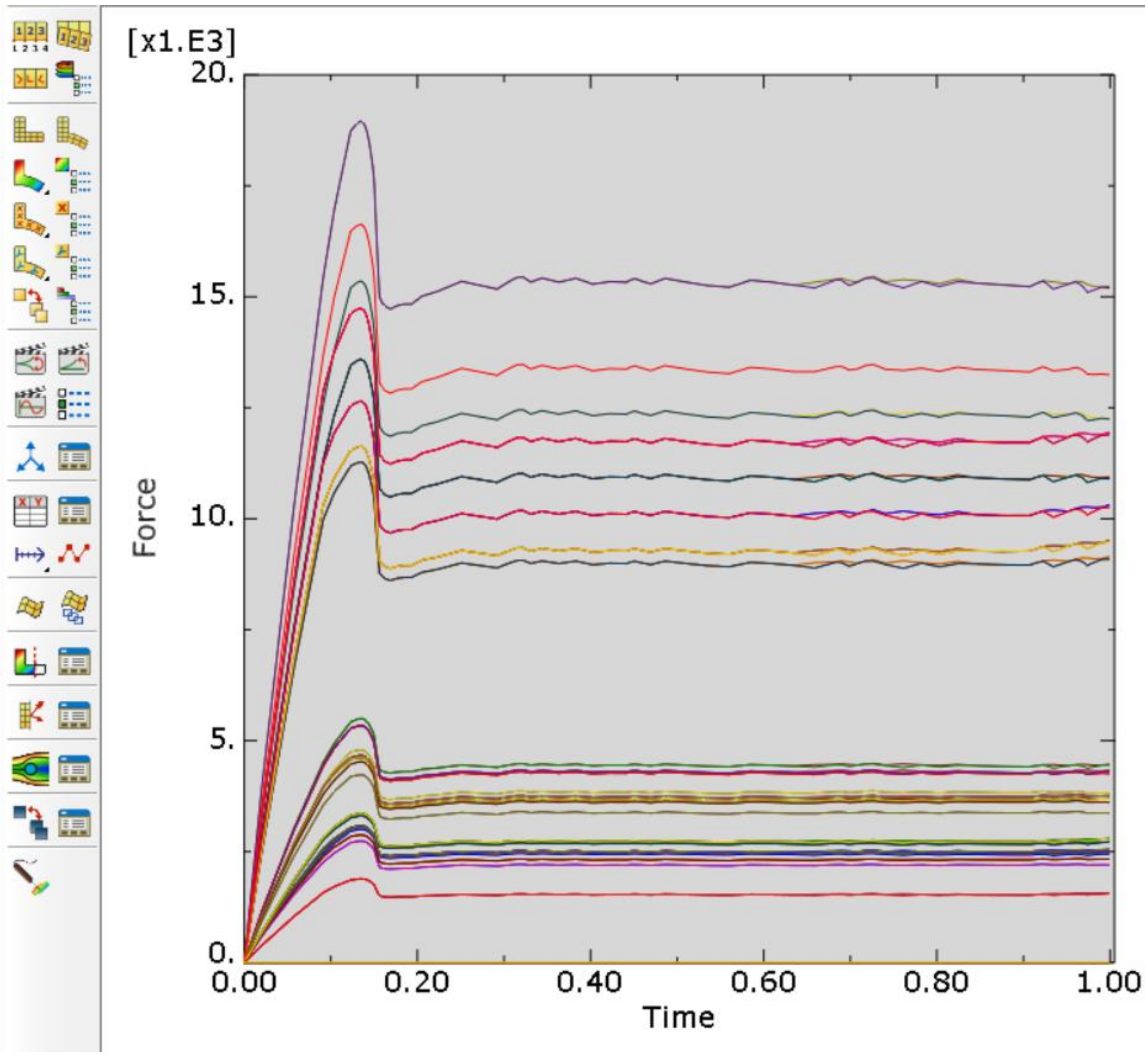

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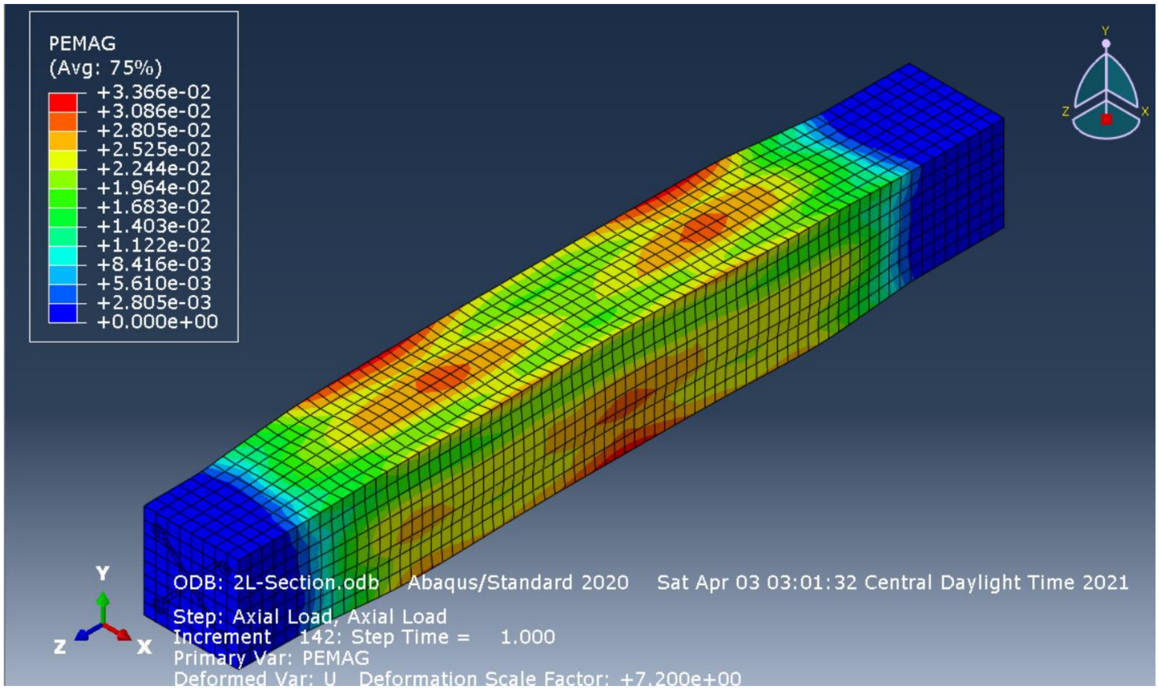

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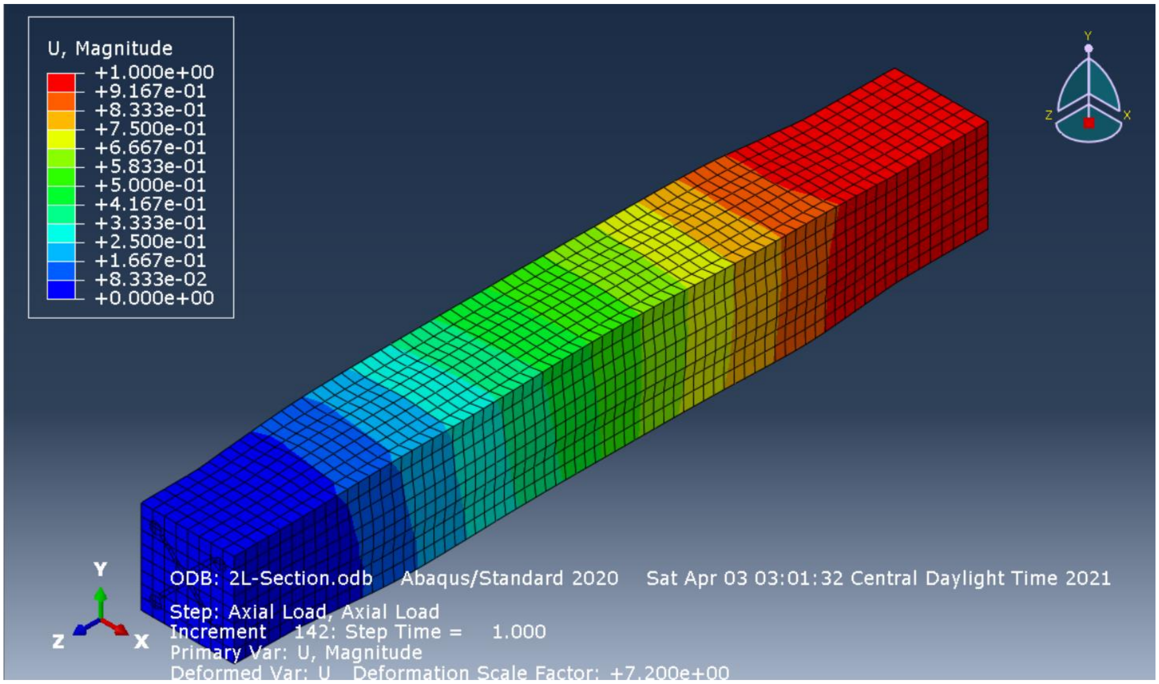

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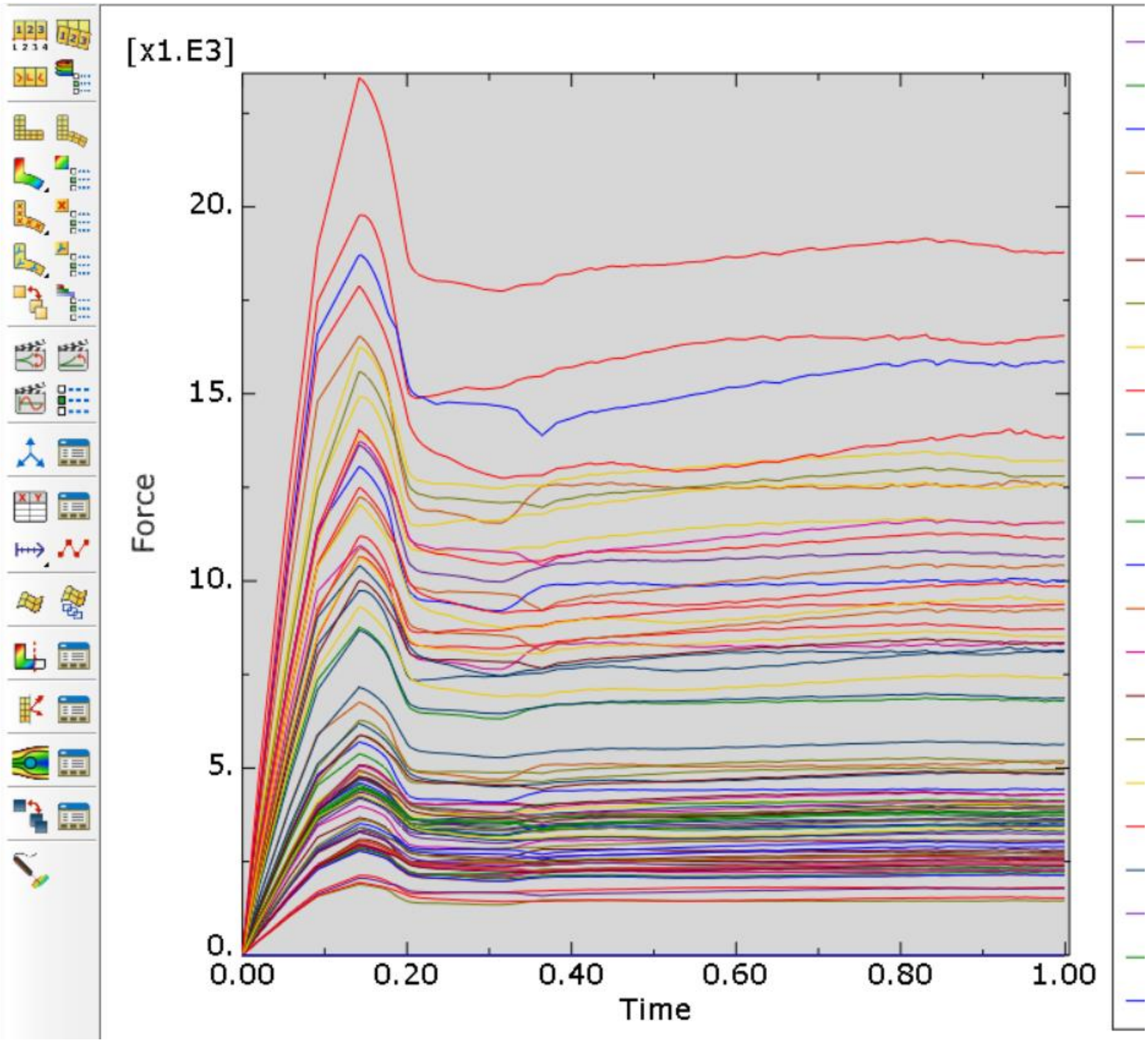

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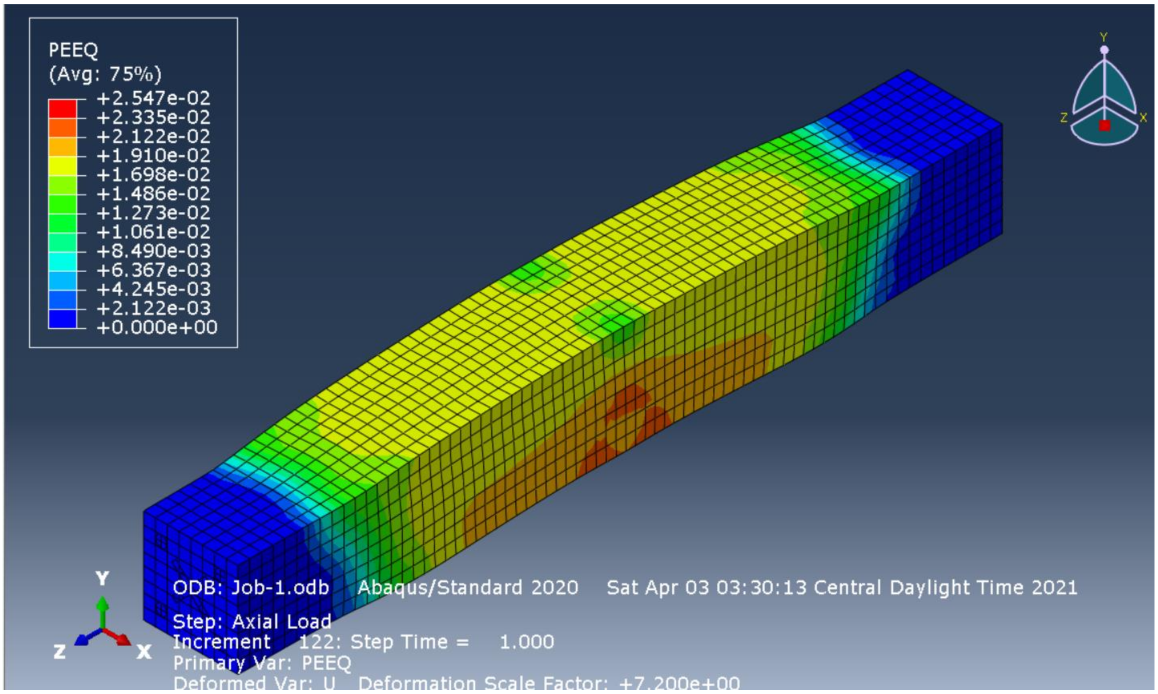

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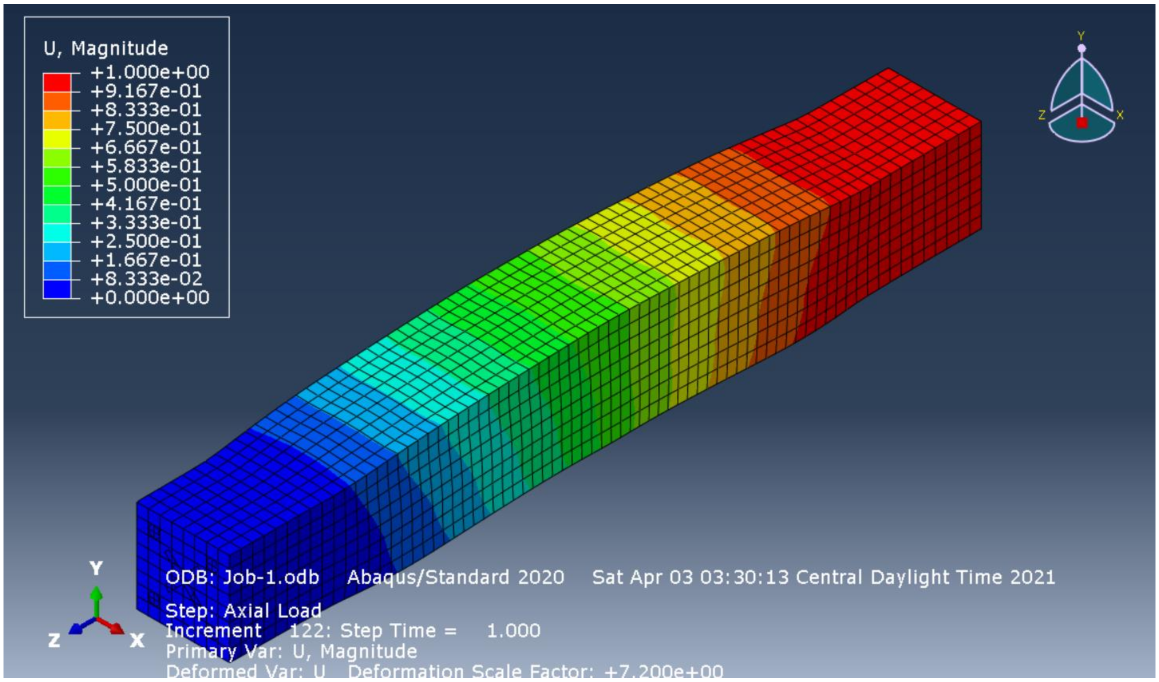

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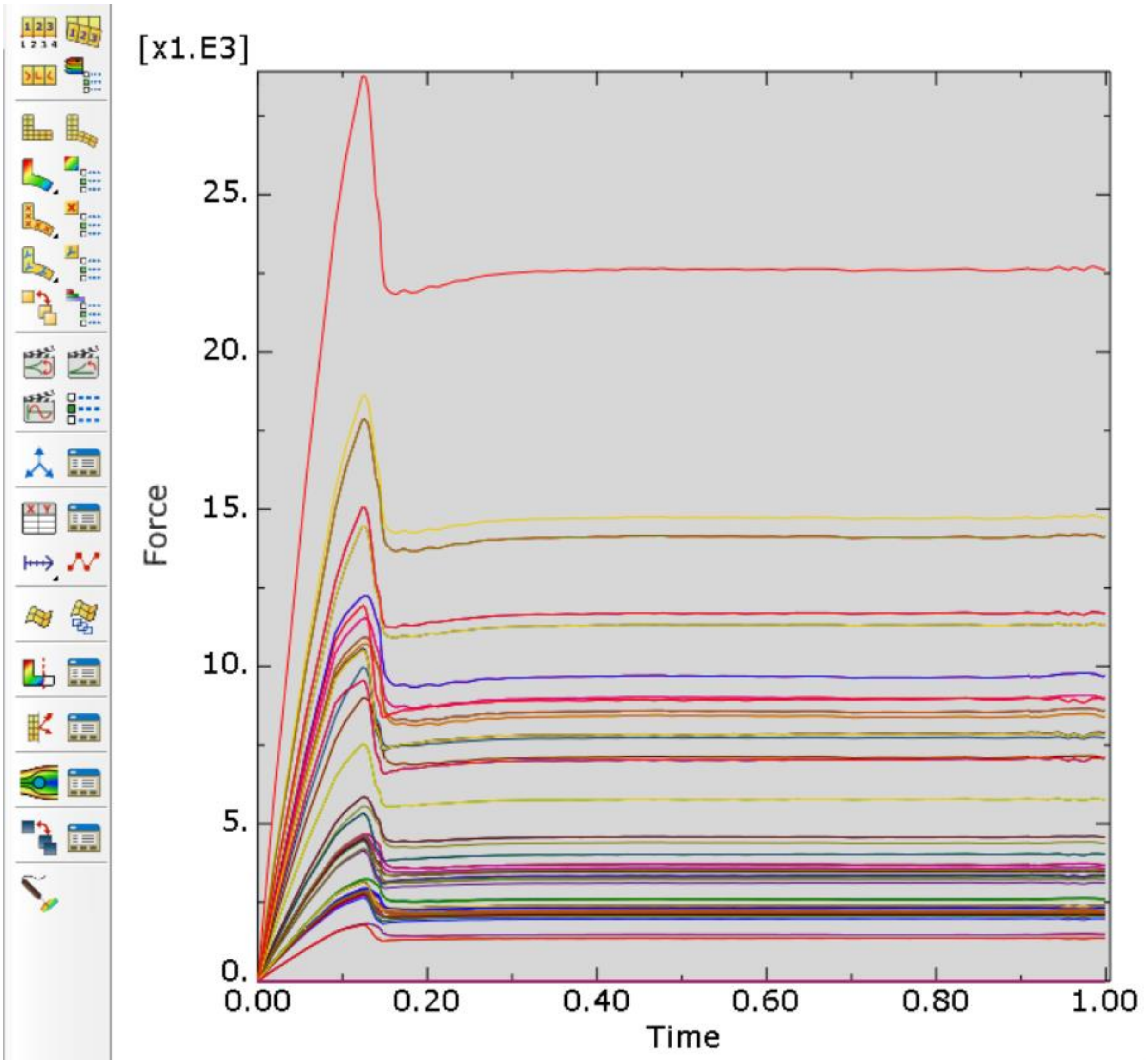

Figure 154 Reaction forces of steel 4L section at the hinge end