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## LOAD-MOMENT INTERACTION DIAGRAMS OF SLENDER PARTIALLY ENCASED COMPOSITE COLUMNS

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**Abstract:** Partially Encased Composite (PEC) Columns consist of thin-walled built-up H-shaped steel sections with links welded near the flange tips and concrete cast between the flanges. To predict the strength and ductility of slender PEC columns, Newmark's numerical iterative procedure is implemented. Overall column slenderness ratio, flange plate slenderness ratio and concrete strength are the selected parameters to observe the variation of strength and ductility of slender PEC column. Bending of column about both the strong and weak axis is considered to observe the significance of the selected parameters. In strong axis bending, a decrease in strength is found with the increase of overall slenderness ratio and flange plate slenderness ratio. Again, failure envelope of column strength curve becomes smaller with the increase of overall slenderness ratio. It implies the ductility of slender PEC column decreases with the increase of the overall slenderness ratio. Moreover, similar behaviour is observed with the increase of flange plate slenderness ratio. As the strength of concrete increases, strength of slender PEC column is observed to increase by significant amount. Similar behaviour is observed in weak axis bending along with some drop in strength.

**Keywords:** *Strength, ductility, composite, slender columns, failure envelope*

### 1.0 Introduction

Partially encased composite (PEC) column is an innovative steel concrete composite column. Again, a steel concrete composite column is a combination of steel and concrete accompanied with or without rebar. It is a compression member, comprising either a concrete encased hot-rolled steel section or a concrete filled tubular section of hot-rolled steel and is generally used as a load-bearing member in a composite framed structure. In composite structure, the existing loading is resisted by both steel and structural concrete. In PEC column, all the elements of the composite section are completely encased by concrete except the flange portion of the hot rolled steel section. Figure 1 and 2 illustrates the cross-section and elevation of a typical PEC column respectively.

This innovative column consists of thin walled built-up steel section and concrete infill is casted between the flanges. To resist local buckling between the flanges, transverse links are provided at constant intervals. PEC columns are more commonly accepted than other steel concrete composite columns as it minimizes the use of higher cost steel. Besides, it enhances the economic compressive load capacity of concrete. The use of this innovative system facilitates simple installation and removal techniques of the formwork from concrete and also standard connections to the steel flange. Consequently, it improves the speed of erection of steel structures.

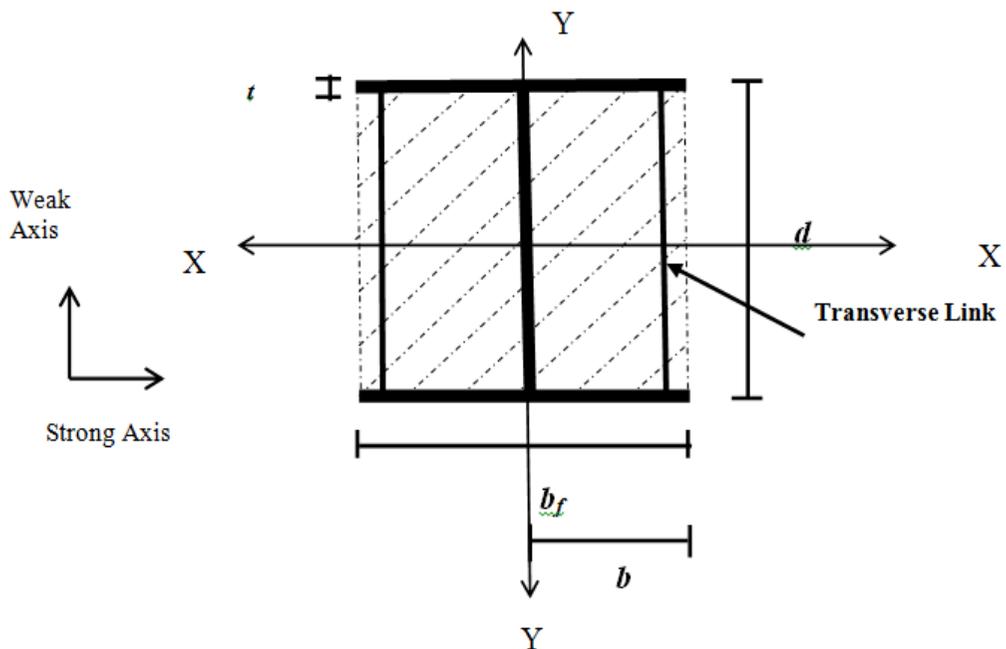


Figure 1: Cross-section of PEC column

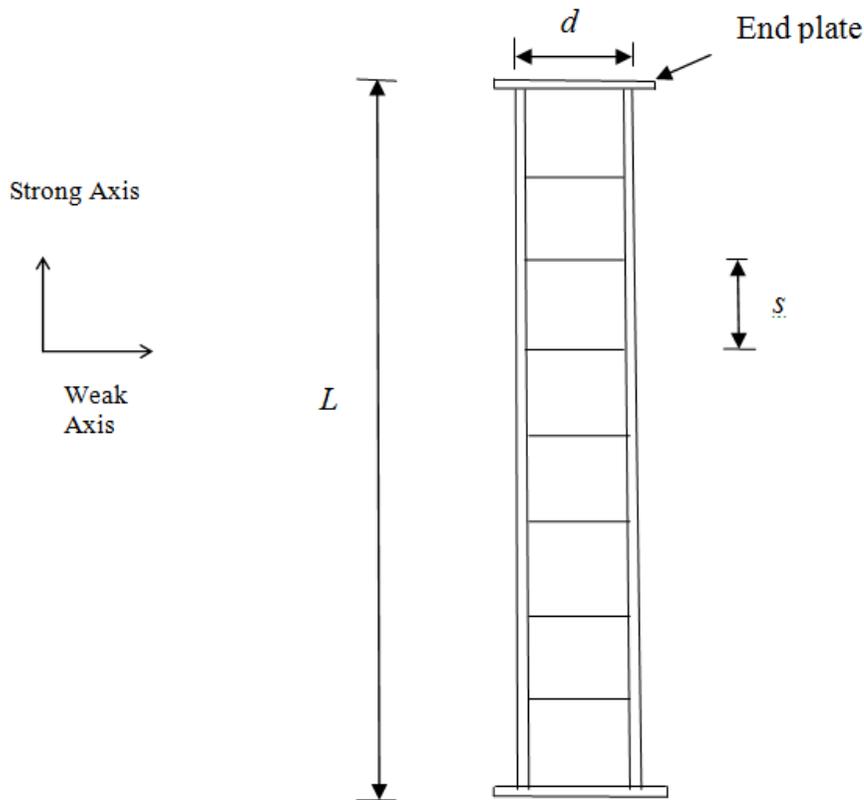


Figure 2: Elevation of PEC column

### 1.1 Background

Extensive experimental research is conducted on thin walled short PEC columns with built up section by several research groups. Among these the work carried out by Fillion (1998), Tremblay *et al.* (1998), Chicoine *et al.* (2000, 2003), Bouchereau and Toupin (2003), Prikett and Driver (2006) is remarkable. A large number of tests were performed on short PEC columns constructed with normal strength concrete subjected to eccentric and axial loads, including static and cyclic conditions. Moreover, short PEC columns with high performance concrete were also tested under pure axial compression as well as combined axial and flexural compression.

Numerical investigations on short PEC column were done by Maranda (1999), Chicoine *et al.* (2002) and Begum *et al.* (2007). All the researchers conducted finite element analysis to study the behaviour of PEC column. Recently, Deng (2008) conducted

research on a half size two storey one bay steel plate shear wall specimen, with PEC columns as the boundary elements. In addition, Dastfan (2011) did two large scale tests on steel plate shear walls with built up PEC columns.

However, limited research works are performed on slender PEC column to predict the strength of this innovative structure. Three long PEC columns were tested by Chicoine *et al.* (2000) to study the overall buckling behaviour of these columns under monotonic loading. Besides, Begum *et al.* (2007) conducted a finite element analysis on slender PEC columns. Three 9.0m long PEC columns with a cross-section of 450mm × 450mm × 9.75mm tested by Chicoine *et al.* (2000) were selected for finite element simulation to predict the global buckling behaviour of slender PEC column. The slender PEC columns were observed to fail by global buckling as well as local flange buckling.

The research on PEC columns with thin walled sections reveals that the behaviour of short PEC column with normal and high performance materials are become relatively well understood from the full scale extensive experimental and numerical investigations. Design guidelines and axial capacity of short PEC column are well established and included in Canadian steel design code (CSA-S16.09). However, design guidelines for slender PEC columns are not included in the design code due to scarcity of ample research on long PEC columns. Moreover, it is not possible to obtain a complete understanding of various components from experimental investigations only due to high cost and time requirement for full scale testing. No numerical study is yet performed to predict the strength and ductility of slender PEC columns. In this regard, through a numerical analysis, an attempt is made to represent the axial load and moment capacity of slender PEC columns and also to observe the influences of several key parameters which could not be studied by the experimental programs.

## 1.2 Objectives

The main objective of this study is to investigate the strength and ductility of slender PEC column. To this end, column strength curve (interaction diagram) of slender PEC column is formulated. Again, to develop the column strength curve of such an innovative system, load to maximum moment curve is constructed of slender PEC column. To formulate the load to maximum moment curve, Newmark's numerical iterative procedure is implemented. The slender column is assumed to bend under single symmetric curvature bending about strong axis and also in weak axis in two parts of this study. Finally, some potential variables that can influence significantly are considered to observe their effects through observing the column strength curve of slender PEC column.

## 2.0 Methodology

A slender column especially when it is loaded eccentrically has a significant reduction in its axial load capacity due to moments resulting from lateral deflections of the column. How the axial load capacity is affected by the lateral deflection, is illustrated in Fig. 3 which shows a pin-ended column and subjected to eccentric loads. The moments at the ends of the columns are

$$M = Pe \quad (1)$$

When the load  $P$  is applied, the column deflects laterally by an amount  $\Delta$ , as shown in Fig. 3. For equilibrium, the internal moment at the mid-height must be,

$$M = P(e + \Delta) \quad (2)$$

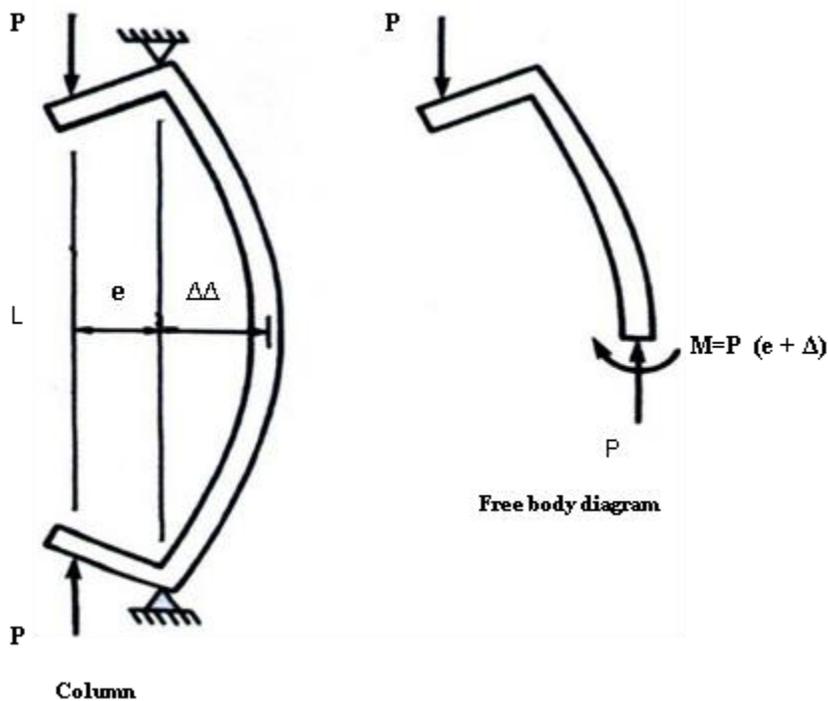


Figure 3: Forces in a deflected column

The ultimate axial load capacity of a slender column is determined using the cross-sectional column strength curve (load-moment interaction diagram) as well as the load

to maximum moment (P-M) curve of slender column. The former one is developed using a procedure commonly adopted for reinforced concrete columns. The load to moment curve for slender PEC column is plotted using the mid height deflections calculated for each load level. The slender column P-M curve is then superimposed on the cross-sectional interaction diagram. The point of intersection is the ultimate capacity of the column (Wight and MacGregor, 2009).

The interaction diagram for short column is formulated as followed by Bouchereau and Toupin (2002) and Prickett and Driver (2006). Bouchereau and Toupin (2002) and Prickett and Driver (2006) predicted the capacity of eccentrically loaded columns from load-moment interaction diagrams constructed using a procedure commonly adopted for reinforced concrete columns. A linear strain distribution along the cross-section, based on observations from the strain measurements taken during the test, is implemented for the construction of this diagram. The extreme compressive strain is set at  $3500\mu\epsilon$ , whereas the extreme tensile strain is varied from 0 to 10 times the yield strain of the steel. For each strain gradient, the ultimate load and moment capacities are calculated from the material and geometric properties of the composite cross-section. The compressive force in the concrete,  $C_c$ , is calculated using the following expression, assuming a rectangular stress block,

$$C_c = \alpha_1 f_{cu} b_c \beta_1 c \quad (3)$$

where,

$b_c$ = Net width of concrete block (i.e. excluding the web thickness of strong axis bending and excluding the flanges for weak axis bending)

$c$  = Distance between the extreme compression fibre and neutral axis

$$\alpha_1 = 0.85 - 0.0015f_{cu} \geq 0.67 \quad (4)$$

$$\beta_1 = 0.97 - 0.0025f_{cu} \geq 0.67 \quad (5)$$

To calculate the contribution of the steel to the capacity of the composite column, the section is discretised in such a way as to have effectively uniform strain in each individual piece. For strong axis bending, the flanges are considered to be one piece, whereas the web is divided into ten pieces. On the other hand, for weak axis bending, the web is considered as one piece and each flange is discretised into ten pieces. (Prickett and Driver, 2006). The resultant force for each individual piece is calculated by multiplying the area of the piece by its average strain. However, if the strain in the individual piece exceeded the yield strain, the force resultant is determined by

multiplying the area of that piece by the yield stress. In calculating the area of a flange piece in compression, the effective width,  $b_e$  is used by (Prickett and Driver, 2006). Finally, the total load capacity of the composite column is determined by adding the force resultants for concrete and steel and the moment capacity are obtained from the summation of each force multiplied by its distance from the centerline of the column cross-section.

To determine the second order deflection of slender PEC column at its mid-height, Newmark's (Newmark, 1943) non-linear numerical procedure is used. The steps followed can be summarized as,

- The length of the slender column is subdivided into several differential segments. A unit deflection is assumed at the mid-height of the slender column and zero at the ends. The deflection at other stations along the length is determined through linear interpolation.
- The total moment at each station along the length of the column is evaluated using Eq. (2) for the selected level of axial load.
- Using the moments obtained from the previous step the curvature at the selected stations along the length of the column is computed.
- Using the conjugate beam method the deflection at each station is calculated. This deflection is compared to the assumed deflection.
- If the computed deflections and the initial deflections are within prescribed limits of 0.05%, an equilibrium solution is obtained. If not, the computed deflections are substituted for the assumed deflections and the process is repeated until the deflections converge.

The interaction diagram or column strength curve of the slender PEC column is constructed using the cross-section interaction diagram and the P-M curves for the slender PEC column at various levels of  $e/d$  ratios as shown in Fig. 4.

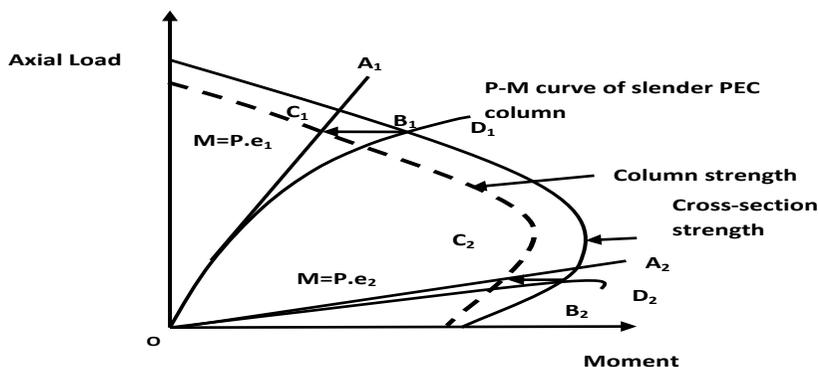


Figure 4: Formation of interaction diagram of slender PEC column

For different  $e/d$  ratios ranging from 0.05 to 50, the P-M curves are constructed using the procedure described above. The selected  $e/d$  ratios are 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 2.5, 5.0 and 50. When  $e/d$  ratio is 50, the amount of axial load is nearly zero. These curves are superimposed on the cross-section strength curve of the column. The  $M=Pe$  diagrams are also plotted for the different values of  $e/d$  ratios. Now, horizontal lines ( $B_1C_1$  and  $B_2C_2$ ) is drawn from the intersection points ( $B_1$  and  $C_1$  respectively) of the cross-section interaction curve and the nonlinear P-M curve (curve  $OD_1$  and  $OD_2$ ) for each eccentricity ( $e_1$  and  $e_2$  are shown). The point of intersection ( $C_1$ ) of the horizontal line ( $B_1C_1$ ) and line  $OA_1$  ( $M=Pe_1$ ) represents the axial load and moment at the end of the column at failure. Similarly, point  $C_2$  represents the end moment at failure at eccentricity  $e_2$ . This process is repeated for the selected PEC column ( $L/d=25$ ) for the selected values of  $e/d$  ratios and the corresponding failure points are determined. The slender column interaction curve (as shown by dashed line in Fig. 4) is then drawn by connecting the failure points (Wight and MacGregor, 2009). This curve shows the loads and maximum end moments causing failure of the given slender column.

### 3.0 Parametric Study

#### 3.1 Effect of overall column slenderness ratio ( $L/d$ ) on column strength

The effects of overall slenderness ratio on the load-moment curve of PEC column are shown in Fig. 5. In order to study the variation of strength, PEC columns of overall slenderness ratio 5, 15, 20, 25 and 30 are selected. Since, slenderness might have a significant effect on column strength, so small increments are considered to observe the effect rigorously.

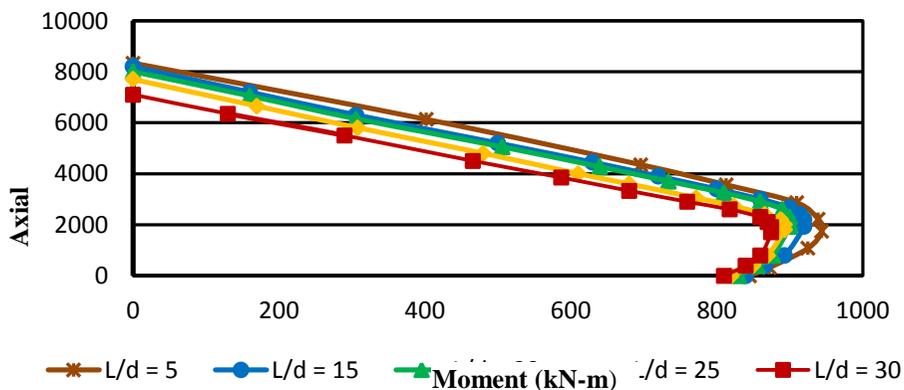


Figure 5: Effect of overall column slenderness ratio ( $L/d$ ) on interaction diagram of slender PEC column (a) Strong axis

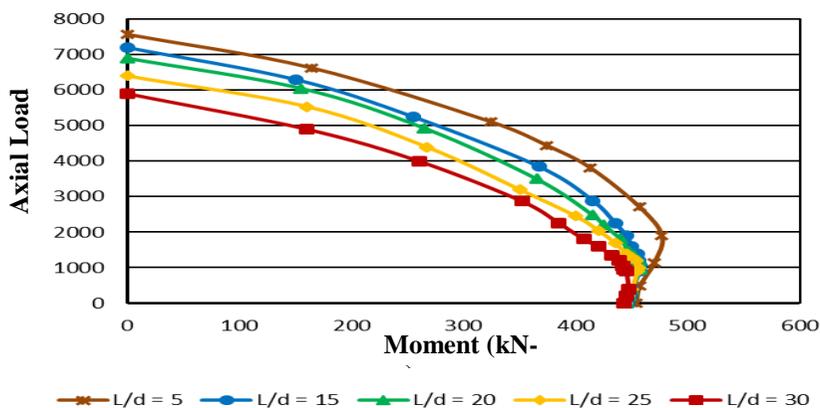


Figure 5(cont'): Effect of overall column slenderness ratio ( $L/d$ ) on interaction diagram of slender PEC column (b) Weak axis

From the interaction diagrams, it can be clearly seen that the area of the failure envelope reduces significantly with the increase of the overall slenderness ratio of PEC column. As the column gets slender, strength as well as ductility of the column reduces. Drop in strength is more significant in weak axis bending compared to that on strong axis bending. With the increase of the overall column slenderness ratio, more brittle behaviour is clearly observed when weak axis bending is considered as the tension zone of column strength becomes smaller. Considerable reduction in strength is found in compression zone as compared to the same in tension zone of the five interaction diagrams. From a short column ( $L/d = 5$ ) to a slender column ( $L/d = 30$ ), an average reduction of 7% is noted. However, as the column slenderness ratio increases from 15 to 20, only 3% average drop in strength is found. On the other hand, as mentioned above, a significant drop in strength is found when slenderness ratio is varied from 20 to 25. An average reduction rate of 8% is found in such condition. Finally, strength of slender PEC column decreases with an average value of 9% as the slenderness of column is turned from 25 to 30. Under weak axis bending, on average 3% greater drop in column strength is observed.

### 3.2 Effect of flange plate slenderness ratio ( $b/t$ ) on column strength

Figure 6 shows effects of flange plate slenderness ratio on the column strength curve of PEC columns. Three different flange plate slenderness ratios ( $b/t = 25$ ,  $b/t = 30$ ,  $b/t = 35$ ) are selected to observe the influence of this parameter on the failure envelope of slender PEC column. From the Fig. 6, it is obvious that a significant reduction in failure envelope is found with the increase of the flange plate slenderness ratio of slender PEC

column. An average reduction in strength of 15% is noted in compression zone, when the flange plate slenderness ratio is varied from 25 to 30 whereas in weak axis bending 2% extra drop in strength is noticed. Moreover, by changing the flange plate slenderness ratio from 30 to 35, average drop in strength is observed as nearly 15% and 16% for strong and weak axis bending respectively. Besides, brittle behaviour of slender PEC column is pronounced with the increase of flange plate slenderness ratio.

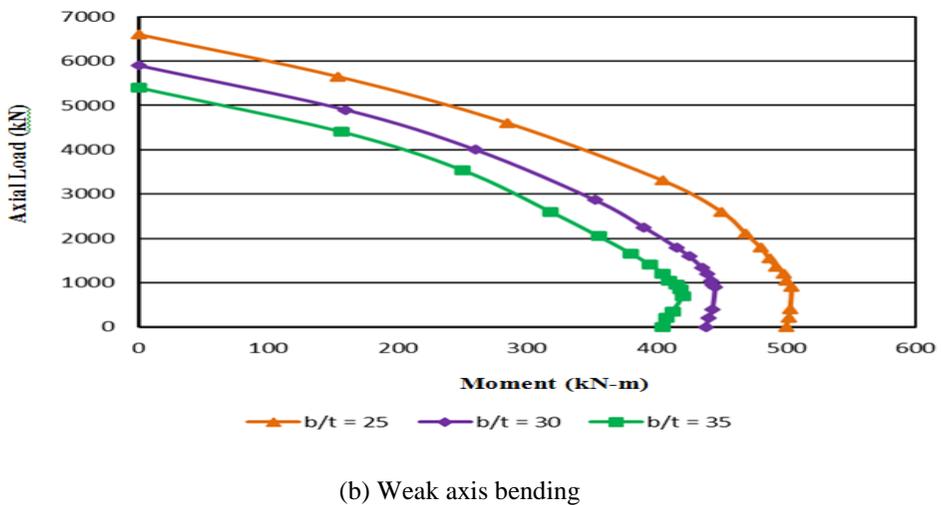
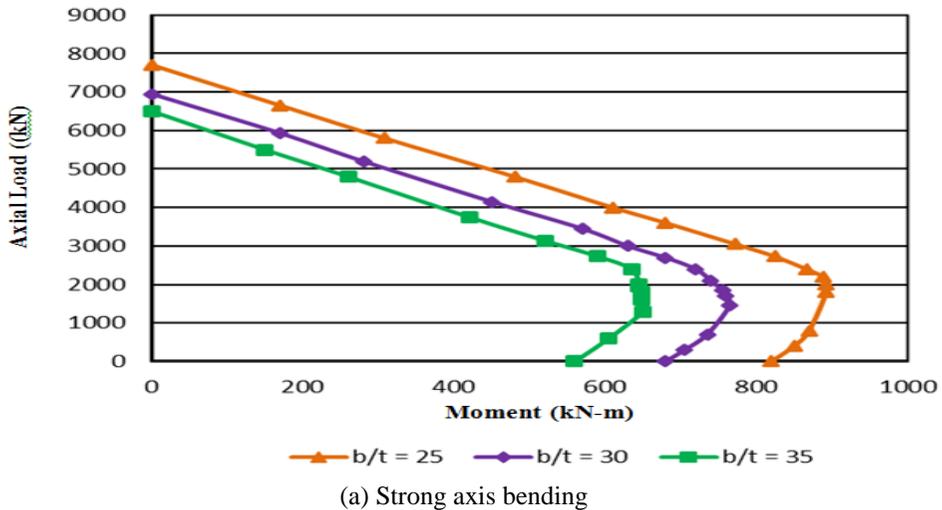
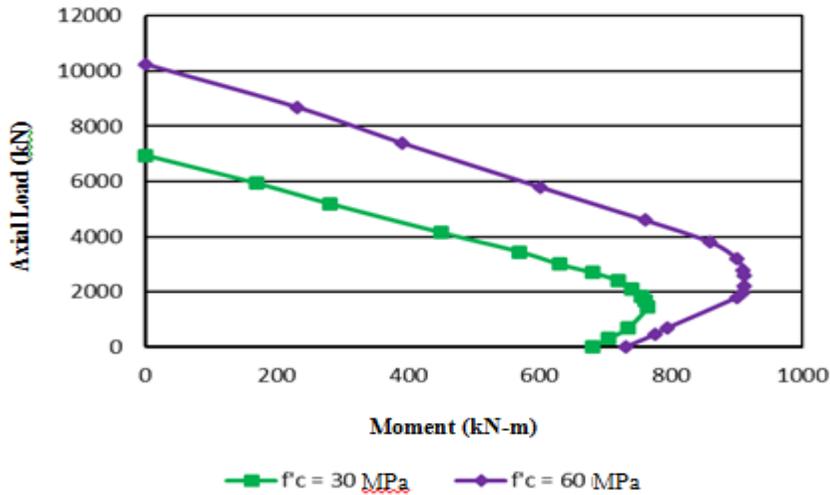


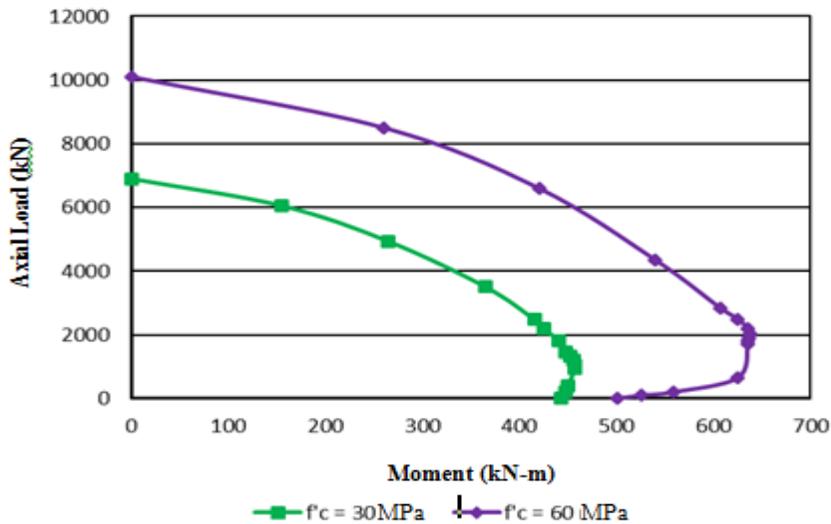
Figure 6: Effect of flange plate slenderness ratio (b/t) on interaction diagram of slender PEC column (a) Strong axis (b) Weak axis

### 3.3 Effect of Concrete Strength ( $F'c$ ) on Column Strength Curve

The effects of concrete strength on the load-moment interaction diagram of PEC columns are illustrated in Fig. 7.



(a) Strong axis bending



(b) Weak axis bending

Figure 7: Effect of concrete strength on interaction diagram of slender PEC columns (a) Strong axis (b) Weak axis

Normal strength concrete of  $f'_c = 30$  MPa and high strength of concrete  $f'_c = 60$  MPa are selected (which are normally used in our country) to observe the overall effect of this parameter on the failure envelope of slender PEC column. The increase in the zone of failure envelope between the two load moment interaction diagrams is found quite significant with the increase of the concrete strength to such large extent. Additionally, a greater increase in strength is found in compression zone compared to that of the tension zone of the interaction diagrams for the increment of 30 MPa in the strength of concrete. An average increase of 40% is noted in compression zone in strong axis bending whereas in weak axis bending it becomes 33% when the concrete strength is varied from 30 MPa to 60 MPa. However, when bending under weak axis is considered, use of high strength concrete can produce brittle concrete. In such cases, high performance (fibre reinforced) concrete can be used to increase ductility of slender PEC column.

#### 4.0 Conclusions and Suggestions for Future Work

The numerical procedure implemented in this study is limited to the following assumptions,

- i) Strains between concrete and structural steel are compatible and no slip occurred.
- ii) The strain is linearly proportional to the distance from the neutral axis.
- iii) The confinement of the concrete provided by transverse links and the structural steel section is not considered.
- iv) The effects of residual stresses on steel section are neglected.
- v) The strain hardening of steel is not included.

To observe the strength and ductility of slender PEC column through column strength curve, Newmark's numerical iterative procedure is used. Several parameters like overall column slenderness ratio, flange plate slenderness ratio and concrete strength are varied to observe the influence of these parameters on column strength curve of slender PEC column. Decrease in strength is found with the increase of overall column slenderness ratio and flange plate slenderness ratio. When the slenderness ratio reaches to 25, the reduction in strength is more significant. Second order moment in column which increases due to the increase of slenderness ratio, is the main reason of lowering the strength of slender PEC column. At the same time, ductility is also reduced with the increase of these variables. As the strength of concrete increases, strength of slender PEC column increases in large amount. It happens due to the increase of stiffness of PEC column with the increase of concrete stiffness. Similar trend in reduction of strength of ductility is found for both strong and weak axis bending. However, the reduction rate is more significant in weak axis bending as lower stiffness is attained here.

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