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INFLUENCE OF INITIAL IMPERFECTION ON ULTIMATE STRENGTH OF T-SECTION STEEL COMPRESSION MEMBERS

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ABSTRACT: The slenderness ratio is one of the most important factors for the steel compression members and the initial displacement and residual stress are most widely used in practical fields while considering initial imperfection factors as they show significant influence in the decreasing of the ultimate strength. Present work emphasizes on the capacity analysis of T-section steel compression member with the initial imperfection to predict the ultimate strength of T-section members as there were some difficulties in fully understanding and introducing initial imperfection into 3D FE models. To fulfill the goal, finite element models with different slenderness ratios are considered to assess the good accuracy in numerical results and ultimate strength formulae of T-section steel compression members are established for both beam and shell element models. Comparison between numerical results of current work and some design strength such as JSBH 2012, AASHTO 2010, etc., were performed to confirm the agreement between current work and existing design strength. Moreover, the influence of initial displacement and residual stress on beam and shell element models was investigated. The parametric study of relative loads Vs relative displacement due to initial imperfection regarding slenderness ratio was also presented. According to the numerical analyses results, initial displacement affects more in beam element models and residual stresses affect more in shell element models. For the models considering both initial imperfection factors, effects in shell elements models are more dominant. The ultimate stresses get form present study's formula show slightly higher values than the design strength of existing codes.

Keywords: Initial imperfections, T-section steel compression member, Ultimate strength, Bridge specifications, Capacity analysis.

1. INTRODUCTION

For the steel members, it's not perfectly straight and the non-uniform cooling or welding will cause the residual stress. The initial displacement combined with residual stress will influence the load-carrying capacity and stability of the members. So it's necessary to consider the initial imperfections for the model. Initial imperfection factor is an important aspect in determining ultimate strength of steel bridge compression members. Initial displacement and residual stress are most widely used in practical fields when taking into account of initial imperfection factors as these factors show significant influence in the decreasing of the ultimate strength in compression members. In general analysis, material, boundary and geometry imperfection and also residual stress effects should be included in determining an ultimate strength of real steel columns. Many studies on various cross-section types of steel columns have proven that initial imperfection has an important influence in the making of the ultimate strength decreasing significantly [1].

Schafer had investigated Computational modeling of cold-formed steel [2] and computational modeling of cold-formed steel concerning geometric imperfections and residual stresses [3] and pointed that initial imperfections impact the solution and the modeler must take care when considering that issues and presenting their results. Ismail et al. [4], also explored the use of initial imperfection approach in the design process and buckling failure evaluation of axially compressed composite cylindrical shells. Trahair and Kayvani [5] studied effects of excessive crookedness on capacities of steel columns using BS950 as the basis of column design methods.

There were many studies about ultimate strength of steel members done by Susanti and Kasai [6], Imamura et al. [7], Susanti et al. [8], etc. Many researchers found difficulties in fully understanding and introducing of initial imperfection in the 3D FE models. But it is very important to fulfill that requirement and needed to develop models that can represent the real behavior of structures to be used as guidance for many researchers. On the other hand, the current production technologies are much developed so that some initial imperfection such as initial displacement can be reduced during the manufacturing and installation process to improve the ultimate strength of the members. In addition, most of these previous studies emphasize the box section beams and the studies concern with T-section beam are very rare. So the present work emphasizes on T-section steel compression members regarding initial imperfection using beam and shell FE models in order to develop new formulations in steel columns ultimate strength to be able to comply with all of those conditions.

2. NUMERICAL ANALYSIS

The numerical study of present work included the 3-dimensional beam and shell elements model as shown in Fig. 1. The FE models were established and analyzed with ABAQUS software [9]. Large displacement theory was considered so as to assist the deformation shape of FE models. The boundary condition applied in this model was simply supported as shown in Fig. 2.

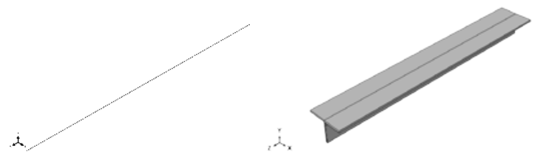


Fig.1 3D beam and shell element models

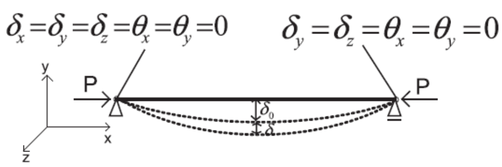


Fig.2 Boundary condition

2.1 Material Properties and Stress-strain Relationship

Grade SMA400w steel was used for the present work and its material properties are shown in Table 1.

Table 1. Material properties SMA400w

Steel grade	Yield stress, σ_y (MPa)	Young's Modulus (G Pa)	Poisson's ratio	ξ	E/E_{st}	$\varepsilon_{st}/\varepsilon$
Sma400w	245	205	0.3	0.06	40	10

The true stress-strain relationship was considered instead of engineering stress-strain and the nonlinear stress-strain relationship is shown in Fig. 3.

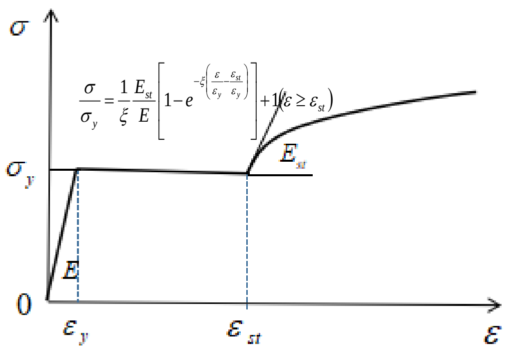


Fig.3 Stress-strain relationship

2.2 Parameters Used for the Analysis

The important parameters for the compression members are slenderness ratio parameter representing the length of the member and the width-thickness ratio parameter representing the thickness of web and flange and can be calculated from Eq. (1) and Eq. (2) [10]. Geometric properties of FE models are shown in Table 2 and cross-section of T-beam can be seen in Fig. 4.

$$R_R = \frac{B}{t}\cdot\sqrt{\frac{\sigma_y}{E}\cdot\frac{12(1-\nu^2)}{\pi^2 k}} \tag{1}$$

$$\bar{\lambda} = \frac{Kl}{r}\cdot\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}} \tag{2}$$

Where

B : plate width (mm)
t : plate thickness (mm)
σ_y : yield stress of steel (N/mm²)
E : Young's modulus of steel (N/mm²)
ν : Poisson's ratio
k : buckling coefficient (0.43 for T-cross section)
K : effective buckling length coefficient
r : radius of gyration of the member (mm)

Table 2. Geometric properties of FE models

Case	$\bar{\lambda}$	R_f	R_w	t_f (mm)	t_w (mm)	r (mm)	L (mm)	B (mm)	h (mm)
Case 1	0.2	0.5	0.6	8	8	27.483	500	152	95
Case 2	0.5	0.5	0.6	8	8	27.483	1250	152	95
Case 3	0.8	0.5	0.6	8	8	27.483	2000	152	95
Case 4	1.0	0.5	0.6	8	8	27.483	2500	152	95
Case 5	1.5	0.5	0.6	8	8	27.483	3750	152	95
Case 6	1.8	0.5	0.6	8	8	27.483	4500	152	95

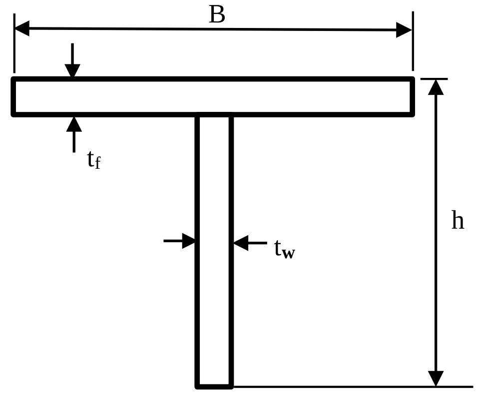
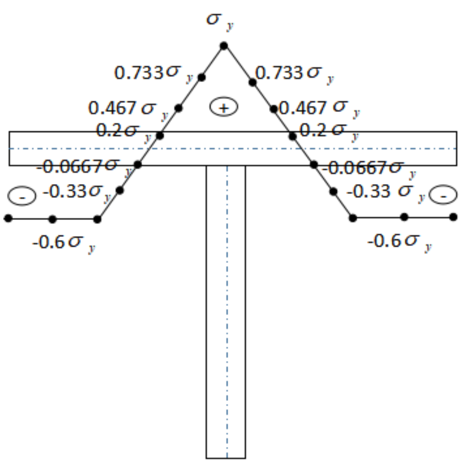


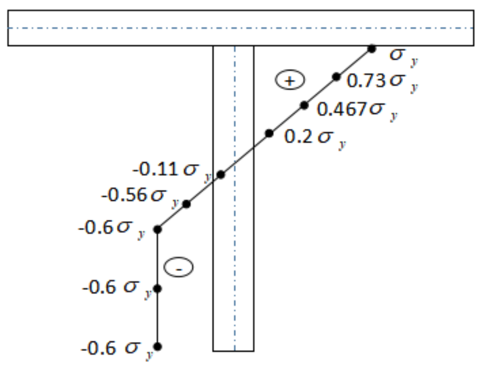
Fig. 4 T-cross section

2.3 Initial imperfection introduced to FE models

According to the previous studies, initial displacement and residual stress are the most important factors that influence the ultimate strength of compression members. So, these two initial imperfections are taken into account in the analysis of recent work.



(a)



(b)

Fig. 5 Residual stress distribution of T-section beam (a) for the flange and (b) for the web

Equation (3) was used to determine the initial displacement [11] and maximum initial used was $\frac{l}{1000}$.

The residual stress was applied by using a subroutine program for beam element model and by introducing directly in input data file for shell element model. Fig. 5 shows the distribution of residual stress for T cross section [12].

$$W_G = \delta_0 \sin\left(\frac{\pi x}{l}\right) \tag{3}$$

Where

$W_G(x)$: Initial displacement for each node

δ_0 : Maximum initial displacement, for the general situation

$\boldsymbol{l}$: Member length

x : Displacement of the defined node

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δ_0 : Maximum initial displacement, for the general situation

l : Member length

x : Displacement of the defined node

3. FORMULATION OF THE ULTIMATE STRENGTH

The "critical load" is the greatest load that will not cause lateral deflection (buckling) and can be calculated by using the Euler's buckling formula as shown in Eq. (4) [13].

$$P_{cr} = \frac{\pi^2 EI}{KL^2} \tag{4}$$

Where

P_{cr} : Critical load

E : Modulus of elasticity

I : Second moment of inertia

L : Member length

The elastic buckling load formulated by AASHTO [14] and AISC [15] in relation with slenderness ratio and the nominal buckling load regarding initial imperfection factors for all types of steel member with concentrated axial compression load is shown in Eq. (5). MNBC [16] also adopted AASHTO code for this portion and so used the same equation.

$$\frac{F_n^*}{F_y} = \begin{cases} [0.658^{\bar{\lambda}^2}], \ \bar{\lambda} \le 1.5 \\ \frac{0.887}{\bar{\lambda}^2}, \ \bar{\lambda} > 1.5 \end{cases} \tag{5}$$

The standard ultimate strength equation prepared by Japan Standard for Highway Bridge (JSHB) in 2002 and 2012 are described in Eq. (6) and Eq. (7).

$$\frac{\sigma_{cr}}{\sigma_y} = \begin{cases} 1.0, \ \bar{\lambda} \le 0.2 \\ 1.109 - 0.545\bar{\lambda}, \ 0.2 < \bar{\lambda} \le 1.0 \\ \frac{1.0}{(0.773+\bar{\lambda}^2)}, 1 < \bar{\lambda} \end{cases} \tag{6}$$

$$\frac{\sigma_{cr}}{\sigma_y} = \begin{cases} 1.0, \bar{\lambda} \le 0.2 \\ 1.059 - 0.258\bar{\lambda} - 0.190\bar{\lambda}^2, 0.2 < \bar{\lambda} \le 1.0 \\ 1.427 - 1.039\bar{\lambda} + 0.223\bar{\lambda}^2, 1 < \bar{\lambda} \end{cases} \tag{7}$$

Current work based on the initial deflection of $\frac{l}{1000}$, the same assumption as JSHB and the formulation also established similar to JSHB. According to the numerical results of recent work, the ultimate strength equations for beam element model and shell element model are formulated depending on the slenderness ratios. There are three equations for each element model one for slenderness ratio less than or equal to 0.2, another for slenderness ratio greater than 0.2 and less than or equal 1 and the last one with slenderness ratio greater than 1.0. The ultimate strength equation of present work for beam equation is as follows.

$$\frac{\sigma_{cr}}{\sigma_y} = \begin{cases} 0.971, \bar{\lambda} \le 0.2 \\ 0.756 + 0.745\bar{\lambda} - 0.863\bar{\lambda}^2, 0.2 < \bar{\lambda} \le 1.0 \\ 2.053 - 1.942\bar{\lambda} + 0.527\bar{\lambda}^2, 1 < \bar{\lambda} \end{cases} \tag{8}$$

The following equation is the ultimate strength equation of shell element formulated from the present work.

$$\frac{\sigma_{cr}}{\sigma_y} = \begin{cases} 0.952, \bar{\lambda} \le 0.2 \\ 1.325 - 0.697\bar{\lambda} - 0.034\bar{\lambda}^2, 0.2 < \bar{\lambda} \le 1.0 \\ 1.670 - 1.4169\bar{\lambda} + 0.340\bar{\lambda}^2, 1 < \bar{\lambda} \end{cases} \tag{9}$$

The ultimate stress models of recent work in comparison with different codes are shown in Fig.6.

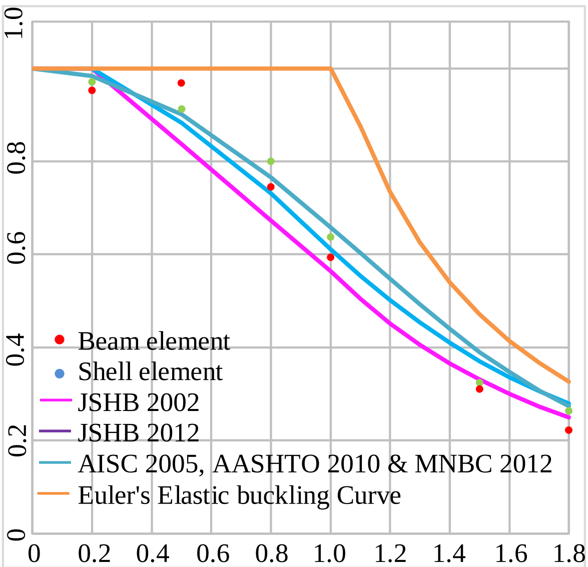
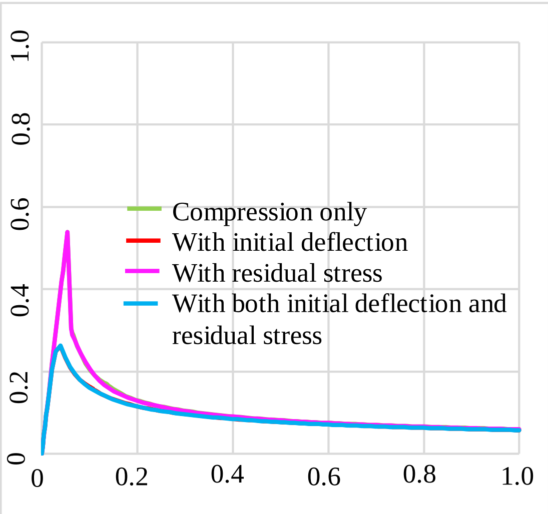


Fig. 6 The relationship between ultimate strength ratio and slenderness ratio of present FE models in comparison with different codes' formulations

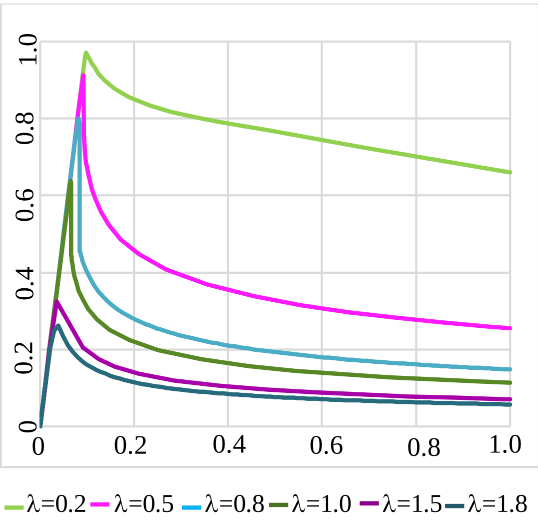
4. STUDY ON INFLUENCE OF INITIAL DISPLACEMENT AND RESIDUAL STRESS

This section presents the influence of initial displacement and residual stresses on beam element models and shell element models. The effect of initial imperfection can be seen clearly in Fig. 7 for beam element models and in Fig. 8 for shell element models.

The comparison of relative load and displacement curves for beam and shell element models with initial imperfection considering both initial displacement and residual stresses for different slenderness ratios can be seen in Fig. 9 to 14.

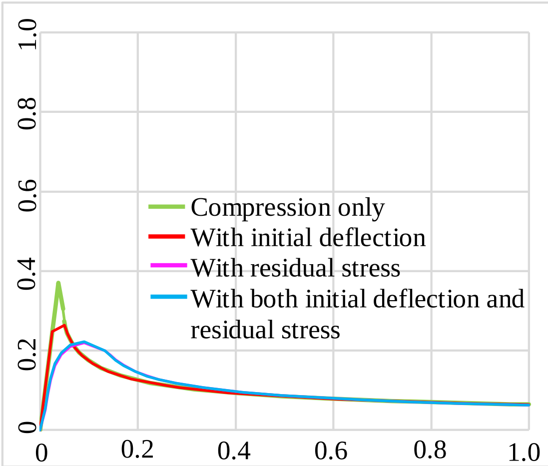


(a)



(b)

Fig. 7 Effect of initial imperfection for beam element (a) for λ=1.8 (b) for different λ



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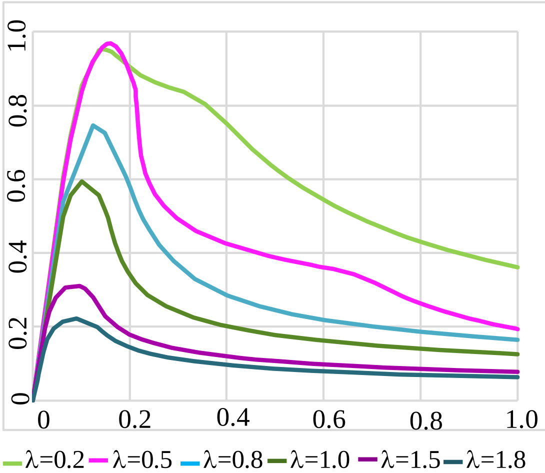

Fig. 8 Effect of initial imperfection for shell element (a) for λ=1.8 (b) for different λ

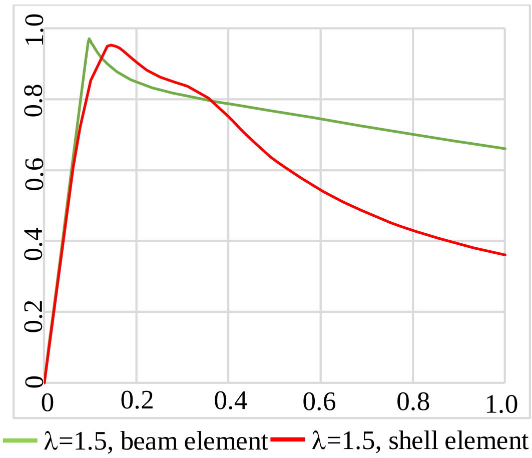

Fig. 9 Load and displacement relationship of beam and shell element models for λ=0.2

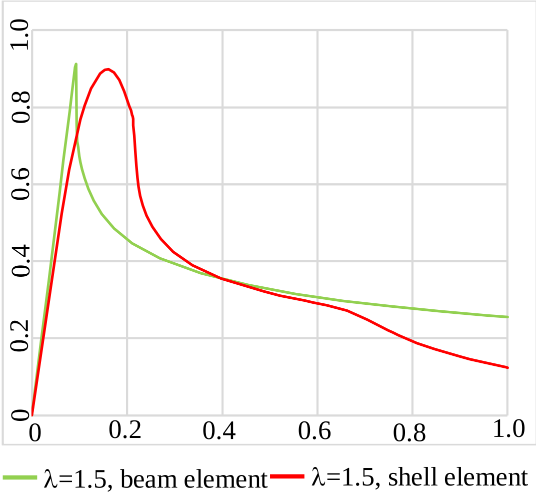

Fig. 10 Load and displacement relationship of beam and shell element models for λ=0.5

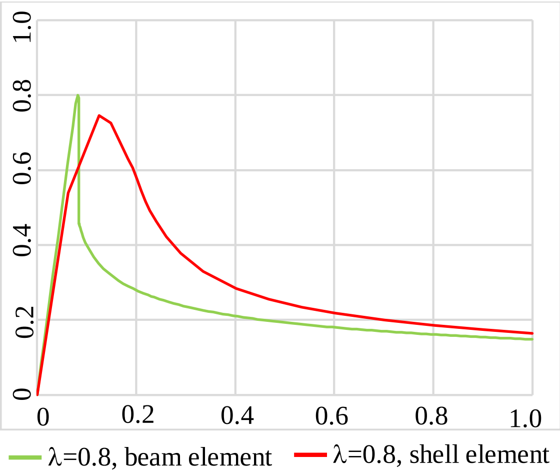

Fig. 11 Load and displacement relationship of beam and shell element models for λ=0.8

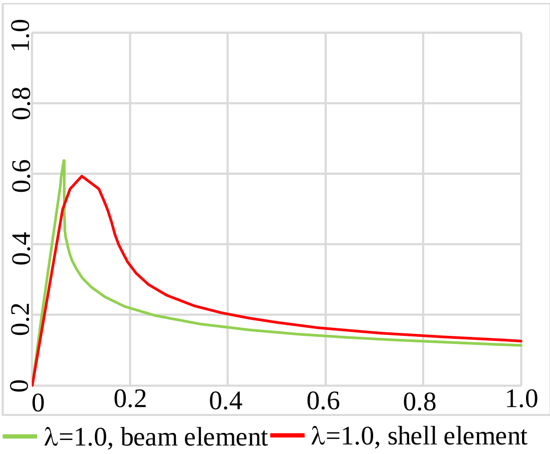

Fig. 12 Load and displacement relationship of beam and shell element models for λ=1.0

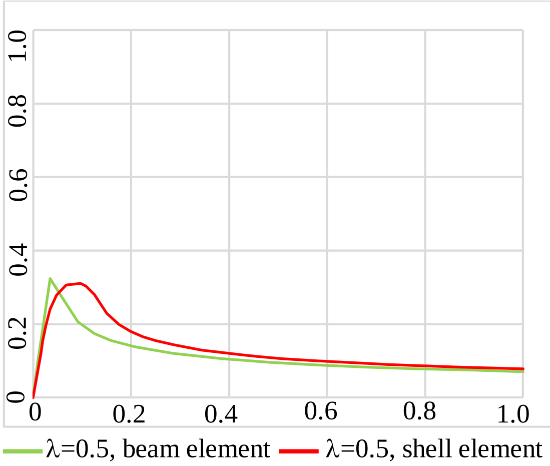

Fig. 13 Load and displacement relationship of beam and shell element models for λ=1.5

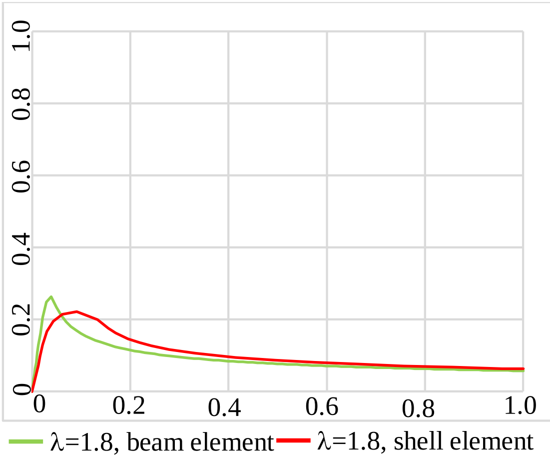

Fig. 14 Load and displacement relationship of beam and shell element models for λ=1.8

The effect of slenderness ratio on the ultimate strength of T-section steel compression member can be clearly seen in the above figures.

5. DISCUSSION AND CONCLUSION

In the present study of investigating the influence of initial imperfection on the ultimate strength of T-section steel compression members, both beam and shell element models are taken into account and numerical analyses were carried out considering initial imperfection effects of initial displacement as well as residual stresses while varying the slenderness ratio. According to the numerical analysis results, it is investigated that the effect of initial displacement is more dominant in beam element models while residual stresses' effect is predominant in shell element models. With the combination of initial displacement and residual stresses' effect, the influence of these initial imperfection factors in shell element models is greater than that in beam element models. The behavior of beam and shell element models under initial imperfection factors are similar. The decreasing of ultimate strength with the increasing of slenderness ratio is investigate for both beam and shell element models. The sharp decrease of stress after reaching ultimate stress can be more clearly seen in shell element models compared to beam element models, especially for low slenderness ratio.

According to the slenderness ratio and ultimate strength relationship of present FE models for both beam and shell element models in comparison with the ultimate strength formulations of specified codes such as JSHB 2002, JSHB 2012, AISC 2005, AASHTO 2010 and MNBC 2012, it can be concluded that there is no much deviation from present ultimate strength formulation form these codes and the formulation driven form these analytical data are reliable to use. According to the numerical study results, the ultimate stresses calculated by a newly established formula from present study show slightly higher value starts from slenderness ratio greater than 0.2 and almost the same for that less than 0.2.

6. ACKNOWLEDGMENTS

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