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Ultimate strength of box section steel bridge compression members in comparison with specifications

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ABSTRACT

Initial distortion and residual stress are well known as the most important initial imperfection factors and have a significant effect in decreasing the ultimate strength of compression members. The present work focuses on predicting the ultimate strength of welded box section steel compression members regarding initial imperfection factors. Beam compared with shell type of Finite Element (FE) models varied in slenderness ratio and initial distortion are used to assess the accuracy of present numerical results. The comparison of result between FE models and design strength formulations in some specifications are used to assess the ultimate strength formulations of bridge specifications according to the behavior of current steel compression members. It can be observed from numerical results that FE models and design strength by JSHB 2012 and AISC 2005/AASHTO 2010 have good agreement each other which means that the specifications have good capability in assessing the ultimate strength of steel compression members. Parametric study of the ultimate strain varied in slenderness ratio and load versus displacement curves of compression members are also introduced in order to perform more detail steel columns displacement behaviour. Finally, present work proposed a flowchart in designing steel compression members with the expectation that it will be helpful as reference for researchers and engineers in practical fields.

Introduction

Initial imperfections factor is an important aspect in determining ultimate strength of steel bridge compression members. Initial distortion and residual stress are most widely used in practical fields. In general analysis, material, boundary and geometry imperfection and also residual stress effects should be included in determining ultimate strength of real steel columns. Many studies in various cross section types of steel columns have proved that initial imperfection has important influence in making the ultimate strength decrease significantly. Schafer and Pekoz [1] have investigated the computational modeling of cold-formed steel members regarding geometric imperfection and residual stress. Study in the impact of global flexural imperfection especially applied in cold-formed steel column curve varied in initial displacement factor is continued project of the previous one [2]. Trahair and Kayvani also explored effects of excessive crookedness on capacities of steel columns using BS950 as basis of column design methods [3].

Some ultimate strength criteria in bridge specifications need to be evaluated and upgraded gradually to maintain the formulations accuracy in real steel members behaviour using recent numerical and experimental study. For example,

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Nomenclature

$\bar{\lambda}$	slenderness ratio
σ_y	yield stress
E	young's modulus
L	column height
R_R	width–thickness ratio
B	flange width
D	web width
t	plate thickness
υ	Poisson's ratio
n	number of panels
w_G	initial displacement in specified node
δ_0	absolute initial displacement
x	distance to specified node
E_{st}	modulus of elasticity in hardening region
ε	determined strain
σ_{cr}	ultimate stress
ε_{ult}	ultimate strain
ε_y	yield strain
ε_{st}	strain in hardening region
σ	determined stress
ξ	constant (for SM490 $\xi = 0.06$)
δ_x, δ_y, δ_z	displacement in x, y and z direction, respectively
θ_x, θ_y, θ_z	rotation in x, y and z direction, respectively
σ_{cr}	ultimate strength
P_e	elastic buckling load
K	effective length factor
F_n^*	nominal buckling stress
F_y	full yield stress
I	moment of inertia about principal axis normal to buckling plane
δ	longitudinal displacement
Δ	lateral displacement
P	load

compression ultimate strength formulation in recent Japan Specification for Highway Bridges (JSHB) 2012 [4]. There are some slight changes in ultimate strength formulations for any slenderness ratio compared to JSHB 2002 version [5]. By various experimental and numerical studies, the newer ultimate strength formulations are considered to have better accuracy in determining real member behaviour.

Previous case study by Ono et al. [6] has introduced ultimate compression strength investigation of welded box section steel columns regarding initial displacement and residual stress in beam models numerical study compared to experimental result. It is continued by numerical case study of Susanti and Kasai [7], where the study used beam and modified shell Finite Element (FE) models. Although it is found that both FE models have good similarity to the previous results, the use of shell models are more suitable in performing global buckling behaviour in coincidence with local buckling. The ultimate strength behavior of beam and shell models indicated good agreement in elastic range but not in non elastic region due to the presence of local buckling in shell models. Parametric study on steel columns using welded box section type is investigated by Imamura et al. [8] and Susanti et al. [9]. The study conducted numerical study in varied slenderness ratio compared to ultimate strength curves of JSHB 2002 and 2012, respectively.

Many engineers in practical fields have difficulties in understanding and performing complicated FE models regarding some initial imperfection factors. Practical simple models neglecting initial imperfection effects are usually chosen in designing a bridge structures, such as simple beam models. It has become very important to introduce many studies in more complex developed models to illustrate the real behavior of structures which can be used as guidance for many practical engineers. On the other side, there are a lot of improvements in factory production technologies that can improve the ultimate strength because some imperfection effects such as initial displacement can be reduced during manufacturing and installation process. New formulations in specifications have to be able to accommodate all of those conditions. According to the explained considerations and some previous studies, the present work investigate compression ultimate strength of welded box section steel columns regarding initial distortion and residual stress using beam and shell FE models in order to develop new formulations in steel columns ultimate strength.

Numerical procedure

FE models

Present study uses beam and shell types of FE models. These are assembled and numerically analyzed in ABAQUS software [10] using large displacement theory in order to accommodate displacement shape on FE models. The most important parameters for columns with thin walled structure are slenderness ratio ($\bar{\lambda}$) and width-thickness ratio (R_R). These parameters are defined according to JSHB 2002 using the following Eqs. (1) and (2), respectively. This numerical work uses thirteen beam and shell models varied in slenderness ratio as shown in Table 1 and global initial displacement (δ_0) as $L/500$, $L/1000$ and $L/1500$. Initial distortion for columns is determined by Eq. (3). Beside, present shell models used local initial distortion in each plate. Local initial distortion $b/150$ is used in shell models only because beam FE models in wire type have no capability in performing local initial displacement on each plate.

$$\bar{\lambda} = \frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}}\frac{L}{r} \tag{1}$$

$$R_R = \frac{b}{t}\sqrt{\frac{\sigma_y}{E}\frac{12(1-\upsilon^2)}{4\pi^2 n^2}} \tag{2}$$

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

All models use SM490 steel grade as material properties (Table 2). Nonlinear stress–strain relationship is used as material property input data (Fig. 1(a)). Simple pinned boundary conditions are used as support in both ends of column structure (Fig. 1(b)). Here, compression load with displacement control method is used. Present FE models use box section type with cross section as shown in Fig. 1(c). Shell type FE models are used with local and global initial distortion with consideration that models should have capability in performing real compression members behaviour. The rigid body beam elements are used in top and bottom part of shell models to connect shell elements and its support (Fig. 1(d)). Shell models are assembled using general S4R conventional type FE while beam models used B31 wire element type in ABAQUS software (Fig. 1(e)). Residual stresses distribution for beam models in ABAQUS software input data is expressed using SIGINI subroutine that is assembled separately from its input data. While in shell models, it is included directly in each element along cross sections using specified initial condition command in the input data. Maximum compressive and tensile residual stresses for both models are determined using the previous work [8] (Fig. 1(f)).

Ultimate strength formulation

Elastic buckling strength is the maximum axial strength which is carried by an ideal column without buckling. AASHTO [11] and AISC [12] derived a formulation of elastic buckling load as shown in Eq. (4). In relation with slenderness ratio, both AASHTO and AISC determined formulation to characterize the nominal buckling load regarding initial imperfection factors for all types of steel member with concentrated axial compression load as shown in Eq. (5). AISC 2005 prescribes maximum initial displacement as $L/1500$.

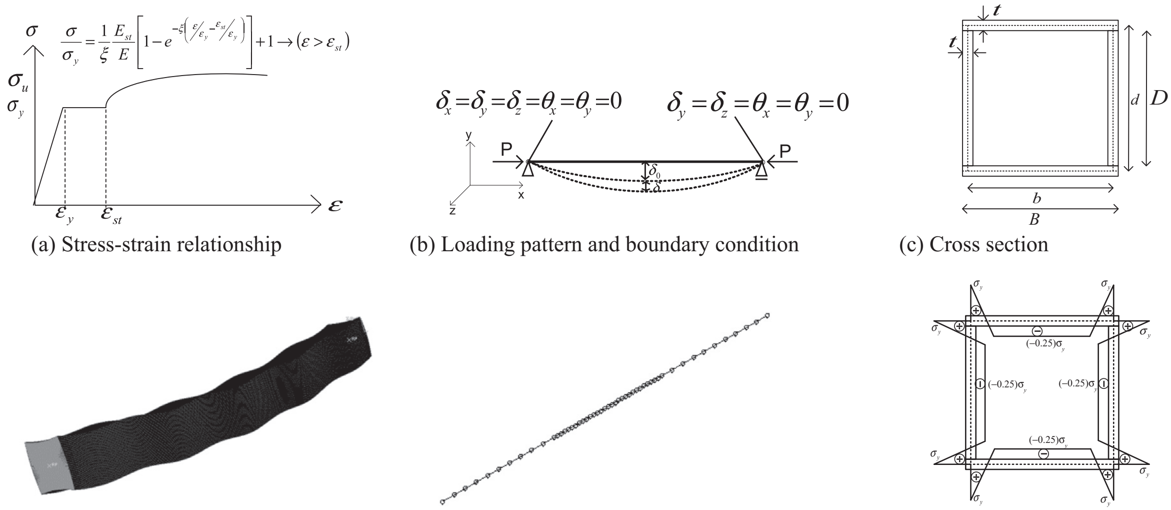
$$P_e(Euler) = \frac{\pi^2 EI}{KL^2} \tag{4}$$

Table 1
Geometrical properties of FE models.

Column	$\bar{\lambda}$	R_R	L (mm)	D (mm)	B (mm)	t (mm)
1	0.2	0.501	1864	276	300	12
2	0.3	0.501	2796	276	300	12
3	0.4	0.501	3728	276	300	12
4	0.5	0.501	4659	276	300	12
5	0.6	0.501	5592	276	300	12
6	0.7	0.501	6523	276	300	12
7	0.8	0.501	7455	276	300	12
8	0.9	0.501	8250	276	300	12
9	1.0	0.501	9319	276	300	12
10	1.1	0.501	10251	276	300	12
11	1.2	0.501	11183	276	300	12
12	1.5	0.501	13979	276	300	12
13	1.7	0.501	15843	276	300	12

Table 2
Material properties of FE models using SM490 steel grade.

Properties	Value
E (GPa)	200
σ_y (MPa)	315
E/E_{st}	30
$\varepsilon/\varepsilon_{st}$	7
ξ	0.06



(a) Stress-strain relationship (b) Loading pattern and boundary condition (c) Cross section

(d) Shell model (e) Beam model (f) Residual stress distribution

Fig. 1. Properties of present FE models.

$$\frac{F_n^*}{F_y}(\text{AISC 2005 and AASHTO 2010}) = \begin{cases} \left[0.658^{\bar{\lambda}^2}\right] & \text{for } \bar{\lambda} \leqslant 1.5 \\ \frac{0.877}{\bar{\lambda}^2} & \text{for } \bar{\lambda} > 1.5 \end{cases} \tag{5}$$

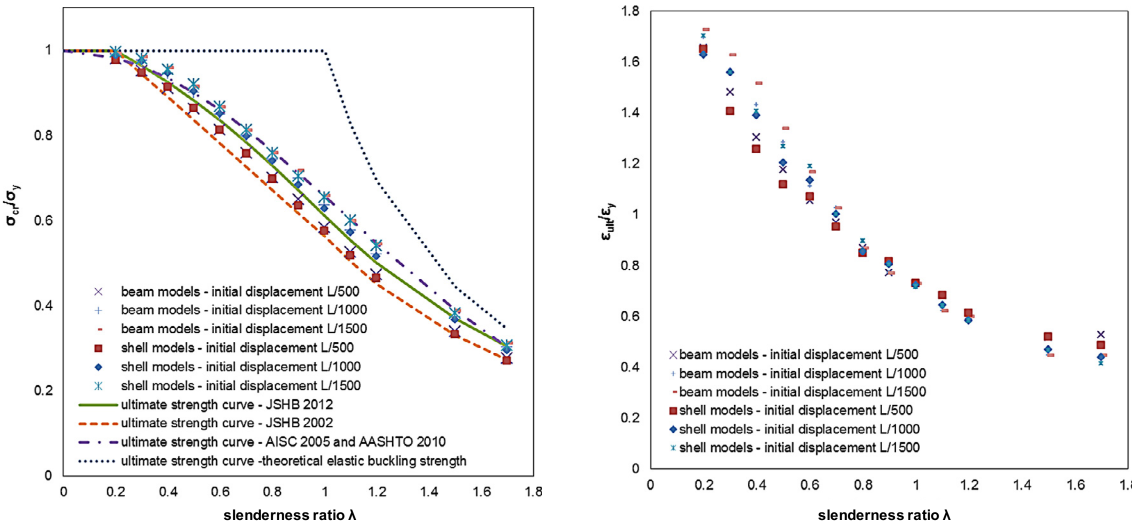
Japan Standard for Highway Bridges (JSHB) prescribes maximum initial displacement as $L/1000$. The formulations to determine ultimate compressive stress related to slenderness ratio in JSHB 2002 and 2012 edition are shown in Eqs. (6) and (7). A slight change in ultimate strength formulation between JSHB 2002 and JSHB 2012 is reflected in these equations.

$$\frac{\sigma_{cr}}{\sigma_y}(\text{JSHB 2002}) = \begin{cases} 1.0 & (\bar{\lambda} \leqslant 0.2) \\ 1.109 - 0.545\bar{\lambda} & (0.2 < \bar{\lambda} \leqslant 1.0) \\ 1.0/(0.773 + \bar{\lambda}^2) & (1.0 < \bar{\lambda}) \end{cases} \tag{6}$$

$$\frac{\sigma_{cr}}{\sigma_y}(\text{JSHB 2012}) = \begin{cases} 1.0 & (\bar{\lambda} \leqslant 0.2) \\ 1.059 - 0.258\bar{\lambda} - 0.19\bar{\lambda}^2 & (0.2 < \bar{\lambda} \leqslant 1.0) \\ 1.427 - 1.039\bar{\lambda} - 0.223\bar{\lambda}^2 & (1.0 < \bar{\lambda}) \end{cases} \tag{7}$$

Results and discussion

All beam and shell FE models are numerically analyzed by varying the slenderness ratio and initial distortion factors. Axial compression loading is applied in both top and bottom part of models until they reach collapse phase. Fig. 2(a) and (b) show slenderness ratio versus ultimate stress and strain relationship of beam and shell models compared to the ultimate strength formulations of specified codes including JSHB 2002, JSHB 2012, AISC 2005 and AASHTO 2010, respectively. They are also compared to Euler's elastic buckling curve. FE models created in present work is observed can perform accurately the ultimate strength of steel compression members. Beam and shell FE models with maximum initial distortion $L/1000$ agree well with the ultimate strength curve of JSHB 2012 (Fig. 2(a)). These results have good agreement with JSHB 2012 that has stated the maximum initial displacement as $L/1000$. As has been mentioned the AISC 2005 prescribes the maximum



(a) Ultimate stress scope (b) Ultimate strain scope

Fig. 2. Slenderness ratio vs. ultimate strength of present work FE models compared to specifications formulation.

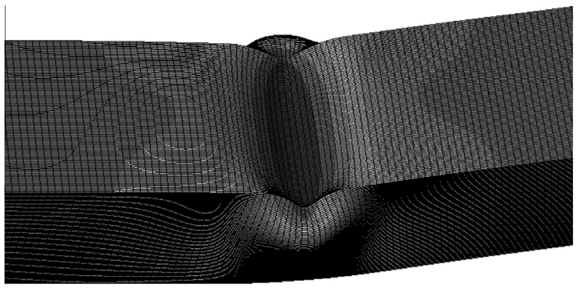
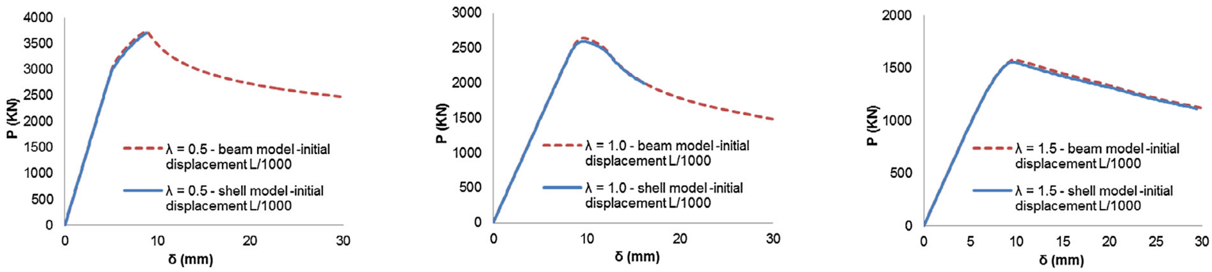


Fig. 3. Deformed shape of shell compression member.

initial distortion as $L/1500$, present beam and shell FE models with initial distortion $L/1500$ also have good agreement compared with AISC 2005 and AASHTO 2010 ultimate strength curve.

In strain scope (Fig. 2(b)), steel columns with beam compared to shell type of FE models show good similarity in each varied initial displacement so that the accuracy can be assessed. All FE models have similar tendency in the graphic shape where in low to intermediate range of slenderness ratio, ultimate strain decrease significantly. It means that initial imperfection has a significant effect in low slenderness ratio structures. Local buckling has more significant effect and must be considered especially for steel columns with low slenderness ratio (Fig. 3). In steel columns with high slenderness ratio, global



(a) $\lambda = 0.5$ (b) $\lambda = 1.0$ (c) $\lambda = 1.5$

Fig. 4. Load and longitudinal displacement relationship for any slenderness ratio ranges.

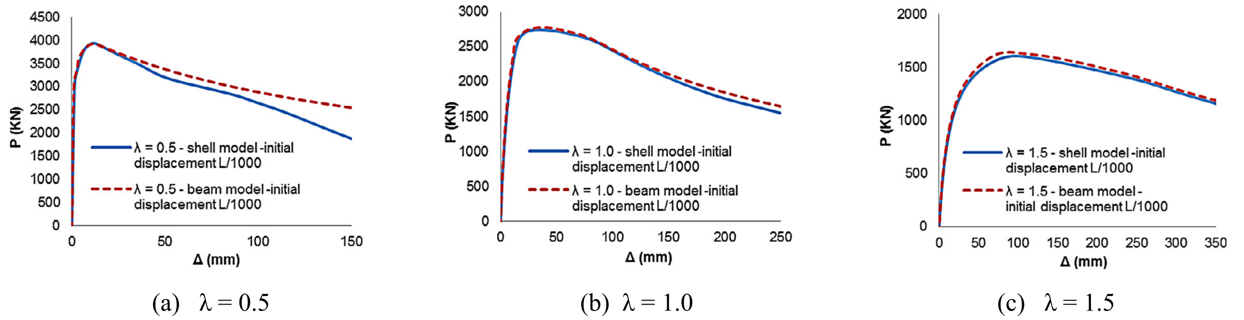


Fig. 5. Load and lateral displacement relationship for any slenderness ratio ranges.

buckling has more dominant effect in the displacement history. Local buckling phenomenon cannot be performed using wire type of beam models even on three dimension axis.

Load versus longitudinal and lateral displacement curves are provided in slenderness ratio ($\bar{\lambda}$) = 0.5, 1.0 and 1.5 (Figs. 4 and 5). Fig. 4 shows load and longitudinal displacement history of beam compared to shell models for small to high slenderness ratio. The figures indicate that in the elastic range generally beam and shell FE models have similar behaviour of load and displacement history. Similar behaviour also occured in load versus lateral displacement history as shown in Fig. 5(a)–(c). The ultimate load decreases as slenderness ratio increases. Otherwise, displacement history shows higher displacement values with increasing slenderness ratio. After they reach ultimate point, load history of shell models decrease more sharply compared to beam models. It may be caused by the effect of local and global buckling combination that is occurred in shell models.

According to the present numerical study results, ultimate stress and strain curves of beam models generally show a slightly higher value. In Fig. 6(a)–(f), ultimate stress and strain curves of beam and shell members are illustrated in maximum initial distortion $L/500$, $L/1000$ and $L/1500$, respectively. This higher ultimate strength in beam models may be caused by incapability of beam models in performing local initial displacement and local buckling behaviour. In shell members, the

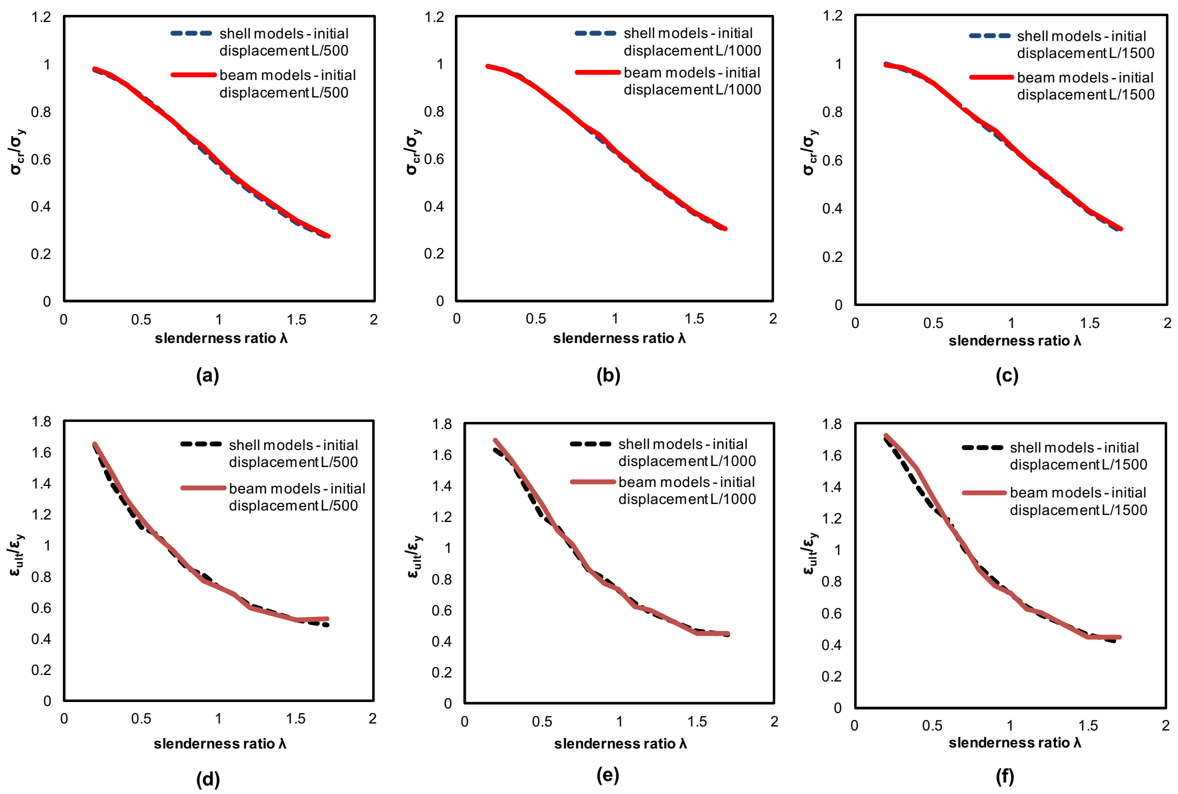


Fig. 6. Ultimate stress and strain curves of compression members.

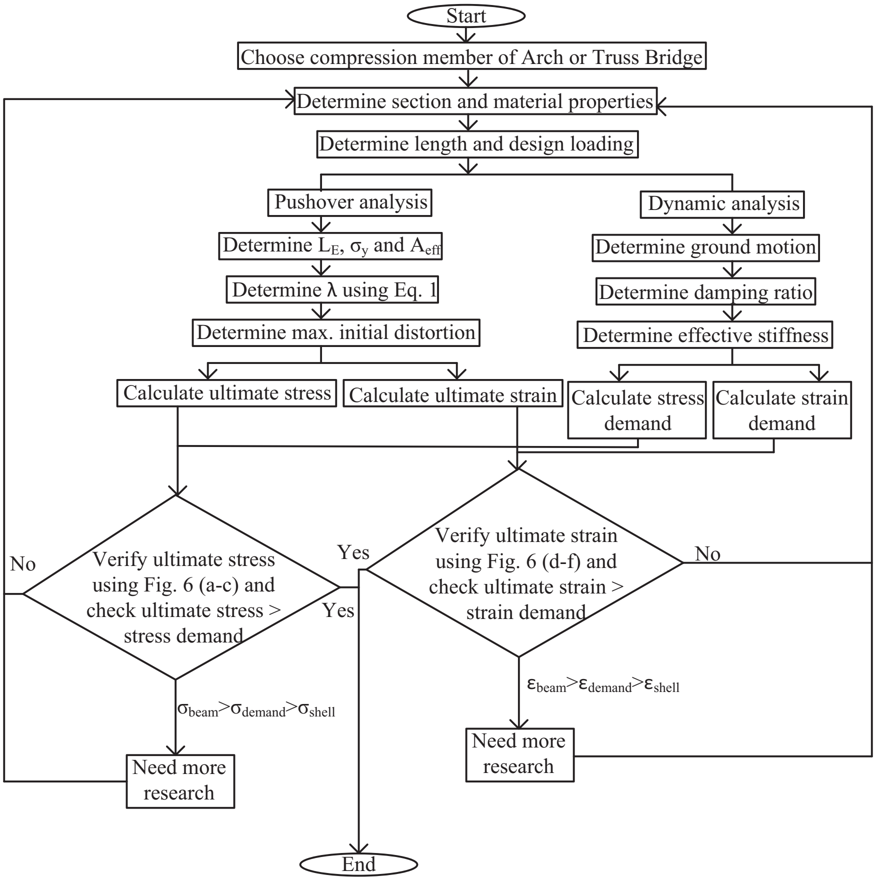


Fig. 7. Flowchart of design for compression members.

combination of local and global buckling have an effect in decreasing the ultimate strength result. Present study result can only be applied for width–thickness ratio that has been specified in previous section. Generally speaking, higher width–thickness ratio may result in bigger difference of the ultimate strength between beam and shell type of FE models. If the stress or strain demand is located under the ultimate stress or strain line of shell members, it means that member has a capability in carrying the designed loads. Oppositely, if the stress or strain demand is located above the ultimate stress or strain line of beam members, it means that structure will collapse because of higher stress or strain demand compared to its ultimate stress or strain.

The procedure to design steel compression members using proposed method is illustrated by flowchart in Fig. 7. Generally, the proposed work early steps are choosing compression member of truss or arch bridge type, material properties, design loading and determining some input parameters such as slenderness ratio and maximum initial distortion. It is continued by verifying the ultimate stress–strain of structure and comparing ultimate stress–strain with its stress–strain demand. In case of secure structure, ultimate stress and strain have to be greater than the stress and strain demand. More research will be needed if the ultimate stress or strain result is located between the ultimate stress or strain line of beam and shell members. In this case, although many engineers in practical fields prefer to use beam models in the design process, but dynamic analysis to determine stress and strain demand using both beam and shell members is needed to check the result validity.

Conclusion

Many studies related to the ultimate strength of compression members have been conducted in order to develop newer and more suitable criteria for current engineering requirements. Hence, the present study considers compression ultimate strength of welded box section steel columns regarding initial distortion and residual stress as initial imperfection factors. From numerical study results, FE models created in present paper can accurately simulate the ultimate strength of steel compression members. The comparison between FE result and ultimate design strength by JSHB 2012 and AISC 2005/AASHTO 2010 shows that the specifications can predict sufficiently safe results for ultimate strength of steel compression members.

For higher safety based design purposes, JSHB 2012 is recommended due to its lower design strength. Local buckling has more significant effect and must be considered in the compression members with small slenderness ratio. Parametric study of the ultimate strain varied in slenderness ratio and load versus displacement curves of compression members are also introduced in order to perform more detail steel columns displacement behaviour. Finally, present work proposed a flowchart in designing steel compression members with the expectation that it will be helpful as reference for researchers and engineers in practical fields.

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