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Buckling of Column of Supporting Frame Structure: A Review

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Abstract

Column is a vertical strut or structural member which is subjected to an axial compressive load used for supporting purpose. For column, materials like reinforced concrete and mild steel are widely used. Angle section, I-section, channel section, box section are the common type of sections used for column. A form of deformation or sudden sideway failure of column which occurs due to high axial compressive force is termed as buckling. When column buckles, there induces eccentricity to the applied load; this eccentricity again induces the additional moment and causes it to deflect more. So, there exists a necessity to control the buckling of column. The buckling load is the significant parameter for stability of a structural compression member. The present work is aimed to evaluate the buckling load and in elastic buckling behaviour of column using various buckling theories, compression loading test and non-linear finite element analysis by considering various parameters like slenderness ratio, end constraint conditions and effective length.

Keywords: *Column buckling, critical buckling load, slenderness ratio, effective length, FE analysis*

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INTRODUCTION

A structural member or bar which is subjected to an axial compressive load is known as strut. A strut may be vertical, horizontal or even inclined. A vertical strut i.e. inclined at 90° to horizontal, subjected to axial compressive load is known as column, stanchion or pillar which is used for supporting purpose in frame.

Buckling of column is a form of deformation or sudden sideway failure of structural member which occurs due to high axial compressive load. For e.g., overloaded column of supporting frame, compressive member in bridges, roof trusses and hull of submarine. Buckling is an instability phenomenon where the change of equilibrium state from one configuration to another occurs at a critical compression load [1]. When column buckles, there induces eccentricity to the applied load; this eccentricity again induces the additional moment and cause it to deflect more. So, there exists a necessity to control the buckling of column.

The buckling load or critical load is an important parameter for stability of a structural compression member. The load at which a member or a structure as a whole, either buckles or collapses in a load test or during service and develops lateral (out of plane) deformation is called buckling load or critical load [2]. When a structural element reaches at its critical load, the element becomes incapable of sustaining the load due to its slenderness and applied load. It is obvious that the column buckles whenever its strength exceeds its plastic limit (Figure 1). But, if the residual strength of the column is more than the applied force, then progressive collapse will not occur. However, structural steel members have a tendency of plastic deformation. This property of structural steel is advantageous for prevention of progressive collapse of structures [3].

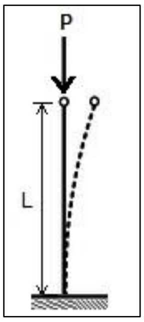


Fig. 1: *Column Buckling.*

CLASSIFICATION OF COLUMNS

Based on the length to diameter ratio or slenderness ratio, columns can be divided in to three types. The columns having lengths less than 8 times their diameters or slenderness ratio less than 32 are called short columns (S<32). The columns having lengths more than 30 times their respective diameters or slenderness ratio lying between 32 and 120 are called intermediate columns (32<S<120). The columns having lengths more than 30 times their respective diameters or slenderness ratio greater than 120 are called long columns (S>120) [4].

Zain *et al*. conducted a study on numerical investigation of channel section column made by steel subjected to axial thrust [5]. By analytical considerations and finite element analyses of channel column it is concluded that the load carrying capacity of column is decreased as column length is increased. Hence, the short columns are strong as compared to the long columns.

Nonaka conducted a study on elastic-perfectly plastic behaviour of a portal frame with variation in column axial forces [6]. By analytical considerations and finite element analyses of channel column, it is concluded that the variation in the column axial forces depends on the depth of column; as the depth of column becomes greater relative to the span, the load carrying capacity decreases.

COMPARISON BETWEEN VARIOUS COLUMN SECTIONS IN TERMS OF STRENGTH

I-section, channel section, angle section, tee section, circular and rectangular hollow sections, bars are the common type of sections used for column. Among which, I-section has greater moment of inertia, hence greater section modulus. Section modulus is the direct measure of strength of column. Higher the section modulus, higher will be the resistance to bending and capable to supporting greater load, and less the stress. As more and more material is concentrated away from the centre, section modulus will increase. Solid sections are advantageous compared to hollow sections because solid sections come out of rolling mill faster than hollow sections; also connections are more complex in hollow sections. Figure 2 shows the various column sections.

Ellobody conducted study on the buckling behaviour of cold-formed high strength stainless steel rectangular hollow section columns [7]. The results showed that the hollow sections failed due to local buckling before the global failure occurred.

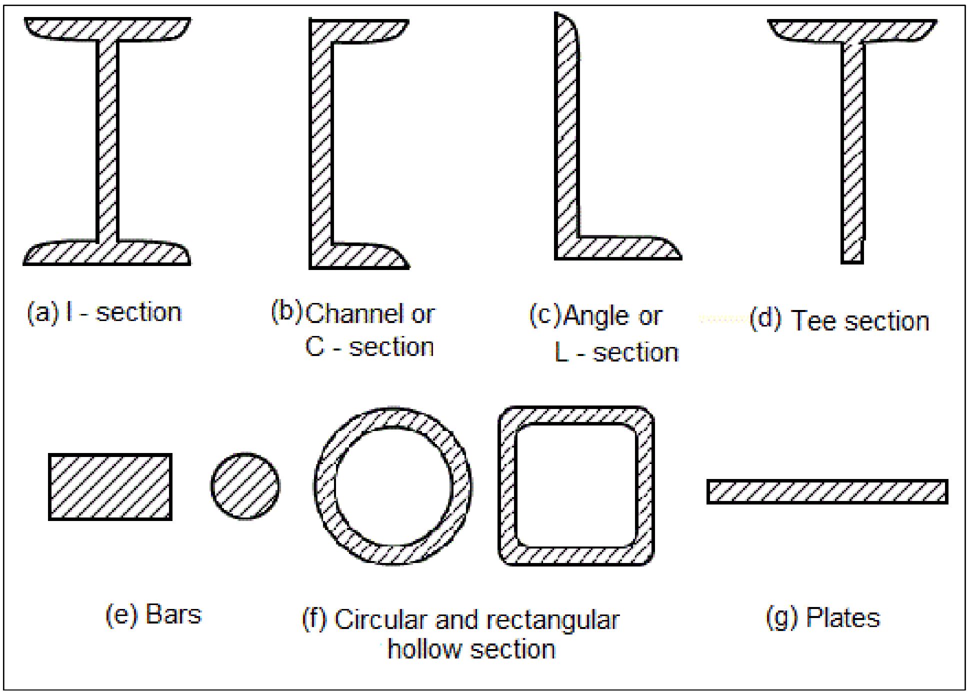


Fig. 2: *Various Column Sections.*

Patton *et al.* investigated fixed-ended hollow columns having square (SHC) and non-rectangular hollow sections (NRHCs) with+- (+HC), T- (THC) and L- (LHC) shaped cross-sections by considering effect of various parameters like end constraint, slenderness ratio and thickness [8]. Variations in buckling strength of column with changes in the slenderness ratio and cross-sectional shapes were observed by considering non-rectangular hollow columns having equal material consumption as that of square hollow columns over various column lengths. Shapes of cross-section were found to become more significant with decreasing column slenderness.

Yousuf *et al.* conducted a study on buckling behaviour of concrete filled and hollow columns made using mild steel and under transverse impact loading [9]. The load-deflection curves, deformed shapes and column strength have been predicted using the FE model and generally agreed well with the experimental result. The results showed that the hollow sections failed due to local buckling before the global failure occurred, and due to the concrete in-fill in mild steel columns, the resistance to local buckling is increased.

MODE OF FAILURE OF A COLUMN

Buckling or structural instability is considered one of the main modes of failure of structural members subjected to compressive forces. The failure of strut or column will occur:

(i) By pure compression;
(ii) By buckling; or
(iii) By combination of buckling and pure compression.

It has been observed that when an axial compressive load is applied on a strut or a column and this applied load is increased gradually, then the column will reach at one stage when it will be subjected to ultimate load. Beyond this ultimate load, the column will fail by crushing and this ultimate load will be known as crushing load. Generally, short columns fail due to their crushing.

It has been noted that, structural compression members do not fail only by pure compression, but also by combination of bending and pure compression i.e. buckling. If a long column is subjected to an axial compressive load, then it is subjected to a compressive stress. If the compressive load is increased gradually, then the column will reach at one stage when it will start buckling. It has been concluded that value of buckling load will be less than the crushing load in case of long columns. Also for long columns, the value of buckling load is low and relatively high for short columns.

The maximum load at which the structural compression member tends to buckle or tends to have lateral displacement is known as buckling load and the member is said to have developed an elastic instability.

Cao *et al.* conducted study on buckling behaviour of angle mild steel (Q420) columns subjected to an axial loading using hydraulic actuator [10]. Finite element models were created using ANSYS and meshed using 3D 8-node structural solid element (SOLID185). It is used for parametric study for validation. It is observed that tested columns buckled about the axis having least moment of inertia or minimum radius of gyration or weak principle axis and mostly the buckling mode was flexural buckling.

PARAMETERS AFFECTING BUCKLING

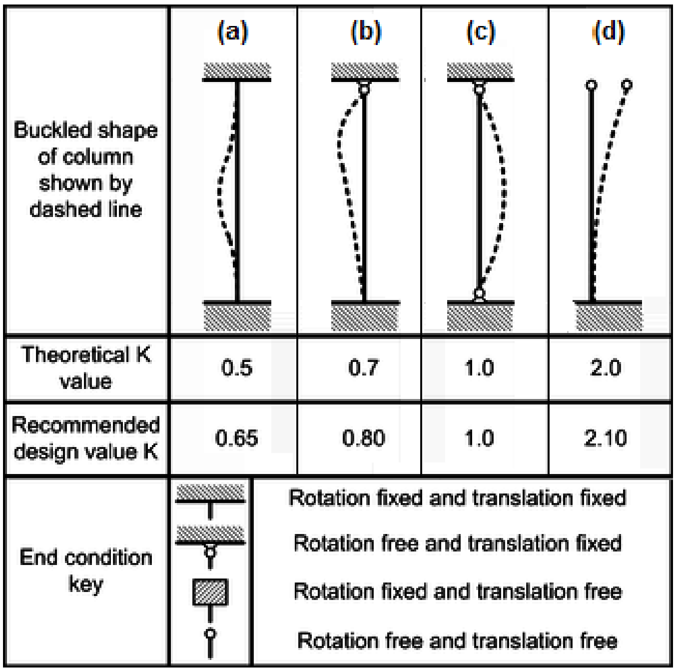
Effective Length of a Column (L_e)

The distance between the adjacent points of inflexion on column is called effective length or equivalent length. The effective length of a given column with given end conditions is the length of an equivalent column of the same cross-section and same material with hinged ends and having value of buckling load or critical load equal to that of the given column. The relationship between the equivalent length and actual length of column depends on end conditions of column.

Types of End Conditions of Columns

Following four types of end conditions are important:

1. Both the ends fixed as in Figure 3(a),
2. One end is fixed and the other pin jointed (hinged) as in Figure (b),
3. Both the ends pin jointed or hinged as in Figure 3(c),
4. One end is fixed and the other end free as in Figure 3(d).



	(a)	(b)	(c)	(d)
Buckled shape of column shown by dashed line				
Theoretical K value	0.5	0.7	1.0	2.0
Recommended design value K	0.65	0.80	1.0	2.10

End condition key
- Rotation fixed and translation fixed
- Rotation free and translation fixed
- Rotation fixed and translation free
- Rotation free and translation free

Fig. 3: *Types of End Conditions of Column.*

The relation between the equivalent length and actual length of column for the various end conditions is shown in the below Table 1.

Table 1: *Values of Equivalent Length L_e.*

Sr. No.	End Conditions	Equivalent Length (L_e)=Kl
1.	Both ends fixed	L_e=0.5 L
2.	One end fixed and other hinged	L_e=0.7 L
3.	Both ends hinged	L_e=1 L
4.	One end fixed and other end free	L_e=2 L

Park *et al.* conducted study on how to prevent the collapse of structures [11]. H-section steel column made with structural steel (mild steel SS400) was tested under concentric loading. The relationship between deformation and stress of column under the hinged-end condition was observed, using the non-linear FE analysis. From test and analysis results, it was concluded that in the hinged-end model, strength degradation was sharp after reaching the maximum load, while the fixed-end model kept the maximum strength to the displacement ratio of 0.02 after reaching the maximum load and then exhibited slow strength degradation. In the hinged-end model local, buckling was observed at the center, but in the fixed-end model, local buckling was observed at the center and at both ends.

Slenderness Ratio (S)

It is the ratio of the effective length of the column to the least radius of gyration of the column section.

$$S = \frac{L_e}{k}$$

Where,

L_e= Equivalent length of the column (mm),

k= Least radius of gyration (mm).

The vertical compression member will have two moments of inertias. It is noted that the column will buckle in the direction of minimum radius of gyration or least moment of inertia, hence the least value of the two moments of inertias (i.e. I_{xx} and I_{yy}) is used.

Mustafa *et al.* conducted study on the compressive behaviour of slender section columns [12]. A FE model was developed using ANSYS program. The model was verified by comparing the FEM results with the experimental tests. Based on the results, it can be concluded that specimens with large slenderness failed due to global buckling, adverse interaction between local and global buckling existed in slender columns which decreased their ultimate strength, the load carrying capacity of specimens.

Yang concluded that for the structural behaviour of columns made using steels, the slenderness ratios of columns and width-to-thickness ratios of steel plates are factors which have significant effect on the failure mode and strength of steel columns [13]. Depending on the slenderness ratio, column's failure modes may change from global buckling at ambient temperature to local buckling at elevated temperature. The column strength decreases as slenderness ratio is increased.

Abebe *et al.* conducted study on effect of slenderness ratio on residual strength and inelastic buckling strength of H-section steel column [14]. A total of 31 H-section steel column members were analyzed and loading test on one sample in both weak axis and strong axis were analyzed under axial compression loads. The load-deformation relationship and inelastic buckling shape with the effect of slenderness ratio on inelastic buckling behaviour of column was observed. A nonlinear finite element analysis carried out was validated through measured data and observed damage state from the experiment by the test done only for one sample. It was observed that the slenderness ratio had significant effect on residual strength of column, as the slenderness ratio is increased, both the rate of decrease of residual strength and load carrying capacity decreases.

Gul *et al.* evaluated buckling strength or ultimate load carrying capacity of stiffened plate used for the marine structures with help of non-linear FE analyses [15]. From the parametric study it is noted that buckling strength of the stiffened plate is affected by the slenderness of plate. Buckling strength decreases as slenderness increases. The post-buckling response of plate also becomes increasingly unstable as slenderness increases.

Gordo *et al.* conducted study on experimental evaluation of the behaviour of a structural steel box girder under axial compression load and bending moment using non-linear finite element analyses and loading test [16]. By comparing result, it is noted that the type of failure of the structure is controlled by the slenderness of column. Long column (slender) leads to more sudden failure.

Angle of Twist (θ)

The critical load of a pretwisted column was always of higher value than that of its corresponding prismatic column.

Abed *et al.* conducted study on the buckling strength of fixed ended pretwisted steel columns having rectangular cross-sections subjected to axial compressive loads using FE analysis [17]. For all analysed rectangular steel columns, the influence of pre-twisting was to increase the buckling strength such that the critical load of a pretwisted column is always higher compared to that of its corresponding prismatic column having unequal principal moments of inertia. The graph of the buckling loads versus the twist angle indicated that there is significant effect on the buckling strength of the pretwisted column at twists angles less than 90°. It can be observed that pretwisting can be taken as a simplest way for strengthening thin columns which are subjected to axial compressive loads or making lighter or more economical (thinner) columns with the same strength.

Buckling Strength

A moment or force which can withstand by a structural member without buckling is called buckling strength [2]. The strength of column depends on the slenderness ratio and end conditions. If the slenderness ratio is increased, the tendency to buckle is increased, hence compressive strength of column decreases [1, 4].

EULER’S COLUMN THEORY

Assumptions

The following assumptions are taken for deriving Euler’s critical load equation:

1. The column is initially straight, and the applied load is truly axial.
2. The cross-section of the column is uniform throughout its length.
3. The material of column is perfectly elastic, isotropic and homogeneous, and obeys Hooke’s law.
4. The column length is very large as compared to its cross-sectional dimensions.
5. The shortening of column, due to direct compression (which is very small) is neglected.

6. The column failure occurs due to buckling alone.
7. The self-weight of the column is neglected.

Euler's Formula

According to Euler's formula, the buckling or crippling load (P_{cr}) is represented by,

$$P_{cr}=\frac{\pi^2 EI}{L_e^{\,2}}=\frac{\pi^2 EAk^2}{L_e^{\,2}}=\frac{\pi^2 EA}{S^2}$$

5

Where,

E= Young's modulus or Modulus of elasticity for column material,

I= Least moment of inertia of the column section =Ak^2,

L_e= Equivalent length of the column,

A= Cross-section area,

S= Slenderness ratio.

Hence, Crippling stress, $\sigma_{cr}=\frac{P_{cr}}{A}=\frac{\pi^2 E}{S^2}$

Limitations of Euler's Formula

In actual practice, the ideal conditions (i.e. the member is initially straight and the load being applied is truly axial through centroid) are never reached. There is always some initial curvature and eccentricity to applied load, present. These factors need to be considered in the given formula.

Avraam *et al.* conducted study on the effect of geometrical imperfections and loading eccentricity (loading imperfection) on the buckling behaviour of a simple rectangular two-bar frame [18]. It has been noted that, due to the imperfections as mentioned above, the structural member will suffer from a deflection and deformation increases with applied load, and consequently a bending moment is induced which causes collapse of structural member before the Euler's critical load is reached. Actually, failure occurs by induced stress rather than by buckling; and the deviation from the Euler's critical load value is more as the slenderness-ratio is decreased. For slenderness ratio (L_e/k)<120 approx., the error in applying the Euler's column theory is too big.

Gul *et al.* evaluated ultimate load carrying capacity of stiffened plate for the marine structures using non-linear FE analyses [15]. By the parametric study it is noted that as the value of slenderness is increased, effect of imperfection becomes significant and post buckling response of plate also becomes more unstable.

Also, buckling in long column occurs at the stress lower than the crushing stress σ_c of the column material (i.e. the critical stress for a column cannot be greater than the crushing stress. For a mild steel column, Young's modulus is 2.0×10^5 N/mm^{2}and crushing stress is 330 N/mm^2 and. So,

$$\sigma_{cr}\leq\sigma_c$$

$$\frac{\pi^2 E}{S^2}\leq 330$$

$$\frac{9.87 \text{ x } 210 \text{ x } 10^3}{S^2}\leq 330$$

$S^2\leq6280.90$

$S\leq79.25$ say 80

Hence, if the slenderness ratio (L_e/k)<80, Euler's critical load formula is not valid [19].

RANKINE'S COLUMN THEORY

Rankine gave the following empirical formula for columns which is applicable to struts/columns of all dimensions.

$$\frac{1}{P_{cr}}=\frac{1}{P_c}+\frac{1}{P_E}+$$

Where,

P_{cr}= Critical load by Rankine's formula,

P_c= Ultimate crushing load for the column =$\sigma_c\times A$,

P_E= Critical load by Euler's formula =$\frac{\pi^2 EA}{S^2}$

So, Rankine's critical load is given by:

$$P_{cr}=\frac{\sigma_c A}{1+\alpha\, S^2}$$

Where,

σ_c= Crushing stress or yield stress in compression,

A= Cross-sectional area of the column,

α= Rankine's constant =$\frac{\sigma_c}{E\,\pi^2}$

S= Slenderness ratio of column.

The value of crushing load P_c will remain constant irrespective of whether the column is short or long. In case of short columns, the value of Euler's critical load P_E will be very high. Hence, the value of $1/P_E$ will be negligible as compared to $1/P_C$. So it is obvious that the Rankine's critical load formula will give the value of critical load (i.e. P_{cr}) approximately equal to the ultimate crushing load (i.e. P_C).

For long columns, the value of Euler's critical load P_E will be negligible, so the value of $1/P_E$ will be considerable as compared to $1/P_C$. So it is obvious, that the Rankine's formula will give the value of critical load (i.e. P_{cr}) nearly equal to the critical load by Euler's formula (i.e. P_E). Thus, Rankine's formula will give correct result for all types of columns, either long or short columns [4, 18]. Table 2 presents the values of Rankine's constant (α) and crushing stress (σ_c) for various materials.

EXPERIMENTAL SETUP

Bhilawe *et al.* conducted an experimental study on equal angle steel column subjected to compression using hydraulic jack [20]. Three nominal section sizes L50×6, L60×5, L65×6 and lengths 900 to 1800 mm were tested. An initial load (about 1/15 to 1/20 of the estimated failure load) was applied to the specimen and all measurement devices were initialized at this load level. Measurements of material properties, residual stresses, and geometrical imperfections were conducted. For column, the out-of-straightness was measured directly about the principal axes. All measurements were taken from a datum formed by nylon wires tightly stretched. No symmetrical residual stresses were observed for the equal legged angles. The test data were compared with the IS 800:2007 for mild steel [2]. It was noted that the measured values of the yield strength were within the acceptable range of the Indian standard specification. The section capacities obtained from the tests were found to be between 15 and 40% higher than those calculated according to the specifications. So, from investigation it is concluded that the design capacities predicted by IS 800:2007 are more conservative compared with the test strength.

Peseka *et al*. conducted experimental verification of the buckling strength of structural column using manually operated hydraulic press [21]. Loading force was measured using force transducer while horizontal (lateral) and vertical deflections at mid-length were measured using wire sensor and linear variable differential transformer (LVDT). Strain gauges glued at mid span were used to measure normal stresses.

Cao *et al.* conducted study on buckling of angle columns made with mild steel (Q420) [10]. Columns were tested using hydraulic actuator. Displacement transducers was used for measuring horizontal and vertical displacement and were located at column's mid-length pointing to the centroid of the mid-length section. Six strain gauges were used to obtain the strain distributions at the column's mid length section (Figure 4). It was observed that tested columns buckled about the axis having minimum moment of inertia or weak principle axis and flexural buckling was most frequent buckling mode. Table 3 presents the specifications of specimen.

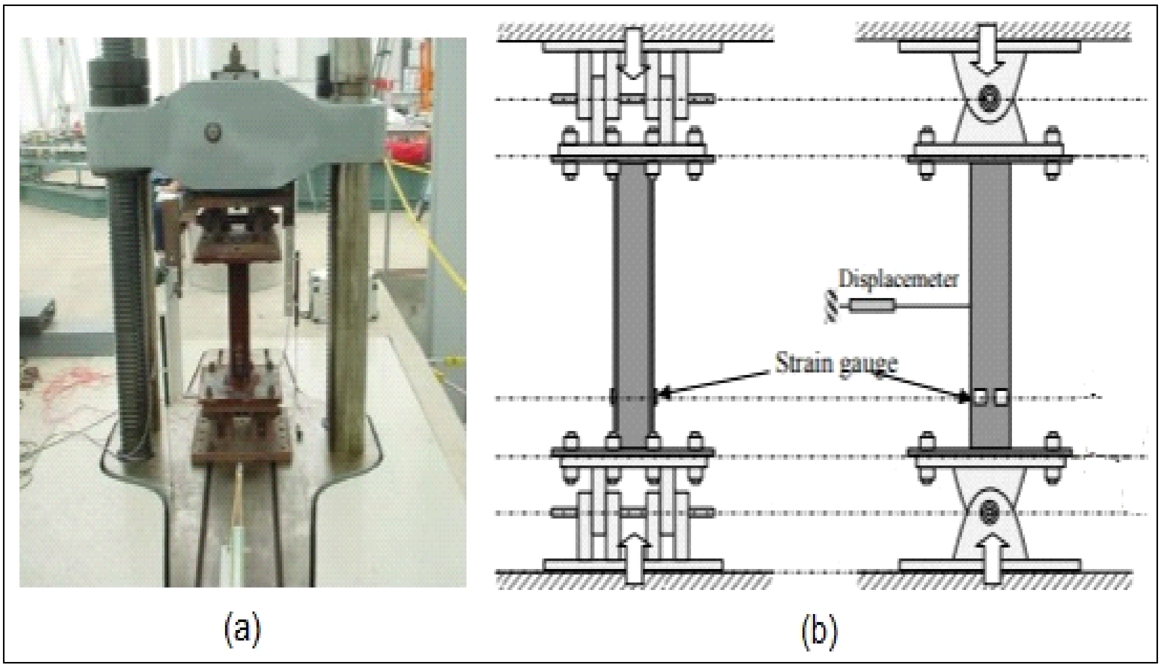


***Fig. 4: (a)** Loading Test Set-up, **(b)** Overview of Specimen.*

Table 2: *Values of Rankine's Constant (α) and Crushing Stress (σ_c) for Various Materials.*

Sr. No.	Material	σ_c (Mpa)	α
1.	Timber	50	1/750
2.	Cast iron	550	1/1600
3.	Mild steel	320	1/7500
4.	Wrought iron	250	1/9000

Table 3: *Specifications of Specimen.*

Section Properties	Specification
Poisson's ratio	0.29
Young's modulus	205 GPa
Density	7845 kg/m^3
Crushing stress	310 N/mm^2

FINITE ELEMENT ANALYSIS

Cao *et al.* conducted study on buckling behaviour of columns made with mild steel (Q420) [10]. Columns were analysed under axial loading using hydraulic actuator. Displacement transducers were used to measure a displacement of column and strain gauges were used to obtain the strain distributions at the mid length of column section. A 3D finite element analysis model with equivalent cross-section area has been established using the finite element analysis software ANSYS and meshed by the 3-D 8-node structural solid element (SOLID185) and then used to perform parametric study. Based on the study, to predict the buckling strengths of columns, a new column curve was proposed. The ultimate buckling strengths obtained through FE analysis were compared with the experimental results. FE results were in good agreement with the experimental results.

Lee conducted study on buckling and post-buckling of thin-walled composite columns with intermediate-stiffened open cross-section under axial compression load [22]. The thin-walled columns were modelled by many plane plates and discretized using shell element S8R in ABAQUS. By the eigen value analyses (for investigate buckling load and buckling mode shapes of the column) and geometry nonlinear analyses using the finite element method, the buckling and post-buckling behaviour of the thin-walled composite columns was studied. It was observed that the finite element analysis results are in well agreement with the compression loading test result.

CONCLUSIONS

On the basis of the present review, the following conclusions are drawn:

1) A frame buckling failure is triggered whenever a degree of freedom becomes unstable.
2) The buckling takes place about the axis having minimum radius of gyration or least moment of inertia.
3) Section modulus is the direct measure of strength of column. Higher the section modulus, higher will be the resistance to bending and capable to supporting greater load, less the stress. As more and more material concentrates away from the centre, section modulus will increase. Solid sections are advantageous compared to hollow sections because solid sections come out of rolling mill faster than hollow sections, also connections are more complex in hollow sections.
4) The strength of columns depends on the slenderness ratio and end conditions of column. If the slenderness ratio is increased, the tendency to buckle is increased, hence compressive strength of a column decreases.
5) The influence of pre-twisting is to increase the buckling load such that the critical load of a pretwisted bar is always higher compared to that of its corresponding prismatic bar having unequal principal moments of inertia. Pretwisting can be taken as a simplest way for strengthening thin columns which are subjected to axial compressive loads or making lighter or more economical (thinner) columns with the same strength.
6) From this study, it is also experienced that material variation along the thickness and strain hardening have significant effect on the buckling strength of stiffened plates. So, for evaluating the actual ultimate load carrying capacity or buckling strength of stiffened plate, both the material characteristics must be taken in to account in the design and analysis of stiffened plates.

7) Initial imperfections, including initial deformation, loading eccentricity and sectional residual stress have significant effects on the buckling behaviour of steel columns.

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