iJRASET
International Journal For Research in Applied Science and Engineering Technology



INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 8 **Issue:** IX **Month of publication:** September 2020

DOI: https://doi.org/10.22214/ijraset.2020.31448

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 8 Issue IX Sep 2020- Available at www.ijraset.com

Improvement in Critical Load for Buckling of Structural Steel I-Section Column in Fixed-Free Condition by Modifying the Cross-Section

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Abstract: ***The study in this paper focuses on increasing the buckling strength of the column by making some slight modifications in its cross-sectional area and making solid models of the columns with different cross-sections on modelling software Solid Works and verifying the results with the help of Finite Element Analysis software ANSYS Workbench 18.2. With the advancement in Finite Element techniques, results can be precisely determined by making Finite Element Models (FEM) on the software without actually testing the physical models. The critical buckling load or buckling strength is calculated using theoretical formulations given by the Euler's theory of buckling and then verified using Finite Element Analysis method on the 'Eigenvalue Buckling' workbench of the ANSYS Software. Eigenvalue buckling or 'Linear buckling' is generally used to determine the critical buckling loads of stiff structures. Stiff structures carry load primarily by axial or membrane action, rather than by bending action. The stiff structures usually involve very little deformation prior to buckling. This method of modifying the cross-section areas of columns to increase the critical buckling loads proves to be very effective and increases the critical load significantly. A trend is observed such that the critical load or buckling strength of the column increases with increase in Moment of Inertia which is ultimately obtained by making modifications in the cross-sections of the columns. To keep the columns within the safety limits, safe working loads for every section are found by introducing Factor of Safety parameter to the critical buckling load obtained from the software.***

Keywords: Critical load, Fixed-Free condition, Buckling Analysis, Moment of Inertia, Load Multiplier.

I. INTRODUCTION

Columns are the structural members which are often subjected to high axial compressive loadings. The most prominent failure of the columns is 'Buckling'. Buckling can be defined as the structural instability that is associated with high compression loading which results in a failure mode of the structural element that is long and slender. When sufficiently large load is applied on the column, there is a possibility that the column will buckle. Buckling of column is the deformation caused due to large axial compressive forces which results in bending of column such as bowing of a column under loading. Efforts are made constantly to increase the buckling strength of the column by making lots of changes, right from the material to the design of cross-sections of the column.

The greatest load that the column will withstand without causing lateral deflection or buckling is called 'Buckling load' or 'Crippling load' or 'Critical load'. The Critical load for buckling depends upon various parameters such as end conditions of columns, material properties, material composition, length of the column, cross-section of the column and many unaccounted parameters.

In this paper, the major aim is to increase the buckling strength of the column by making suitable minor modification in the cross-section of the column and then performing buckling analysis of the column. The buckling analysis or the buckling simulation is performed on the 'Eigen value Buckling' workbench of Finite Element Analysis software ANSYS 18.2. Column buckling analysis comprises of determining the maximum load a column can support before buckling or in simple words, determining the 'Critical load' for the column under axial compressive loading conditions.

Short columns fail mostly due to crushing failure and not by buckling failure. Thus, for a pure buckling analysis, long columns are considered for the analysis since long columns fail due to pure buckling. A column is said to be a 'long column' when ratio of Effective length (L_e) to Least lateral dimension (LLD) is very large. Generally it is considered to be greater than or equal to 50.

Thus, for long column condition,

Effective Length (L_e) / Least Lateral Dimension ≥ 50

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Volume 8 Issue IX Sep 2020- Available at www.ijraset.com

II. EULER'S THEORY OF BUCKLING

Leonhard Euler in 1757 developed the theory for buckling of columns. According to this theory, the column will buckle when the axial compressive force exceeds a particular value. This value that the column will withstand without buckling is called as 'Euler's critical load' or 'Buckling load'. Euler's theory determines the 'critical load' for long columns only because the direct stress induced in long column is negligible as compared to bending stress.

A. Assumptions Made in Euler's Theory

Some of the assumptions made in Euler's theory for buckling are as follow –

1) The load acting on the column is axial only.
2) The column material is homogeneous, isotropic and perfectly elastic and thus obeys Hooke's law.
3) The column is perfect straight before loading and uniform in cross-section.
4) Length of the column is large as compared to its cross-sectional dimensions.
5) Self weight of the column is neglected.

According to Euler's theory of buckling, the maximum load that a column can withstand without buckling or the 'Critical load' is given by the formula –

$$Pc = \frac{n\pi^2 EI}{L^2}$$

Or

$$Pc = \frac{\pi^2 EI}{(kL)^2}$$

Where,

P_c = Euler's critical load for buckling
E = Young's modulus of elasticity of material of column
I = I_{min} = Least moment of inertia of cross-section of the column among I_{xx} and I_{yy}
L = Actual length of the column
L_e = (kL) = Effective length of the column
n = Factor accounting for end condition
k = Effective length factor [$K=(1/n)^{0.5}$]

The factor accounting for end condition (n) depends on the type of end condition of column. Following are the four end conditions for the column –

a) Columns with both ends are pinned or hinged.
b) Column with both ends are fixed.
c) Column with one end fixed and other is pinned or hinged.
d) Column with one end fixed and other is free.

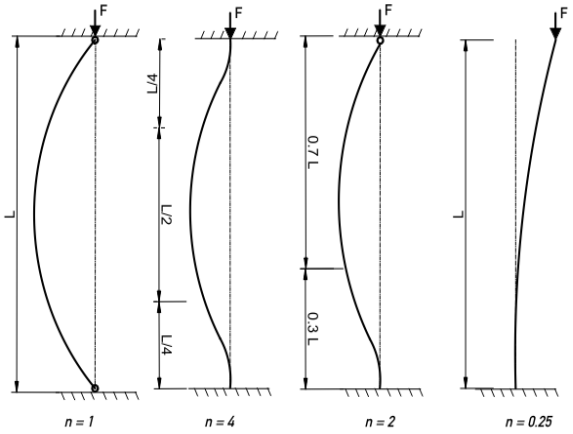


Fig.1 End conditions for the column (Source: The Engineering toolbox)

In this paper, entire focus is on 4th condition that is the Fixed-Free end condition for the column where n = 0.25 or ¼.

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III. IMPROVEMENT IN BUCKLING STRENGTH OF COLUMN FOR FIXED-FREE CONDITION –

From the above Euler's equation for buckling, it can be seen that the 'Critical load' can be increased by the following methods –

A. Reducing the length of the column (L).
B. Increasing the Young's modulus (E) – by replacing the material with high Young's modulus.
C. Increasing the moment of inertia of the column (I).

In this paper, focus is done more on improving the buckling strength by keeping Length of the column (L) and Young's modulus (E) constant whereas increasing the moment of inertia (I) of cross section of the column to increase the buckling strength of the column. Moment of inertia of the column can be increased by adding material away from the central axis, that is, increasing the area as well as increasing the radius of gyration since $I = Ar^2$.

Also, moment of inertia plays a very crucial role in buckling of columns because the column under loading will tend to buckle in that direction where its moment of inertia is less. Thus, increasing moment of inertia in that direction will increase the buckling strength of the column significantly.

IV. MATERIAL USED FOR THE BUCKLING SIMULATION ON ANSYS –

Structural steel is by far the most common material used for manufacturing of all the structural elements such as I-section, C-section, T-section, etc.

The material used for all the columns in this paper is 'Structural steel' with following properties –

Density (σ) = 7850 kg/m^3; Young's Modulus (E) = 2 × 10^5 N/mm^2; Poisson's ratio = 0.3; Ultimate tensile strength = 460 N/mm^2; Tensile and Compressive yield strength = 250 N/mm^2

Outline of Schematic A2: Engineering Data

Properties of Outline Row 3: Structural Steel

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	7850	kg m^-3
4	Isotropic Secant Coefficient of Thermal Expansion		
5	Coefficient of Thermal Expansion	1.2E-05	C^-1
6	Isotropic Elasticity		
7	Derive from	Young's Modulus and Poisson's...	
8	Young's Modulus	2E+05	MPa
9	Poisson's Ratio	0.3	
10	Bulk Modulus	1.6667E+11	Pa
11	Shear Modulus	7.6923E+10	Pa
12	Alternating Stress Mean Stress	Tabular	
13	Interpolation	Log-Log	
14	Scale	1	
15	Offset	0	Pa
16	Strain-Life Parameters		
17	Display Curve Type	Strain-Life	
18	Strength Coefficient	920	MPa
19	Strength Exponent	-0.106	
20	Ductility Coefficient	0.213	
21	Ductility Exponent	-0.47	
22	Cyclic Strength Coefficient	1000	MPa
23	Cyclic Strain Hardening Exponent	0.2	
24	Tensile Yield Strength	250	MPa
25	Compressive Yield Strength	250	MPa
26	Tensile Ultimate Strength	460	MPa

Fig. 2 Material used for buckling simulation in ANSYS – Structural Steel.

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V. I-SECTION

The material used for I-Section is 'Structural Steel' with all the properties mentioned in figure no. 2.
All the solid modeling of columns is done on Solid Works 2018 software and are saved as .igs files and then imported on the ANSYS Workbench 18.2. 'Static Structural' and 'Eigenvalue Buckling' workbench are used for performing buckling simulation in ANSYS software.

A. Simple I-section

1) Solid Modelling

For the simple I-section as shown in figure, the dimensions are as follow –
Flange width (B) = 80mm; Flange thickness (h) = 10mm; Web depth (H) = 80mm; Web thickness (b) = 8mm; Length of the column (L) =1000mm (for long beam condition)

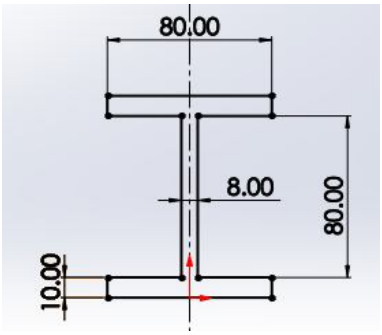


Fig. 3(a) Sketch for simple I-section

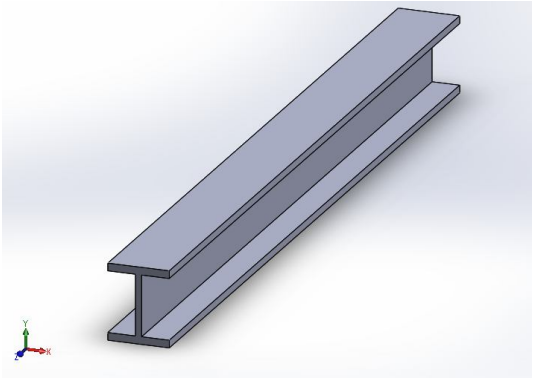


Fig. 3(b). Solid model of simple I-section column on SolidWorks

2) Simulation on ANSYS: By performing simulation on ANSYS software for the above column, we can get the critical buckling load by applying a force of 1 Newton on the free end of the column, so that we can get the actual 'load multiplier' value on the software. 'Load multiplier' value is the amount of force required to buckle the column which is ultimately the 'Critical buckling load' value for the column. We will verify this by comparing the 'Theoretical critical buckling load' with the 'Load multiplier' value from the software for the simple I-section as shown below.

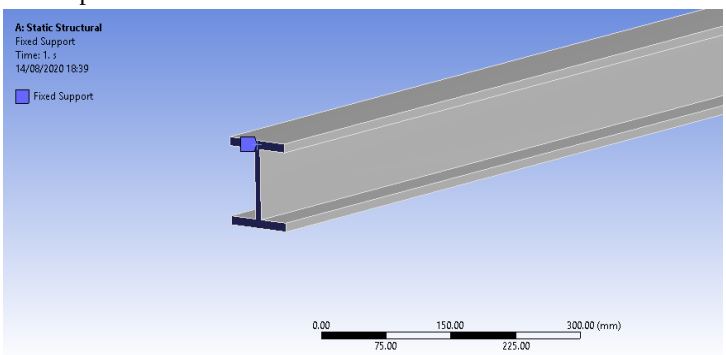


Fig. 4(a) End condition – Fixed support

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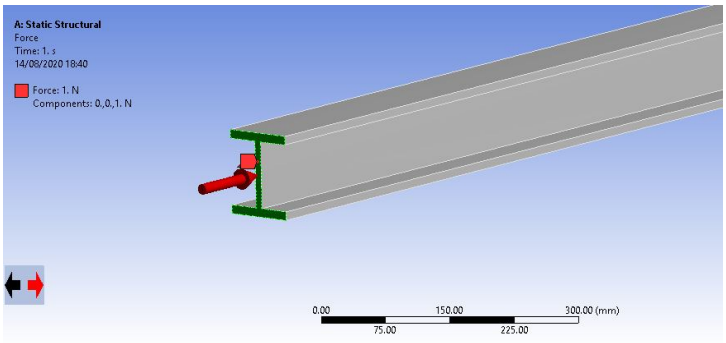


Fig. 4(b). End condition – Free end with applied force of 1N

On the 'Eigenvalue workbench' of the ANSYS software, we get the load multiplier value which is the amount of force required to buckle the column or in short, the 'critical load' for the column.

So, Applied force × Load multiplier = Critical load for buckling

Thus, load multiplier = Critical load for buckling

(When applied force F = 1 N).

So we are applying Force F = 1 N on the free end to get 'critical load' from the software.

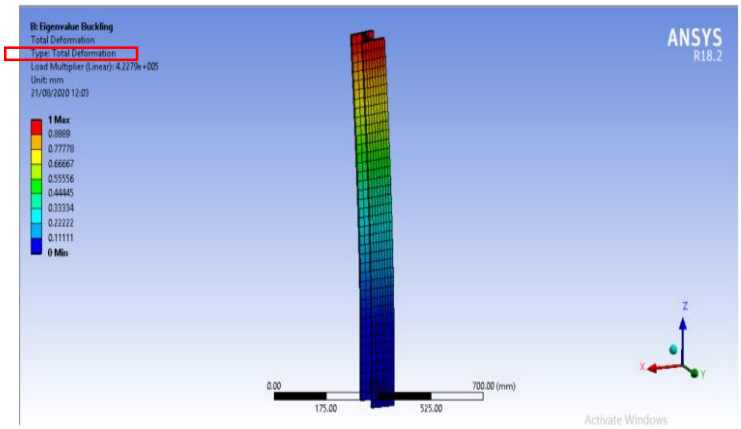


Fig. 4(c) Buckling simulation of I-section column on ANSYS software

Critical buckling load value from the software Pc –

$P_c = 4.2279 \times 10^5$ N = 422790 N = 422.79 KN (I)

3) Sample Calculations

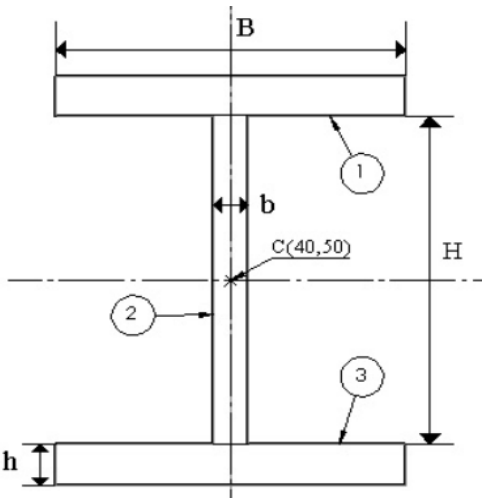


Fig.5 Cross section of I-section beam with parameters

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For the above column, theoretical value of critical buckling load can be found out using Euler's formula for buckling,

$$Pc = \frac{n\pi^2 EI}{L^2}$$

Here, n = 0.25 (for column with one end fixed and one end free)

$E = 2 \times 10^5$ MPa (for structural steel)

$I = I_{min}$:

$I_{xx} = 2[(Bh^3/12)+Ah^2] + bH^3/12$

$= 2[(80\times10^3/12) + 800\times(45)^2] + 8\times80^3/12$

$I_{xx} = 3594666.667\ mm^4$

$I_{yy} = 2(hB^3/12) + Hb^3/12$

$= 2(10\times80^3/12) + 80\times8^3/12$

$I_{yy} = 856746.667\ mm^4$

So, $I_{min} = I_{yy} = 856746.667\ mm^4$

L = 1000mm

Thus, by substituting all the values we get,

P_c= 422787.5338 N = 422.788 KN (II)

From (I) and (II), it can be seen clearly that the theoretical value of critical buckling load and the value obtained from the ANSYS software are exactly the same. Hence, the buckling analysis performed on the I-section is valid.

In similar way, we can modify the cross-section and get the 'Load multiplier' value from the ANSYS software which is ultimately the 'Critical load' for the column.

VI. MODIFICATION IN THE CROSS-SECTION

Buckling strength can be improved by increased by following modifications –

1) Adding material or increasing the chamfer/fillet between web and flange.

2) Adding material away from the central axis on the inner side of the flange.

3) Adding material away from the central axis on both sides of the flange.

A. Modification 1: Increasing the chamfer/fillet Between web and Flange

Buckling strength can be increased by increasing the chamfer/fillet between the web and the flange as shown in figure below. This increases the area thereby increasing the moment of inertia of the beam which indeed increases the buckling strength of the column. The increase in buckling strength increases by a very small amount by this method. To avoid sharp corners, fillets can be used instead of chamfers.

1) Solid Modelling

For the column section, the dimensions are as follows –

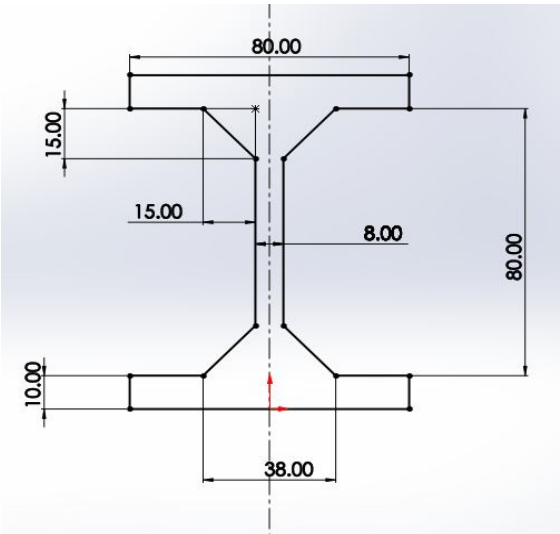


Fig.6(a) Sketch for I-section with increased chamfer

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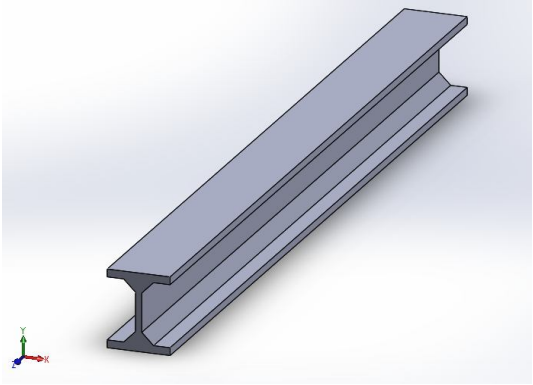


Fig.6(b) Solid model of I-section column with increased chamfer

2) Simulation on ANSYS

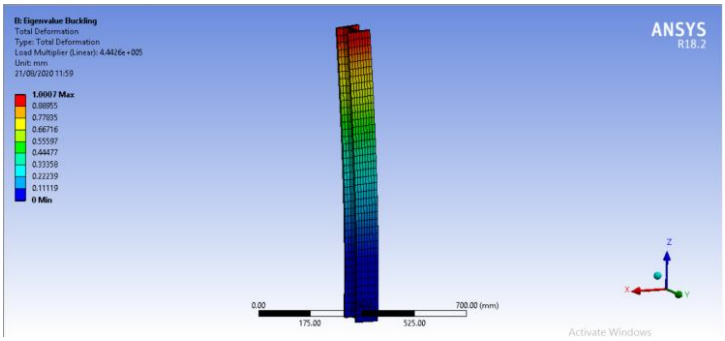


Fig.7 Buckling simulation of I-section with increased chamfer on ANSYS software

Critical buckling load value from the software,

$P_c = 4.4426 \times 10^5 = 444260$ N = 444.26 KN

B. Modification 2: Adding Material Away from the Central axis on the Inner side of Flange

Moment of inertia can be drastically increased by adding material away from the central axis. As shown in the figure below, material can be added on the ends of the flange on the inner side which indeed increases the moment of inertia of the structure which ultimately increases the buckling strength of the column.

1) Solid Modelling

For the column section, the dimensions are as follows –

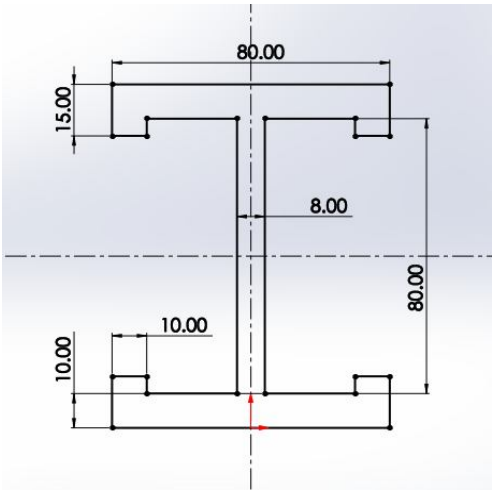


Fig.8(a) Sketch for I-section with material added on the inner side of the flange

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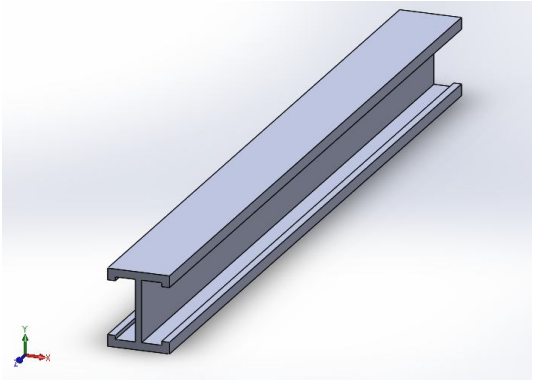


Fig.8(b) Solid model for I-section with material added on the inner side of the flange

2) Simulation on ANSYS

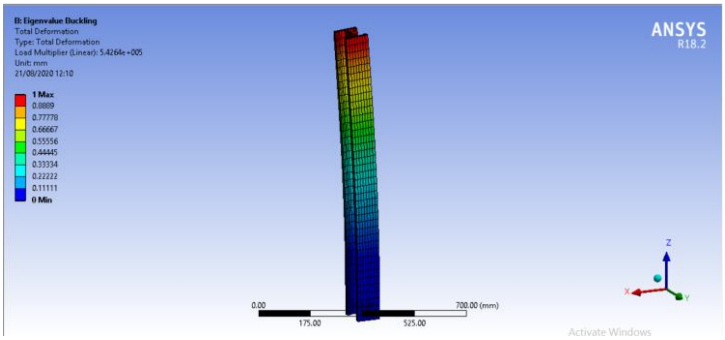


Fig.9 Buckling analysis for I-section with material added on inner side of the flange on ANSYS software

Critical buckling load value from the software,

$P_c = 5.4264 \times 10^5$ N = 542640 N = 542.64 KN

C. Modification 3: Adding Material away from the Central Axis on Both Sides of the Flange

Moment of inertia of the column can be further increased by adding material on the ends of the flange on both the sides. This modification provides the best buckling strength among all the modifications.

1) Solid Modelling

For the column section, the dimensions are as follows –

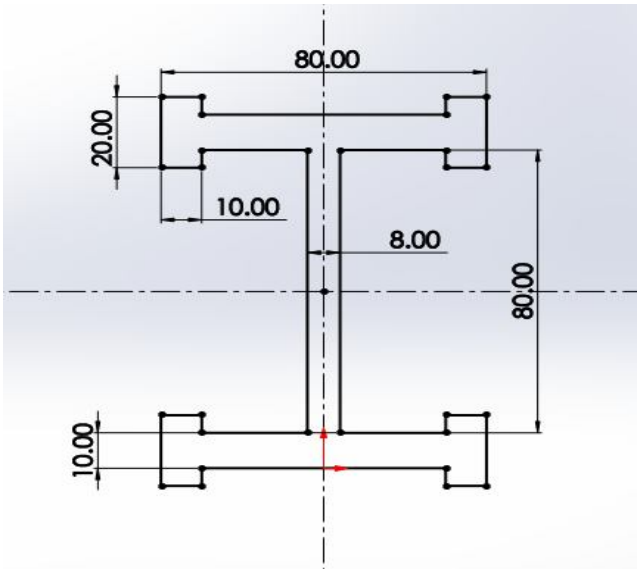


Fig.10(a) Sketch for I-section with material added on both sides of the flange

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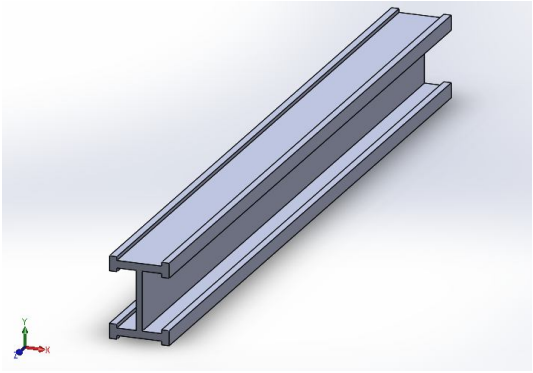


Fig.10(b) Solid model for I-section with material added on both sides of the flange

2) Simulation on ANSYS

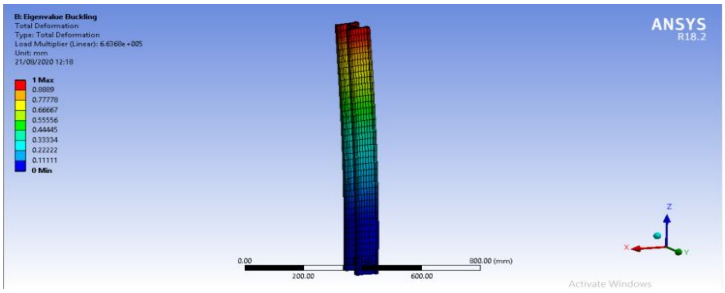


Fig.11 Buckling analysis for I-section with material added on both sides of the flange on ANSYS software

Critical buckling load value from the software,
$P_c = 6.6368 \times 10^5 = 663680$ N = 663.68 KN

Thus, from the above 3 modifications, we can conclude that the Critical buckling load is increased significantly from 422.79 KN to 663.68 KN.

VII. STRESSES INDUCED IN THE COLUMN –

We will find the normal stresses induced in the each of the section of the column with the help of 'Static structural' workbench in the ANSYS software. An equal force of 1 KN will be applied to all the sections. Since, Force is same for all the sections, we will know the stresses generated due to change in the cross-sectional area.

A. Simple I-section

Here, Force F = 1 KN =1000 N; Cross-sectional area = 2240 mm^2
Therefore, normal stress induced in the body $\sigma = F/A = 1000/2240 = 0.4464$ N/mm^2 which is exact same as shown on the software.

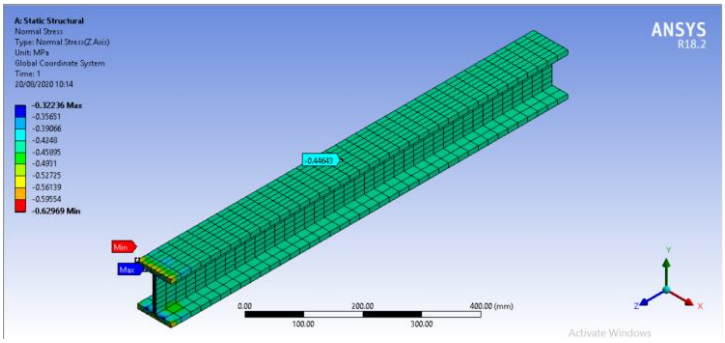


Fig.12 Normal stresses induced in the simple I-section column (Negative sign indicates compressive stress)

Now, stresses induced at the fixed support due to loading –
Minimum (σ_{min}) = 0.3224 N/mm^2 (Compressive)
Maximum (σ_{max}) = 0.6297 N/mm^2 (Compressive)

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B. I-Section with Increased Chamfer

Here, Force F = 1 KN =1000 N; Cross-sectional area = 2690 mm^2

Therefore, normal stress induced in the body $\sigma = F/A = 1000/2690 = 0.37175$ N/mm^2 which is exact same as shown on the software.

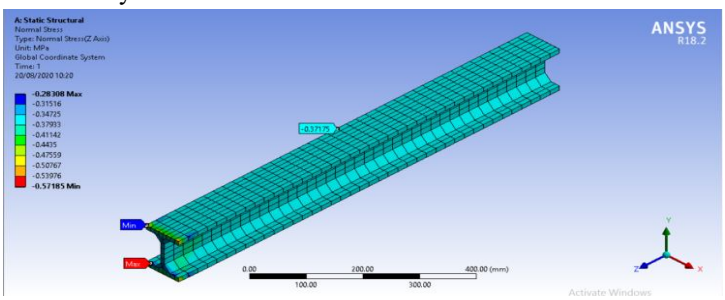


Fig.13 Normal stresses induced in the I-column with increased chamfer

Now, stresses induced at the fixed support due to loading –

Minimum (σ_{min}) = 0.28308 N/mm^2 (Compressive)

Maximum (σ_{max}) = 0.57185 N/mm^2 (Compressive)

C. I-Section with Material added on the Inner side of the Flange

Here, Force F = 1 KN =1000 N; Cross-sectional area = 2440 mm^2

Therefore, normal stress induced in the body $\sigma = F/A = 1000/2440 = 0.40984$ N/mm^2 which is exact same as shown on the software.

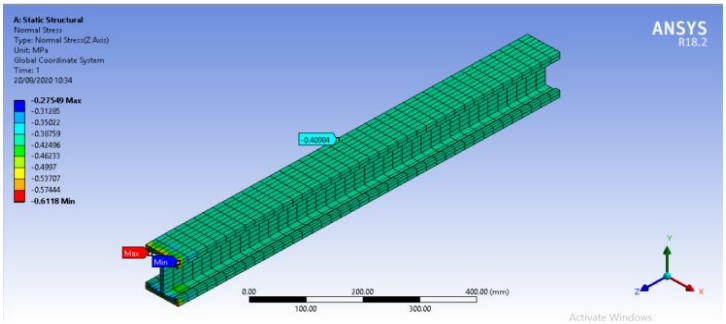


Fig.14 Normal stresses induced in the I-section column with material added on the inner side of the flange

Now, stresses induced at the fixed support due to loading –

Minimum (σ_{min}) = 0.27549 N/mm^2 (Compressive)

Maximum (σ_{max}) = 0.6118 N/mm^2 (Compressive)

D. I-Section with Material added on the Both Side of the Flange

Here, Force F = 1 KN =1000 N; Cross-sectional area = 2640 mm^2

Therefore, normal stress induced in the body $\sigma = F/A = 1000/2640 = 0.37879$ N/mm^2 which is exact same as shown on the software.

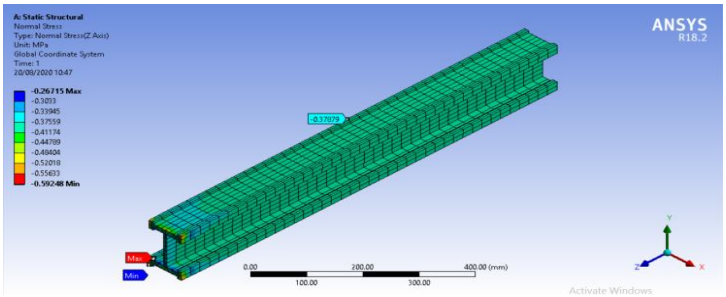


Fig.15 Normal stresses induced in the I-section column with material added on both sides of the flange

Now, stresses induced at the fixed support due to loading –

Minimum (σ_{min}) = 0.26715 N/mm^2 (Compressive)

Maximum (σ_{max}) = 0.59248 N/mm^2 (Compressive)

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VIII. RESULT

Table 1
Result obtained for the I-section column

Section	Simple I-Section	Modification 1	Modification 2	Modification 3
Cross-sectional area (mm^2)	2240	2690	2440	2640
Critical load for buckling (KN)	422.79	444.26	542.64	663.68
Safe load to avoid buckling (with FOS 1.5) = Critical load/FOS (KN)	281.86	296.17	361.76	442.45
For applied load of 1 KN				
Maximum Displacement (mm)	0.0022	0.0019	0.0020	0.0018
Normal stress induced in the body (σ) = F/A (N/mm^2)	0.44640	0.37175	0.40984	0.37879
Minimum Normal stress (σ_{min}) (N/mm^2)	0.3224	0.2831	0.2755	0.2676
Maximum Normal stress (σ_{max}) (N/mm^2)	0.6297	0.5719	0.6118	0.5925

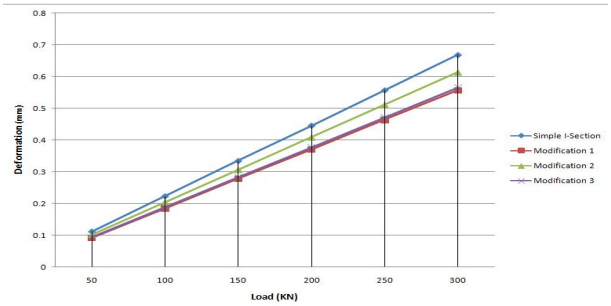


Fig.16 Result – Deformation (mm) Vs Load(KN)

To avoid buckling of the column, a Factor of safety (FOS) of 1.5 is introduced. Thus, for a particular cross-sectional area, the applied force should be less than the allowable force to avoid buckling issues.

IX. CONCLUSION

Thus, we have verified the theoretical results with the values obtained from the software and from that we can conclude that the 'buckling strength' or 'Critical load' for buckling can be significantly increased by making some slight modifications in the cross-section of the columns. Since, columns tend to buckle in the direction where its moment of inertia is least, preference should be given to increase the moment of inertia in that direction by adding material in the same direction.

It can be seen that modification 2 has cross-sectional area of 2690 mm^2 as compared to modification 3 which has cross-sectional area of 2440 mm^2. Still the buckling strength of the 3rd modification is higher than the 2nd. Thus, it is clear that increase in cross-sectional area will not decide the buckling strength but where the material is placed from the central axis will determine the increase or decrease in the critical load or buckling strength of the column.

Also, the Normal stresses induced in all of the columns are less than the Normal induced stress in the Simple I-section. Also, from the Fig.16, the displacement under loading is also reduced with modification in cross-section of the columns which is a desirable result. Thus, we have successfully improved the 'critical load' of a simple T-section column from 422.79 KN to 663.68 KN by making minor changes in the cross-section of the column.

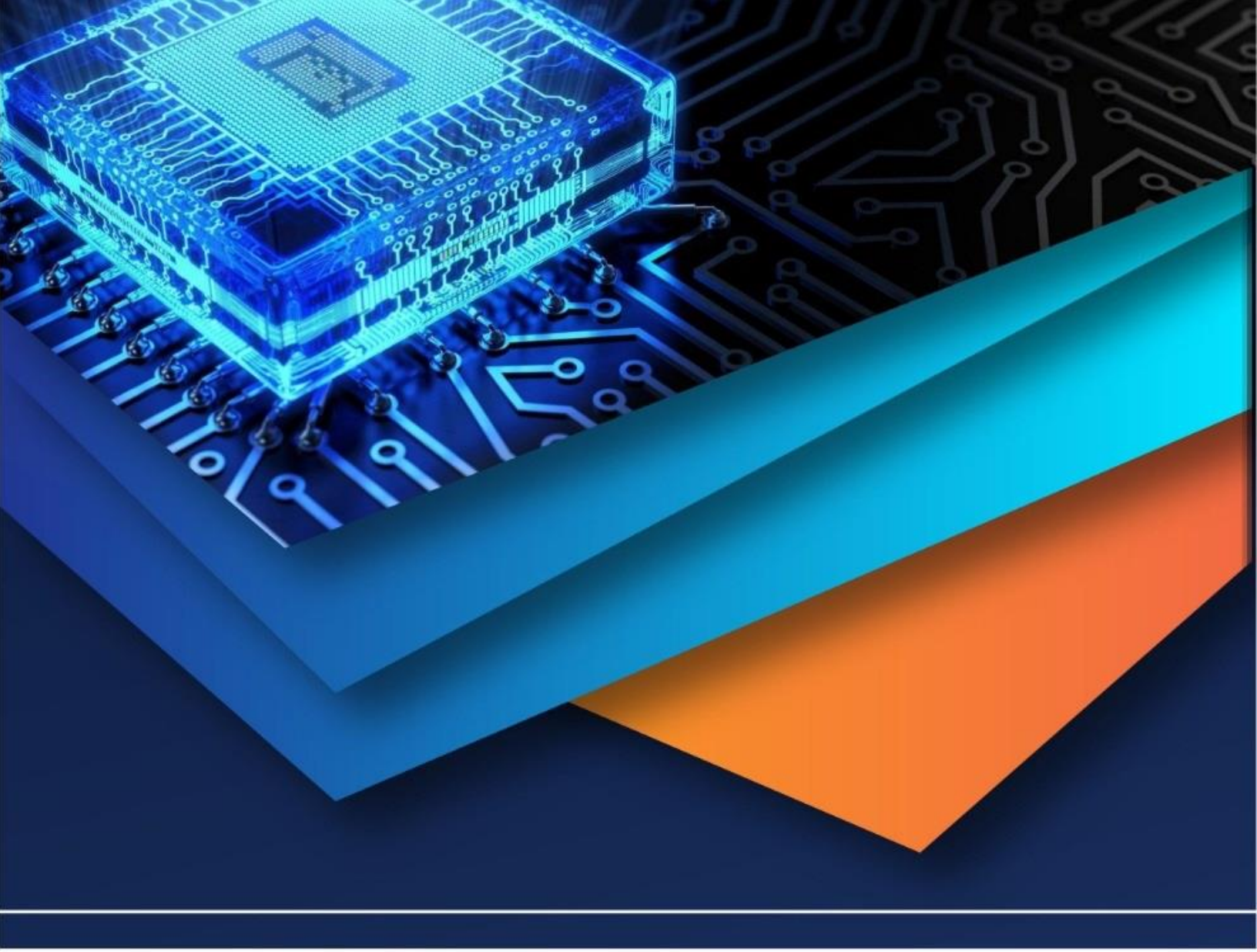
In the similar fashion, we can also increase the buckling strength of other standard cross-sectional columns like C-section, T-section L-section, Z-section, H-section, etc. This method of increasing buckling strength can be significantly used when there is constraint on the length of column as well as on material of the column. To keep the columns within safety limits, safe working loads are also determined by introducing Factor of Safety to the value of critical buckling load to avoid issues related to buckling of columns.

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