FEA OF CARBON COMPOSITE AS A SUBSTITUTE FOR STEEL (A992) IN CASE OF SQUARE OR RECTANGULAR HOLLOW CROSS-SECTIONS AS BEAMS AND COLUMNS.

by

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THESIS

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Abstract

FEA OF CARBON COMPOSITE AS A SUBSTITUTE FOR STEEL (A992) IN CASE OF SQUARE OR RECTANGULAR HOLLOW CROSS-SECTIONS AS BEAMS AND COLUMNS.

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The University of Texas at Arlington, 2018

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Improvement to an existing design is an ongoing and never-ending process in every field. The improvement can be in a myriad of areas like an increase in strength, reduction in weight, stiffness to a loading condition and so on. The way it is achieved can range from changing the properties of the material used by incorporating various manufacturing processes or by using an alternative material which can sustain the same loading conditions or for that matter, work better than the existing material. Composite materials like Carbon Fiber, Glass Fiber or Kevlar Fiber reinforced plastics, to name few, are being used to achieve the latter.

Carbon Fiber/Epoxy can come remarkably close or even go beyond the strength and stiffness of Steel with strategically placed ply angles to resist various loading conditions. Besides strength and stiffness, an important factor to consider for Carbon Fibers is its low mass. Thus, having a higher strength or stiffness to mass ratio as compared to Steel cross-sections of identical dimension and loading conditions. This is beneficial in case of buildings because it reduces the dead load of the entire structure by a significant margin. Glass fiber reinforced plastics are stronger but less stiff than steel. An increase of wall thickness gives an opportunity to come close to effective stiffness of the steel structure but, with lower mass and much higher fracture load, use of carbon fiber reinforced plastic looks more attractive mechanically, but the cost of structures is much higher. This study focuses on performing buckling, bending and torsional analysis on square and rectangular hollow cross-sections of varying dimensions resulting in Carbon composite being beneficial in lieu of Steel (A992) as beams and columns.

Acknowledgement

First and foremost, I would like to thank Dr. Andrey Beyle for giving me an opportunity to work on a topic this interesting. He was always there to guide me through every difficulty I faced in the past two semesters while I was working on my thesis. His insightful knowledge helped me achieve my goals on time.

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Secondly, I would like to thank all my colleagues who helped me when I had any issues. I will be forever indebted to all the friends who supported me and helped me get through this hectic time during my Master's.

Last but not the least, I would like to thank my parents for making it possible to start with this journey and being the pillar of support throughout these past two years and always believing in my abilities.

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1 Introduction

1.1 Overview

This study is a comparison between steel A992 and carbon-epoxy as materials for closed contoured hollow cross-sections in a civil structure. The intent behind this comparison study is to try to replace steel A992 by carbon-epoxy as the primary material for columns and beams. Reason for this is that carbon-epoxy is much lighter as compared to steel thus reducing the dead load of the entire structure. Columns are the vertical load-bearing elements of a structural frame[1]. Whereas, beams are the horizontal or inclined load-bearing elements of a structural frame[2].

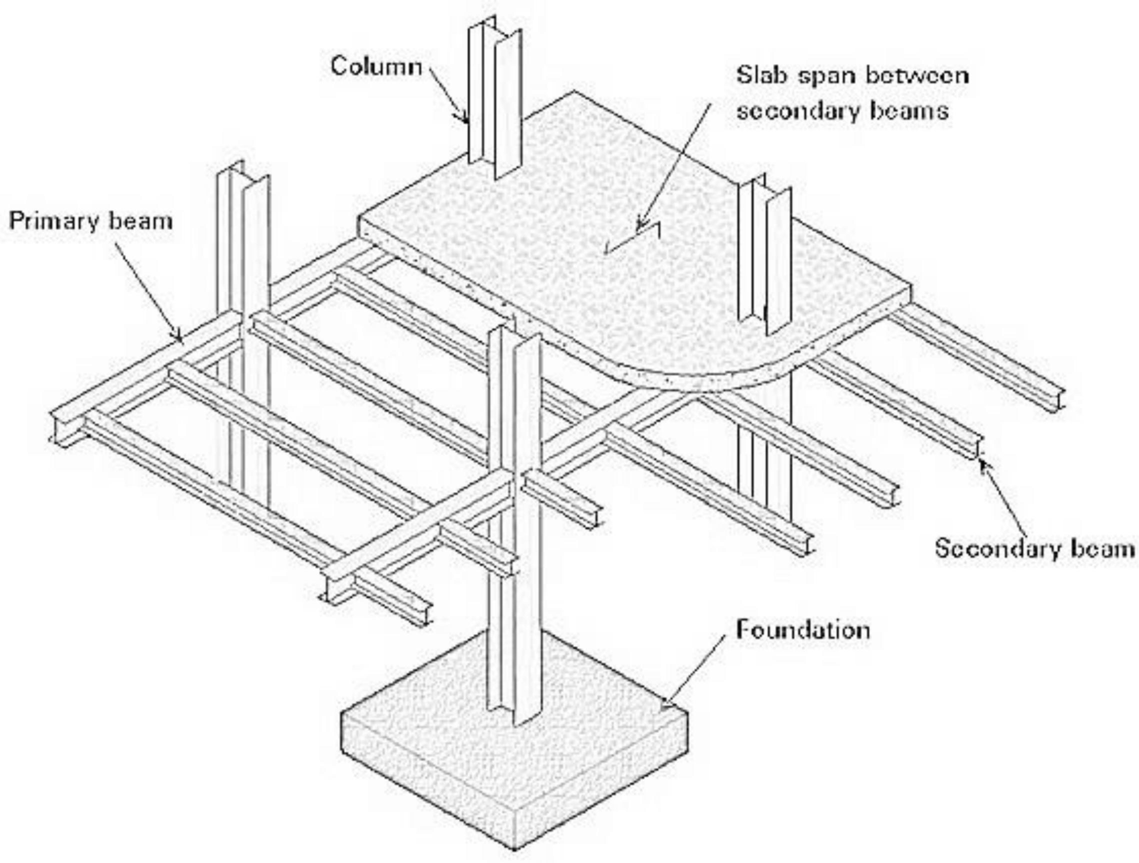

Figure 1-1 Typical Structural Frame

In the above figure, we can see a typical structural frame with beams and columns. The above figure shows ‘I’ sections but, there are other cross-sections also used such as ‘T’ sections, ‘C’ Channels, ‘L’ angles, and hollow cross-sections like a square, rectangle, or circular cross-sections.

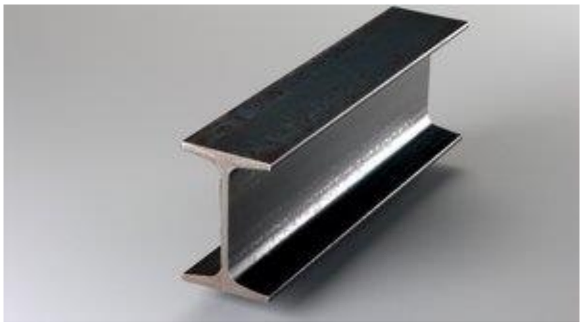

Figure 1-2 ‘I’ Cross-Section

Figure 1-3 Angle

Figure 1-4 'T' Cross-Section

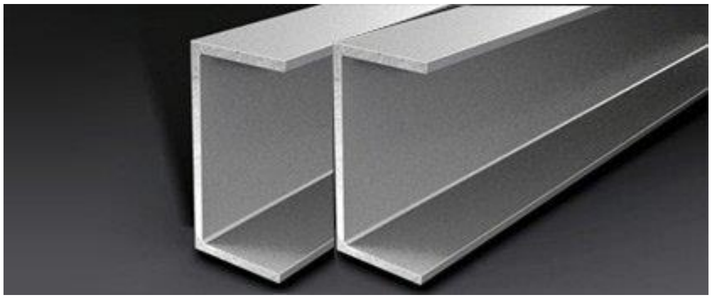

Figure 1-5 Channel

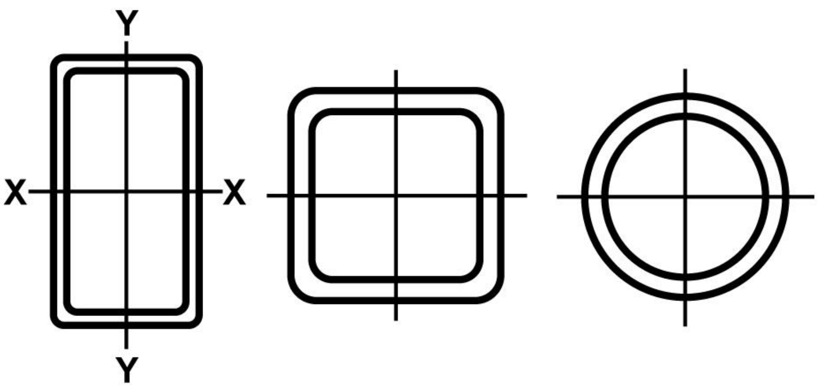

Figure 1-6 Hollow Cross-Section

Of all these cross-sections, we will be concentrating on the closed contoured cross-sections, namely the square and the rectangular cross-section. The square cross-sections considered are 2x2x0.25 and 5x5x0.5. The rectangular cross-section considered is 5x4x0.5.

We have considered three types of loading situations on each of these cross-sections. They are buckling, bending, and torsion. The details about each of these loading conditions are explained in chapter 4[3].

1.2 Composites

What are composites?

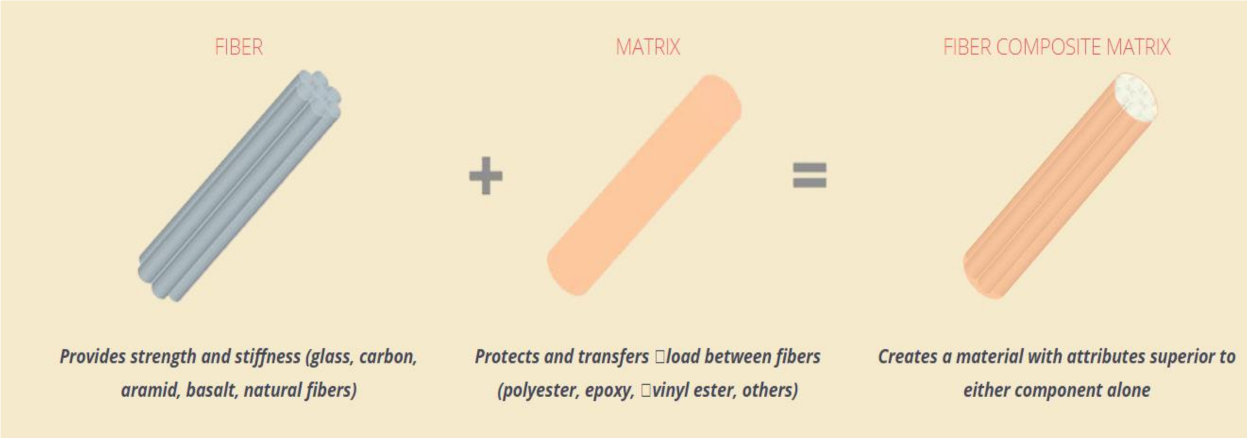

Figure 1-7 Composite

A structural composite is a material consisting of two or more phases on a macroscopic scale, whose mechanical performance and properties are designed to be superior to those of the constituent materials acting independently. One of the phases is usually discontinuous, stiffer, and stronger and is called the reinforcement (fiber), whereas the less stiff and weaker phase is continuous and is called the matrix[4]. The matrix protects the fiber from environmental damage along with transferring loads between them and the fiber resists cracks and fractures by reinforcing the matrix[5].

Why composites?

- They have high static and fatigue strength[6].
- Resistance to chemicals and corrosion[6].
- Low density.
- High specific stiffness.
- High specific strength.

2 Geometry

This chapter comprises of the CAD geometry used for this study. As mentioned earlier, we will be dealing with square and rectangular hollow cross-sections. Three different cross-sections are considered for each of the different types of loading conditions. As mentioned in the previous chapter, one of them is rectangular and the remaining two are square cross-sections. The cross-section dimensions for each of these are chosen according to the AISC specifications[7].

Since we have three different types of loading conditions, we have considered different lengths to run simulations for each type of condition.

Analysis Type	Length of each cross-section
Buckling Short Column	3 ft
Buckling Long Column	10 ft
Bending	6 ft
Torsion	6 ft

Table 2-1 Cross-section lengths

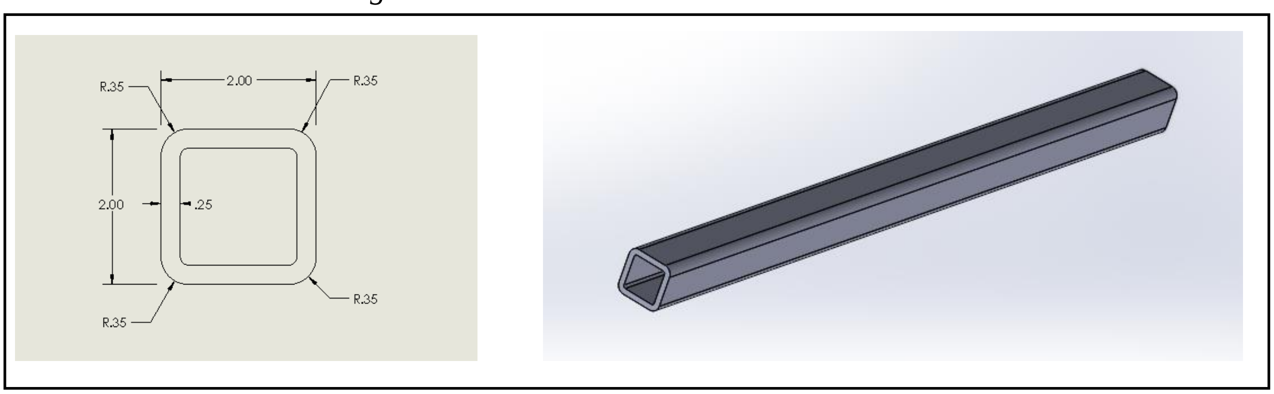

Figure 2-1 2x2x0.25

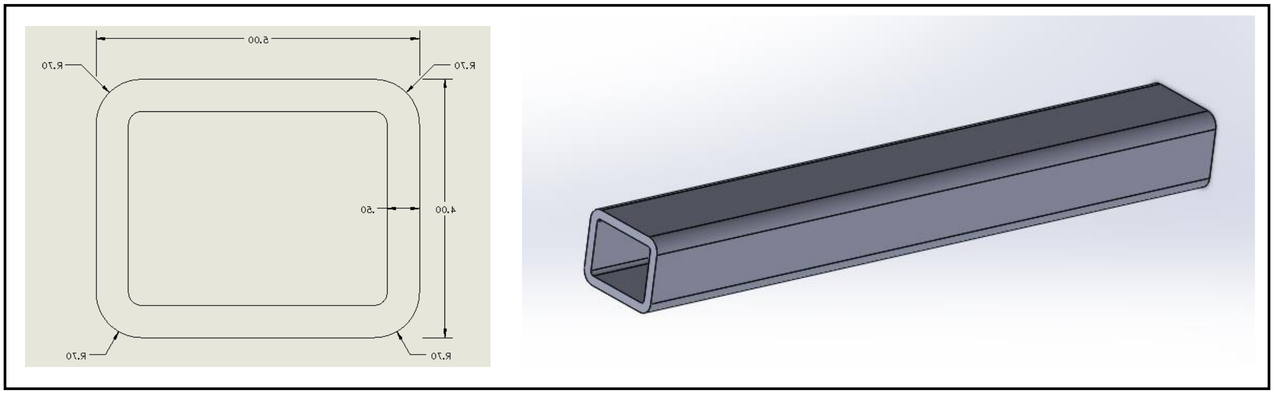

Figure 2-2 5x4x0.5

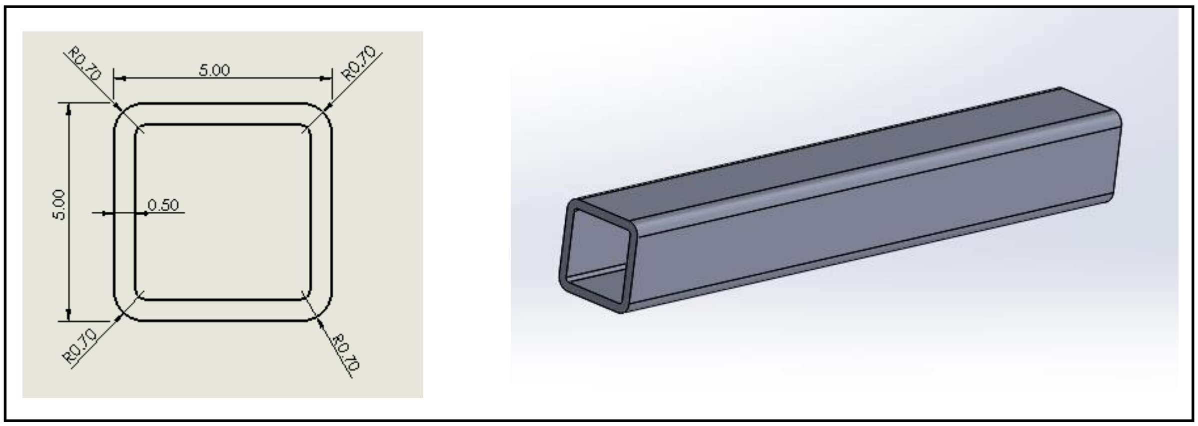

Figure 2-3 5x5x0.5

3 Materials

The materials that have been considered for analysis are Steel A992 and Carbon-Epoxy composite. The properties of these materials are as listed below.

3.1 Steel A992

Density	7.85 g/cm^3
Poisson’s Ratio	0.3
Young’s Modulus	2E11 Pa
Tensile Yield Strength	3.45E8 Pa
Tensile Ultimate Strength	4.5E8 Pa

Table 3-1 Steel Properties

3.2 Carbon Fiber[8]

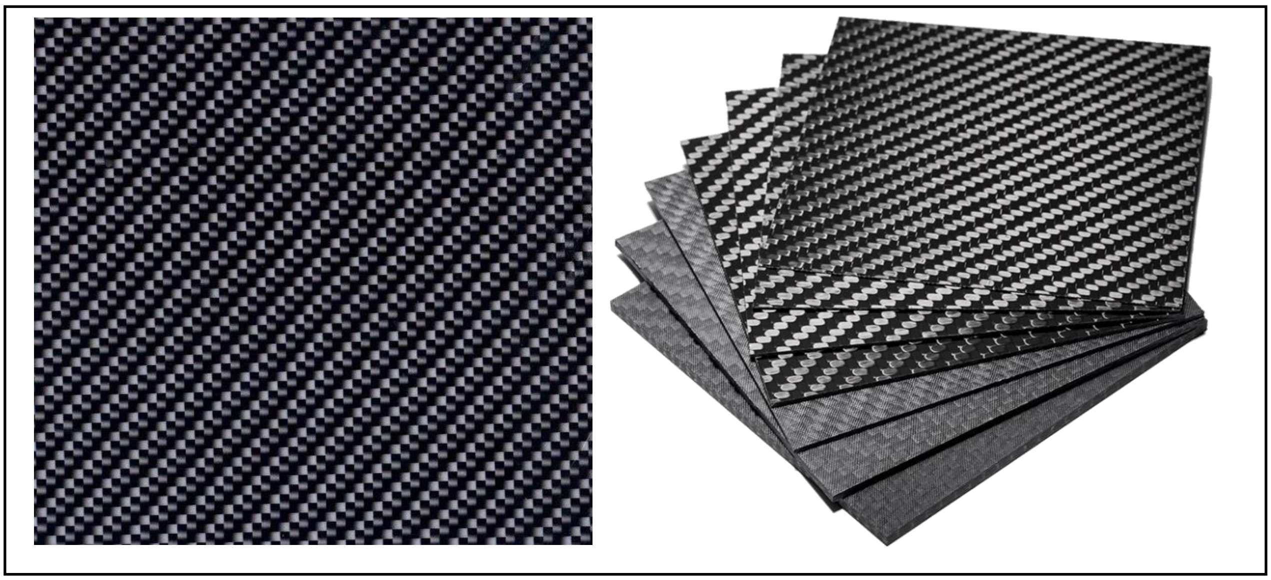

Figure 3-1 Carbon Fiber

Density	1.54 g/cm^3
Young’s Modulus	4.14E11 Pa
Tensile Yield Strength	1.38E9 Pa

Table 3-2 Carbon Fiber Properties

3.3 Epoxy Matrix

Density	1.16 g/cm^3
Poisson's Ratio	0.35
Young's Modulus	3.78E9 Pa
Bulk Modulus	4.2E9 Pa
Shear Modulus	1.4E9 Pa

Table 3-3 Epoxy Matrix Properties

3.4 Carbon-Epoxy Composite (60% fiber volume)

Figure 3-2 Carbon-Epoxy

Young's Modulus 'X' direction	2.49E11 Pa
Tensile Stress 'X' direction	8.28E8 Pa

Table 3-4 Carbon-Epoxy Properties

4 Boundary Conditions

In this chapter, we shall discuss the various boundary conditions used for the simulations of the different load cases. There are primarily three load cases observed, buckling, bending and torsion.

4.1 Buckling

Buckling is characterized by a sudden sideways deflection of a structural member[9]. In case of buckling, there are typically 4 types of boundary conditions, pinned-pinned, fixed-fixed, fixed-pinned, fixed-free. Out of these four, the one that we have considered for our study is the fixed-free condition[10].

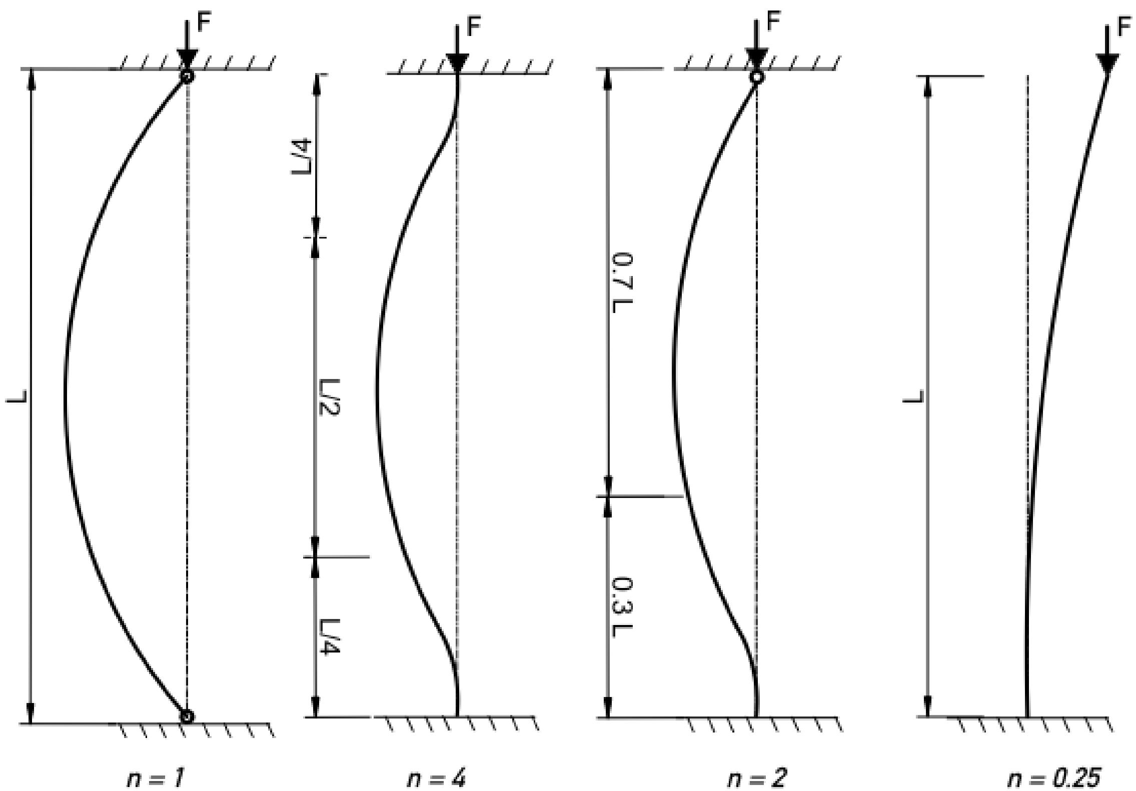

Figure 4-1 Buckling End Conditions

While simulating Eigenvalue buckling in Ansys, the way it works is, we fix one end of the column in all degree of freedom. Then on the other end, we apply a load of 1 lbf. What this does is that, at the end of the simulation, we get a load multiplier value. This load multiplier, as the name suggests, gets multiplied by the applied load to run the simulation which in our case is 1 lbf. This, in turn, gives us the critical buckling load, that is the maximum compressive load the column can withstand before it buckles.

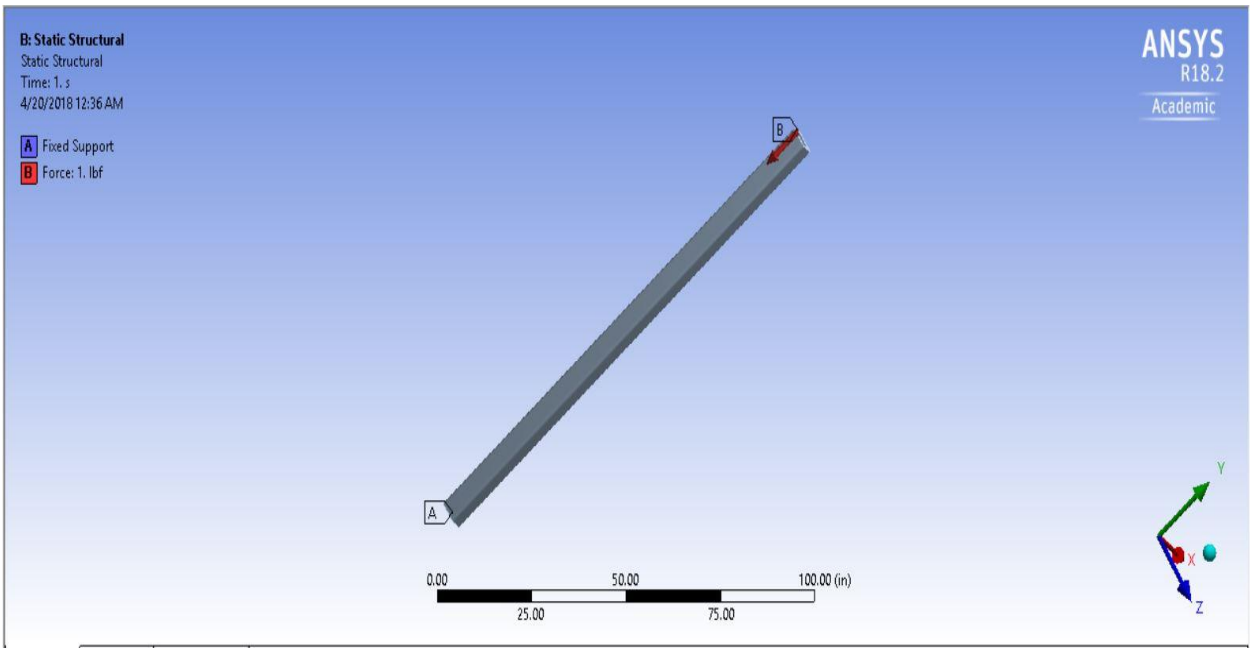

Figure 4-2 Buckling Boundary Condition

In the above figure, the face marked ‘A’ is fixed in all degrees of freedom and the face marked ‘B’ has a compressive force of 1 lbf.

4.2 Bending

We have tried to simulate a 3-point bend test to observe the deformations of the beam to a bending load[11]. The beam is fixed at two places on one face, 2 inches from either end in all degree of freedom and on the face opposite to the one that is fixed, a concentrated load is applied such that safety factor values are within 1.3 and 1.4.

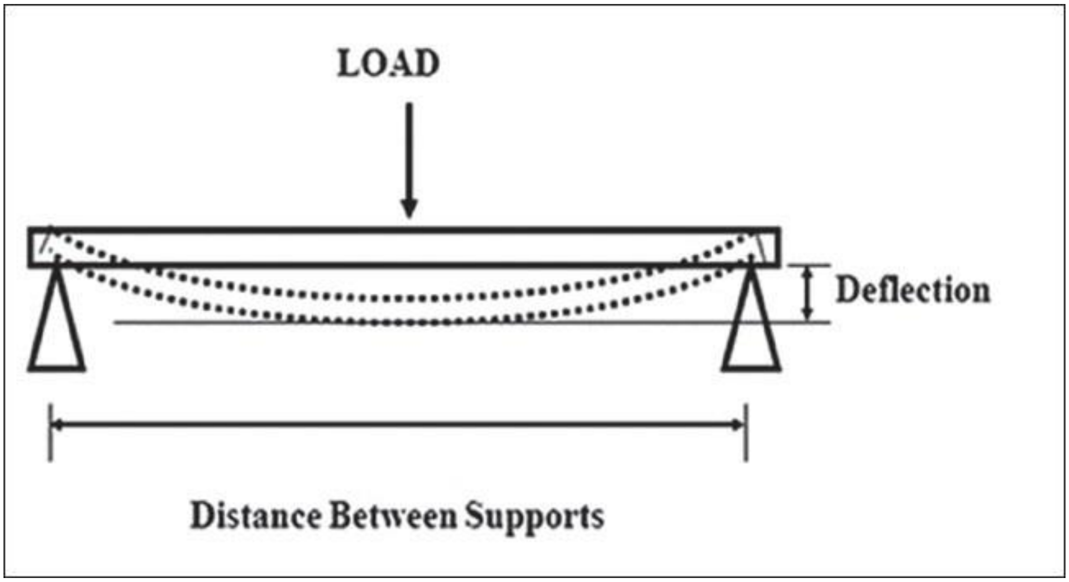

Figure 4-3 Three Point Bend Test

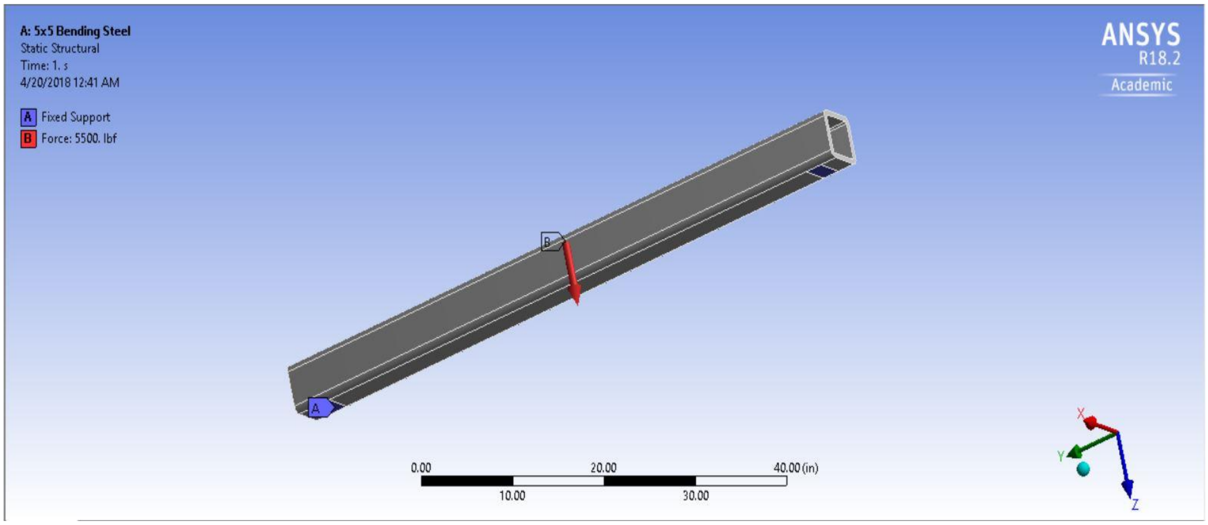

Figure 4-4 Bending Boundary Condition (a)

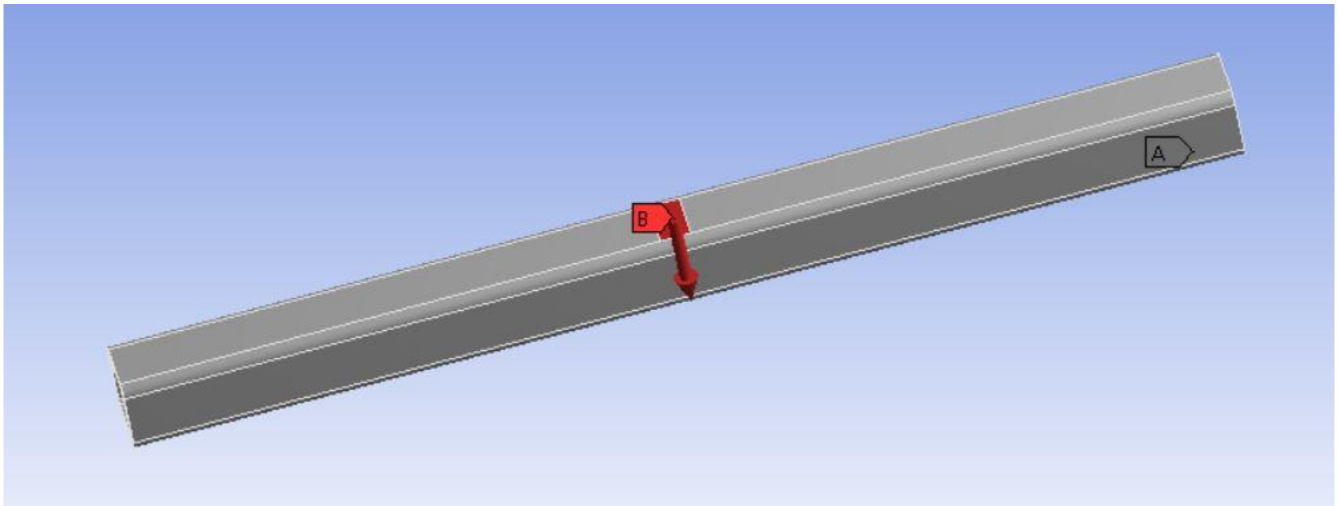

Figure 4-5 Bending Boundary Condition (b)

Figure 4-4 shows the face where the fixed supports are, while the figure 4-5 shows the face opposite to that where the concentrated load is applied, marked as ‘A’ and ‘B’ respectively.

4.3 Torsion

For torsion, the boundary conditions are applied to the same face as that of buckling, one end is fixed and the other end, in place of the compressive force, a moment is applied. The applied moments are different for different cross-sections so that safety factor values are maintained between 1.3 and 1.4.

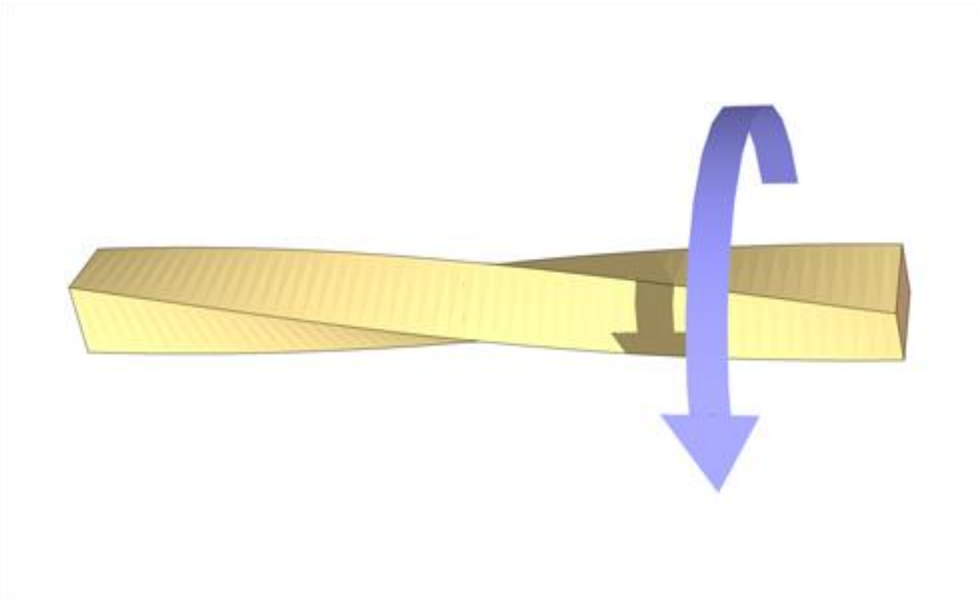

Figure 4-6 Torsion

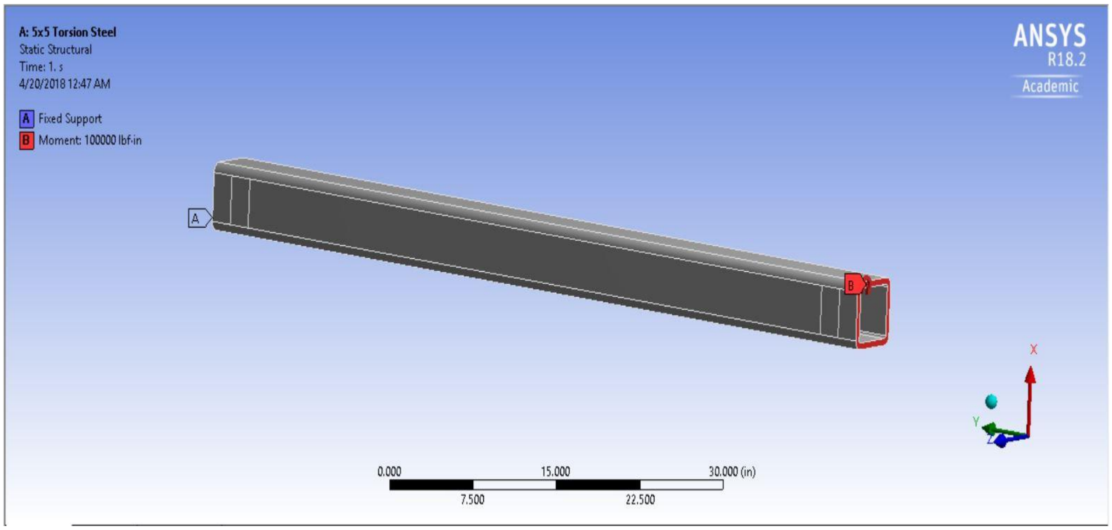

Figure 4-7 Torsion Boundary Condition

As shown in the figure 4-7, the face marked as ‘A’ is fixed in all degrees of freedom and the face marked as ‘B’ has an applied moment.

5 Analysis Set-up

5.1 Project schematic

All the simulations for this study are run using Ansys 17.2. For steel A992 the static structural module is used and for composites, Ansys Composite PrepPost module is used.

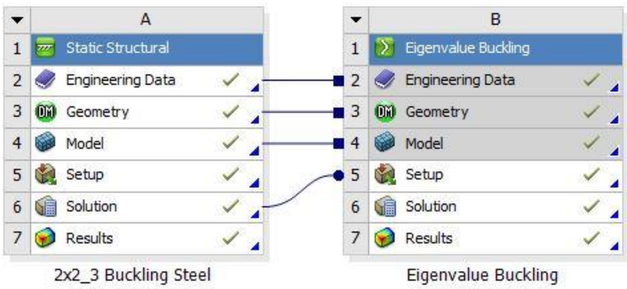

Figure 5-1 Buckling Steel Project Schematic

For buckling analysis of steel member, the project schematic in Ansys is as shown in figure 5-1. The initial analysis to pre-stress the column is done using the static structural module and then the solution obtained is then taken as the input for the eigenvalue buckling module to get the load multiplier to find critical buckling load.

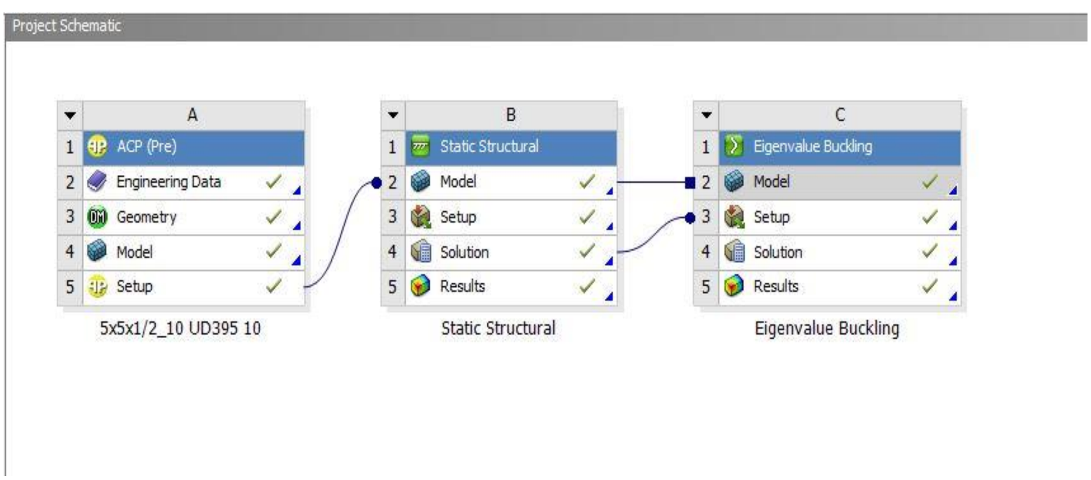

Figure 5-2 Buckling Composite Project Schematic

For buckling of the composite member, the initial lay-up with specific fiber directions are done using Ansys Composite PrepPost module and this is used as an input for the static structural analysis which in turn provides input for the eigenvalue buckling module.

Figure 5-3 Bending and Torsion Steel Project Schematic

Similarly, for bending as well as torsion, just the static structural module is used for analyzing the steel member and for the composite member, the static structural module gets input about lay-up and fiber directions from the Ansys Composite PrepPost module.

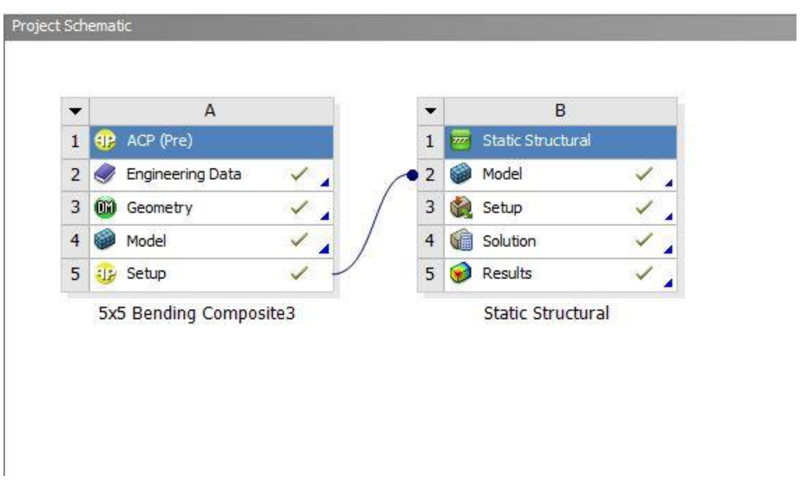

Figure 5-4 Bending and Torsion Composite Project Schematic

5.2 Meshing

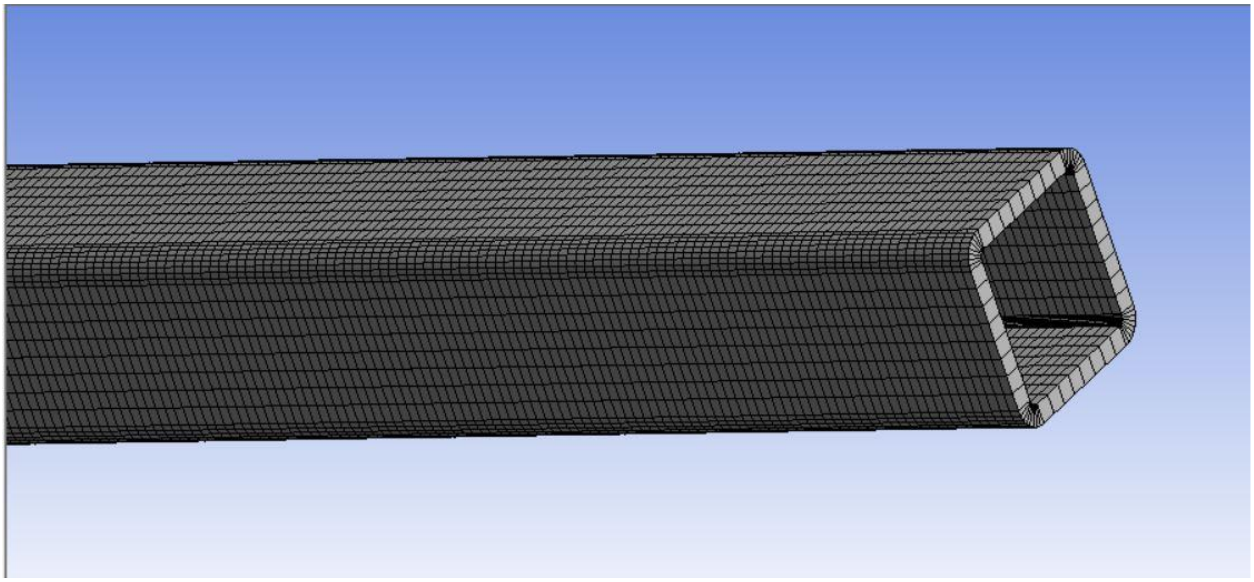

Figure 5-5 Solid Mesh Generated

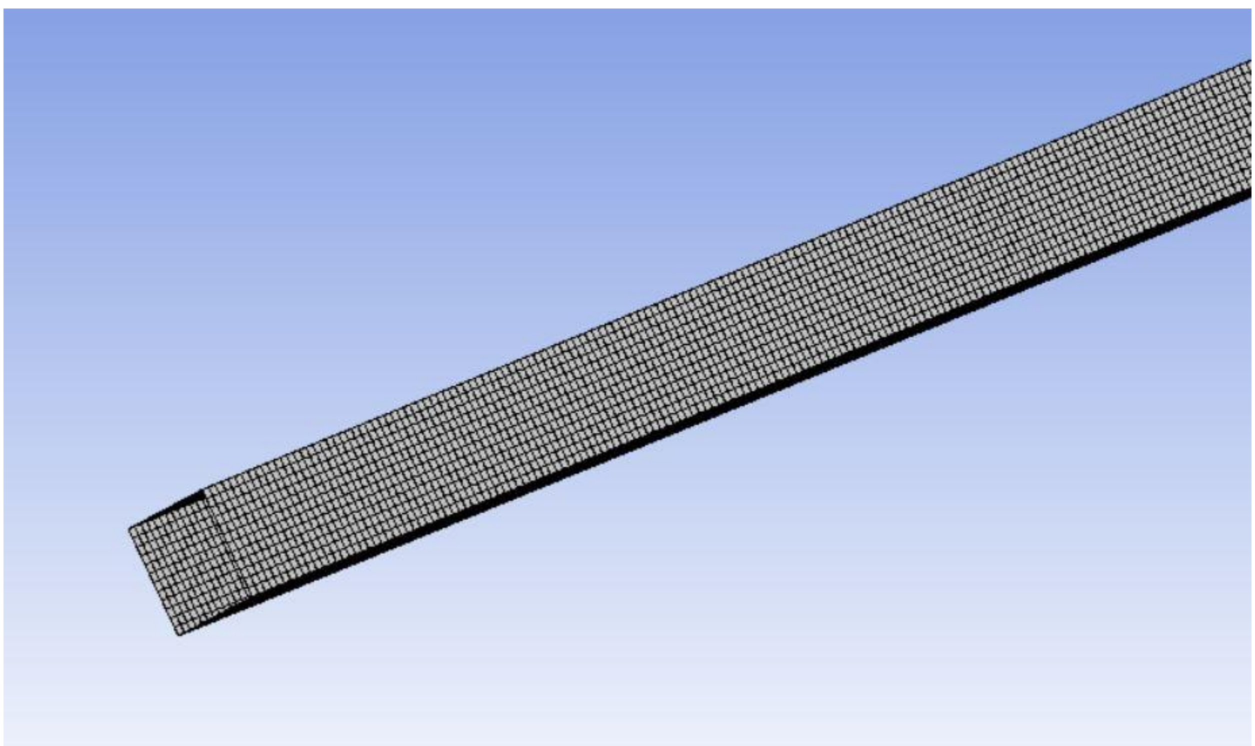

Figure 5-6 Surface Mesh Generated

The meshing for the model has been done in the above depicted manner. Figure 5-5 shows a mesh on a steel member which is a 3-D model. The mesh thus generated comprises solid elements. Figure 5-6 shows a surface body on which the composite layers are going to be laid having a surface mesh, that is it comprises shell elements.

Apart from this, we have used face meshing, edge sizing and body sizing to improve the quality of mesh to the one that is desirable so that we can capture the deformations and stress values more efficiently. For the same reason, all the elements used are higher order quadratic elements. The large deflections feature is also kept 'ON' to incorporate non-linear behavior of the member during simulations.

5.3 Composite lay-up

How the composite layers are laid is determined in the Ansys Composite PrepPost module[12]. Here, the surface geometry of the part is imported which forms the skeleton for the layers to be laid on. The surface model is meshed, and this meshed model is then used as a guide to accurately represent reference fiber directions and the direction of thickness.

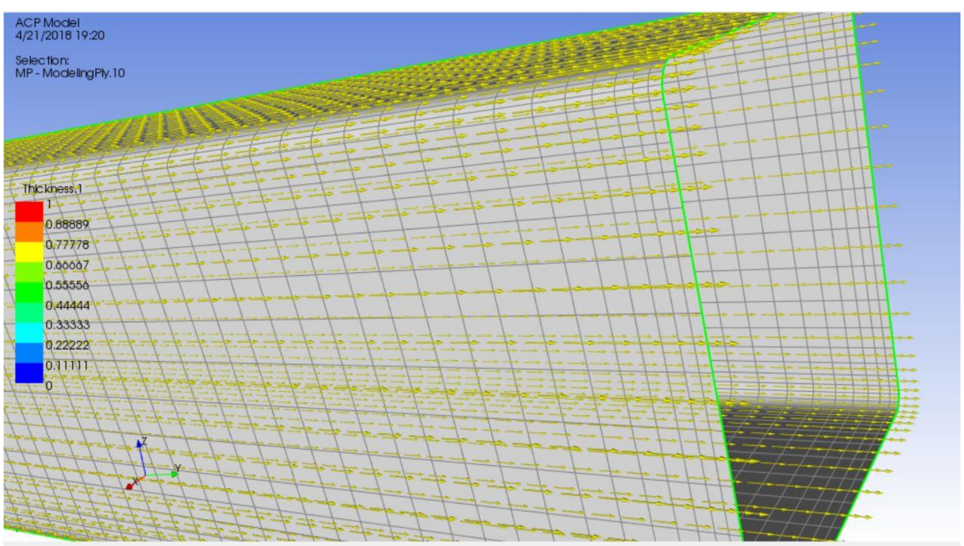

Figure 5-7 Reference Fiber Direction

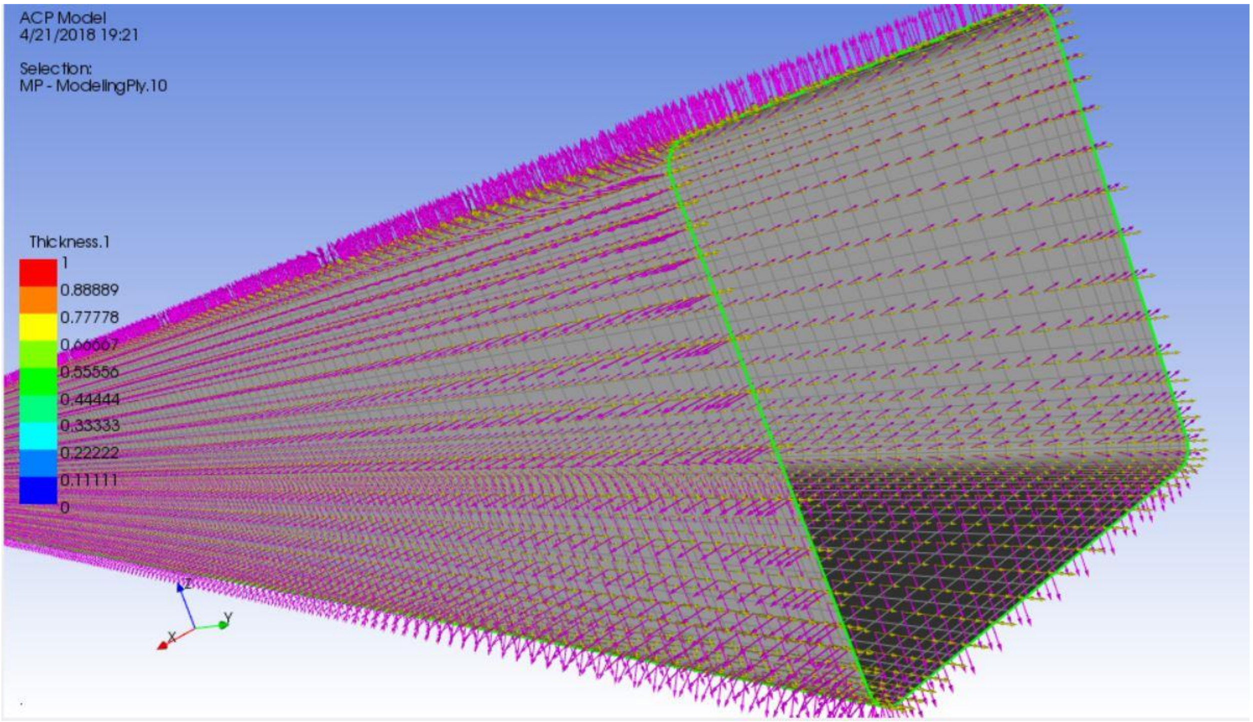

Figure 5-8 Direction of Thickness

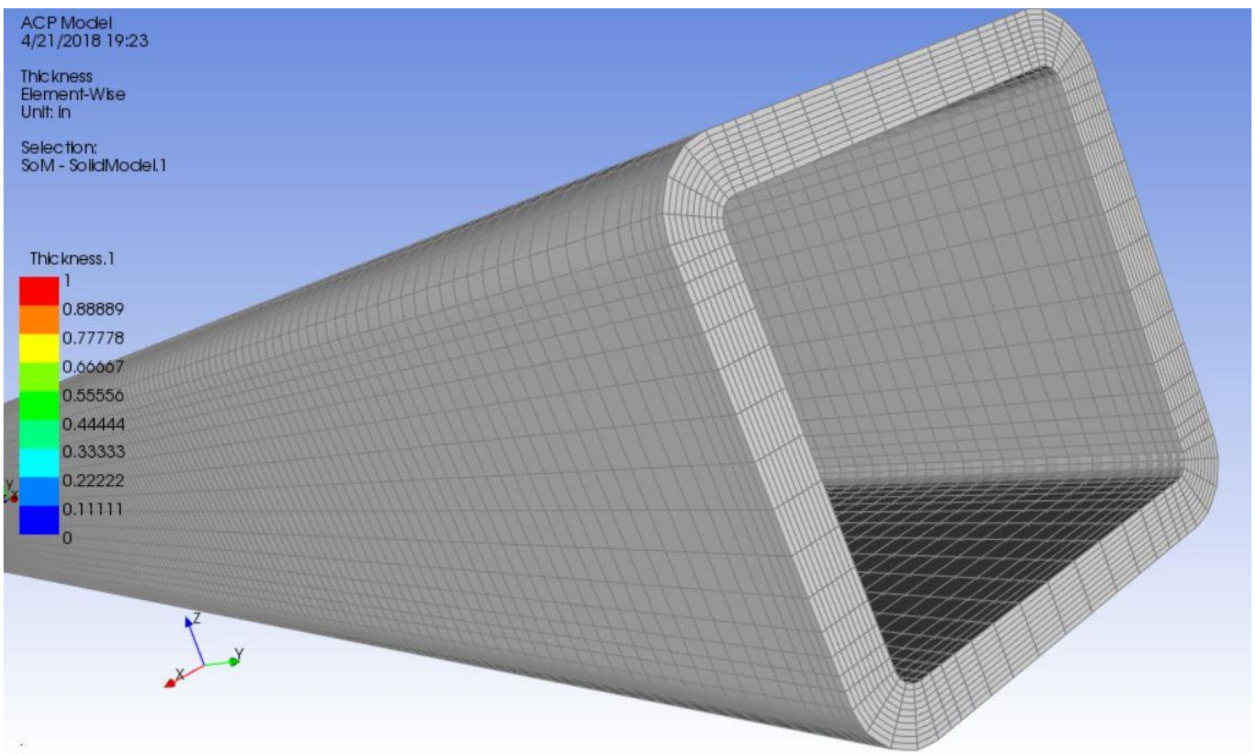

Figure 5-9 Composite Solid Model

Figure 5-7 shows the reference fiber directions on the member, that is the direction in which 0° fibers lie. Figure 5-8 represents the direction for increment in thickness resulting in the solid model shown in figure 5-9. This model is used as an input for running simulations of the various load cases.

6 Results and Comparison

In this chapter, we will be looking at and comparing the results obtained for the different simulations.

6.1 Buckling

In case of buckling, since the load is along the length of the member, we have considered all the layers along the direction of applied force, that is in 0°. Each ply is 10% the thickness of the member. That is, if the member is 0.25” thick, the ply thickness is 0.025” and similarly if the member is 0.5” thick then the ply is 0.05” thick. This leads to a total of 10 plies in 0° direction making up the entire thickness. The stacking sequence is represented as $[0_{10}]$.

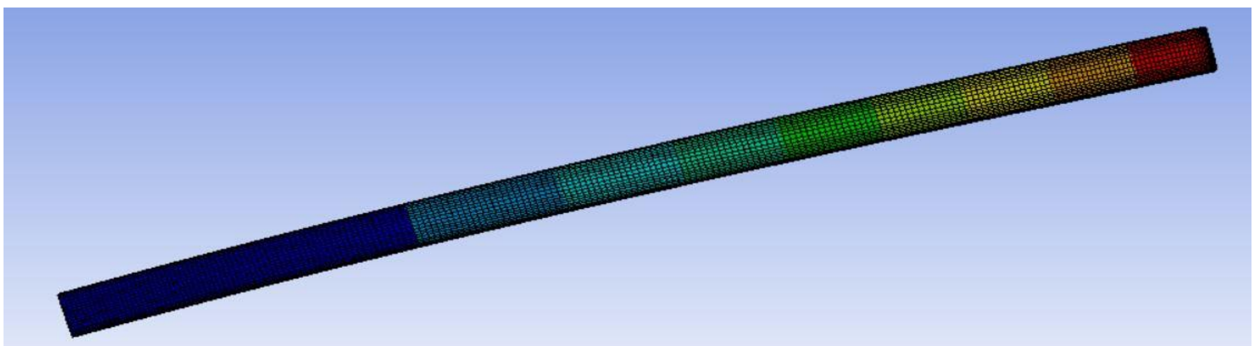

Figure 6-1 Buckling Deformation

Figure 6-1 shows the deformation of the column under buckling load. The critical buckling load for steel and composite columns are as follows.

Cross-section Inch	Length Feet	Steel lbs	Carbon-Epoxy lbs
2x2x0.25	3	4.55E4	5.19E4
2x2x0.25	10	4.14E3	5.07E3
5x4x0.5	3	8.8E5	6.92E5
5x4x0.5	10	8.1E4	9.66E4
5x5x0.5	3	1.52E6	8.2E5
5x5x0.5	10	1.4E5	1.6E5

Table 6-1 Critical Buckling Load

From data in table 6-1, we can see that in case of carbon-epoxy, the critical buckling load is more than that of steel A992 in every case except for two cases where the column is short with a wide cross-section. But, in every situation where the column length is long, carbon-epoxy has a much higher resistance to buckling as compared to steel A992.

6.2 Bending

Unlike the stacking sequence used for buckling, the composite lay-up for bending consists of +/-45° plies towards the center of the stacking sequence. This helps in resisting the bending force in a much better way. The ply thickness remains the same as the one used for buckling resulting in a lay-up as shown. [0_4/+45/-45/0_4]

But, with this, we could not achieve the resistance to bending as shown by steel. Hence, we increase the wall thickness by 20% (2 extra plies) and then by 40% (4 extra plies). The idea was to maintain the outer dimensions while increasing the wall thickness. The stacking sequence used was [0_5/+45/-45/0_5] for 20% increment in thickness and [0_6/+45/-45/0_6] for 40% increment.

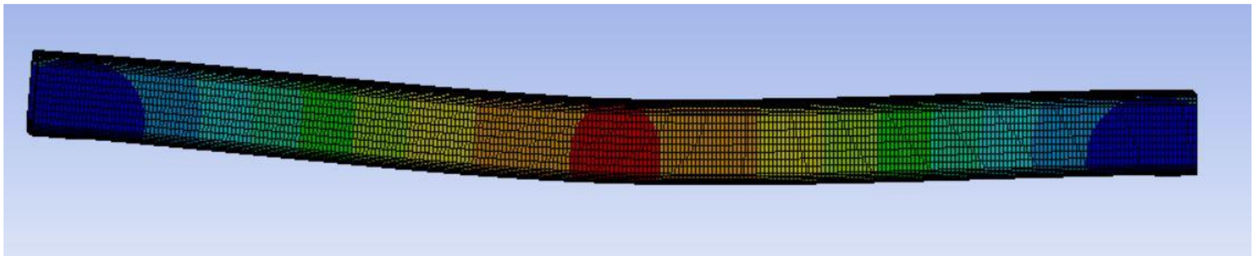

Figure 6-2 Bending Deformation

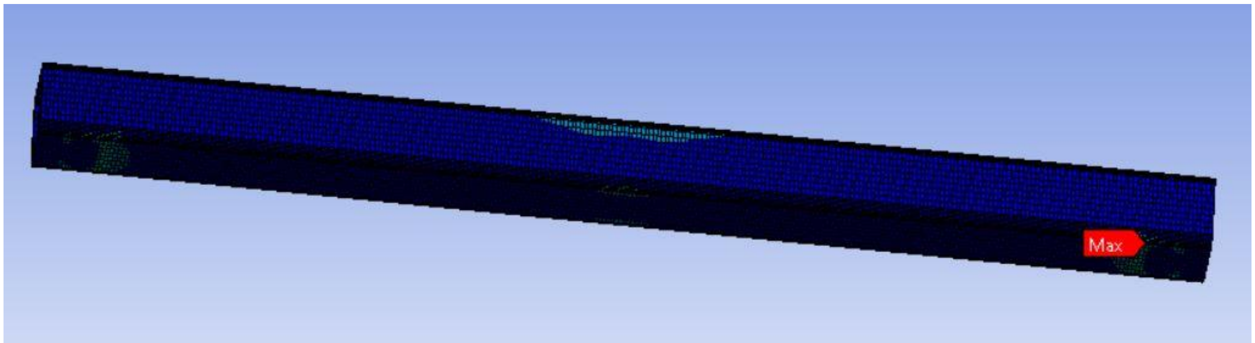

Figure 6-3 Bending Stress

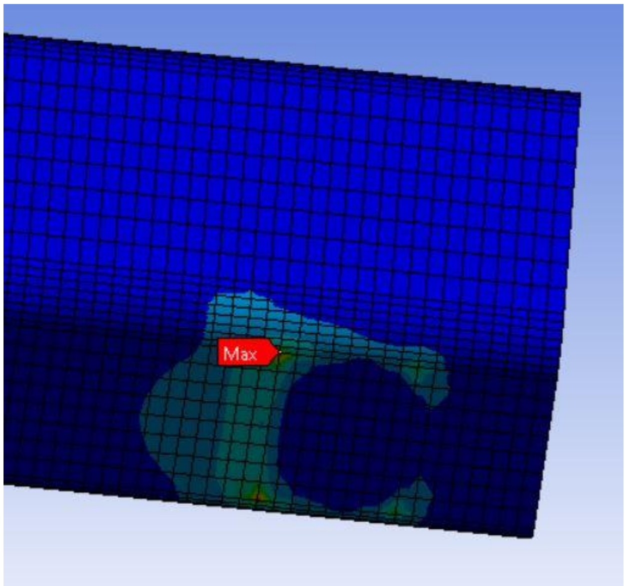

Figure 6-4 Bending Stress Magnified

Figure 6-2 shows the deformation observed during bending and figures 6-3 and 6-4 show the location of maximum stress experienced. We can see that the maximum stress is observed at the edge where the beam was fixed, and the maximum deformation is observed at the point of application of concentrated load.

The deformation for steel and composites with varying wall thickness are tabulated below along with their safety factor.

Cross-section Inch	Thickness Increased %	Load lbf	Steel Deformation Inch	Carbon-Epoxy Deformation Inch	Steel S.F	Carbo-Epoxy S.F
2x2x0.25	0	500	0.037	0.062	1.41	0.27
	20			0.051		0.33
	40			0.039		1.36
5x4x0.5	0	3500	0.024	0.051	1.31	1.05
	20			0.038		1.13
	40			0.027		1.21
5x5x0.5	0	5500	0.027	0.062	1.43	0.64
	20			0.043		0.93
	40			0.031		1.24

Table 6-2 Bending Deformation and Safety Factor

From data in table 6-2, we can see that the deformation and safety factor values for steel (green text) and carbon epoxy composite with 40% increased wall thickness (red text) are very close to each other.

To get a better idea of the resistance to bending, we calculated the bending stiffness and the specific bending stiffness, that is the bending stiffness per unit mass for both steel and carbon-epoxy. The formula for bending stiffness is given by the applied force divided by the amount of deflection. The results of which are as follows.

Bending Stiffness

Cross-section Inch	Steel lb/in	40% thick Carbon-Epoxy lb/in
2x2x0.25	1.32E4	1.28E4
5x4x0.5	1.45E5	1.29E5
5x5x0.5	2.04E5	1.77E5

Table 6-3 Bending Stiffness

Specific Bending Stiffness

Cross-section Inch	Steel	40% thick Carbon-Epoxy
2x2x0.25	400.28	1386
5x4x0.5	932.65	3026.75
5x5x0.5	1159.88	3669.91

Table 6-4 Specific Bending Stiffness

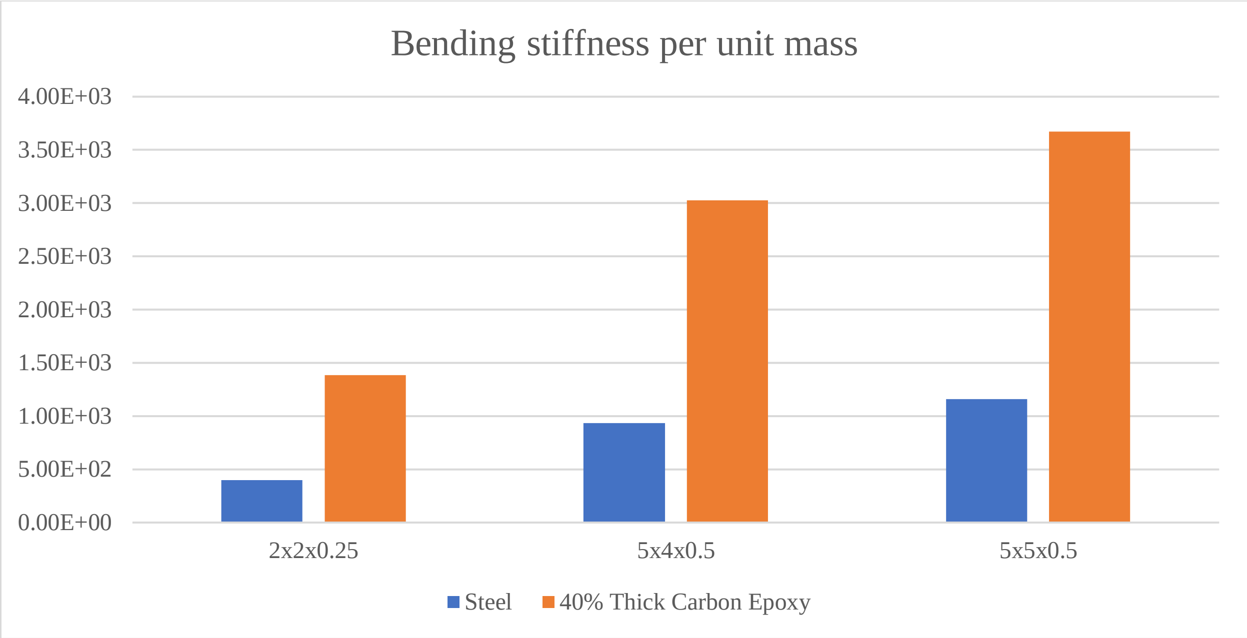

Figure 6-5 Specific Bending Stiffness

From data in table 6-4 and graph in figure 6-5, we can see that even though the bending stiffness for carbon-epoxy is a bit less than that of steel, the specific bending stiffness is three times the value of steel.

6.3 Torsion

In case of torsion though, as compared to bending and buckling, it took a lot more iterations to get the degree of rotation and safety factor values of composite close to steel. First, the number of +/-45° plies had to be increased to accommodate the torque, second, we had to incorporate 90° plies in the stack up for increasing the safety factor values.

The stack up sequences that were experimented with are as follows

$[0_4/+45/-45/0_4]$ for 0% increase in wall thickness.

$[0_5/+45/-45/0_5]$ for 20% increase in wall thickness.

$[0_4/+45/-45/+45/-45/0_4]$ for 20% increase in wall thickness.

[0/90/0/+45/-45/+45/-45/+45/-45/0/90/0] for 20% increase in wall thickness.

[0/90/0/90/+45/-45/+45/-45/+45/-45/90/0/90/0] for 40% increase in wall thickness.

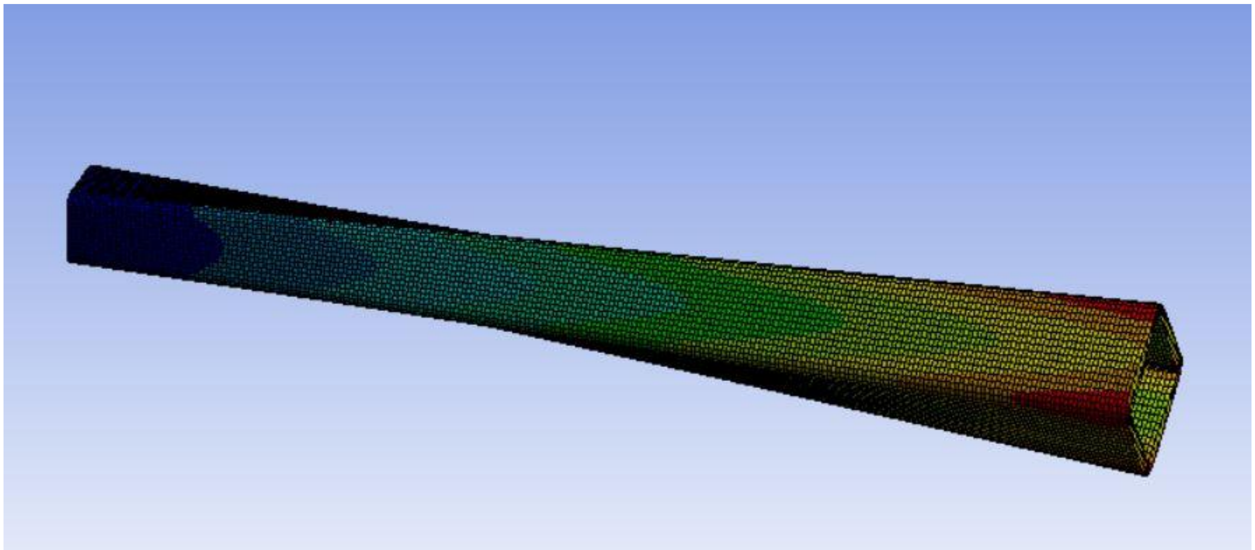

Figure 6-6 Torsional Deformation

The degree of rotation and safety factor values for each of the cross-sections with the above-mentioned stack up sequences are as follows.

2x2x0.25: 10,000 lbf-in

Thickness increased %	Steel Rotation Degrees	Steel S.F	+/-45° Plies	Carbon-Epoxy Rotation Degrees	Carbon-Epoxy S.F
0	2.61	1.41	1	12.07	0.26
20			1	12.25	0.31
20			2	7.54	0.32
20			3	5.41	1.12
40			3	5.83	0.98

Table 6-5 Torsional Deformation and Safety Factor for 2x2x0.25

5x4x0.5: 80,000 lbf-in

Thickness increased %	Steel Rotation Degrees	Steel S.F	+/-45° Plies	Carbon-Epoxy Rotation Degrees	Carbon-Epoxy S.F
0	0.9	1.31	1	4.41	0.22
20			1	4.3	0.23
20			2	2.73	0.24
20			3	1.9	0.98
40			3	2.03	0.35

Table 6-6 Torsional Deformation and Safety Factor for 5x4x0.5

5x5x0.5: 100,000 lbf-in

Thickness increased %	Steel Rotation Degrees	Steel S.F	+/-45° Plies	Carbon-Epoxy Rotation Degrees	Carbon-Epoxy S.F
0	0.7	1.31	1	3.64	0.29
20			1	3.61	0.33
20			2	2.23	0.35
20			3	1.59	1.23
40			3	1.67	0.44

Table 6-7 Torsional Deformation and Safety Factor for 5x5x0.5

From data in tables 6-5,6-6, and 6-7, we can see that the closest we got to the values of steel were when we used three pairs of +/-45° plies along with 90° plies while increasing the wall thickness by 20%.

Just as we did for bending, to get a better idea of the resistance to torsion, we calculated the torsional stiffness and the specific torsional stiffness, that is the torsional stiffness per unit mass for both steel and carbon-epoxy. The formula for torsional stiffness is given by the applied torque divided by the amount of rotation. The results of which are as follows.

Torsional Stiffness

Cross-section Inch	Steel Torque/degree twist	20% thick Carbon-Epoxy Torque/degree twist
2x2x0.25	3.83E3	1.84E3
5x4x0.5	8.88E4	4.21E4
5x5x0.5	1.42E5	6.28E4

Table 6-8 Torsional Stiffness

Specific Torsional Stiffness

Cross-section	Steel	20% thick Carbon-Epoxy
2x2x0.25	113.48	238.19
5x4x0.5	566.03	1173.83
5x5x0.5	807.36	1546.42

Table 6-9 Specific Torsional Stiffness

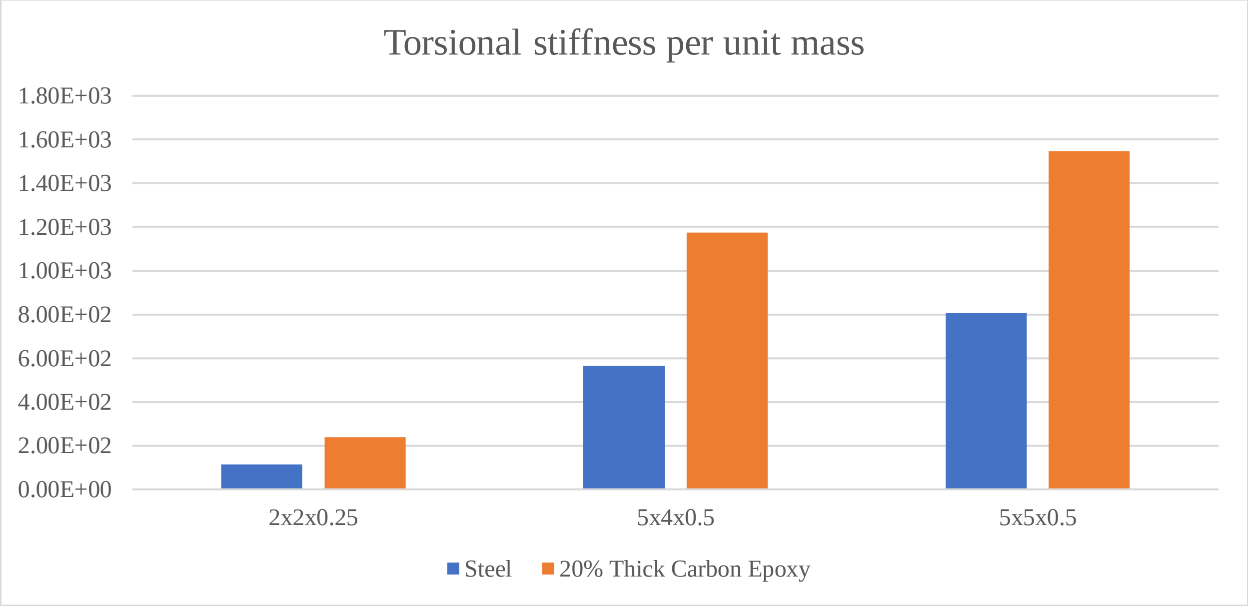

Figure 6-7 Specific Torsional Stiffness

From data in table 6-9 and graph in figure 6-7, we can see that even though the torsional stiffness for carbon-epoxy is considerably less than that of steel, the specific torsional stiffness is almost two times the value of steel.

6.4 Weight

The major advantage of using composites (Carbon-Epoxy in this case) instead of steel is the fact that composites are very light as compared to steel.

Cross-section Inch	Steel lbm	0% lbm	20% lbm	40% lbm
2x2x0.25	33.76	6.62	7.76	9.25
5x4x0.5	155.47	30.49	35.87	42.62
5x5x0.5	175.88	34.51	40.67	48.23

Table 6-10 Weight

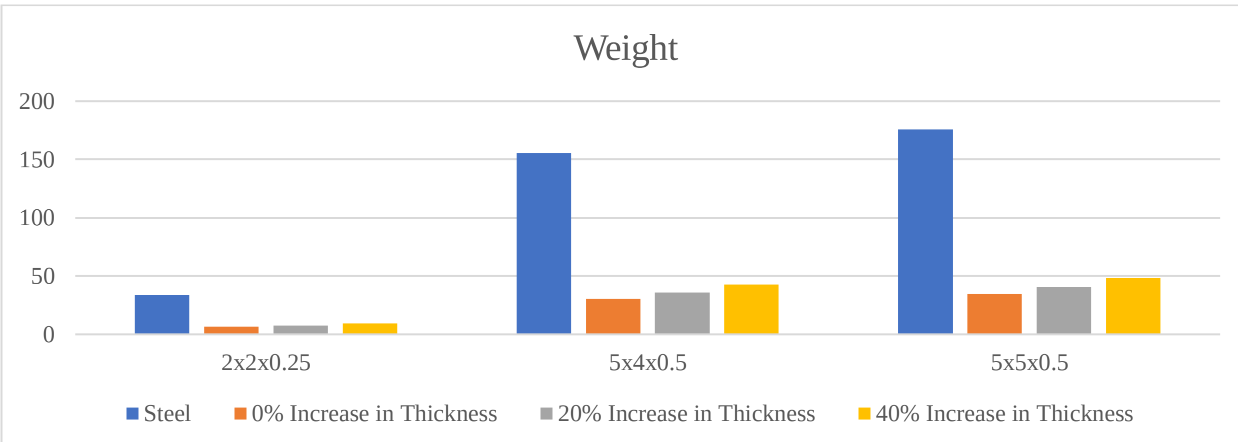

Figure 6-8 Weight

As we can see from the table 6-10 and graph in figure 6-8, the weight of carbon epoxy even after a 40% increase in wall thickness is just one third that of steel.

7 Conclusion

Looking at the results from the above tabular and graphical data, we can conclude that steel A992 has a better resistance to an applied load and good safety factor values along with it as compared to the same applied load on a carbon-epoxy composite member in a lot of cases, especially torsional load cases.

In case of buckling, we can see that the critical buckling load for a carbon-epoxy composite member is a lot higher than the critical buckling load for steel A992 except in two situations, 5x4x0.5 and 5x5x0.5 that are 3 feet in length.

As for bending, after increasing the wall thickness by 40% in case of the composite, the difference in bending deformation and safety factor values are minimal for steel A992 and carbon-epoxy composite. When we look at the specific bending stiffness of both these materials, the situation is different. Carbon-epoxy composites have almost three times the specific bending stiffness as compared to steel A992.

Now going to the torsional load case, even with the increase in wall thickness by 20% and increasing the number of +/-45° plies along with incorporating 90° plies, the deformation for carbon-epoxy is twice the deformation of steel A992 and the safety factor values are also comparatively bad. Although the specific torsional stiffness is twice that of steel A992, which is a good thing.

From the different conditions considered in this study, we can infer that the advantage in using composites is the weight difference. Even with a 40% increase in wall thickness, the weight of carbon epoxy composite is one third that of steel A992. This results in reducing the actual load acting on composite members and the loads never reaching the values used to compare steel A992 and carbon-epoxy in the above simulations. Thus getting better safety factors and lesser deformation for carbon-epoxy which steel A992 will not be able to achieve. Also, one other advantage is that in composites we can change the direction plies are laid up in to suit different loading conditions.

8 Future Work

Some suggestions that can be made to analyze using of composites to replace steel in civil engineering applications are as follows.

- Analysis on open contoured cross-sections.
- Use of hybrid composites.
- Design and analysis of connections to adjacent members.
- Analysis as a frame to account for the combined effect of more than one type of loading condition mentioned in this study.

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