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Torsional Stiffness Comparison of Different Tube Cross-Sections of a Formula SAE Car Space Frame

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Abstract. Since torsional loading and the accompanying deformation of the frame and suspension parts can affect the handling and performance of the car, torsional stiffness is generally thought to be a primary determinant of frame performance for a FSAE car. According to the FSAE Rules, different tube cross-sections are available for some members of a space frame. By finite element simulation, this research compared different tube shapes and thicknesses. Compared with 1.6 mm thickness round tube, square tube with the same wall thickness can improve the torsional stiffness by 23% in test Mode I, and 65% in test Mode II. The 1.2mm thickness square tube also can improve the torsional stiffness by 6% and 39% in test Mode I and Mode II. From these comparisons, it can be found the usage of square tube can improve the frame torsional stiffness efficiently.

1 Introduction

FSAE is a competition sponsored by the Society of Automotive Engineers (SAE). Several kinds of frame styles are available in this competition, space frame, monocoque frame, and ladder frame etc. The most commonly used are monocoque frame and space frame [1, 2]. A space frame is a kind of separate frame construction. The purpose of the frame is to rigidly connect the front and rear suspension while providing attachment points for supporting the different systems of the car [3].

The original frame of this research is from a FSAE electric car, which successfully performed in 2016 competition season.

Based on the original frame design, this research focus on how different tube cross-sections effect on the torsional stiffness of a vehicular frame. Comparisons were simulated by considering different boundary conditions.

2 Modelling

2.1 Finite element model

A frame is mainly consisted by tubes, which can be simplified to beam elements in a finite element (FE) analysis. This research conducted the analysis of the space frame by commercial finite element software ABAQUS.

As shown in Figure 1, the frame is constructed by 86 members, and the cross-sections are defined as beam section. The selected material is Steel 4130, mechanical properties is listed in Table 1. Steel 4130 is a very commonly used material for making a space frame due to its good structural property [4].

The model is meshed by 2-node linear beam elements; element type is B31 in ABAQUS. The approximate global mesh size is 5mm, total number of elements used in this frame model is 7652.

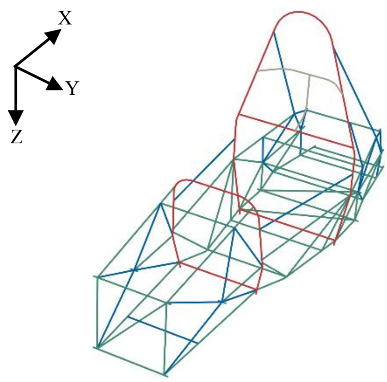

Figure 1. Tubular frame FE model.

Table 1. Material Properties

Properties	**4130 Steel**
Young’s Modulus (GPa)	210
Density (g/cm^3)	7.8
Poisson's Ratio	0.27

2.2 Different tube shapes

The FSAE rules [5] define a minimum size for all the frame members, to avoid adding un-necessary weight, the frame design should make best use of the required members and optimize the size of the members. The rules require different cross-sections of the tubes according to the components location, as shown in Figure 1 and Table 2, different colours represent different tube cross-sections. The parameters in Table 2 were used in the competition of year 2016, which were proofed to be satisfied FSAE rules. However, the rules also provide alternative shape of some members. For example, the green members in Figure 1 can be manufactured by square shape tubing.

Table 2. Member size.

Colour	Outside Dimension(mm) ×Wall Thickness(mm)
Red	Round 25.4×2.4
Green	Round 25.4×1.6
Blue	Round 25.4×1.25
Grey	Round 14×1.5

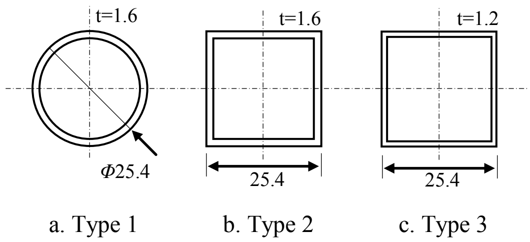

Figure 2. Square and round tubing.

This research studied three different tube shapes of green members, as illustrated in Figure 2, Type 1 is the original cross-section; Type 2 is square shape with outside dimension 25.4mm and wall thickness 1.6mm; Type 3 is square shape with outside dimension 25.4mm and wall thickness 1.2mm. All types are allowed by the rules.

2.3 Boundary Conditions

To make the simulation more accurate, the frame model is connected with MPC control points. This model verifies the condition to be the most related to the real rods and frame connection.

Torsional stiffness is an important influence factor of the racing car riding performance. Since the frame is not equidistant in the longitudinal direction, two modes will be considered and two kinds of boundary conditions are applied to the model.

Mode I is explained by Figure 3, the load F=1000N is perpendicularly applied on the two front sides with opposite directions at point A and B. The rear sides are fixed at point C and D [6].

Similarly, Mode II is explained by Figure 4, the load F is perpendicularly applied on the two rear sides with opposite directions at point C and D. The front sides are fixed at point A and B.

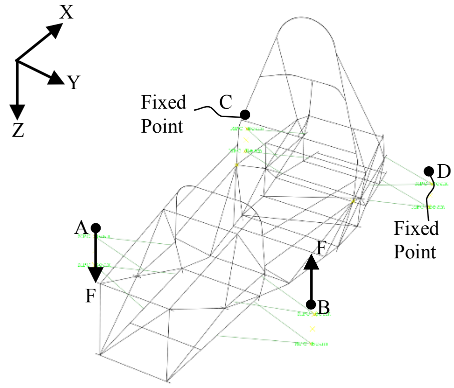

Figure 3. Mode I boundary conditions.

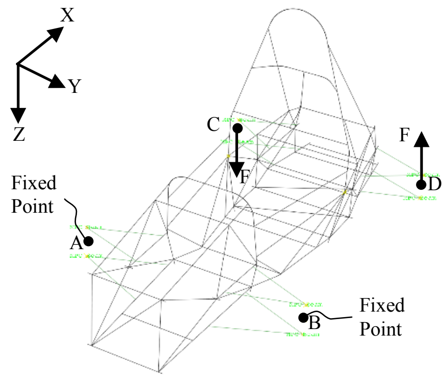

Figure 4. Mode II boundary conditions.

3 Torsional stiffness calculation

The torsional stiffness simulation was performed as shown in Figure 3 and Figure 4. The load is applied and produced the torque to the frame. Then, the torque applied on the frame can be determined by

$$T=FL \tag{1}$$

Where L is the distance between point A and B (Mode I), or C and D (Mode II).

The torsional stiffness can be described by the rotation angle produced by torque load [7, 8], the angle can be calculated from

$$\theta=arctan[(z_1+z_2)/L] \tag{2}$$

Where z1 and z2 are the magnitude of the vertical displacement caused by the torque on point A and B (Mode I), or C and D (Mode II) of the chassis.

And the torsional stiffness, K can be determined from

$$K=T/\theta \tag{3}$$

4 Results and Discussion

4.1 Torsional Stiffness

Three types of tube cross-sections and two test modes, total six combinations were simulated to calculate the torsional stiffness.

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The compared results are listed in Table 3, it clearly shows that in both Mode 1 and Mode 2, if the green members use Type 2 and Type 3, the space frame have considerable improvement compared with Type 1.

In the condition of Mode 1, the torsional stiffness of Type is 23% higher than Type 1; Type 3 is 6% higher than Type 1.

In the condition of Mode 2, the comparison is more obvious, the torsional stiffness of Type 2 is 65% higher than Type 1; Type 3 is 39% higher than Type 1.

Gross mass value also can be outputted from ABAQUS data file, and the results are compared in Table 4. This table present that if the square tube Type 2 has the same wall thickness with the original round tube Type 1, the frame weight is 18% increased; however, if the square tube reduced the wall thickness to 1.2mm (Type 3), the weight is 2% decreased.

From Table 3 and Table 4, it can be found that the usage of Type 3 in green members is the better alternative choice, it can reduce the weight slightly and increase the torsional stiffness considerably. Also the choice of Type 3 is allowed by the competition rules.

Another phenomenon also should be pointed out, in comparison of Mode I and Mode II, the torsional stiffness of the rear fame is higher than the front frame, especially when the square shape tubing is used. This is a reasonable distribution of torsional stiffness, the rear frame has more important influence on the vehicle handling stability and riding performance; if the rear frame suffers large deflection, it will change the roll stability and rear axle steering characteristic [9].

Table 3. Frame torsional stiffness (Unit: Nm/Deg).

	Type1	Type 2 (Difference)	Type 3 (Difference)
Mode1	1438	1765 (23%)	1522 (6%)
Mode2	1553	2556 (65%)	2153 (39%)

Table 4. Frame mass (Unit: Kg).

	Type1	Type2 (Difference)	Type3 (Difference)
Mass	33.39	39.46 (18%)	32.74 (-2%)

4.2 Torsional Angle Curve

To plot the torsional angle curve, a set of data point points should be selected on both bottom sides of the frame along longitudinal direction, as marked in Figure 5. The displacement magnitude in Z direction of left and right sides points (total 434 points) will be outputted. The distance between each pair of left and right point is known, the torsional angle can be determined by using Equation (2).

The results of torsional angle are plotted in Figure 6 and Figure 7. Horizontal axis is the coordinate of the frame in X direction, the original zero-point means front wheel vertical centre line; vertical axis is the torsional angle of the selected points.

Figure 6 shows the results of Mode I, the angle decreases as the data points change from front to rear. The trend of Figure 7 is on the contrary, the angle increases as the data points change from front to rear.

For different cross-section types, these comparisons show that the maximum torsional angle of Mode I is higher than Mode II, this also confirm that the space frame has higher torsional stiffness at the rear part.

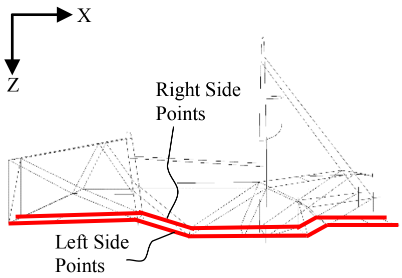

Figure 5. Data points location on the frame.

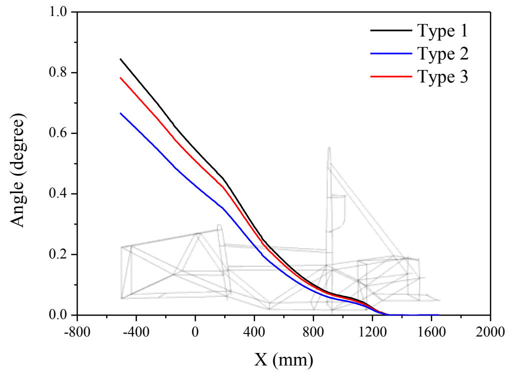

Figure 6. Frame torsional angle curve (Mode I).

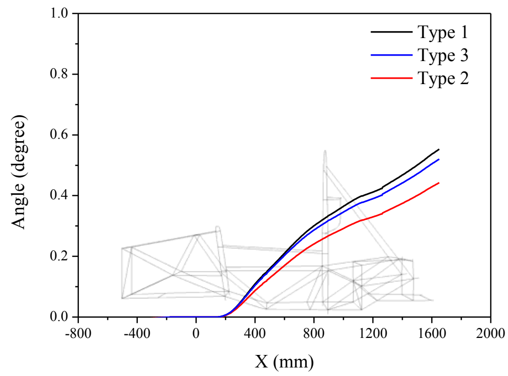

Figure 7. Frame torsional angle curve (Mode II).

Under the condition of satifying FSAE rules, every team intends to make the racing car have lighter weight and better riding performance. During the frame design process, works are usually done by optimizing the geometry structure. Based on the frame model of privious optimization study, this research additionally studied the influence of the different cross-section of the tubes.

Two different torsional stiffness test modes were considered, it can be clearly conclued the rear part has higher torsional stiffnes than front part. As disscussed in

Part 4.1, this trend accords with the ride characteristics of a FSAE car.

There tube types tube were disscussed, Type 1, Type 2 and Type 3. If green members have the same 1.6mm wallthickness (Type 1 and Type 2), square tubing has much better performance in torsional stiffness ; if the square tubing wallthickness is 1.2mm (Type 3), it also performs better than round tubing with 1.6mm wallthickness (Type 1), and even has 2% lighter weight.

This research studied the simulation methods of torsional stiffness test of a FSAE car frame, and disscussed the feasibility of square tubing. It can be seen that square tubing can be used in frame optimization to improve the torsional stiffness and frame weight.

Acknowledgment

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