SAE Student Formula Space Frame Design and Fabrication

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Abstract

The purpose of this research is to design and manufacture a space frame for Chulalongkorn University FSAE team in "The FSAE Student Formula 2011 Competition". The requirements for the frame are mass less than 30kg and torsional stiffness of the whole car more than 1200Nm/deg, which are important values that determine the frame performance level. The design is generated using the computer aided program, CATIA, and then the finite element analysis (FEM) is performed in order to determine the mass and torsional stiffness of the frame. After analysis, the frame is constructed and the torsional test is performed to determine the torsional stiffness of the frame. The results are compared and the 2011 frame is decided. The 2011 frame has torsional stiffness of 1030Nm/deg and with the mass of 29.8kg which accomplish the requirements of the frame.

***Keywords**:* Space frame, SAE student formula, Torsional stiffness.

1. Introduction

Frame is one of the most important parts in automobile is the frame. It is the main structure in order to create car. 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. Relative motion between the front and rear suspension attachment points can cause inconsistent handling. The frame must also provide attachment points which will not yield within the car's performance envelope. There are many different styles of frames for example space frame, monocoque, and ladder frames [1]. A frame for competitive car would have high rigidity and lightweight which are important factors in every frame of vehicles. The most common frame styles used in the FSAE competitions are the monocoque and space frame.

Monocoque is a construction technique that supports structural load by using an object's exterior. It is generally made as one piece. The use of composite materials in monocoque skins allows strength, stiffness and flexibility to be controlled in different directions. A space frame or space structure is a truss-like, lightweight rigid structure constructed from interlocking struts in a geometric pattern. Space frames are series of tubes which are joined together to form a structure that connects all the necessary components together.

Space frame style is chosen for this research due to the ease of analyzing and manufacturing. In addition the space frame style is the most popular frame style in the FSAE competitions. The objectives of this research are to design, manufacture and perform a torsional test a space frame for the FSAE student formula 2011 competition.

2. Requirements

To compete in the FSAE student formula 2011 competition, the frame must pass all the rules and regulations of FSAE 2011 [2]. In order to have a good performance, the frame is aimed to have the mass less than 30kg, which is reasonable when comparing to the mass of other team cars from past competitions. Moreover the frame needs to be stiffed to withstand the load under the racing condition. The requirement of the car torsional stiffness for this research is 1200Nm/deg.

Torsional stiffness is the resistance of an elastic body to deform by an applied torque along a given degree of freedom. For 2011 TSAE frame, one degree of angle of twist at maximum load is allowed. One degree is considered to be a small twist angle due to the fact that the frame should not twist under load. The maximum load condition is when cornering assumingly at 1g. The forces applied to the car are from the four main components; the racer, the engine, the frame, and the miscellaneous components as shown in figure 1. The inertia forces is calculated from,

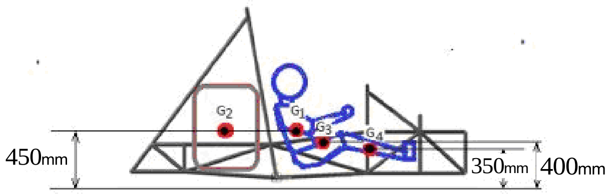
$$F = ma \qquad (1)$$

The axis of rotation is assumed at the floor. The applied torque from inertia force can be obtained to be 800Nm. Figure 2 shows the rotation of the car at angle θ. The minimum requirement of torsional stiffness, K, of the car with one degree of allowable angle of twist and considering the safety factor 1.5 is,

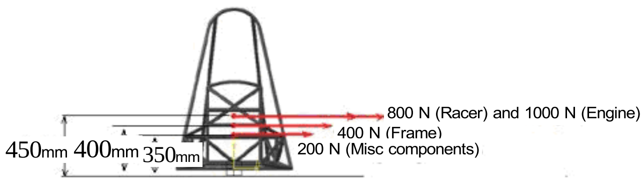
$$K = \frac{T}{\theta}(safety\ \ factor) = 1200\frac{N.m}{\deg} \qquad (2)$$

Where K is torsional stiffness, T is torque applied, and θ is the angle of twist.

So the requirement for torsional stiffness of the whole car is 1200Nm/deg.



(a) Side view



(b) Rear view

Figure 1 Center of gravity and forces on car

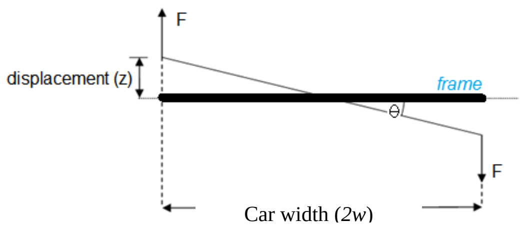


Figure 2 Angle of twist

3. Definitions

The definitions of frame's parts as shown in figure 3 that will be used throughout this research are as follows.

Main Hoop – A roll bar located alongside or just behind the driver's torso.

Front Hoop – A roll bar located above the driver's legs, in proximity to the steering wheel.

Roll Hoops – Both the Front Hoop and the Main Hoop are classified as "Roll Hoops."

Roll Hoop Bracing Supports – The structure from the lower end of the Roll Hoop Bracing back to the Roll Hoop(s).

Frame Member – A minimum representative single piece of uncut, continuous tubing.

Frame – The "Frame" is the fabricated structural assembly that supports all functional vehicle systems. This assembly may be a single welded structure, multiple welded structures or a combination of composite and welded structures.

Front Bulkhead – A planar structure that defines the forward plane of the Major Structure of the Frame and functions to provide protection for the driver's feet.

Side Impact Zone – The area of the side of the car extending from the top of the floor to 350mm above the ground and from the Front Hoop back to the Main Hoop.

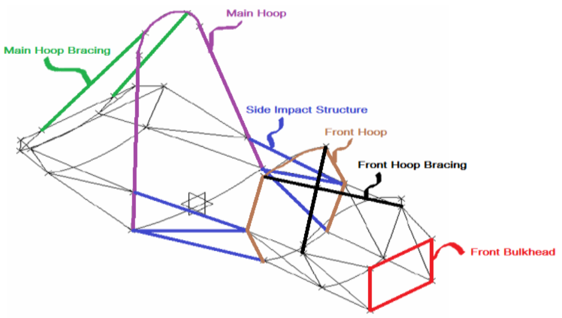


Figure 3 Definitions of frame's parts

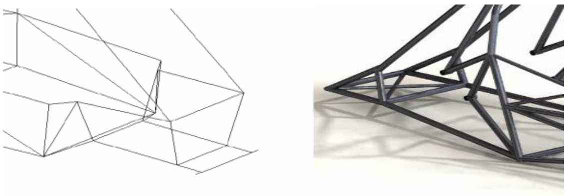
4. Design Process

The 2011 frame design is created by using the program CATIA. The design starts from gathering information such as dimensions, weak points and strong points of the 2010 frame, because the 2010 and 2011 frames use the same engine and share many components that needed to be mounted onto the frame. The dimensions on area such as the engine compartment on the 2010 frame can be used as a minimum requirement for the design of the 2011 frame.

The wheel base of the 2010 car and 2011 car are set to be the same with the value of 1600mm. The front section of the frame, from the front bulkhead to the front hoop, is designed based on the rules and regulations requirements. The floor of the frame is designed to be a curved member across the width of the frame to keep the center of gravity of the frame low and to provide extra clearance off the ground when the frame roll. The front hoop is inclined 10 deg rearward.

The 2010 frame has a rectangular mesh rear as shown in figure 4(a). To improve the torsional stiffness of the 2011 frame, the frame should be designed with triangular rear mesh as shown in figure 4(b). Minor adjustments should be made to the cockpit design of the 2011 frame. The seat should be inclined 10 to 30 degree to shorten the frame overall length. These are the concept of the 2011 frame.

The final design for the 2011 frame is shown in figures 5 and 6. The frame would use steel tube sizes at the minimum required materials size as stated by the rules and regulations as shown in table 1. The frame's mass is estimated to be 26.9kg. The finite element analysis (FEM), by using the program CATIA, is performed to determine the torsional stiffness of the 2011 frame. Figures 7 show the model used in the FEM analysis when fixed at the front and applied the torque to the rear. The torsional stiffness from the FEM analysis is 971Nm/deg.



(a) Rectangular mesh (b) Triangular mesh

Figure 4 Mesh type

Table. 1 The steel tube sizes

Items	Rules and regulations	Test frame	Future frame
Main & Front Hoops	Round 25.0mm x 2.50mm	Round 26.7mm x 2.87mm	Round 26.7mm x 2.87mm
Side Impact Structure, Front Bulkhead, Roll Hoop Bracing, Driver's Restraint Harness Attachment	Round 25.4mm x 1.60mm* (Round 25.0mm x 1.75mm)	Round 25.4mm x 1.35mm	Round 25.2mm x 1.75mm
Front Bulkhead Support, Main Hoop Bracing Supports, Other Frame Members	Round 26.0mm x 1.20mm* (Round 25.0mm x 1.5mm)	Round 26.0mm x 1.10mm	Round 25.4mm x 1.35mm
Mass estimate	25.3kg	24.3kg	28.1kg

*the smallest sizes used in FEM analysis.

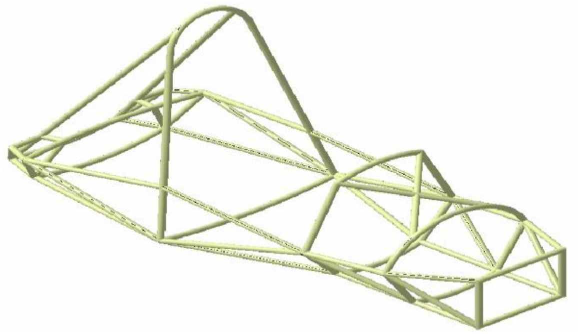
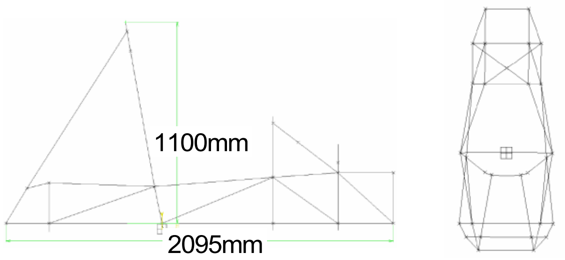


Figure 5 Final frame design



(a) Side view (b) Top view

Figure 6 Final frame design

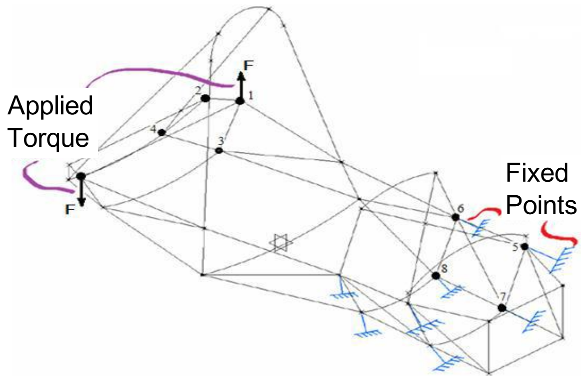


Figure 7 Model for FEM analysis

5. Manufacturing Process

The steel tube used in manufacturing process of the test frame is shown in table 1. Since the steel sizes available in the local area are limited combine with error in measuring, the steel sizes are different from the minimum requirement of the rules and regulations.

Two steel tables are used in the construction process. One large table is used to create the drawing of the floor of the frame and also to be use as frame main assembly area.

Another smaller table is used to create each vertical sections of the frame such as the front bulkhead or the front hoop, then welded together to form the frame on the large table. The large table is use to draw actual dimensions of the frame member, as shown in figure 8. The floor outline is being drawn onto the table, and then angled steels are used to create a socket to keep the steel member in position so each section of frame can be welded to form the frame as shown in figure 9. The frame was manufactured starting from the front bulkhead as shown in figure 10, and then work toward the rear to complete the frame. Figure 11 shows the next step in constructing the frame.

For the main hoop, it is manufactured from a single piece of steel tube which is bent in the middle. Forces are applied to the ends of the main hoop to change the radius of the main hoop. When the radius is achieved the main hoop is welded to the frame and then connects it to the front hoop with side impact members as shown in figure 12. For the curve floor of the frame, the frame needed to be turned upside down to work on the curved members of the floor as shown in figure 13. The frame is welded back onto the table top with metal supports holding as shown in figure 14.

To construct the main hoop bracing, the angle of the main hoop bracing needed to be measured. This is done by marking on the main hoop. The mark needed to align on the same height both left and right side of the main hoop, using a steel plate clamping onto the main hoop, as shown in figure 15, then measure the level of the plate by using water level measurement tool to makes sure that the mark is leveled. Another steel plate is placed from the mark down to the very end of the frame; this would show the alignment of the main hoop bracings as shown in figure 15. The main hoop bracings also need to be removable so that the engine can be move in and out of the frame, so instead of welding the bracings are being joined with the frame using nuts and bolts as shown in figure 16. All joints then get re-welded to complete the frame construction. The mass of the frame is found to be 25.5kg.

Figure 8 Guide drawing on the flat steel table

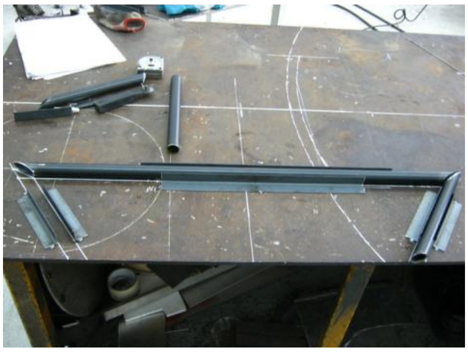


Figure 9 The use of guide during construction

Figure 10 Front bulkhead welded to the floor

Figure 11 Section vertical welded to the frame

Figure 12 Side impact members and main hoop

Figure 13 Floor members

Figure 14 Metal supports holding

Figure 15 The angle of the main hoop bracing

Figure 16 Complete frame

6. Experiments

6.1 Torsional Test [3]

The frame is fixed at the front part as shown in figure 17, the rear part is connected to the steel beam at point *A* and *B* as shown in figure 18. The pivot point is set at the center to allow rotation of both the beam and the frame. Mass is hanged on one end of the beam. The amount of torque transferring to the frame can be controlled by altering the hanging mass. Isolating the frame from the steel (figure 19), the torque, T, transferred from the beam into the frame is,

$$T = mgL = (F_1 + F_2)w \qquad (3)$$

The moment from weight of the frame and the steel beam are negligible because they passed the pivot point. The hanging mass is increased and the measurement of distance a and b is taken. Distance a and b are the height from the ground to the left and right side of the frame as shown in figure 18.

The angle of rotational, θ, of the frame as shown in figure 20 can be calculated from,

$$\theta = \tan^{-1}\left(|a-b|/2w\right) \qquad (4)$$

And the torsional stiffness, K, is

$$K = \frac{T}{\theta} = mgL \Big/ \tan^{-1}\frac{|a-b|}{2w} \qquad (5)$$

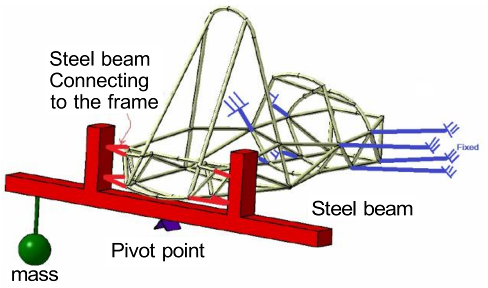


Figure 17 Torsional test

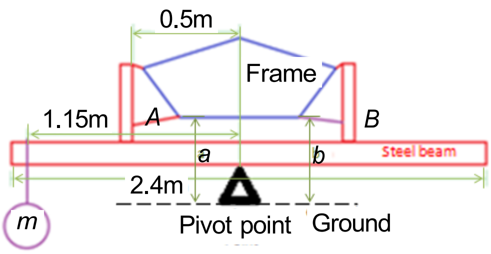


Figure 18 Tosional test (rear view)

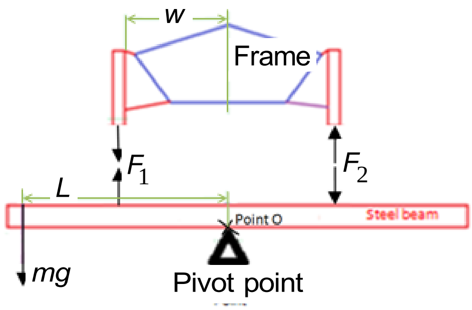


Figure 19 Forces acting on the frame

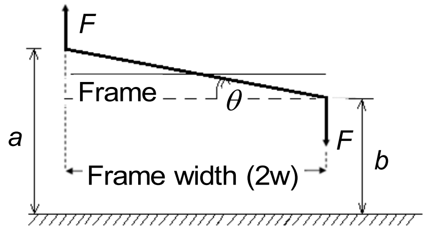


Figure 20 The twist angle

6.2 Experimental Setup

The front end of the frame is fixed by connecting all the front suspension mounting points to the table top using metal tubes. The rectangular steel beam is cut to have the length of 2.40m. The rear of the frame is welded to connect all rear suspension mounting points to the steel beam. Angle steel is placed under the beam to provide a pivot point as shown in figure 21. The weights are suspended on one end at the location 1.15m from the center of the frame.

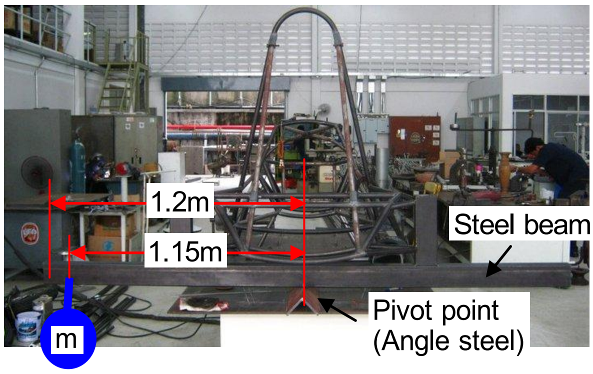


Figure 21 Beam construction on the rear

7. Results and Discussions

7.1 The effect of extra crossbar member

Torsional test is performed on the frame without and with extra crossbar member as shown in figure 22.

Figure 23 shows the relationship between the torque and the angle of twist. The gradient of the graph represent the torsional stiffness of the frame. The torsional stiffness of the frame without extra crossbar member is 787 Nm/deg while the torsional stiffness of the frame with the extra crossbar member is 869Nm/deg. It can be seen that there is 10.4% increase in torsional stiffness by adding the extra crossbar member under the driver's seat.

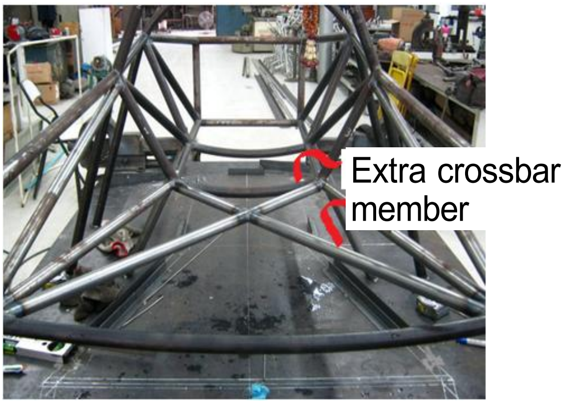


Figure 22 Extra crossbar member

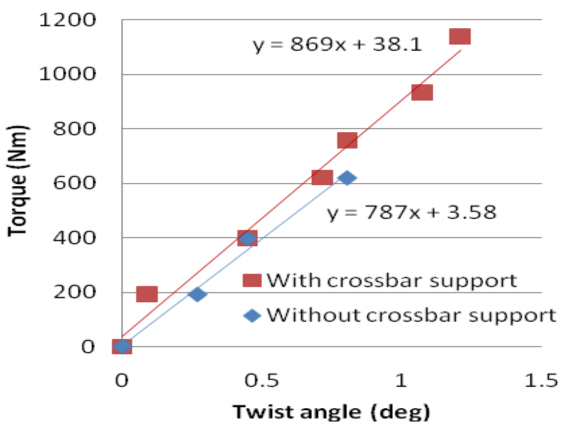


Figure 23 Torsional stiffness from test

7.2 FEM analysis and actual testing

The FEM analysis with the same steel tube sizes used for the test frame without extra crossbar member is performed. The model when the front part is fixed and the angle of twist at the rear is calculated is used to determine the torsional stiffness. The torsional stiffness from FEM analysis is 1270Nm/deg. It can be seen that the torsional stiffness of the actual testing is 38.0% less than the value achieved from the FEM analysis.

7.3 The effect of steel tube sizes

For this comparison, three sets of steel sizes (Table 1) are used to perform FEM analysis to find out the effect of different steel tube sizes to the value of torsional stiffness of the frame without extra crossbar member. The torsional stiffness from rules and regulations, test frame, and future frame are 971 Nm/deg, 955 Nm/deg, and 1500Nm/deg, respectively. All of the values of torsional stiffness are being measured from point 7 on the frame (figure 7) since that point shows the lowest torsional stiffness. There is a 57.1% increase from the test frame to the future frame.

7.4 Estimating the values of the future frame

The future frame uses larger steel tube sizes than the test frame and also have the extra crossbar member. The mass of the future frame is 29.8kg. The value of the torsional stiffness of the future frame can be estimated as follows,

$$K = 1500\text{Nm}/\deg(1-0.38)(1+0.104)$$
$$K = 1030\text{Nm}/\deg \quad (6)$$

7.5 Discussions

The objective of this research is to design and manufacture a frame for a FSAE

2011 competition with the requirement of having the mass less than 30kg and torsional stiffness of the whole car more than 1200Nm/deg. A test frame was designed and manufactured with mass of 25.5kg and torsional stiffness from the experiment of 787Nm/deg. Further study of torsional stiffness by adding extra crossbar member to the frame shows that the torsional stiffness increased by 10.4% from 787Nm/deg to 869Nm/deg. Another factor of steel tube sizes was studied using FEM analysis to show an increase in sectional area of the tube would in effect the increase in the torsional stiffness of the frame as well. FEM analysis shows that the future frame would have torsional stiffness 57.1% more than the torsional stiffness of the test frame, 1500Nm/deg for future frame in addition of 955Nm/deg for the test frame. Lastly, comparing the torsional stiffness from FEM analysis against the actual testing value shows that the test value is 38.0% less than the analysis value, 787Nm/deg to 1270Nm/deg from analysis. An estimated mass and torsional stiffness values for the future frame with extra crossbar member was found to be 29.8kg and 1030Nm/deg, respectively. So we can conclude that the future frame would pass the rules and regulations and also the weight requirement. Even though our future frame's torsional stiffness is less than 1200Nm/deg, but the 1200Nm/deg of torsional stiffness is required for the whole car and not only the frame. The frame would have more components such as anti-roll bars and engine mounted to the frame. When these components attached to the frame would increase the overall torsional stiffness of the car [4], it can be concluded that the torsional stiffness of the car would be more than the required 1200Nm/deg even though the frame has torsional stiffness of only 1030Nm/deg.

8. Conclusions

This research has succeed in designing and manufacturing a frame and used by the Chulalongkorn University FSAE student formula team with the designed mass of 29.8kg and estimated frame's torsional stiffness of 1030Nm/deg.

However the 2011 frame is currently on design stage. In advance dimension details could be change due to the assembling, manufacturing, etc. After the 2011 final frame is made, the improved experiment and analysis will be conducted and the requirement of the car torsional stiffness of 1200Nm/deg will be clarify.

9. References

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