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Finite Element Modeling and Analysis of Vehicle Space Frame with Experimental Validation

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***Abstract*—The frame is the most important part of any vehicle. The frame supports the body and different parts and systems of the vehicle. So it must be rigid enough to withstand the shock, twist, vibration and other loads. The most important consideration in chassis/frame design is to have adequate torsional stiffness for better handling characteristics. This paper present a Finite element model for space frame of a single seated race vehicle, the model was developed to evaluate the torsional stiffness of the frame. Also, the paper shows a design of a test rig to measure the torsional stiffness of the space frame. The measured data was used for the model validation. The deflection and the twist angle of the frame was measured also by the test rig.**

Keywords—Space frame; Finite element analysis; Torsional stiffness; Single seated frame;

I. INTRODUCTION

The main purpose of the frame is to connect all four wheels with a structure which is rigid in bending and torsion-that is one which will neither sag nor twist. It must be capable of supporting all components and occupants and should absorb all loads fed into it without deflecting unduly [1] .The torsional stiffness of chassis have a significant effect on the vehicle handling specially race cars [2]. As in cornering, the vertical load on the outside tire increases while that on the inside tire decreases. This lateral load transfer is vital to acquire a decent handling balance, which can only be optimally controlled if the structure is rigid enough to transmit torques [3, 4].

Frame flexibility must be minimized so the suspension can control the vehicle's motion. For race cars frames there are several modifications and additions that can be made even the design was built to significantly increase the torsional stiffness.

The most important way to predict the torsional stiffness of frame designs is using finite element analysis (FEA). In order to validate these finite element models an experimental method is needed to directly measure torsional stiffness. The aim of this paper is to design and build a simple test rig for measuring the torsional stiffness vehicle frame designs. The measurement of torsional stiffness allows different frame designs to be evaluated and compared. The measured data can also be used to validate finite element models.

II. VEHICLE FRAME FEA MODELING

The finite element method (FEM) is sometimes called finite element analysis (FEA), it is a computational technique used to acquire inexact solutions of boundary value problems [5].

A. Frame modeling

An existing race vehicle frame was chosen to be modeled and analyzed so the model can be validated by an experiment later on. The vehicle was built as a race car with a very limited budget. The frame of the vehicle was drawn and modeled by Solidworks software so that it can be analyzed accurately as shown in fig 1.

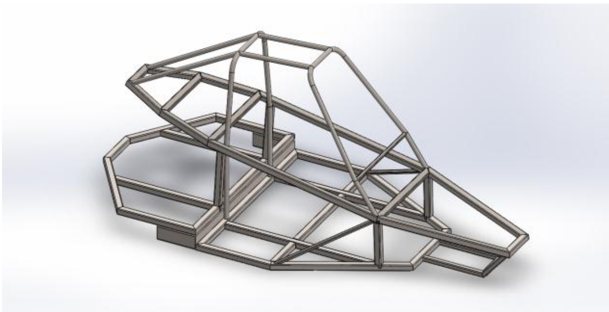

Figure 1 CAD model of race vehicle frame

B. Material Properties

After drawing the frame the material properties was defined. The material used to build this frame was Alloy steel its properties is shown in the table 1. Defining the material is done in Solidworks by choosing from Solidworks material library. If the material used is not in Soildworks library it can be added by defining its properties.

Table 1

Name:	Alloy Steel
Model type:	Linear Elastic Isotropic
Yield strength:	6.20422e+008 N/m^2
Tensile strength:	7.23826e+008 N/m^2
Elastic modulus:	2.1e+011 N/m^2
Poisson's ratio:	0.28
Mass density:	7700 kg/m^3
Shear modulus:	7.9e+010 N/m^2
Thermal expansion coefficient:	1.3e-005 /Kelvin

C. Loads and Fixtures

To simulate the torsional Stiffness we must put the frame under a torque and measure the deflection that caused by that torque. So the torque could be any amount which produce a measurable deflection. For this reason the rear end of the frame was fixed from the arms points and the load were applied as a coupling force act on the end of the beams created to transfer load without being deflected as shown in the fig 2.

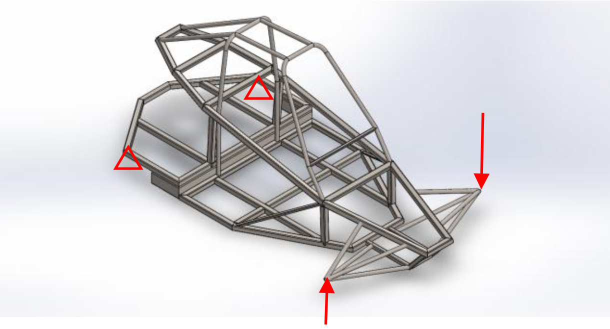

Figure 2 Frame fixers and loads

D. Meshing

Beam mesh was used for this model as shown in fig 3. As you can see the front arms are not meshed that's because they were defined as trusses to only transfer the load to the frame. The meshed model consist of 692 total nodes and 642 total elements.

In beam meshing, the cross-section of a beam is assumed to be constant throughout its length. Solidworks meshes each beam by creating a number of beam elements. Each beam element is defined by two end nodes and a cross-section. When viewing the mesh and results, beam elements can be represented on actual beam geometry or by cylinders regardless of the actual cross-section. [6]

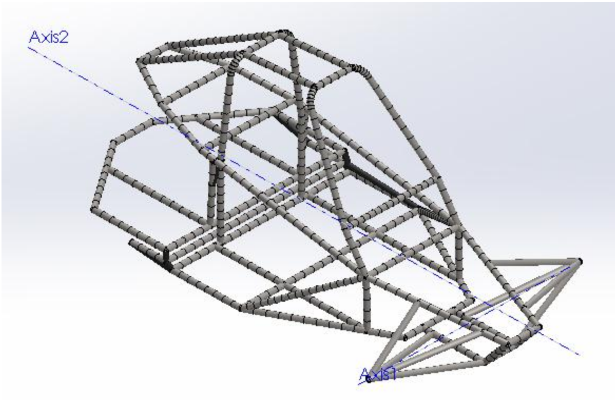

Figure 3 Beam mesh for the frame CAD model

E. Results of the analysis

SOLIDWORKS Simulation plots the results using a Cartesian coordinate system. But also it's possible to convert the results in cylindrical coordinate. This method was used to find out the angular deformation of the frame required to calculate torsional stiffness. The following fig 4 and fig 5 shows deformation and stresses that are shown in a Cartesian coordinate system, The maximum deformation was observed at Node: 21 and was 0.885294 mm which is not in the frame it's on the beams created to transfer the load as shown in fig 3. The tangential displacement was evaluated at which where the load was applied so a probe was used to pick up that point. It was equal to 0.9999mm

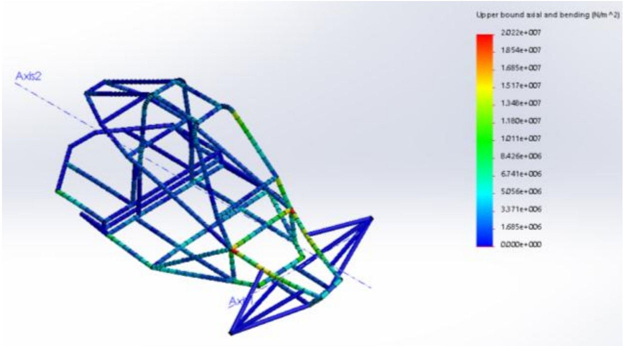

Figure 4 Maximum axial and bending stresses found

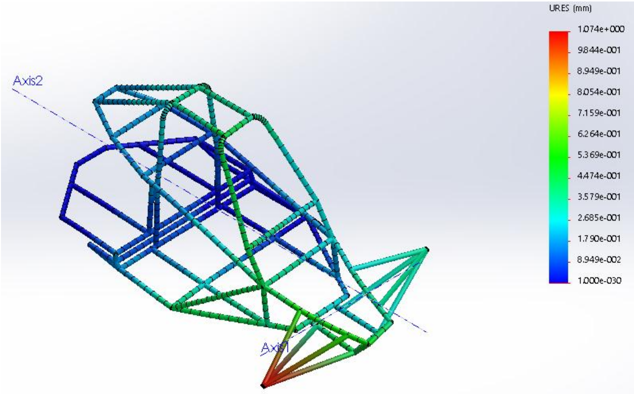

Figure 5 Displacement and deformations

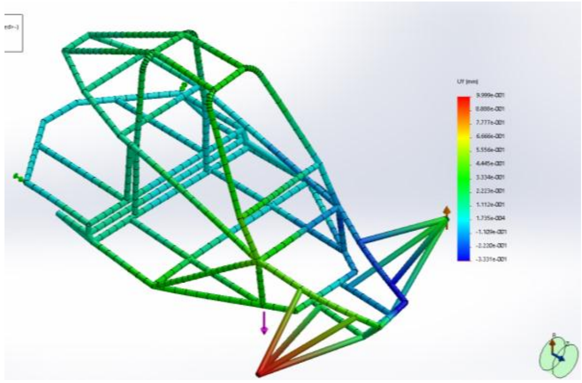

Figure 6 Tangential displacement of the frame

After the angular deformation of the end of the frame was calculated. Twist angle can be calculated by equation (1).

$$Twist\ angle\ in\ radians = \frac{Displacement\ at\ where\ the\ force\ was\ applied}{Distance\ between\ where\ the\ force\ was\ applied\ and\ the\ neutral\ axis\ of\ the\ frame} \quad (1)$$

$$Twist\ angle\ in\ radians = \frac{0.9999\ mm}{700\ mm} = 1.428428571E-3\ rad$$

The torsional stiffness of the frame can be calculated from equation (2) [7, 8].

$$Torsional\ Stiffness = \frac{Torque\ Load}{Angular\ Deflection} \quad (2)$$

$$\tau = \frac{140\ Nm}{1.428428571E-3} = 98009.80098\ \frac{Nm}{rad}$$

$$\tau = \frac{98009.80098\ \frac{Nm}{rad}}{57.2957795} = 1710.593\frac{Nm}{deg}$$

III. Experimental Setup

A. Final design proposal of test rig

SOLIDWORKS was used to design the test rig and make many prototypes till we stilled on the final design which is shown in the fig 7and fig 8 The rig consists of mainly 2 parts, the front part and the rear part, this allows the rig to test any wheelbase chassis as the front part is not attached to the rear part.

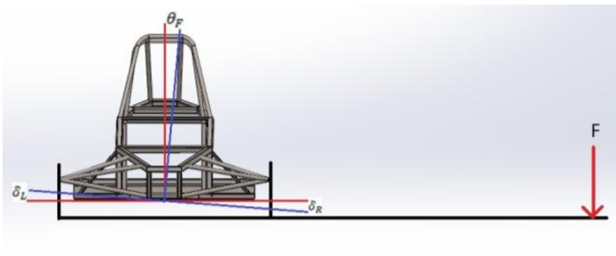

Figure 7 Sketching for the theory of operation of the test rig

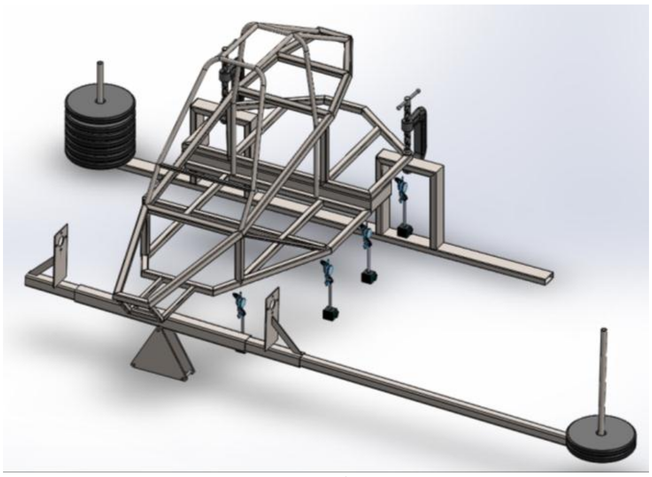

Figure 8 CAD model of the torsion test rig

B. Tools and measuring equipment

The test rig itself does not require much tools due to its tool-less design, however for attaching the rig to the hubs with wheel bolts a wrench or a socket tool of the wheel bolt size will be used. Also for dissembling the rear suspension and replacing the front struts a set of tools may be used depend on suspension and vehicle type. A weights will be needed to do the experiments about 80 kg depend on the amount needed to fix the rear rig and the amount needed to twist the chassis to give a measurable deflections. All deflections was measured by dial indicators and all the forces was measured by a weight scale.

C. Frame preparation

In order to run the experiments the front suspension coil and dampers must be all replaced by rigid members as shown in fig 9 and 10. And as for the rear suspension, the rear arms were disassembled as the rear suspension won't be used for fixation.

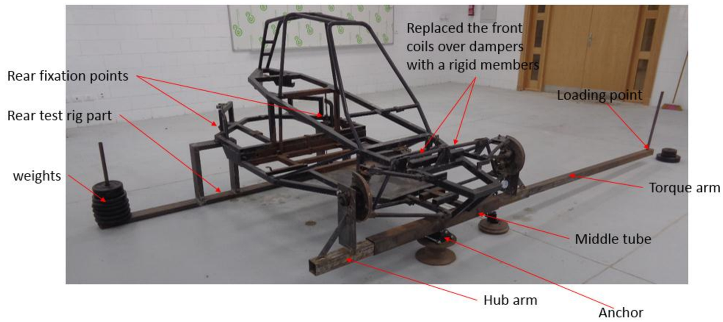

Figure 9 Frame mounted on the test rig

D. Measuring the torsional stiffness for validation of FEA model

For measuring the torsional stiffness the twist angle of the frame, and the torque must be measured. For given small deflections d, the front twist angle is calculated from equation (3).

$$\theta_F = \frac{\delta_R + \delta_L}{L} \quad (3)$$

Where,

θ_F: The front twist angle

δ_R : Deflection in the right side

δ_L : Deflection in the Left side

L: Distance between the two dial indicators

And the torque is calculated from equation (4)

$$T = L_A \times F \qquad (4)$$

Where,

T: is the torque applied

L_A: Torque arm length

F: force applied

The force applied is calculated from equation (5)

$$F = m \times g \qquad (5)$$

Where,

m: is the mass used.

g: is the gravitational acceleration

E. Test preparation for Measuring the torsional stiffness

To measure the torsional stiffness, two dial indicators will be used to measure the opposite resultant vertical deflection at the left and right front knuckles.

The chassis is twisted in increments by loading masses in steps with deflection data recorded at each step. After several steps the twist angle is reversed until reaching zero by unloading masses in steps.

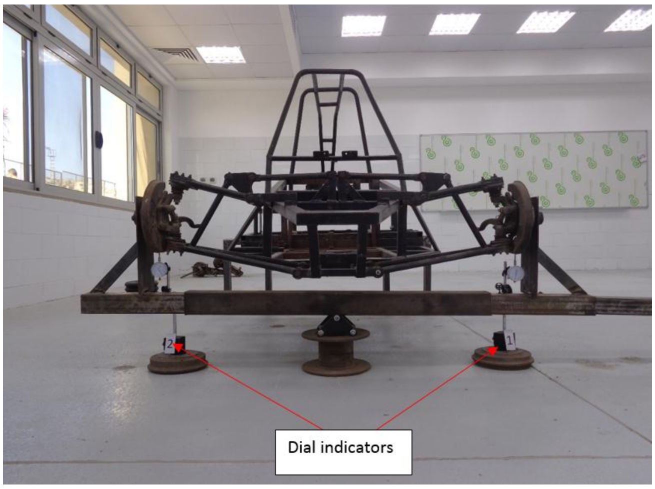

Figure 10 using two dial indicator to measure the deflection

IV. EXPERIMENTAL RESULTS AND VALIDATION

The dial indicator values was recorded at each loading and unloading step, and they were entered into a spreadsheet to calculate the twist angle. The twist angle results was plotted verse the torque applied and least-squares regression is performed on the data and the slope was calculated to find the measured torsional stiffness and it was 1661.8 Nm/deg. As shown in fig 11. The error was found to be 2.936% between the least square fit linear regression and the FEA results.

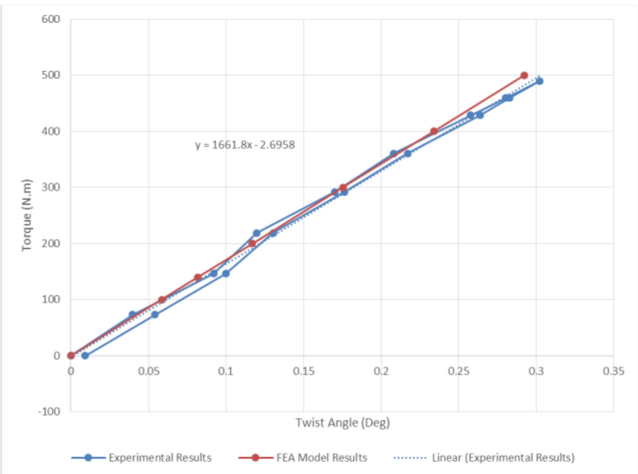

Figure 11 Validation between the FE model and experimental results

V. MEASURING THE DEFLECTION AND THE TWIST ANGLE ALONG THE FRAME

A. Test preparation

To measure the deflection along the frame, a multiple dial indicators were used. The dial indicators were placed along the frame. The dial indicator number one is placed at the front knuckle with a distance of 377 mm from the front frame end, the dial indicator number two is placed at front hoop support with a distance of 744 mm from the front frame end, the dial indicator number three is placed at the middle of lower frame structure with a distance of 1295 mm from the front frame end, the dial indicator number four is placed at the main hoop with a distance of 1781 mm from the front frame end, and the last dial indicator is placed at the fixation point of the frame on the rear rig with a distance of 2291 mm from the front frame end. The dial indicators arrangement is shown in fig 12

After doing all test preparation, the rig was preloaded with the torque arm weight which was 19 kg and that's to eliminate all the clearances in the front suspension mechanism and all the dial indicators were calibrated to zero. A mass of 6.8 kg (torque = 206.7948 Nm) was loaded to the system and read value from the dial indicators was taken.

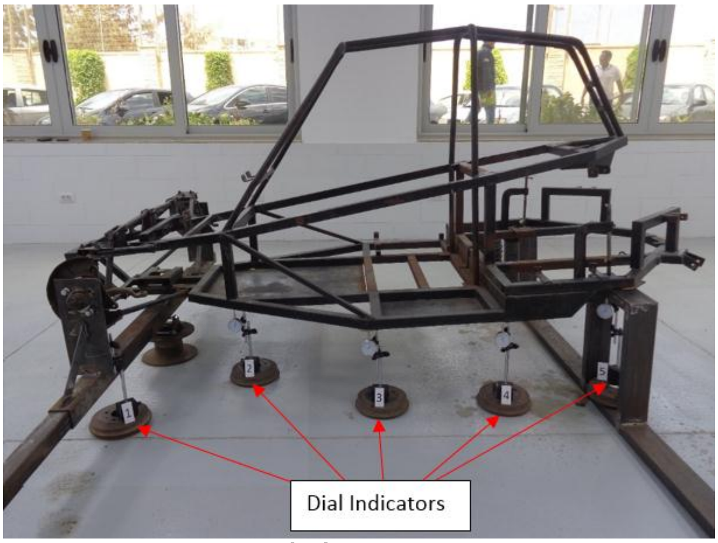

Figure 12 Dial indicators arrangement

B. Results of measuring the deflection and the twist angle along frame length

The dial indicators values were recorded and they were entered into a spreadsheet to calculate the twist angle. The distance along the frame was plotted versus twist angle, and vertical deflection.

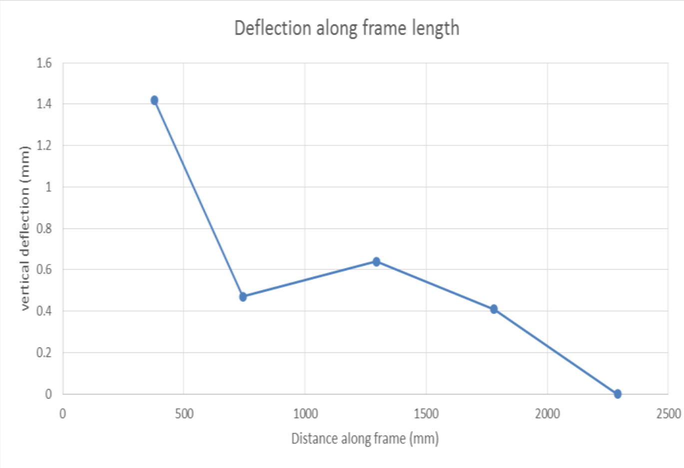

Figure 13 Results of the deflection along the frame

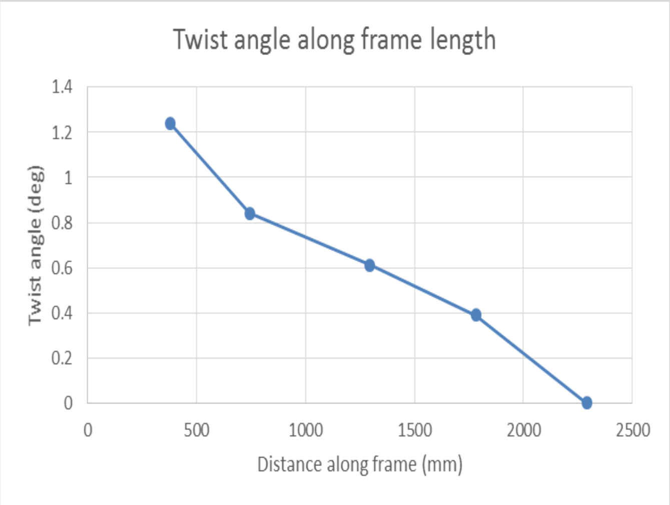

Figure 14 Results of twit angles along the frame

VI. CONCLUSIONS AND RECOMMENDATIONS

A FEA model was made to test torsional stiffness of race vehicle chassis. It was found that the torsional stiffness of the race vehicle chassis was 1710.593 Nm/deg with 74 kg for weight which makes the torsional stiffness to weigh ratio 23.11 (Nm/deg)/Kg. A test rig was designed and manufactured to test the torsional stiffness of race vehicle frame and it was used also to find the deflection and the twist angle along the vehicle frame. The results of the experiment was used validate the FEA model. The results of torsional stiffness from the experiment is 1661.8 Nm/deg. The error was found to be 2.936%.

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