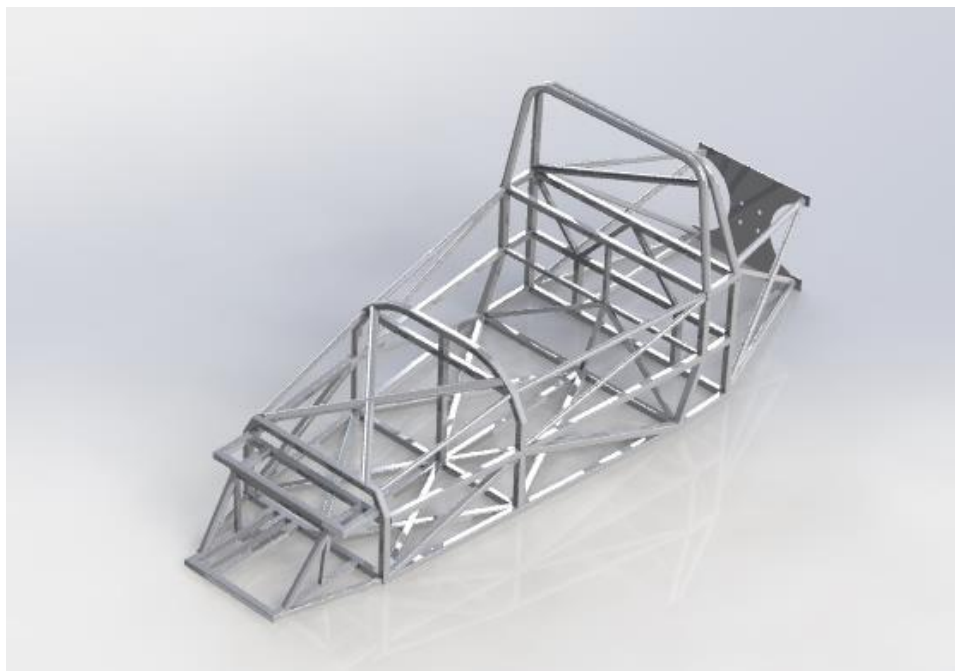




Optimising the Torsional Rigidity of the MCR 2000 Chassis Using Finite Element Analysis

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Torsional Rigidity Test Validation

1) Abstract

This project will attempt to explain to the reader the importance of FEA in conjunction with live testing and how this is a useful tool during the validation. It is a validation exercise in demonstrating the FEA, theoretical and analytical methods. It will also address the limitations and accuracies of these methods. The test being carried out is a “torsional stiffness test”. This is widely used throughout the automotive and motorsport industries and is the basis for the design of a competitive vehicle chassis.

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2) Nomenclature

FEA – Finite element analysis

DTI – Dial test indicator

CAD – Computer aided design

BC – Boundary conditions

RHS – Right hand side

LHS – Left Hand Side

1D - One Dimensional

2D - Two Dimensional

NDT – Non-destructive testing

3) Introduction

The project is being carried out is an investigation into the torsional stiffness of a space frame chassis of the MCR 2000 (3D Beam structure), how it affects the vehicle dynamics and how can it be optimized. The Chassis has been modeled in SolidWorks to enable the modifications to the chassis (supports). Live testing has been carried out on the chassis. The MCR 2000 is a sports prototype race car designed to compete in the Sports 2000 championship. *“It has a Box tubular space frame construction with integral safety cage, anti-intrusion side structures, stressed aluminium alloy panels, Rack-and-pinion steering, aluminium crash box.”* » (mcrracecars.co.uk)

The aim of the project is to test, analyze and interpret the torsional stiffness of a space frame chassis of the MCR 2000 using existing industry standard methods. The chassis will then be modelled in SolidWorks to enable modifications to the chassis and then analyzed using finite element analysis (FEA).

This report will examine and attempt to answer some of the fundamental questions with regard to chassis stiffness.

- What is torsional stiffness?

The amount of force you would need to apply to ‘twist’ the chassis by 1 degree

- Why is it important?

Lack of chassis torsional stiffness can affect the lateral load transfer distribution

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4) Literature review

a) Strength and stiffness

The performance of a vehicle chassis is related to its *strength* and *stiffness*. These constraints are applied with the reduction to mass and without sacrificing the performance of the chassis.

The strength requirement implies that no part of the structure will lose its function when subjected to high loads. Any failure which may occur would be noted to material fatigue and extreme load cases.

The stiffness (K) of a structure relates to the deflection (Δ) when load (P) is applied therefore:

$$p = K\Delta$$

(Brown, 2002)

The above equation only applies to structures in the elastic range. The stiffness of a vehicle structure has important influences on its handling characteristics.

There are two types of stiffness:

- **Bending Stiffness** – This relates to the symmetrical deflection of a point near the centre of the wheelbase to multiples of total static loads on a vehicle.
- **Torsional Stiffness** – This relates to the torsional deflection (θ) of the structure to an applied torque (T) about the longitudinal axis of the vehicle.

(Brown, 2002)

b) Chassis purpose

The basic requirements that a chassis must meet are as follows:

- To provide protection for driver from impacts and crashes.
- To comply with relevant regulations for series.
- To provide anchoring for safety harnesses.
- To house all the vehicle's components, engine, gearbox, suspension, fuel tank, battery.
- To provide enough strength to resist forces experienced during operation e.g. braking forces, cornering forces
- To support the aerodynamic devices

c) Chassis structure types

Throughout the history of modern race cars there have been two main types of chassis structure as Steward Mentions;

*"The **Space-frame** which is a 3-d structure formed from tubes. This is then clad with non-structural body work.*

*The **monocoque** which consists of plates and shells constructed to form a closed box or cylinder. The monocoque can thus replace some of the bodywork. Modern monocoque are invariably made from carbon fibre composites."* (Steward, 2014)

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“Torsional stiffness- torsional stiffness refers to how much a frame will flex as it is loaded when one front wheel is up and the other is down, while the rear of the car is held level. This condition is seen at every corner on the road, so its importance to proper handling should be obvious.” Chassis engineering (Adams, 1993)”

(Adams, 1992)

Improving the torsional rigidity of a vehicle allows the suspension to work more efficiently and predictably. Vehicles with high torsional rigidity will see more travel in the suspension, as the chassis does not move.

It is important to design a chassis with high torsional stiffness as the suspension will act more independently. This is due to the more effective translation front to rear of the cornering forces that the vehicle experiences. Another reason why a vehicle with a high torsional stiffness is important is that if the chassis twists as the vehicle is going around a corner the chassis may “load up” like torsional spring and then “unload” on the exit of the corner. This may lead to some undesirable handling characteristics. The importance of the project is to see if this process is a valid method of testing vehicle chassis rigidity. If successful how can it be improved, and does it have a commercial application.

d) Weight distribution and handling balance related to chassis stiffness

A simple model of a vehicle’s chassis stiffness can be thought of as two masses with a torsional spring in-between, as seen in fig 1. A more realistic model would be multiple masses and springs all with different values in-between representing the different chassis sections.

Looking at steady state equations, you can see that;

$$\text{Total Roll Stiffness} = \text{Front Roll Stiffness} + \text{Rear roll Stiffness}$$

$$K_t = K_f + K_r \text{ Equation 1}$$

Calculating weight transfer of a vehicle during a steady state turn where WT is Weight transfer, M is vehicle Mass, “ay” is the lateral acceleration of the vehicle during the turn, H is centre of gravity height and T is the vehicles track width.

$$W_t = \frac{M \times a_y \times H}{T} \text{ Equation 2}$$

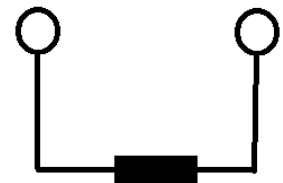


Figure 1 idealised chassis model

Both equations [1], [2], can only be true if the chassis is thought of as infinitely stiff. The stiffness of the chassis would need to be factored in for this to be true. As the roll stiffnesses front and rear are translated to each other through the vehicles chassis, some of the moment will be absorbed by the “flexible” chassis. This means that the “handling balance” can only be controlled effectively if the chassis is stiff enough to effectively transmit the cornering forces from the front of the vehicle to the rear. Previous research has shown that although total weight transfer is always the same, the individual wheel loads from real track data are not the same as those calculated using steady state equations. One of the reasons for this may be due to the torsional stiffness.

A more rigid chassis will allow the suspension to act more independently, therefore more predictably. This is important as handling balance is one of the most crucial factors in vehicle dynamics.

Chassis stiffness is important as ideally the “flex” in the chassis should be linear. This is because the vehicle’s handling characteristics need to be predictable. If certain sections of the chassis are less rigid the feedback to the driver may be that the handling characteristics are “vague” or “sloppy” due to the unpredictability.

“It has been shown that tuning to be at least 80% effective, the torsional stiffness of the chassis need to be at least approaching the total roll stiffness of the car”

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(William F Milliken, 1991)

From steady state equations we can see;

$$K\theta = K\theta_f + K\theta_r = \frac{Tf^2K_{wf}}{2} + \frac{Tr^2K_{wr}}{2}$$

The total roll stiffness has been calculated as

$$K\theta = K\theta_f + K\theta_r = \frac{1.63^2 \times 140}{2} + \frac{1.5^2 \times 140}{2} = \text{Radians/degree}$$

This means that the chassis stiffness would need to be in the region of **3649Nm/degree** according to Milliken. Although this is a good starting point, this cannot be said for every vehicle so a better question to ask is: how stiff does the chassis need to be before performance is affected?

e) Materials research

Table 1 Material Data taken from SolidWorks

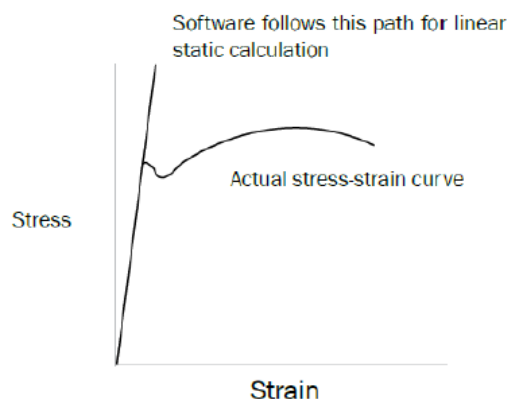
Material Data					
Plain Carbon Steel			AISI 1015 Steel, Cold Drawn		
Elastic Modulus	2.10E+11	N/m ²	Elastic Modulus	2.05E+11	N/m ²
Poisson's Ratio	0.28	N/A	Poisson's Ratio	0.29	N/A
Tensile Strength	4E+08	N/m ²	Tensile Strength	385000000	N/m ²
Yield Strength	2.21E+08	N/m ²	Yield Strength	325000000	N/m ²
Mass Density	7800	kg/m ³	Mass Density	7870	kg/m ³

Due to the material of the chassis not being known, analysis in SolidWorks was carried out using these two materials. The materials have comparable properties, being the same material, but the higher grade 1015 steel has a much higher yield strength. As the elastic modulus of the two materials is comparable it is unlikely to have a drastic effect on the deflections of the chassis.

f) Outcome

The outcome of the project will be the ability to validate the FEA using live testing which will give a numerical value for the stiffness of the chassis. The assumption that is being made in this is that the CAD drawing of the chassis, including modifications, is relatively accurate, although some assumptions have been made.

It can be assumed that if the Von Mises stresses are greater than the yield stress of the material, then the component will have failed. Due to the linear nature of the FEA solver it will not display whether or not the component has yielded as seen below figure [1]. To see whether a component has failed, it would be necessary to reference the UTS of the material and the stresses experienced by the model.



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Figure 2 (Stress/ strain graph. K. Lake)

The purpose of the analysis is not to check the strength of the chassis as it is already established that the chassis is strong enough for its purpose. The specific purpose of the analysis is to perform NDT. It is being tested as a spring would be, e.g. it is obeying Hooke's law. Few materials deform "plastically" but metal does. The forces being exerted on the chassis will not be high enough for the chassis to yield, therefore we can use a linear elastic model as this would be most suitable for our application.

If there were no time constraints an investigation into bending of the chassis would be carried out. This is very important to ensure that the chassis does not have natural frequency that is like one it may experience during normal operation.

g) Space Frame Principles

An efficient space frame design uses tubes jointed to form triangular shapes. Each joint should have 3 points at which the tubes meet. Three such triangles form a tetrahedron.

"The beauty of such structure is that the tubes are loaded almost entirely in each other's pure tension or compression i.e. there is virtually no bending"

(Steward, 2014)

Due to the design requirements of a vehicle chassis, including packaging, protection for the driver and regulations, it is not possible to create a chassis completely out of tetrahedral prisms, which means the overall stiffness of the structure suffers.



Figure 3 Unsupported box section and a supported box section

The effectiveness of the triangular box section is demonstrated in figure 3.

5) Methodology

"Definition: Optimize Make the best or most effective use of (a situation or resource)

1.1 Computing Rearrange or rewrite (data, software, etc.) to improve efficiency of retrieval or processing."

(Oxford English dictionary, 2018)

To optimise something is to make effective use of something without sacrificing its function. Therefore, one of the main goals of the project is to increase torsional stiffness, without adding any additional weight or sacrificing its centre of gravity height.

i. Objectives

- Testing the vehicle's torsional stiffness within realistic limits that the vehicle would experience.
- Testing whether installing bracing bars affects the torsional stiffness of the vehicle chassis and to what degree.
- Use of FEA to validate the results acquired from live testing.

ii. Aims

- To gather an accurate and consistent set of results from the live testing.
- To produce an accurate working model of a vehicle chassis validated using the results from the live testing.

The purpose of the project is to see whether using SolidWorks in conjunction with FEA is a good method of validation for this problem. This type of modelling is an important engineering exercise because producing prototypes is expensive and time consuming. Having a FEA lead project can also greatly reduce the time

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taken for a product to “get to market”. Research has been carried out to make assumptions for the calculations and limitations.

Timeframe

	Description of Work	Start and End Dates
Phase One	Live testing of MCR chassis torsional stiffness	Oct 17- Oct 28
Phase Two	Producing drawings of Chassis	Dec 17- Mar 17
Phase Three	Carrying out FEA analysis	Jan 17 - Feb 17

For more detailed time scale, see Gantt chart, project diary

a) Project Resources Required

- SolidWorks
- MCR 2000 Chassis
- Chassis Twist Rig
- Corner Weight Scales
- Data logging equipment

b) Test plan

The test was carried out using a “twist rig”. The vehicle chassis is mounted on the twist rig, it is fixed at the rear via the shear plate and it is supported at the front. The “twisting” of the chassis is to simulate a condition where one wheel is up, E.g. going around a banked corner or going over a bump. The deflections of the chassis are measured using DTI gauges. These were placed at 5 predetermined points on either side at set intervals shown in figure 4. As a load is applied to the bar, the values on the DTI gauges are noted and the difference between the deflections are used to calculate the “twist angle”.

Point	(mm)
D1	230
D2	383.4
D3	1203.4
D4	1473.4
D5	2233.4

Figure 4

The vehicle has been tested in its standard form, with various bracing bars installed, and with the engine removed*. This allows an investigation to be carried out with regard to the effect the various set ups have on the overall torsional stiffness, weight and the vehicle’s dynamics.

* The vehicle will not be used without an engine, but as the engine block is a load bearing member it is important to remove it in order to acquire a value for chassis stiffness in its most basic form and to quantify how much the engine block increases the overall stiffness of the chassis.

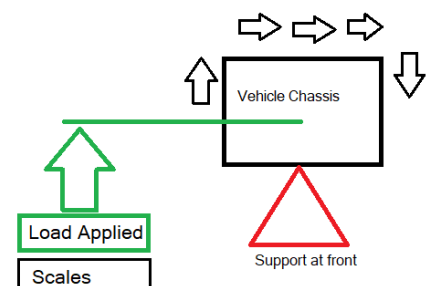


Figure 5 Chassis twist Rig

Torsional Rigidity Test Validation

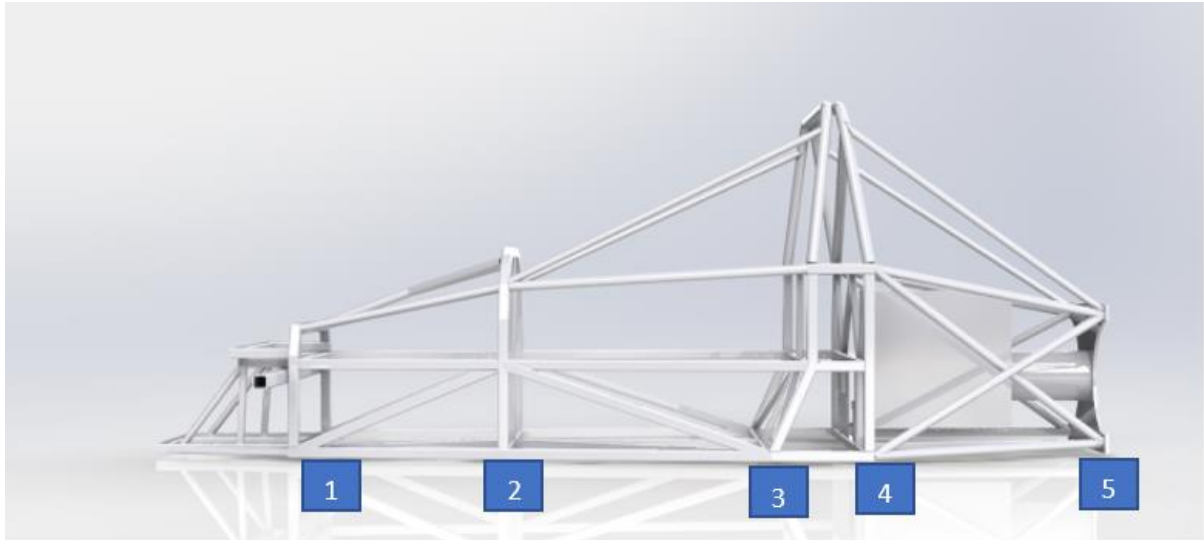


Figure 6 SolidWorks screen shot of chassis

Figure 6 Demonstrates at what points the measurements were taken in reference to figure 4.

To calculate torsional stiffness;

$$\text{Torsional stiffness} = \frac{\text{Torque}}{\frac{180}{\pi}} \times \frac{\text{Spread Distance}}{\text{Deflection}} = \frac{\text{nm}}{^\circ} \quad \text{Equation 3}$$

Chassis engineering (Adams, 1993)



Figure 7 Chassis twist rig (Picture: Kristian Jennings)

Torsional Rigidity Test Validation

i. Twist Rig Modifications

During the initial test phase, it was noticed that part of the rear shear plate came in contact with the test rig. The decision was made that the test rig should be modified so as to not give inaccurate results. This was achieved by elongating the holes found in the base of the twist rig, thereby enabling it to be adjustable, and by the use of additional spacers between the shear plate and the twist rig. These improvements solved the issue that was encountered at the beginning of testing. The modifications were carried out by our workshop technician, Paul.

ii. Data points

The data points at which the measurements were taken were also reviewed, as they were situated on the main cross members of the chassis. The data collected from these points were inaccurate due to the points being too close to each other. One of the data points was moved to the rear shear plate to give a more realistic view of the overall stiffness of the chassis.

Torsional stiffness of MCR 2000 Chassis												
Force n	Load kg	Torque applied Nm	Deflection right					Deflection Left				
			D1 mm	D2 mm	D3 mm	D4 mm	D5 mm	D1 mm	D2 mm	D3 mm	D4 mm	D5 mm

Table 2 layout for data acquisition of torsional stiffness test

The table above was produced in order to log data from the live testing of the MCR chassis. As the vehicle is “twisting” around a central axis the deflection on the right will be positive (up) and the deflection on the left negative (down).

The chassis was tested in various design setups,

Set-up 1, was the standard chassis with the engine in place but no bracing installed.

Set-up 2, Engine was in place and all the bracing available was installed.

Set-up 3, the engine was removed, and the bracing was installed.

Set-up 4, was the bare chassis with no engine and no bracing installed.

c) Design process

A investigation into the correct mesh for the FEA is the first step. A simple cantilever beam 30x30x200mm is modelled and fixed at the rear. An 8KN load is applied to an edge as shown fig. In order to carry out a mesh study, various mesh sizes will be used ranging from 1mm-12mm. All the results from these will then be compiled into a table, including, for example, deflection, stresses, solve time, elements, and nodes. Although this will not be a torsional analysis that is being used it is important to do this to show what is happening in the background of the FE model.

Torsional Rigidity Test Validation

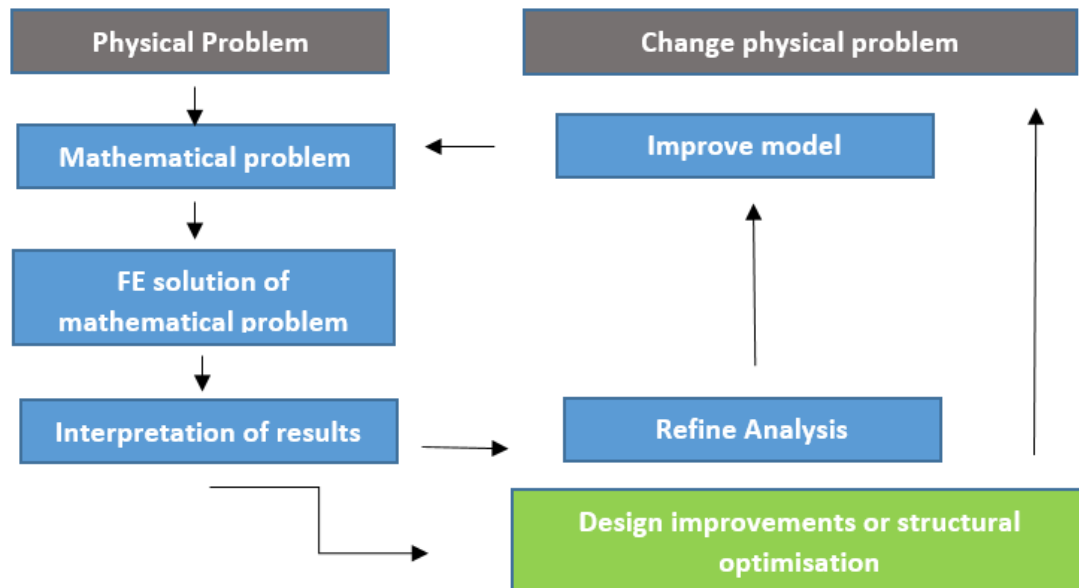


Figure 8 Design process (Picture: my own)

The results from these will be compared to the results from hand calculations of a cantilever beam of the same dimensions and material. The relevant sized elements will then be selected. Taking into account the solving time, the results that correlate to results from hand calculations will be the starting point for the main study. This is a basic exercise in understanding the process of FEA validation.

Table 3 Results from mesh study

Mesh (mm)	δ (mpa)	Z (cm)	Time (s)	Nodes	Dof
1	67	1.527	44	1024321	3076800
2	3	1.527	7	175815	524721
5	392	1.527	0	15875	47118
10	338	1.524	0	2568	7581
20	330	1.512	0	306	855
30	316	1.502	0	215	618

Hand Calculations for mesh study comparison

Max Deflection [y]

$$Y_{max} = -\frac{wl^2}{3EI}$$

Equation 4

$$Y_{max} = -\frac{8000 \times 200 \times 10^{-3}}{3 \times 210 \times 10^6 \times 6.75 \times 10^{-8}} = 1.505mm$$

Stress [δ]

$$\delta_{Max} = \frac{My}{I}$$

Equation 5

$$\delta_{Max} = \frac{8000 \times 0.2 \times 15 \times 10^{-3}}{6.75 \times 10^{-8}} = 355.6 Mpa$$

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The results from the hand calculations would suggest that the required mesh size needed would be between 5-10mm as these are the closest to the results from the hand calculations. The results from this analysis demonstrate why refining the mesh to the smallest possible size is not always the most accurate. Another factor in selecting mesh size is the solving time, as the table 3 above shows the 1mm mesh size took 44s to solve whereas the 5mm mesh took 0s. While this is negligible at this model size, it could become a problem for much larger or complicated models.

“Fillets, cut-outs and complicated geometry features cannot be represented accurately by 1D elements.

3D elements, because of 3 dimensions, can capture all the minute details accurately.” (Altair.2015)

For this reason, a “blended curvature mesh should be used, 1d beam elements are to be used for the structure of the chassis, and the 3d elements be used on the shear plates, panels and features”.

Beam elements have been used as Donald mentions;

“they are used to model beam problems where tension, compression and bending of the element are allowed. These elements allow the definition of section properties to model the beam cross sectional shape and hence accurately predict bending behaviour” (Donald,2015)

The solution type should be a 3D analysis with a linear elastic model of the torsional stiffness as the deflections are small.

d) Modifications to the model

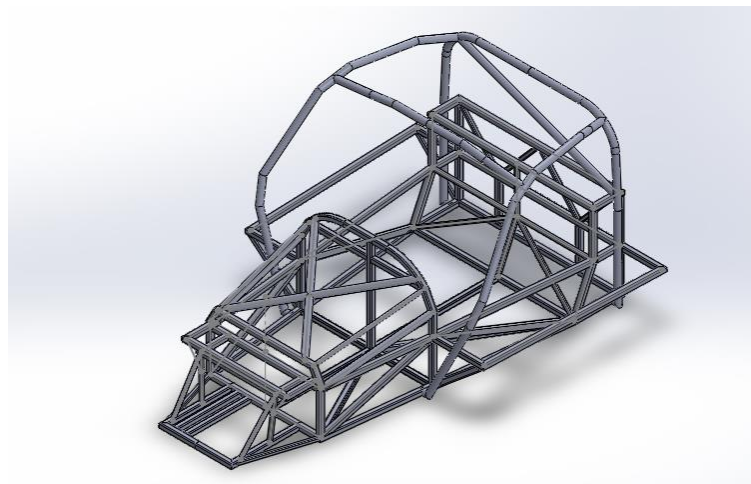


Figure 9 Darrian MCR model

The Darrian MCR Model was acquired from Roger Dowden for the purpose of investigating the similarities between the two chassis and see if it was viable to do this using the drawing or if a new model would need to be produced. Measurements were taken comparing the two, ensuring they were comparable. Check measurements of the general dimensions and bar dimension were carried out to ensure they were consistent. The roll hoops were removed as well as the side impact bars. The rear frame section that houses the engine and gear box, roll hoops and the rear shear plate off the MCR 2000 chassis that was being investigated were modelled.

Torsional Rigidity Test Validation

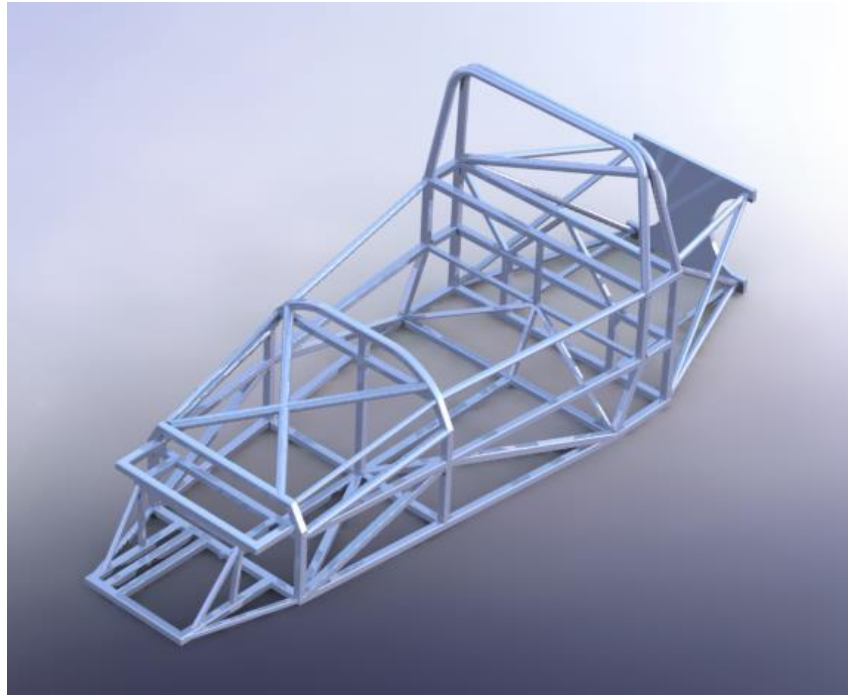


Figure 10 Final model MCR 2000

The final model is shown above after modifications. Some assumptions have been made to simplify the model for FEA. Throughout the real chassis there are mounting points, holes and gaps that have not been modelled. The chassis has shear panels covering sections, the effect that this has on the overall stiffness is unclear due to them being riveted to the chassis. This is the base model for all the optimisations that were carried out.

1) FEA Model Assumptions

To simplify the model, assumptions were made that the holes in the beams found throughout the chassis (seen in Figure 4 below) have not been included in the FEA model. Due to the number of features of this kind found throughout the chassis it would greatly increase complexity of the model. They have been assumed to have no effect.



Figure 11 Chassis bars showing drilled holes.

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As drilling holes in a bar affects its second polar moment of area, a study into the effect that these features have on the overall results from the FEA was carried out. Two 300mm square tubes [30x30x2.65] were modelled. These are the same dimensions found on many of the bars throughout the chassis.

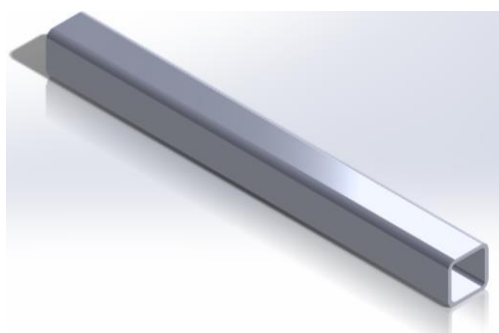


Figure 4 300mm Bar

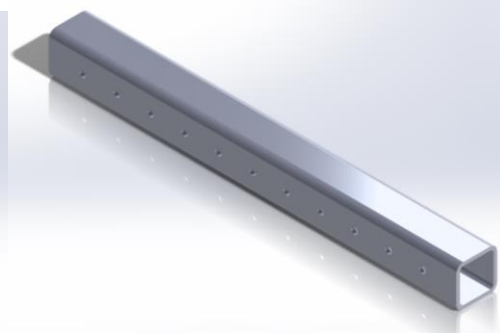


Figure 5 300mm Bar With holes

i. FEA analysis of Holes

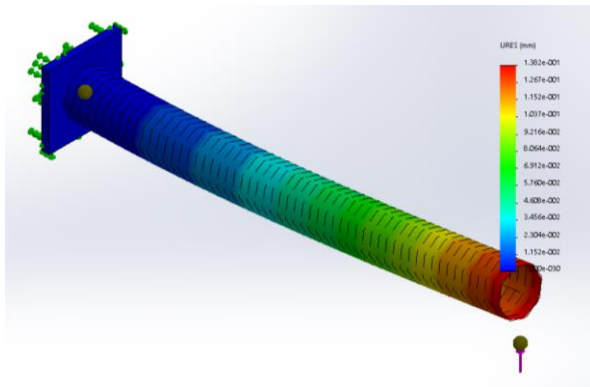


Figure 12 FEA investigation (Standard)

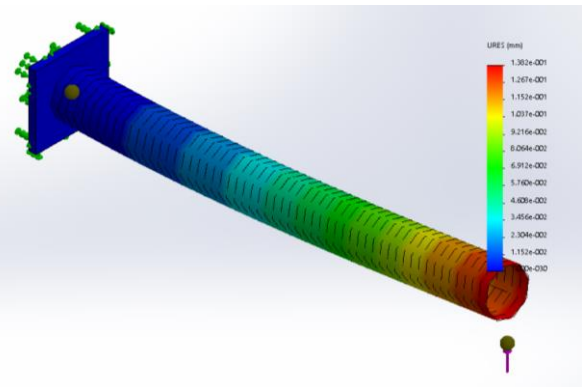


Figure 13 FEA investigation (Modified)

Table 4 Results from FEA

	Deflection (m)	Difference
Standard Bar	0.0001083	N/A
Modified Bar	0.0001382	-24%
Modified Bar 2	0.000132	-20%

Table 3 above shows the deflections from the investigation into the effect that drilling holes in the chassis structure has on torsional stiffness. The bar modelled was 300mm long, the “modified bar had 11 holes drilled at 25mm intervals. “Modified Bar 2” had 5 holes at 50mm intervals. The Standard Bar showing the smallest deflection. With the modified bar showing a decrease of 24% stiffness and the second modified bar showing a 20% difference. While these are not conclusive results, they may help in explaining the discrepancies between the live testing and the FEA results.

One of the largest assumptions of the FE model is that all bars of the same size are considered to have the same wall thickness. This would not be the case, due to manufacturing processes and natural variation in materials they would more than likely be different.

ii. Welds

Throughout the chassis there are welds connecting the bars and due to the simplification of the FE model these features have not been modelled. Ideally to assess the effect this has on the results, a study into welded joints would need to be carried out.

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Most importantly the welds that connect the roll hoops shown below in figure 7 have been considered due to the bars coming apart during the initial FEA. This was carried out as it was affecting the accuracy of the results, as the forces were not being transferred through the chassis correctly.



Figure 14 Roll hoop welds

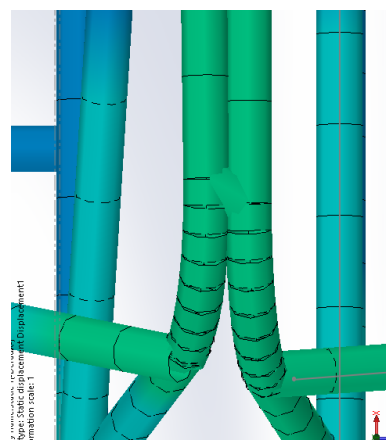
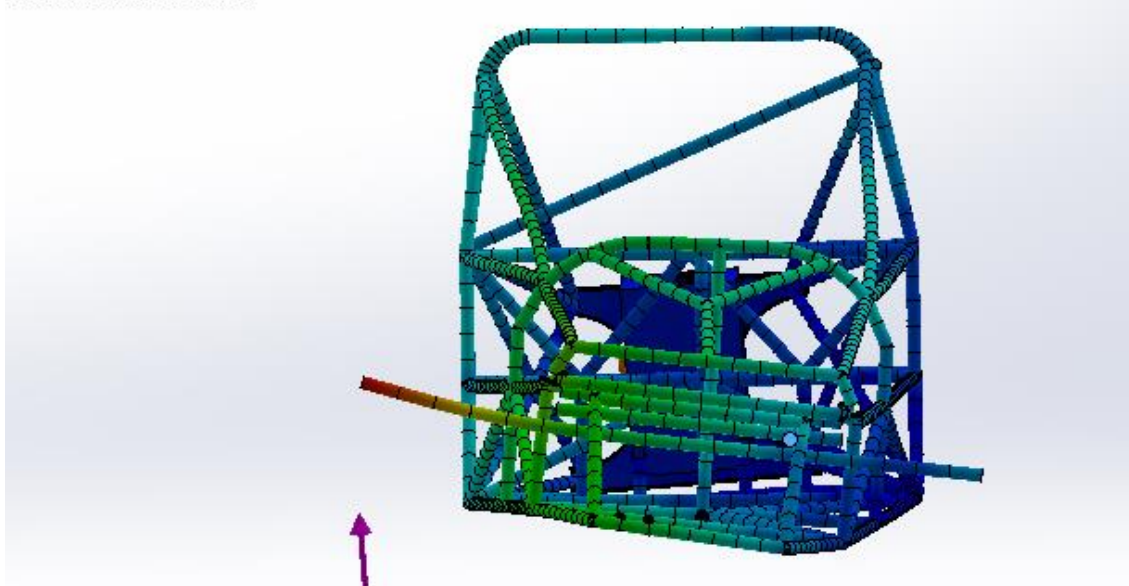


Figure 15 FEA Roll Hoop Welds

Figure 10 above showing the modelled welds in the roll hoops, ensuring the bars do not come apart during the FEA run.

Model name: Assem 6 take 1
Study name: Static 1(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 114.95



The screen shot above shows one of the initial FEA runs. It shows the bar that the load is applied to has excessive deflection (scale 114.95:1) This will affect the result as a portion of the forces are not being transferred to the chassis effectively. The material choice (plain carbon steel) was reviewed for the beam to more accurately replicate the live testing. It is also worth noting that the bar that is clamped to the chassis will increase the stiffness of the chassis structure and therefore will affect the total stiffness.

iii. Engine Block

The dimensions of the engine block were measured and used to model a simplified version of the block currently in the MCR chassis. As the relative stiffness of the engine block is much greater than that of the

Torsional Rigidity Test Validation

chassis, a crude engine block was modelled for the purposes of the FE model (shown below). It is unlikely that a more refined block would affect the results significantly.



Figure 16 Rendering of engine block and gearbox for FE model

For the initial FEA the front cross members were slightly different to the MCR 2000 Chassis. These were redesigned at a later point but they were not seen to make a significant difference to the vehicles structure.

e) Cog calculator

It is said that vehicle handling balance is influenced by the stiffness of the chassis, as is the centre of gravity. An investigation has been carried out to monitor the influence additional bracing to the chassis has on the overall COG. A COG calculator has been produced to be able to quickly input locations and weights of components to give an updated view on COG throughout the optimisation phase of the project.

Table 5 Initial Cog Data

Cog (x)	Cog (y)	Cog (z)
0.4875	0.309	1.2771
Total Length [m]	Width [m]	Total weight [Kg]
2.7322	0.975	60

Table 6 Cog Data with Bracing installed

Cog (x)	Cog (y)	Cog (z)
0.488	0.379	1.259
Total Length [m]	Width [m]	Total weight [Kg]
2.7322	0.975	72.6

Table 5 shows the data from the COG Calculator with the chassis in its initial design phase. Table 6 shows the chassis with bracing installed. The increase in mass is 12.6Kg 19%. The COG longitudinally (Z) axis has moved 0.08m towards the front, the COG height has increased by 20% in the (Y) axis.

f) FEA Software

SolidWorks has been chosen to carry out the FEA because it meets all the requirements, modelling, FEA and analysis. The skill set to use the modelling software effectively, has already been learnt. Ideally the NX 12 would be used due to it being a more focused programme, but due to time constraints as well as the steep learning curve there was not enough time to be able to use the software effectively. Alternatively, the ADAMS software could have been used due to it being specific to chassis stiffness for further validation. This was not possible as due to licensing restrictions it was not available to use.

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2) Results

To collect data from SolidWorks, the deflections would be taken at specific nodes using the “probe” tool, the distance between the points was taken into consideration as it would be at different radii, e.g. the distance between D1 left and D1 Right was 1450mm, but the distance between Node D1 Left and D1 Right was 850mm this was factored in when calculating the “twist Angle” to enable comparable results.

a) Initial Live Testing

Table 7 shows a chassis deflection table for test 1 of live testing

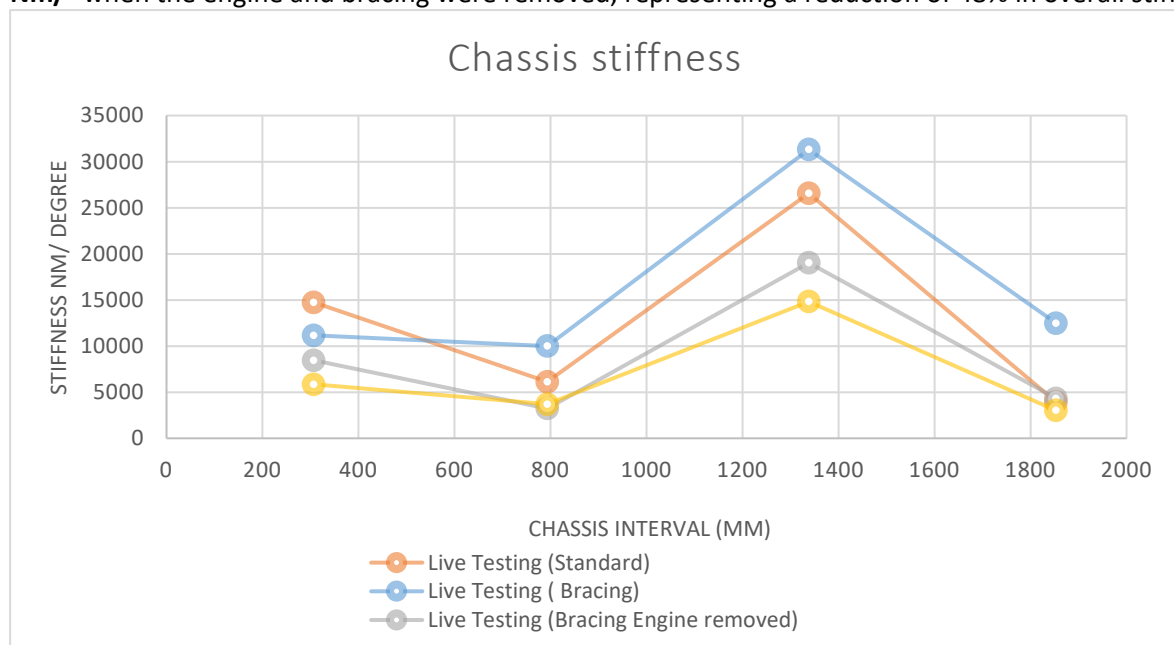
Torque applied Nm	Deflection right					Deflection Left				
	D1 mm	D2 mm	D3 mm	D4 mm	D5 mm	D1 mm	D2 mm	D3 mm	D4 mm	D5 mm
63.765	0.91	0.781	0.45	0.39	0.07	-0.867	-0.68	-0.45	-0.412	-0.09
127.53	1.45	1.195	0.661	0.64	0.14	-1.28	-1.12	-0.69	-0.61	-0.178
191.295	2.01	1.655	0.975	0.88	0.212	-1.645	-1.31	-0.93	-0.89	-0.27
255.06	2.8	2.33	1.432	1.257	0.34	-1.921	-1.695	-1.15	-1.03	-0.43
318.825	3.63	3.06	1.934	1.75	0.529	-2.59	-2.14	-1.57	-1.45	-0.34
382.59	3.8	3.33	2.432	2.257	0.84	-2.921	-2.695	-1.85	-1.71	-0.43

The RHS was the side the load was applied which shows why the deflections were larger on that side. (Positive up, negative down). Three tests were planned for the twist rig. A “standard test”, a setup with the bracing installed and a setup with the bracing installed and engine removed.

Table 8 comparison of live test results

Live Testing	Stiffness Nm/°	% Difference
Standard	1911.40	from standard
Bracing	2945.1	43%
Bracing/No Engine	1405.12	-31%
No Engine/No Bracing	1190.11	-47%

From preliminary live testing, installing bracing increased stiffness by **1007.1 Nm/°**, which is an increase of 41%, while increasing the increased overall weight by **12.4kg**. This equates to an overall stiffness increase of **81.21Nm/° per KG** added. The chassis with the engine removed reduced the stiffness by 32% or **618 Nm/°**. The bare engine block (no head, sump or crank,) that was installed into the car increases the torsional stiffness by **921.1 Nm/°** with bracing. The “Standard” chassis’ stiffness was reduced by **748.04 Nm/°** when the engine and bracing were removed, representing a reduction of 48% in overall stiffness.



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Figure 17 A comparison between the results from the live testing

The above chart shows the chassis stiffness by section, as expected the setup that experiences the highest stiffness is set up with the bracing and the engine installed. The chart shows the highest stiffness between points 3-5 this is because it is the region that the engine and bracing is installed. The bare chassis (setup 4) shows the chassis in its completely bare form has a much more linear behaviour compared to the chassis with the bracing and engine installed. The stiffness is reduced in section 2-4 when the bracing is removed.

b) Initial FEA

FEA	Stiffness Nm/°	% Difference
Standard	1847.4	from standard
Bracing	3330.0	57%
Bracing/No Engine	846.2	-74%
No Engine/No Bracing	668.2	-94%

The table above shows the comparison between the various set ups on the FE model. The “standard” set up saw **1847.4 Nm/°**, whereas in set up 2 the chassis displayed **3307 Nm/°**, an increase of **57%** which equates to **137.5 Nm/°**. This is significant difference to the live testing results. There is a drastic difference between stiffnesses of set-up 3 and 4 experiencing a reduction in chassis stiffness by **74%** and **94%**.

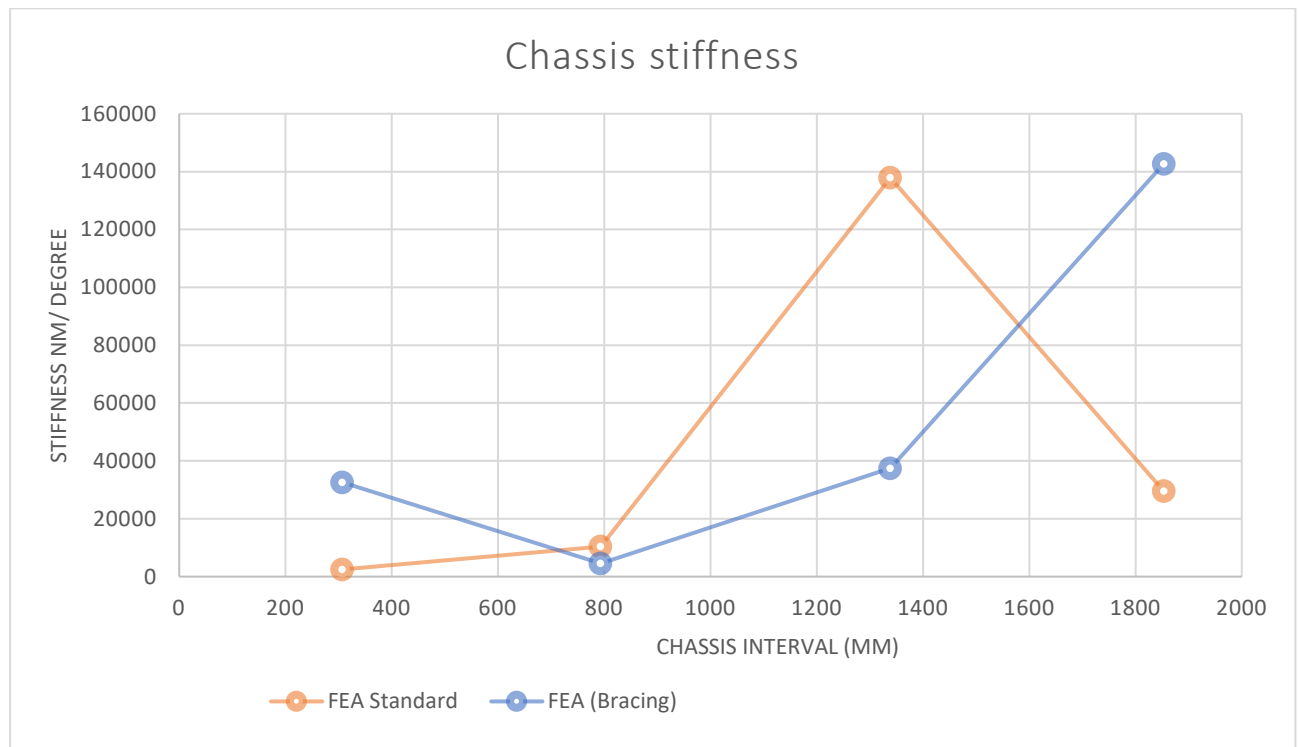


Figure 18 Comparison between FEA set up 1 and 2

The above chart shows the data from the live testing would suggest that there are comparable trends in the data. Although the difference in stiffness is greater from the live data set. There is a 98% difference between the overall torsional stiffness of the real chassis and the FEA in Set-up 4. This would suggest that there is a significant issue with the model. The results from the live testing were reviewed and the model examined to see where the mistakes were made. The significant difference in stiffness figures between the live testing and FE model may be due to the engine not being modelled in the initial investigation.

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Table 9 showing a comparison between the the live testing results and FEA and a % difference between them

Live Testing	Live testing Stiffness Nm/°	FEA Stiffness Nm/°	% Difference
Standard	1911.40	1847.41	-3.40%
Bracing	2945.1	3329.96	12.27%
Bracing/No Engine	1405.12	845.62	-49.72%
No Engine/No Bracing	1190.11	647.63	-59.04%

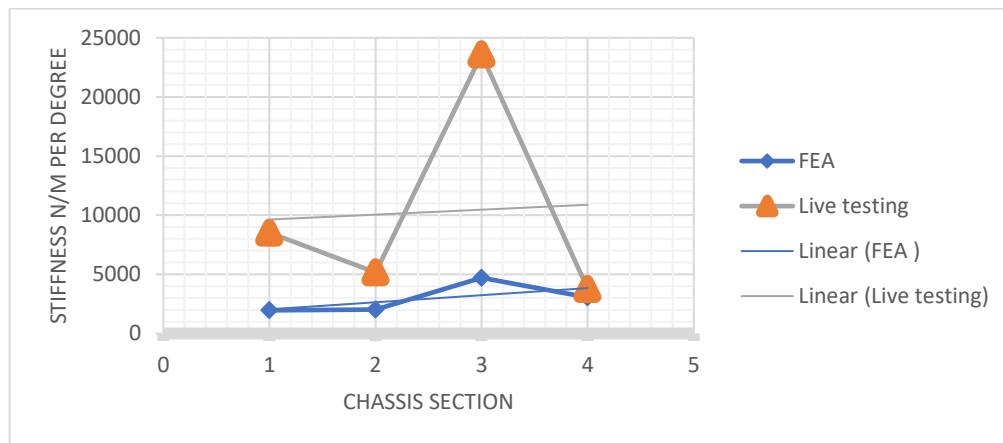


Figure 19 Correlation between FEA and live testing

The figures from the initial FEA were compiled for examination (shown in table 4). The difference in overall chassis stiffness from the testing is shown below. This shows a significant difference between the live testing and the FEA figures. Installing bracing during live testing increased the chassis stiffness by 20.8% whereas modelling the additional bracing on the FE model increased the stiffness by 27.49%. This gives a variation of 7.31%. Further model improvements may reduce this figure. As the data from the live testing was taken from extended measuring points not on the vehicles chassis, this was taken into consideration when recording the data from the FE model and factored into the results to enable accurate results.

	Live Testing	FEA	
Standard	1911.4	647.6	Nm/°
Bracing	2355.2	854.1	Nm/°
Difference	20.8%	27.5%	

Table 10 comparison between the live Testing and FEA Chassis stiffness

c) Initial FEA comparison

The significant difference in stiffness figures between the live testing and FE model may be due to the engine not being modelled in the initial investigation. Once it was, it was found that there was a 3.4% difference in total overall stiffness.

FEA	Live Testing	Difference
1847.409	1911.4	3.40%

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Figure 20 Figures from the live testing and the FEA

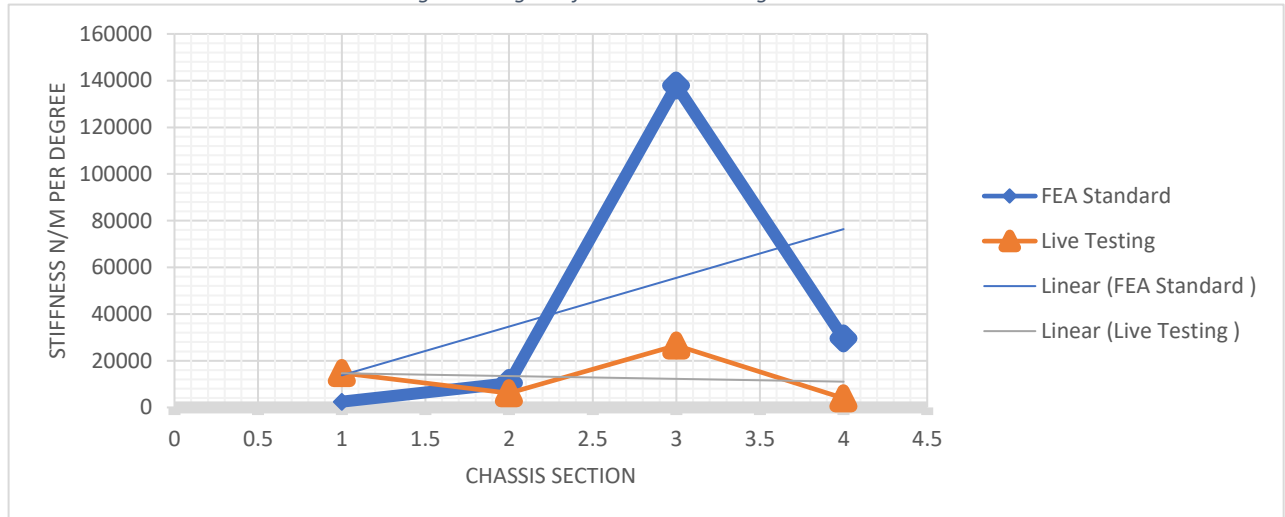


Figure 21 Correlation between FEA and live testing

The correlation in overall stiffness between the FE model and the live testing was within 3.4%. This is a significant difference to the previous FE model of a 96% difference. Modelling the engine block has improved the accuracy of the results. Examination of the stiffness by section shows that although the overall stiffness is comparable, there are inaccuracies between the two (seen above in figure 10). However, although the figures are significantly different, the general trend can be observed, section 2-4 being the stiffest sections for both the live testing and the FE model. The trend line shows the stiffness being relatively linear along the length of the real chassis whereas the trend line for the FE model shows the chassis stiffness increase along the length of the chassis. The variation in section 1-2 between the data would suggest that the model's front section is not as stiff as the FE model. Examining section 3-4 shows a trend, the increase in stiffness between these sections being due to the engine block. Although there is both an increase in both sets of data, the FE model suggests that it is much stiffer than the live testing demonstrates.

i. Variance in Data

- The data variance in the front sections' design of the FE model should be reviewed
- The engine block design and configuration.
- The engine blocks mating to the chassis and shear plate
- Fixtures of shear plate may be causing a variance due to being "too stiff"

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Chassis Deflection FEA comparison

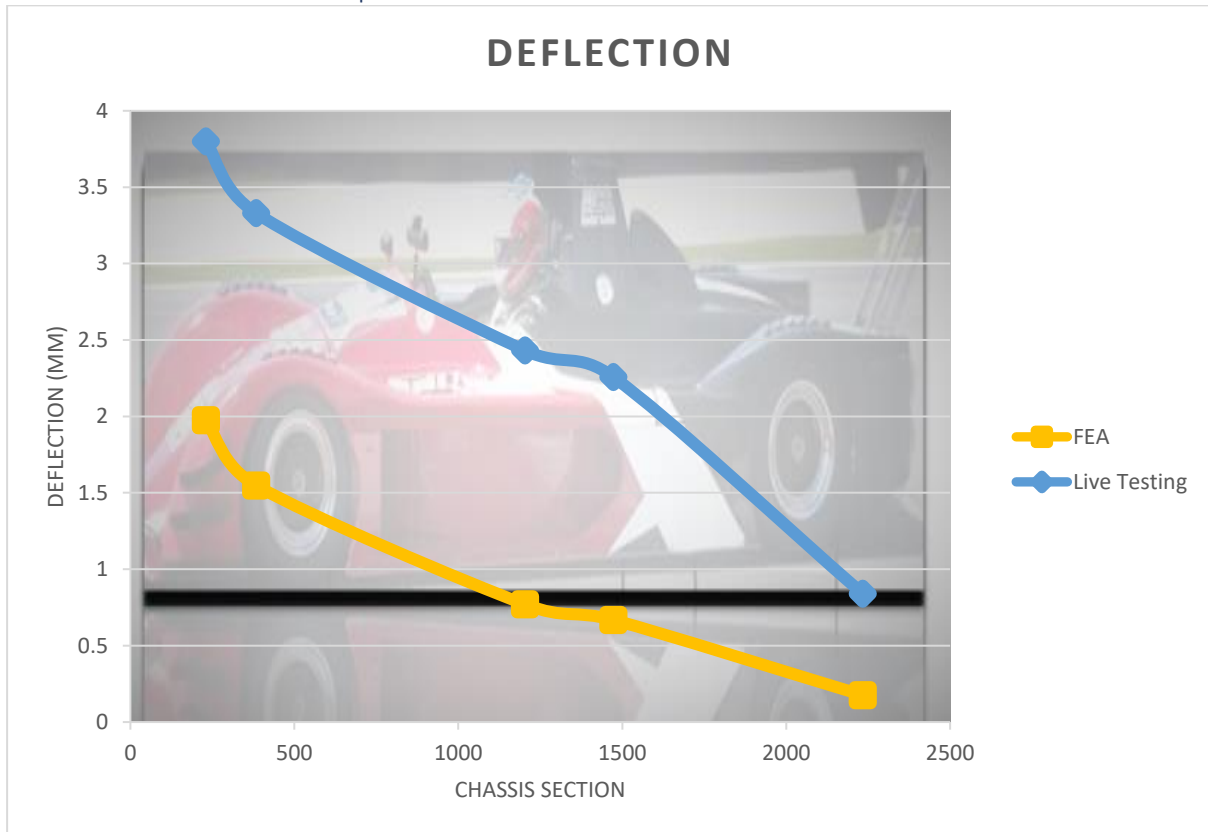


Figure 22 Graph showing RHS deflection vs Chassis section

The table above shows the deflection of the chassis RHS. The deflections are correlated between section 2-3, which demonstrates that the accuracy of the chassis model at this point. The graph shows the greatest deflection nearest where the load is applied, and it decreases towards the rear of the chassis. The overall path of the data is trending.

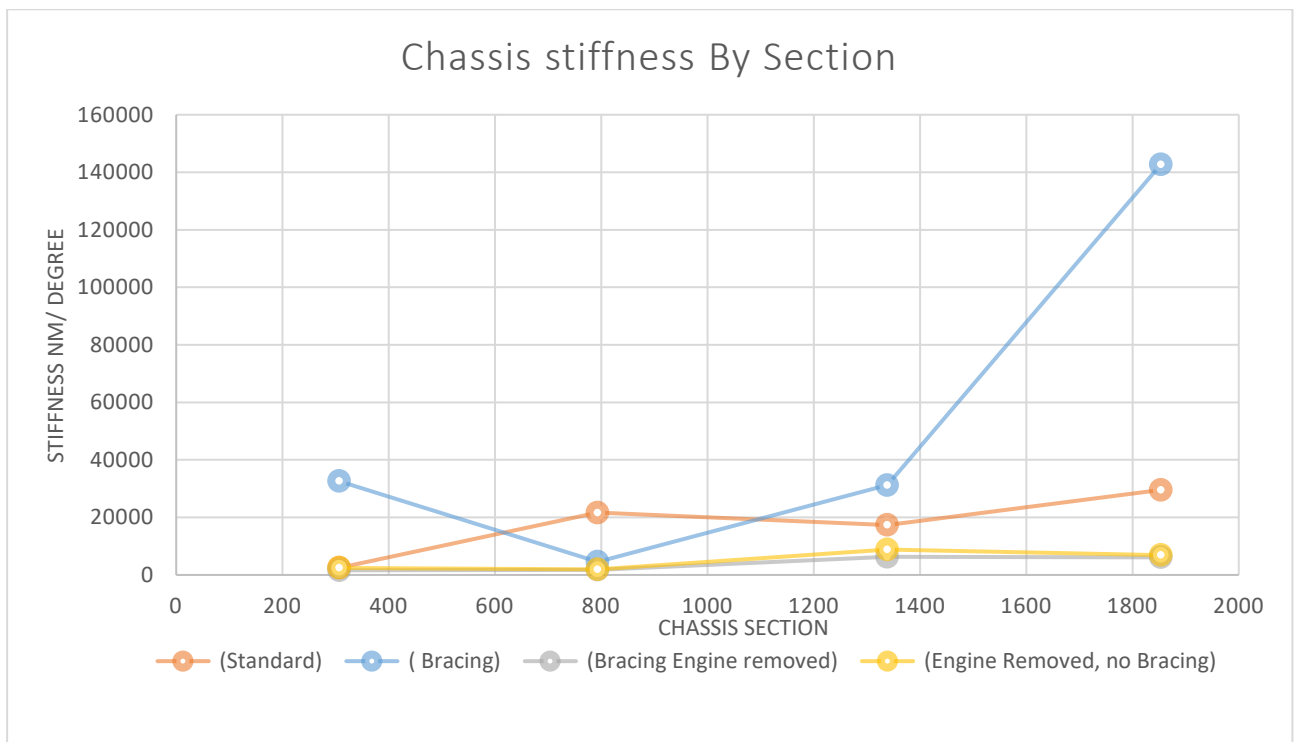


Figure 23 Comparison between Standard set up and FEA

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The chart in figure 8 above shows the standard FEA in comparison to the standard with the engine removed. With the engine removed the FEA shows that the stiffness is relatively linear along the length of the chassis. With the engine installed the stiffness has increased at points 3-4, and 4-5. This is to be expected as the engine contributes to a significant amount of stiffness.

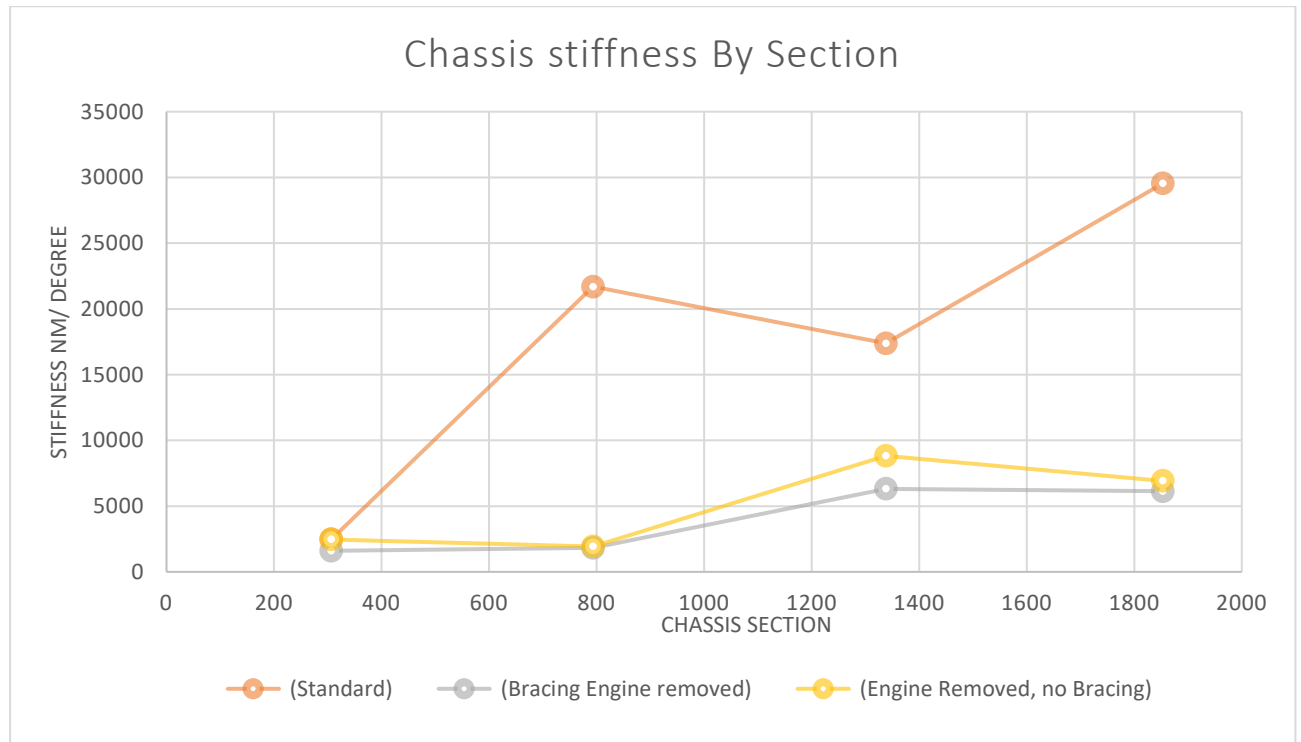


Figure 24 Graph showing Chassis stiffness by section

The graph above shows Chassis stiffness by section. Shown in blue is the standard chassis with the engine installed, and shown in orange is with the bracing installed. The stiffest section in the standard chassis is point 3-4. This is most probably due to the two measuring points 3-4 being closer to each other than others. With the bracing installed the point 4-5 greatly increases in stiffness, although this is expected as the bracing was installed between sections 2-4. The reason for the variation may be due to the forces being transferred through different beams due to the engine essentially “short circuiting” the chassis.

d) Secondary FEA Results

Live Testing	Stiffness Nm/°	Stiffness Nm/°	% Difference
Standard	1911.40	1847.41	-3.40%
Bracing	2945.1	3607.83	20.23%
Bracing/No Engine	1405.12	845.62	-49.72%
No Engine/No Bracing	1190.11	647.63	-59.04%

Figure 25 Comparison of FEA results

The above charts show an increased stiffness between sections 2-4 when the engine was installed in the vehicle with a slight increase with the bracing installed. This is pattern was seen during the examination of

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the live testing results.

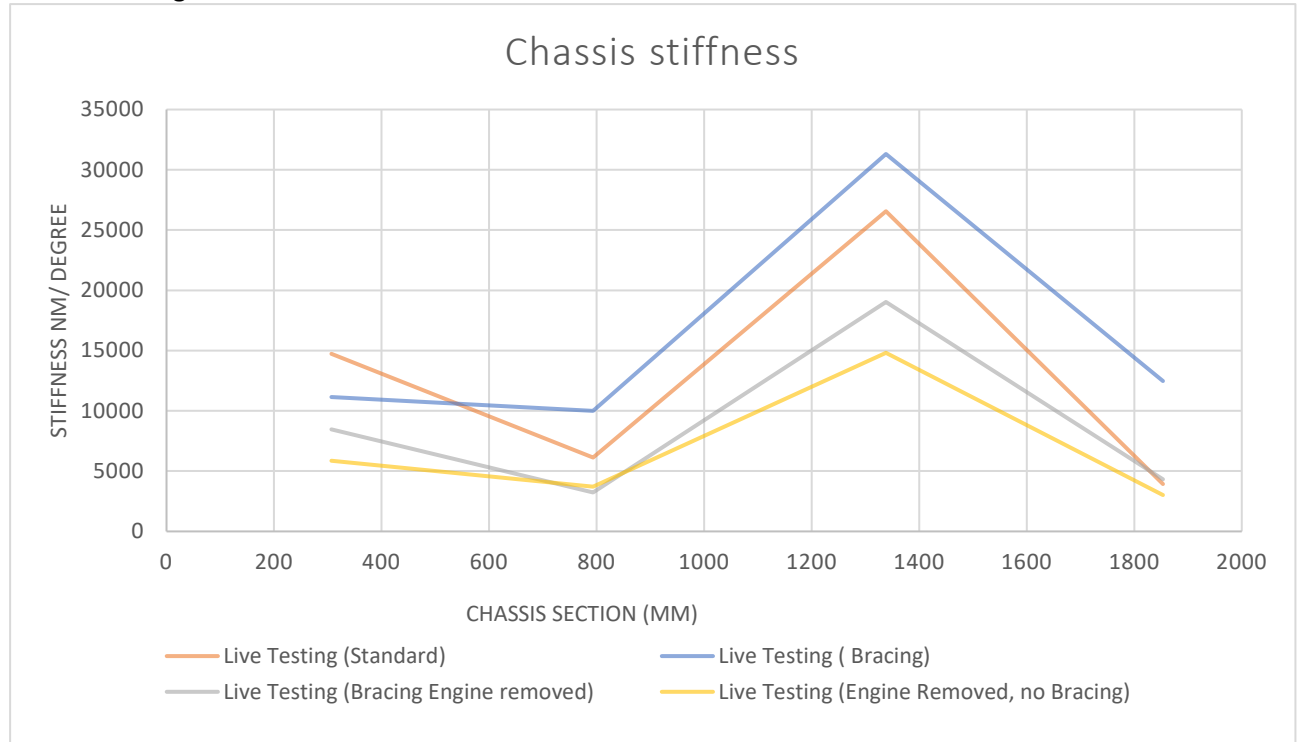


Figure 26 A comparison of live test results

Figure 21 is the same as figure 20 but has not omitted the live testing (with bracing) results. These were originally left out due to the figures being much higher, which caused the scale of the charts become misleading.

The chart shows the chassis stiffness is like previous FE runs but increases greatly towards the rear of the chassis.

3) Analysis

Data from the live testing has been compiled. This shows the vehicle's chassis stiffness by section. Ideally the chassis stiffness would be linear, but due to the complex structure of the chassis, this is not the case. Hopefully one of the outcomes of using FEM, is that the chassis can be examined in greater detail and some of the variations in stiffness can be reduced to become closer to an 'ideal' chassis model.

4) Discussion

While optimisation of the MCR chassis is the goal of this project, it is not difficult to design a stiff chassis. The chassis construction could, for example, be replaced with thicker or larger diameter bars. This is not done due to the increase that it would produce in weight and cost. For continuing work an investigation would be carried out into how stiff the chassis needs to be for handling balance to be properly controlled. An investigation could also be carried out into the effect that the original roll hoops from the Darrian MCR have on the overall chassis stiffness compared to that of the MCR 2000. It is acknowledged that there are some major assumptions made throughout the project, but it would be impossible to carry out this sort of analysis without them. Each of these could be investigated in detail and their effect on the overall result assessed.

Torsional Rigidity Test Validation

a) Model optimisation

Optimising the chassis stiffness can be a relatively simple task, e.g. The beams used to construct the chassis could be made thicker or of larger diameter, and extra-large roll hoops could be used. The restrictions of whatever class the vehicle would be competing in may, however, limit aspects such as roll hoop height, ride height, width, and length of chassis, etc.

“The Particular formula regulations appropriate to the car, these are likely to require minimum ground clearance, size, height of roll hoops, and possibly other driver protection structures.” (Steward, 2014)

On analysing the results from the FE, a strategy has been developed to stiffen the chassis. Examining the chassis by section and “ironing out” the fluctuations to ensure the chassis stiffness is more linear along its length as-well as examining the load paths from the results in the chassis.

i. Configuration 1, Front Bracing

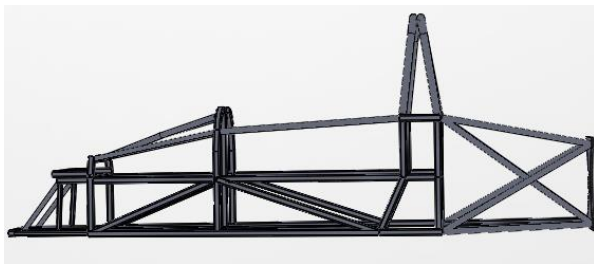


Figure 27 FE chassis in its standard form

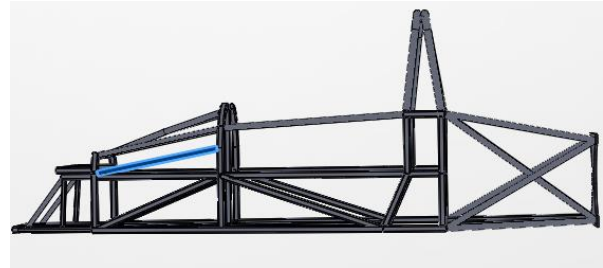


Figure 28 FE model with new front bracing

Figure 27 shows the chassis in its standard form, the decision was made after examining the data to model front bracing bars highlighted in figure 28 the bar of 26.9 x 3.2 mm weights 1.085kg 2.17kg total and was fitted on both sides of the chassis.

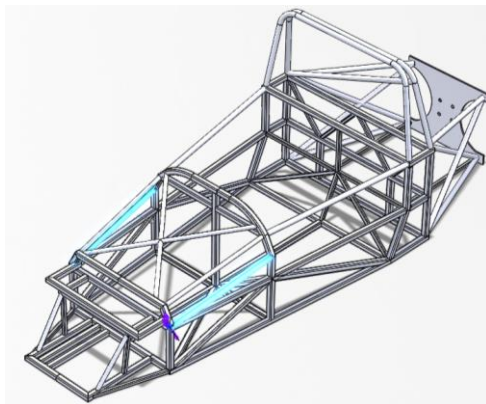


Figure 29 Screen shot showing supports modelled

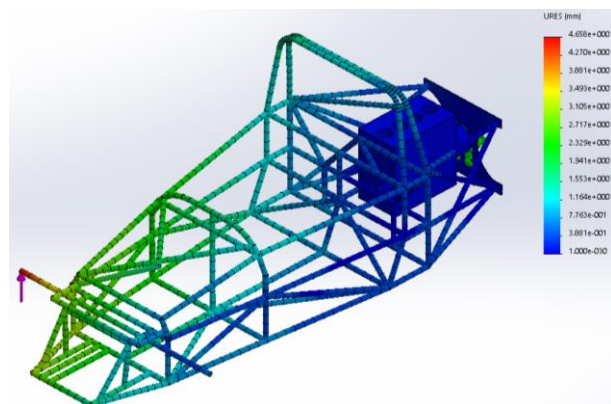


Figure 30 Showing FEA Chart of displacements

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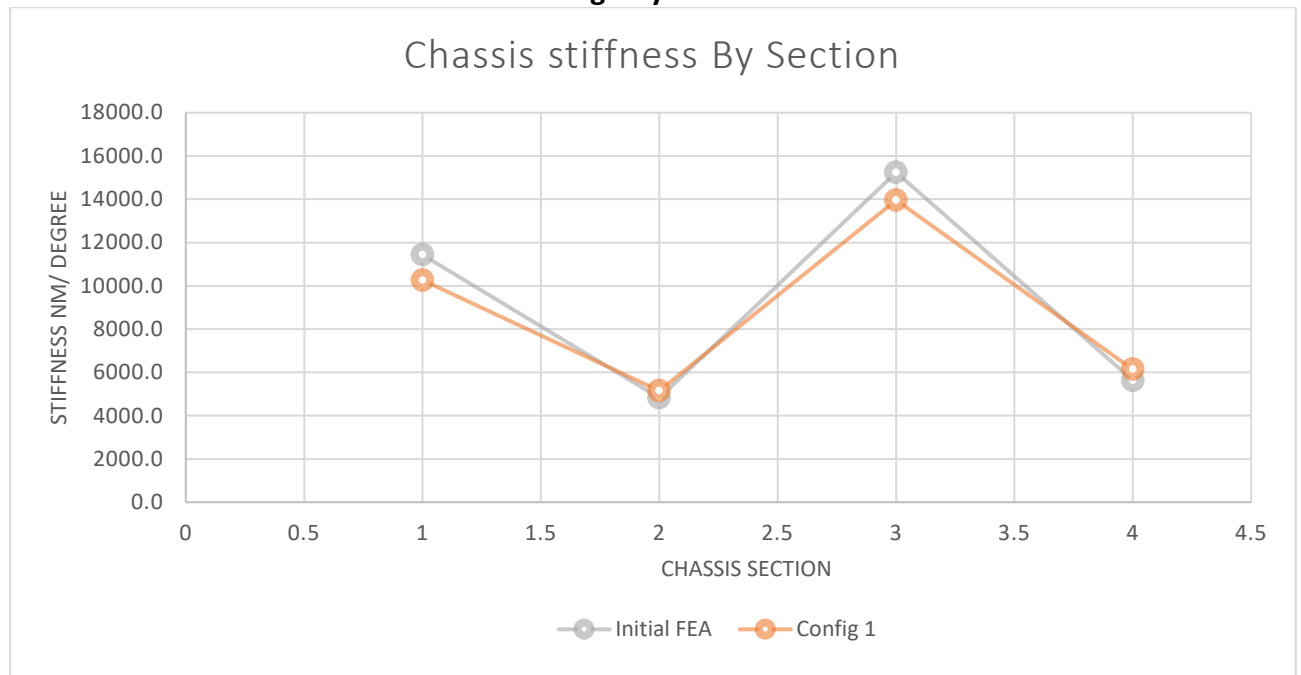


Figure 31 Comparison of initial FEA and Configuration 1

Stiffness by section					
	1 to 2	2 to 3	3 to 4	4 to 5	Total
	Nm/°	Nm/°	Nm/°	Nm/°	Nm/°
Initial FEA	11436.7	4821.8	15243.0	5630.8	1858.6
Config 1	10257.8	5151.0	13960.8	6141.6	1900.9
Δ %	-11%	7%	-9%	9%	2%

Figure 32 comparison of chassis stiffness by section

Modelling the bars shown in configuration 1, shows a total overall stiffness difference of 2%. As the variation in stiffness by section has varied greatly, this would suggest that the modifications to the chassis are causing the load paths to differ as the forces are being transferred in different directions causing the results to differ. This is a relatively simple modification and can be seen to make minimal gains. It equates to 38.04 **Nm/°** per KG added.

ii. Configuration 2, Front Cross Members



Figure 33 Initial FE Model

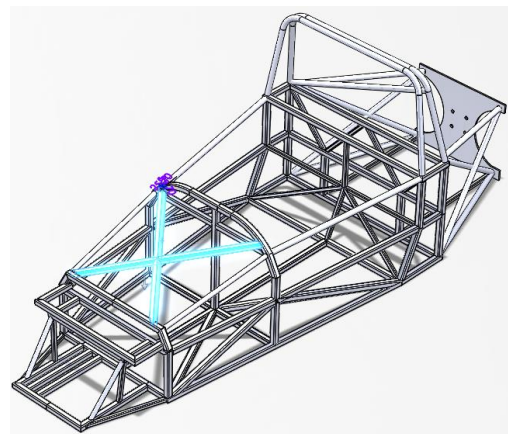


Figure 34 FE model of Configuration 2

The second configuration consist of 37x4.0mm cross bracing (shown above) added to the front of the chassis replacing the “y” bracing. An additional 2.38kg was added to the chassis.

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iii. Configuration 3, Footwell crossmembers

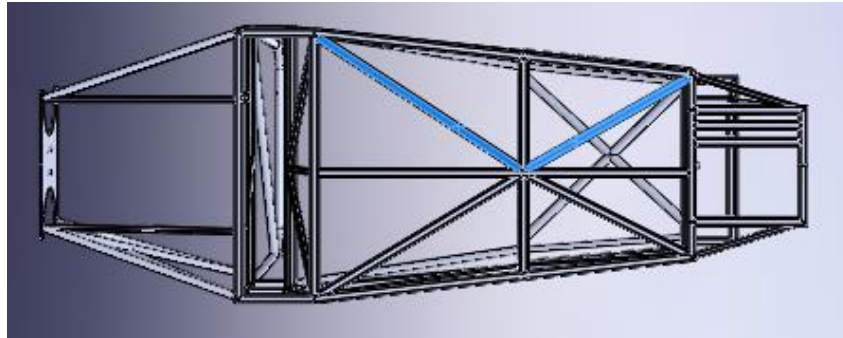


Figure 35 Floor plan optimisation

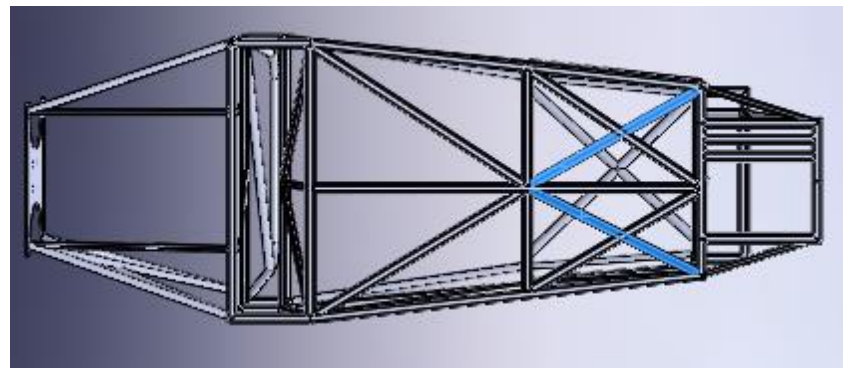


Figure 36 Floor plan Cross-members

Fig 30 shows areas of optimisations on chassis floor plan, in addition to the top cross brace the floorplan was the next area of investigation. It was observed that large areas were not being supported.

After examining data from initial FEA the floor plan was revised 30x30x2.6mm square beam was added 1.345kg of mass to either side of the vehicle chassis 2.690kg in total.

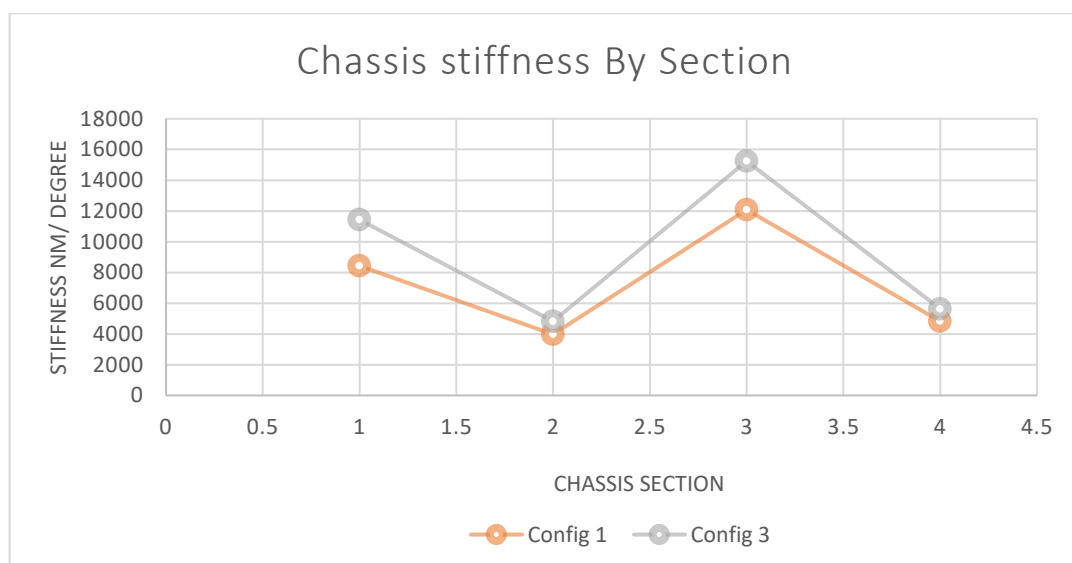


Figure 37 Data from FEA chassis stiffness by section

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The charts above show an increase in stiffness throughout the model with the additional floor plan bracing. The overall chassis stiffness is improved by **21%** through the floor plan bracing as shown below in Table 10, with the greatest increase in stiffness between section 1-2, as expected, as it is within this region the bracing was modelled. The increase tails off towards the rear of the vehicle chassis. Due to the bracing being lower down, this modification is a more viable option as it does not increase the height of the centre of gravity and it is very much more efficient at increasing stiffness at **147.2 Nm/° per kg** added.

Table 11 showing chassis stiffness by section

Stiffness by section					
1 to 2	2 to 3	3 to 4	4 to 5	Total	
Nm/°	Nm/°	Nm/°	Nm/°	Nm/°	
11146.9	3985.3	15139.7	8465.7	1905.5	
16652.2	4797.8	18809.3	9484.3	2341.5	
Δ %	40%	19%	22%	11%	21%

iv. Configuration 4, Centre section cross members

For Configuration 4 the mid-section chassis bracing was considered. As this is on the floorplan of the vehicle, it would not infringe any regulations that may be relevant to the vehicle class. Additional 30x30x2.6 square tube was added (seen below in figure) to the chassis adding a total of 3.32kg, 1.660kg on either side,

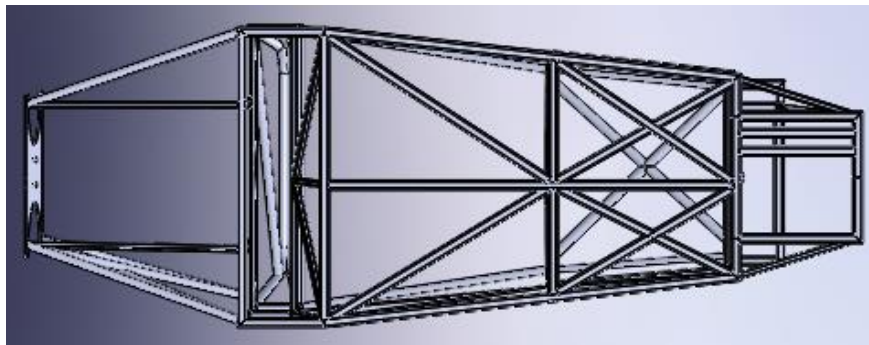


Figure 38 Chassis in previous design phase

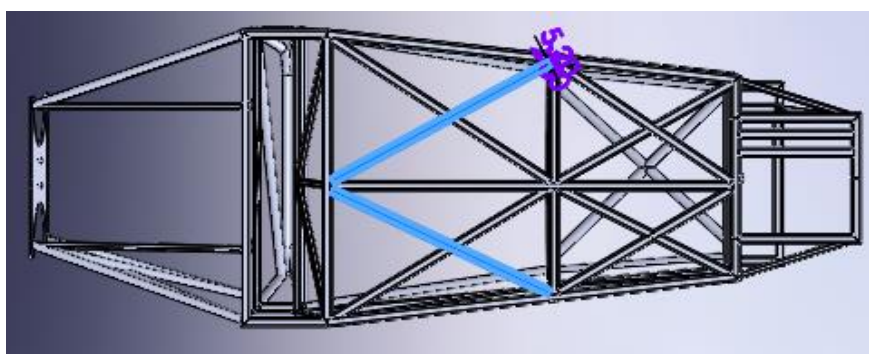


Figure 39 Addition floor pan Bracing

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Table 12 Stiffness comparison of Configuration 1 and 2

	Stiffness by section				
	1 to 2	2 to 3	3 to 4	4 to 5	Total
	Nm/°	Nm/°	Nm/°	Nm/°	Nm/°
Config 1	10257.8	5151.0	13960.8	6141.6	1900.9
Config 4	13154.4	6898.8	21370.9	8098.0	2555.9
Δ %	25%	29%	42%	27%	29%

As the weight added in the previous configuration studies is relatively small, they would be considered for the final design. Through the floor plan optimisation, all sections of the chassis saw improvements, with an increase of 29% overall. The results between points 3-4 saw the largest increase of 42%, although this was expected as this was the region that was not supported initially. This configuration saw an increase of 655 Nm/° per which equates to an increase of 72.3 Nm/° per for every KG added. This is a significant improvement over configurations 1 and 2.

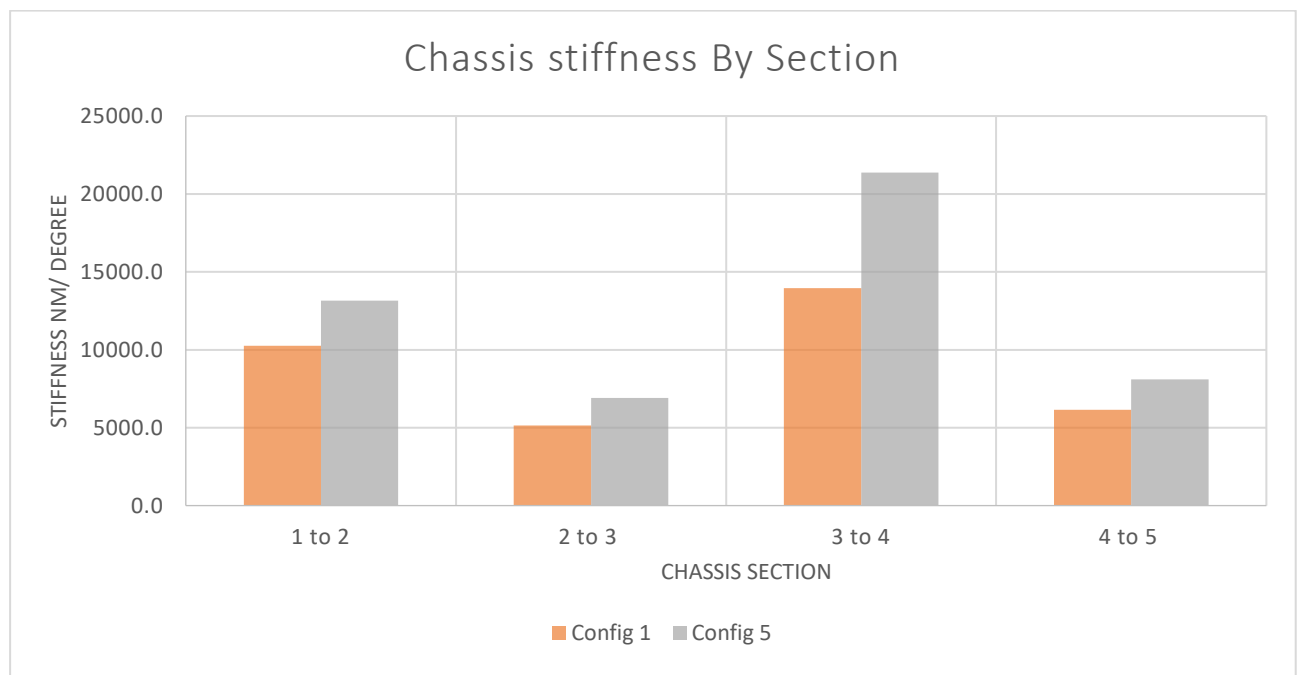


Figure 40 Chassis stiffness by section

As the chart above suggests, the largest improvements are found in regions 2-4, with the smallest increase at points 4-5, which is what would be expected. Adding floor plan bracing has made a positive effect on the overall chassis stiffness. In comparison to the roll hoop bracing investigated in chapter 3, this increased the stiffness of the chassis by 65% but increased the total weight of the chassis by 19%, significantly increasing

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the height of the COG, as the current suggested modifications increase the vehicle weight by 5.9kg in total 9% increase.

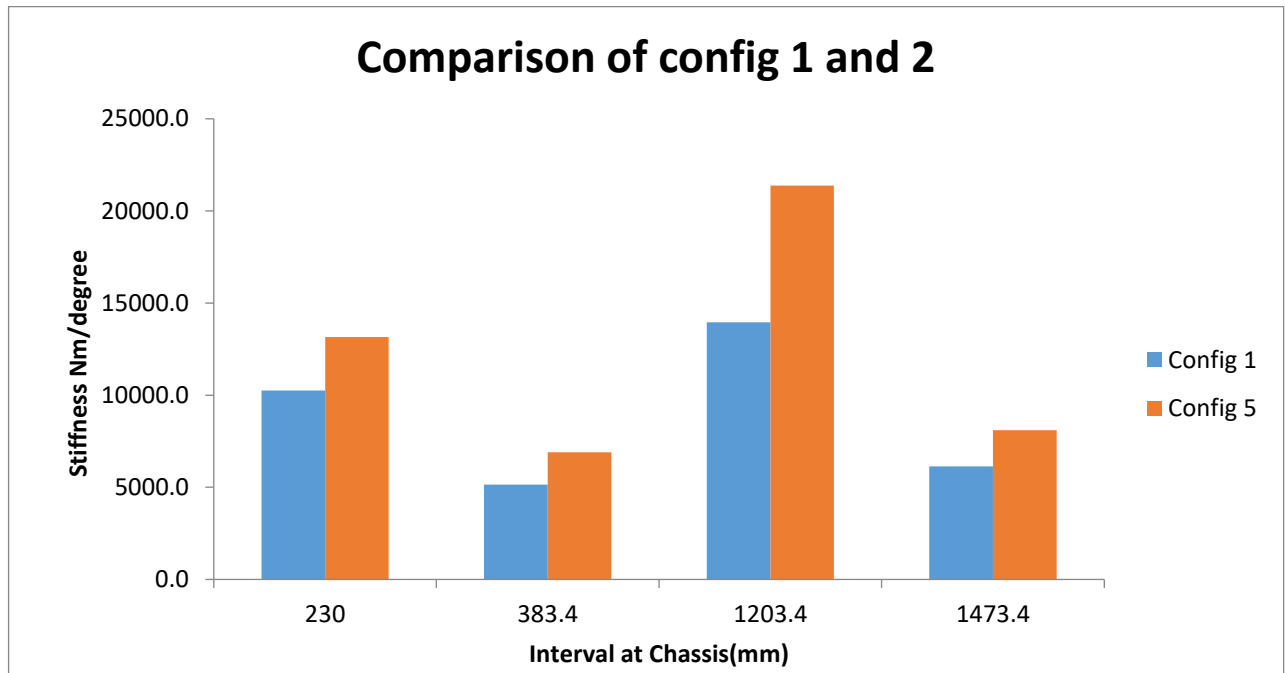


Figure 41 Correlation between Configuration 1 and 5

As none of the current optimisation suggestions change the height, length or width due to them being confined within the current structure of the chassis, they are viable options due to them not interfering with any regulations. The weight added is relatively negligible and they have proven to display significant improvements over the “standard” chassis.

Although the overall stiffness been increased through the optimisation of the cross-members, figure 36 would still suggest that the structure does not behave in a linear fashion, which may affect its performance.

v. Configuration 6, Front Supports

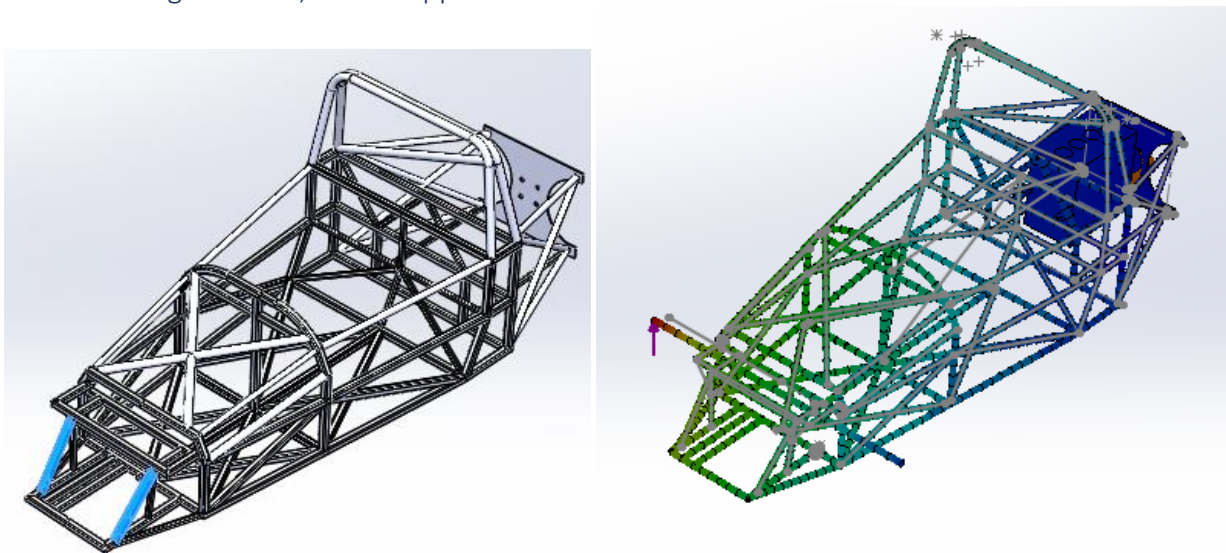


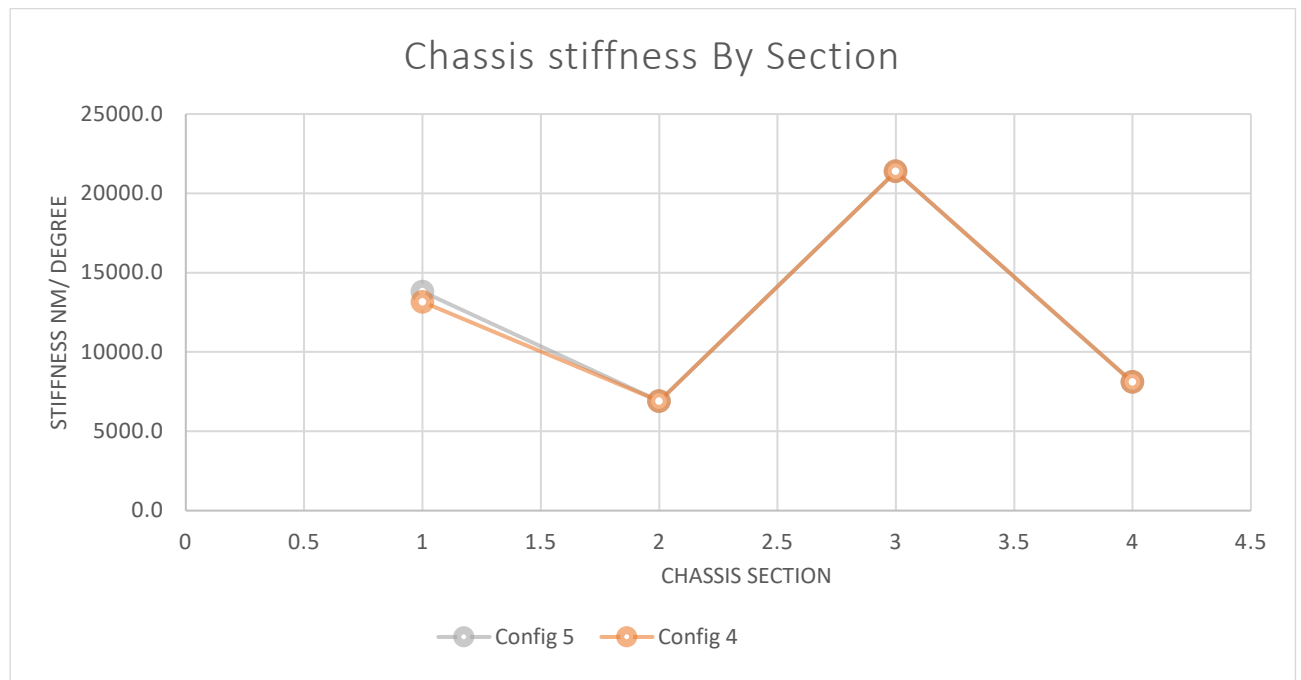
Figure 42 Front Bracing optimisation

Current mass 69.732kg

Initial investigations show that the chassis is lacking stiffness towards the front. The decision was made to experiment with increasing the diameter of the front support bracing, although this is in front of the

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suspension rockers. The bars were increased in diameter from 26.1x3.2mm and 512.3g each to 37.1x4mm and has a mass of 0.816kg each.



Increasing the thickness of the front braces was seen to have no significant effect on the overall stiffness or the stiffness by section. This would, therefore, produce no benefit.

vi. Configuration 7, Side bracing

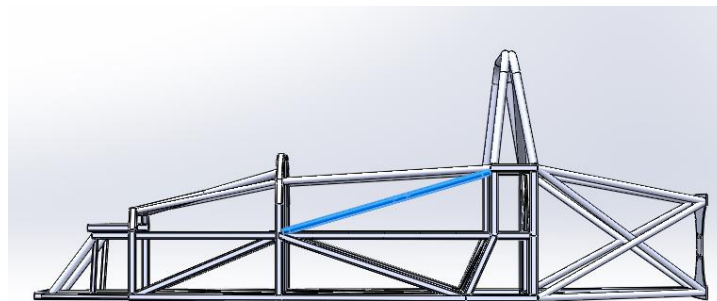
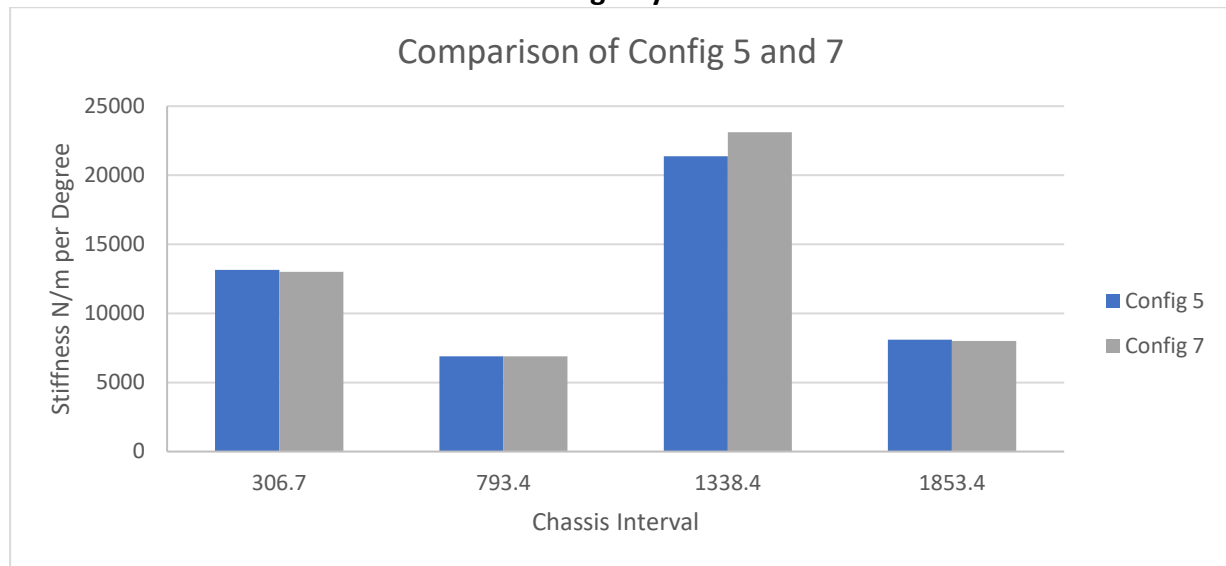


Table 13 Config 7

Current mass 67.8kg

Bracing fitted to the side of the chassis (highlighted in blue) was modelled due to this area being largely unbraced. Standard 21.3x2.6mm Bar was added, which increased the total mass by 1.83kg. In addition to the floor cross bracing the mass has increased by approximately 7.8kg. the bracing in this area is beneficial as it adds increased crash protection for the driver.

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The additional bracing between points 3-4 were largely unnoticed during testing, increasing the total overall stiffness by just 10.2 Nm/° this is unlikely to be beneficial to the structure.

Configuration 8 Side bracing/2

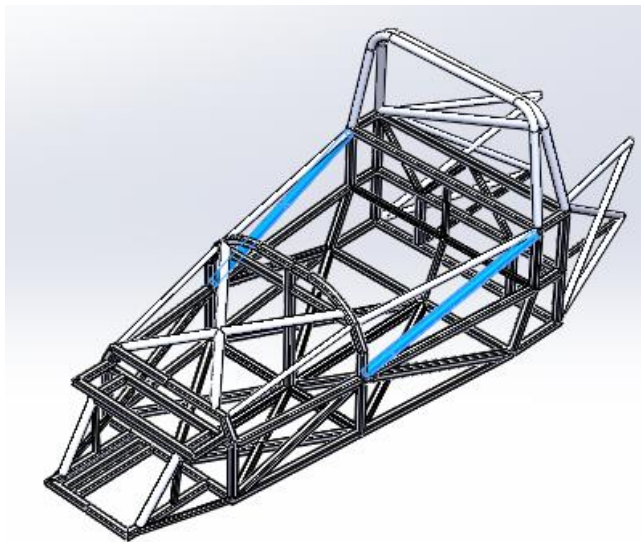


Figure 41 Config 8

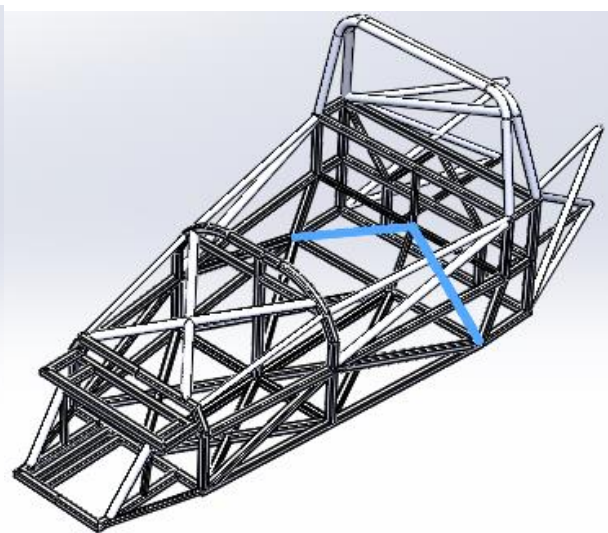


Figure 42 Fuel tank bracing

An investigation into increasing the diameter and thickness of the side bracing (fig41) included the removal of the fuel tank cross members shown in fig 42. The increased diameter bars are significantly heavier than those in configuration 7, being 2.6kg, 5.2kg in total increase in weight either side. Due to the significant increase, removal of the fuel tank cross members shown in fig to was necessary in order not adversely to affect the mass of the chassis. The horizontal bracing was also relocated creating a cross bracing as shown below in fig 43

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Config 9 Cross Bracing (side)

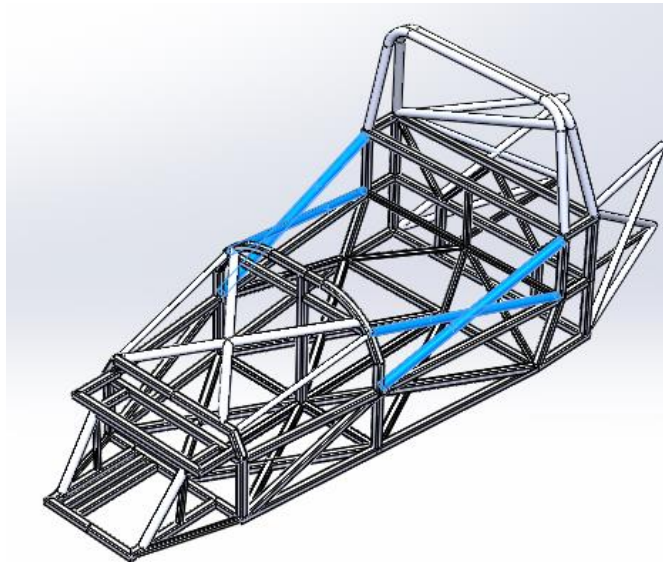


Figure 43 Configuration 8, cross-bracing (Side)

The increase in mass between config 7-8 is negligible as the bars have simply been relocated. This would have an effect on the height of the COG, which is a benefit.

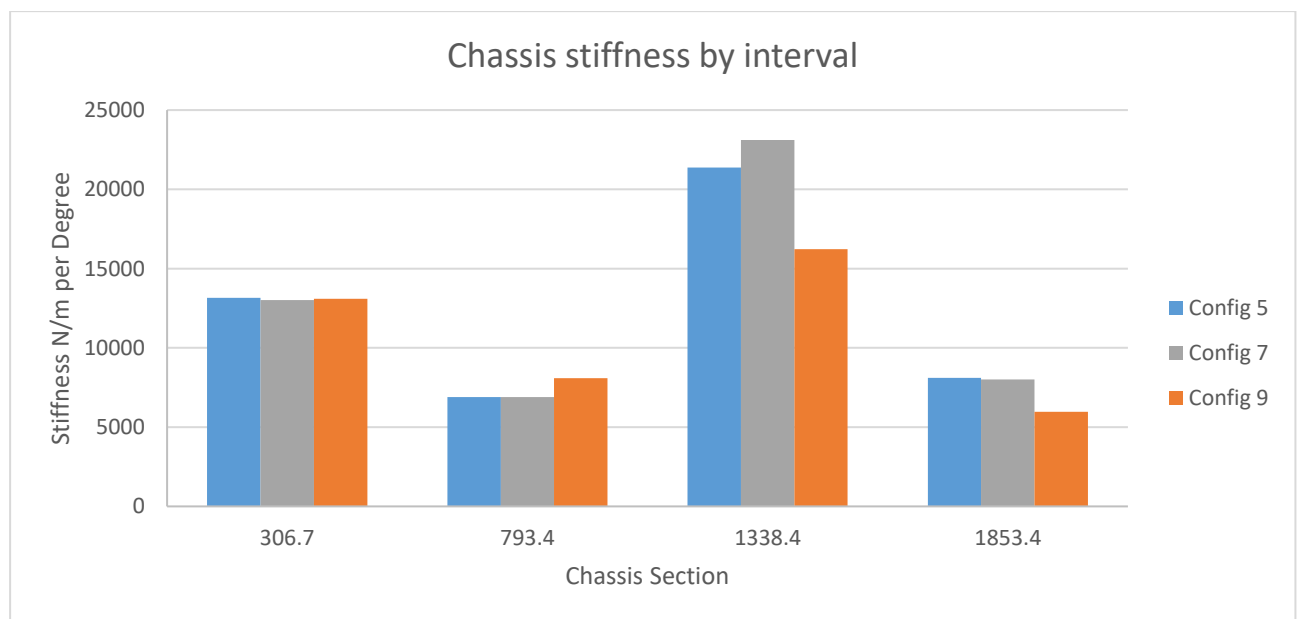


Figure 44 Histogram comparison of figures

The chart above shows configuration 5, 7 and 8. Configuration 7 performed the best of the 3, albeit only marginally. Configuration 8, with the relocated bracing, improved between points 2-3 but performed worse at all the other sections and overall at 2331.3 Nm/°. Due to the increased weight, it would be unlikely that any of these configurations would be used.

Test optimisations

The suspension is connected to pushrods, which in turn push the rockers, transferring the forces from the road the chassis and vice versa. On the test rig, they are not in use as the bar was simply clamped to the chassis frame. This is not fully representative of how the chassis behaves. For more accurate results this should be considered along with the possibility of modelling of rockers and pushrods.

Further improvements involve relocating the data points along the chassis. During the testing there were 5 points on either side of the chassis. Although located at crucial chassis sections, they are all at different intervals. To produce a more accurate representation, the data points should be at equal distances from

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each other and ideally the number of data points should be increased. This would allow a more detailed look at the chassis structure. Examining the stresses experienced in beams would be another indication of what areas are highly stressed under torsion and would need to be optimised. This was largely ignored for the purposes of this study. Stressed skin chassis structures and hybrid carbon-fibre/ spaceframe structure such as this are becoming more popular in the industry. An aluminium honeycomb or carbon structure could be used in improving the chassis overall stiffness.

9) Conclusions

It was found that modified cross-bracing at floor level (configuration 5) of the chassis resulted in the most effective design. The mass of the vehicle was reduced by 6.7kg over “Set up 2” (roll hoop bracing) and increased the overall stiffness by 653.9Nm/° over the “Set up 1” standard set up.

The project’s goal of increasing the stiffness without adversely affecting the mass of the vehicle has been achieved, and some of the suggestions could be incorporated into the current MCR’s chassis

However, as the results between the live testing and the FEA were not 100% correlated due to the highly complex nature of the chassis and the number of assumptions made, further investigation into the problem would be needed to be able to say with certainty that it is possible to predict exactly what would happen if the modifications were carried out. By examining patterns in the real vehicle and the FE model, it is possible to make educated assumptions with regard to how the chassis will behave under torsion and to suggest possible methods of stiffening the chassis. Whereas the suggestions found in this report are a useful starting point in the optimisation of the chassis, there are many different methods of doing this with cost and weight being the penalties. It has been found that due to the complexity of SolidWorks modelling and the FEA package, it is relatively simple to get vastly different results for two similar problems if the boundary conditions are not set correctly.

10) Evaluation

The project has been relatively successful. It has enabled the researcher to gain a valuable insight into the depth and complexity of chassis structures and testing. It has also allowed an important insight into how the torsional stiffness affects the overall vehicle dynamics and why this is important.

a) Further Work

The following are some suggestions for continuing work.

i. Further FEA

The testing carried out was a static analysis of the MCR’s torsional stiffness. A dynamic investigation into the vehicle’s chassis using the ADAMS software would be beneficial including further validation work. This would be needed in order to produce more conclusive results and to build on from the project by carrying out modifications on the real chassis and then producing further correlation with the FE model. This would include investigation of the effects of bending forces, their influence on the vehicle’s dynamics on the chassis and how they can be mitigated if they are an issue.

ii. Investigation into installation stiffness

An investigation into what effect a fully built up chassis would have on the overall torsional stiffness. Due to the testing being carried out on a bare chassis and engine block, a further question to be considered is how much does the “installation stiffness” change in comparison.

iii. Further live Testing

The possible use of strain gauges to quantify the vehicle’s stiffness from track data. Various set-ups could be tested, and the results could be analysed using the MoTec software. This would give a more “real situation” outlook on the problem and demonstrate why it is important to have a stiff chassis.

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a) *Problems encountered during the project*

i. *Modifications to the twist rig*

During the initial testing phase, as described in chapter 2, problems with the twist rig affected the timeline set out for each individual task. It was intended that the initial testing would commence on October 29th 2017, but it was not possible to carry this out until four weeks later. Once initial testing was carried out, it was realised that further modifications were needed to relocate the data points. This in turn also slowed the pace of the project down.

ii. *SolidWorks model*

During the initial redesign phase of the chassis, problems were encountered due to the fact that part of the model had been produced by somebody else. An in-depth investigation was carried out to establish how it was all put together. As much of the model was redrawn, it became apparent that it would have been more efficient to start from scratch ensuring all aspects of the model were put together correctly, rather than to modify existing drawings.

iii. *FEA Model*

Once the model was created research was carried out to establish how best to create the FEA model. As this had not been done previously, it was a steep learning curve. Initially, problems with meshing the initial model due to the complex geometry of the chassis required further research to mitigate the issue. Once this was solved, interfering bodies caused the FEA model to be “unstable”. Due to the FEA models not resolving, a review into how the model was put together was carried out. This further slowed the momentum of the project and increased the time it took to obtain some initial results.

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12) Appendices

Deflections Rhs/Lhs for FEA runs 1 to 38

FEA Run	Deflection right					Deflection Left				
	D1 mm	D2 mm	D3 mm	D4 mm	D5 mm	D1 mm	D2 mm	D3 mm	D4 mm	D5 mm
1	1.975	1.548	1.1	0.668	0.176	-0.862	0.5952	0.25	0.1956	0.03909
2	4.3	3.4	2	1.4	0.4	-3.9	-2.3	-1.28	-0.84	-0.24
3	3.57	2.837	1.49	1.233	0.3803	-2.752	-2.081	-1.087	-0.7568	-0.209
4	0.9752	0.7792	0.3987	0.373	0.008262	-0.3519	-0.235	-0.119	-0.1001	-0.0093579
5	3.5	2.83	1.659	1.23	0.03354	-2.672	-2.077	-0.1084	-0.07499	-0.0204
6	2.883	2.06	0.8538	0.4868	0.003017	-2.907	-2.156	-0.844	-0.4673	-0.00003628
7	1.144	0.9459	0.08503	0.041	0.01339	-0.2146	-0.1412	-0.00565	-0.0056	-0.019
Chassis Optimisations										
9	1.058	0.8762	0.476	0.3466	0.09186	-0.312	-0.2311	-0.05729	-0.03821	-0.00218
10	4.98	4.2	2.18	1.808	0.6	-4.646	-3.89	-1.94	-1.58	-0.04688
11	1.355	1.115	0.6199	0.4539	0.1472	-0.009	-0.00509	-0.007453	-0.00973	-0.003
12	1.423	1.14	0.637	0.468	0.446	-0.128	-0.005098	-0.008839	-0.009338	-0.0002675
13	1.37E+00	1.10E+00	6.36E-01	4.62E-01	1.35E-01	-1.24E+00	-9.87E-01	-5.53E-01	-4.01E-01	-1.06E-01
14	1.16E+00	9.83E-01	5.52E-01	3.96E-01	1.17E-01	2.46E-01	1.71E-01	6.23E-02	5.95E-02	2.02E-02
15	1.25E+00	1.00E+00	5.47E-01	3.98E-01	1.22E-01	3.40E-01	2.14E-01	6.23E-02	2.45E-02	6.04E-03
16	1.41E+00	1.15E+00	6.58E-01	4.86E-01	1.54E-01	-3.11E-01	-1.96E-01	-8.48E-02	-9.76E-02	-4.60E-02
17	3.11E+00	2.57E+00	1.48E+00	1.07E+00	3.18E-01	-2.29E+00	-1.84E+00	-9.62E-01	-6.69E-01	-1.81E-01
18	1.21E+00	1.02E+00	5.94E-01	4.42E-01	1.19E-01	-4.53E-01	-3.32E-01	-1.86E-01	-1.55E-01	-3.51E-02
19	1.20E+00	1.01E+00	5.91E-01	4.31E-01	1.11E-01	-4.46E-01	-3.25E-01	1.80E-01	1.50E-01	-3.06E-02
20	1.49E+00	1.27E+00	7.46E-01	5.53E-01	1.37E-01	-2.95E-01	-2.57E-01	-2.58E-01	-2.21E-01	-1.02E-02
21	1.59E+00	1.33E+00	7.89E-01	5.80E-01	1.41E-01	-3.41E-01	-2.88E-01	2.79E-01	2.45E-01	-1.72E-02
22	2.99E+00	2.52E+00	1.47E+00	1.07E+00	3.35E-01	-2.80E+00	-2.35E+00	-1.32E+00	-9.45E-01	-2.67E-01
23	3.43E+00	2.88E+00	1.61E+00	1.15E+00	3.17E-01	-1.05E+00	-7.70E-01	-5.35E-01	-4.76E-01	-4.17E-02
	Deflection right					Deflection Left				
	D1 mm	D2 mm	D3 mm	D4 mm	D5 mm	D1 mm	D2 mm	D3 mm	D4 mm	D5 mm
24	3.18E+00	2.73E+00	1.50E+00	1.07E+00	2.86E-01	9.92E-01	7.34E-01	5.11E-01	4.43E-01	4.06E-02
25	2.84E+00	2.43E+00	1.34E+00	9.51E-01	2.65E-01	-8.24E-01	-6.35E-01	4.47E-01	3.86E-01	3.31E-02
26	2.87E+00	2.39E+00	1.32E+00	9.42E-01	2.57E-01	-8.65E-01	-6.54E-01	-4.54E-01	-4.04E-01	-3.04E-02
27	2.68E+00	2.29E+00	1.28E+00	9.23E-01	2.47E-01	-8.58E-01	-6.61E-01	-4.40E-01	-3.93E-01	-5.62E-02
28	3.40E+00	2.94E+00	1.70E+00	1.28E+00	3.24E-01	1.32E+00	1.01E+00	5.56E-01	4.46E-01	1.15E-01
29	3.22E+00	2.69E+00	1.61E+00	1.21E+00	2.95E-01	-1.25E+00	-9.58E-01	-5.26E-01	-4.28E-01	-1.16E-01
30	2.33E+00	1.93E+00	1.08E+00	7.84E-01	1.99E-01	-7.73E-01	-5.15E-01	-3.62E-01	-3.20E-01	-5.94E-02
31	2.19E+00	1.93E+00	1.09E+00	8.05E-01	2.08E-01	-7.16E-01	-5.41E-01	-3.70E-01	-3.32E-01	-6.00E-02
32	1.14E+00	9.49E-01	5.56E-01	3.95E-01	8.71E-02	-4.63E-01	-3.46E-01	-1.84E-01	-1.51E-01	-4.79E-02
33	2.50E+00	2.13E+00	1.20E+00	8.87E-01	2.19E-01	-7.67E-01	-5.87E-01	-3.99E-01	-3.60E-01	-6.81E-02
34	1.40E+00	1.39E+00	1.08E+00	7.61E-01	2.11E-01	-6.92E-01	-5.29E-01	-3.60E-01	-3.25E-01	-6.00E-02
35	2.14E+00	1.82E+00	1.03E+00	7.11E-01	1.53E-01	-6.59E-01	-5.04E-01	-3.41E-01	-3.08E-01	-6.89E-02
36	1.62E+00	1.38E+00	7.79E-01	5.75E-01	1.52E-01	-4.99E-01	-3.71E-01	-2.59E-01	-2.33E-01	-5.22E-02
37	1.54E+00	1.31E+00	8.38E-01	6.71E-01	1.67E-01	-6.90E-01	-5.56E-01	-2.84E-01	-2.25E-01	-6.86E-02
38	1.72E+00	1.49E+00	9.88E-01	7.21E-01	1.35E-01	-5.64E-01	-4.23E-01	-3.21E-01	-2.87E-01	-5.24E-02

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Raw Data from Excel FEA run 1-38

twist angle					Stiffness					
D1	D2	D3	D4	D5	1 to 2	2 to 3	3 to 4	4 to 5	1 to 5	
°	°	°	°	°	Nm/°	Nm/°	Nm/°	Nm/°	Nm/°	
0.173290015	0.158130012	0.078352	0.049783	0.019462	25593.66	4863.482	13581.32	12796.5	2522.303	2522.303
0.290655229	0.242734402	0.070752	0.044751	0.018375	8096.688	2256.044	14922.49	14710.42	1425.003	1425.003
0.295917248	0.241228704	0.140918	0.106596	0.02281	7094.722	3867.963	11304.7	4630.858	1420.686	1420.686
0.280059868	0.234072675	0.136416	0.104289	0.024038	8437.132	3973.113	12077.13	4834.81	1515.496	1515.496
0.165389062	0.152471756	0.091015	0.065926	0.016539	30037.22	6313.433	15464.52	7856.334	2606.648	2606.648
0.353918328	0.289205004	0.169391	0.12972	0.032547	5995.674	3238.354	9780.398	3992.878	1207.326	1207.326
0.245920142	0.193688264	0.114568	0.087473	0.020468	7428.414	4903.914	14320.17	5790.599	#REF!	1720.986
0.230015214	0.196089456	0.115622	0.090168	0.02126	11436.74	4821.812	15243.05	5630.77	1858.64	1858.64
0.12721565	0.102601446	0.058683	0.043221	0.010698	15763.26	8834.478	25095.17	11929.7	3329.956	3329.956
0.25907519	0.214894834	0.126907	0.098869	0.022723	8782.184	4409.68	13838.52	5095.452	1641.615	1641.615
0.165793223	0.152091369	0.114457	0.086078	0.021448	28317.34	10309.68	13672.35	6003.393	2688.005	2688.005
0.221670476	0.183845752	0.108521	0.080729	0.017553	10257.84	5151.044	13960.84	6141.58	1900.869	1900.869
0.167956674	0.138460838	0.082219	0.064063	0.016151	13154.4	6898.785	21370.87	8098.028	2555.892	2555.892
0.176792745	0.147954662	0.088852	0.071013	0.018702	13454.43	6564.853	21750.63	7417.16	2454.292	2454.292
0.181341538	0.151710982	0.103766	0.07985	0.014832	13094.59	8092.673	16222.89	5967.612	2330.196	2330.196
twist angle					Stiffness					
D1	D2	D3	D4	D5	1 to 2	2 to 3	3 to 4	4 to 5	1 to 5	
°	°	°	°	°	Nm/°	Nm/°	Nm/°	Nm/°	Nm/°	Check
0.224824518	0.068154081	0.050259	0.027932	0.014801	2476.536	21682.49	17378.04	29546.73	1847.409	1847.409
0.649827651	0.407722776	0.193942	0.132448	0.069187	1602.611	1814.947	6309.567	6133.312	668.2278	668.2278
0.50100127	0.351786072	0.152138	0.117654	0.063706	2600.271	1943.423	11251.63	7192.11	887.2732	887.2732
0.105169058	0.072546042	0.030611	0.027974	0.001905	11893.44	9252.397	147128.9	14883.57	3757.351	3757.351
0.489114179	0.350999239	0.104504	0.077162	0.005831	2809.254	1574.068	14190.76	5439.411	802.8423	802.8423
0.45884172	0.301571793	0.100389	0.056415	0.00033	2467.096	1928.593	8823.382	6918.11	846.2162	846.2162
0.107665347	0.077760602	0.005362	0.002755	0.003546	12974.53	5359.205	148864.5	-490859		3726.488
0.108568766	0.079205514	0.031533	0.022753	0.010166	13213.8	8138.825	44194.16	30825.15	3942.987	3942.987
0.762834265	0.57868022	0.243611	0.200328	0.069931	2106.932	1157.968	8964.412	2975.525	559.9628	559.9628
0.108093283	0.080120387	0.037095	0.027414	0.016237	13870.57	9017.85	40079.58	34715.81	4224.009	4224.009
0.122912523	0.081909217	0.038188	0.028224	0.048244	9462.652	8874.342	38943.09	-19381.2	5196.289	5196.289
0.117167095	0.149412515	0.070286	0.051004	0.026032	-12032.7	4903.563	20122.51	15536.94	4257.404	4257.404
0.090486916	0.05807546	0.028948	0.019921	0.010511	11971.08	13320.88	42981.26	41232.72	4851.465	4851.465
0.098580836	0.056415957	0.028649	0.022054	0.012482	9201.971	13973.48	58835.73	40534.6	4506.468	4506.468
0.115697059	0.096301258	0.043928	0.034512	0.021605	20004.33	7408.353	41207.92	30060.16	4123.614	4123.614
0.260438243	0.315591734	0.144398	0.102724	0.053955	-7034.91	2266.443	9310.371	7955.859	1879.09	1879.09
0.09842987	0.096415707	0.046132	0.035276	0.016611	192635.9	7716.258	35740.46	20787.82	4742.209	4742.209
0.097679398	0.095664639	0.024296	0.016615	0.015296	192578.8	5436.563	50515.39	294078.9	4709.676	4709.676
0.118490525	0.108947817	0.059383	0.045789	0.015891	40659.32	7828.137	28542.62	12977.52	3781.711	3781.711
0.127365427	0.115464229	0.030173	0.01982	0.017101	32601.76	4549.142	31210	142710.3	3518.819	3453.717
0.258155922	0.348638738	0.164969	0.119026	0.065047	-4288.11	2112.49	8445.237	7187.942	2009.228	2009.228
0.275280465	0.261042719	0.127009	0.096067	0.038798	27251.5	2894.785	12539.56	6775.089	1640.713	1640.713