Abstract: The Formula SAE and Formula Student competitions, held every year in the USA and UK, challenge teams of engineering students to design and build a small single-seater racing car. The University of Leeds has entered teams into these competitions for the past four years and has developed an award winning hybrid monocoque chassis design. The design allows a light, stiff and extremely safe chassis to be produced at a reasonable manufacturing cost.

A chassis which is torsionally stiff enables a desirable roll moment distribution to be achieved for good handling balance. A chassis which can absorb high energy impacts whilst controlling the rate of deceleration will increase the likelihood of drivers surviving a crash without injury.

This paper describes how a common model of the chassis was developed using HyperMesh to allow both linear and non-linear Finite Element Analysis to be performed, using ANSYS and LS-DYNA respectively, without the need to create two separate models.

Keywords: Optimisation, Torsion, Crashworthiness, ANSYS, LS-DYNA, HyperMesh

1.0 INTRODUCTION

The University of Leeds has been competing in the Formula SAE competition since 1997 and were the first non-North American entry at the competition. Through their continual use of computer analyses the Team has managed to develop a winning car which, each year, has continued to improve. This year the Team came 5th out of 100 competitors and won 7 design prizes.

The analysis of the school's Formula SAE racing car is undertaken by final year undergraduate students as their major project. The two aims in the design of the 2000 year
chassis were to continue to use finite element techniques to model and optimise the torsional stiffness and crashworthiness of the racing car chassis.

Each aim required a different solution processor, ANSYS for torsional stiffness (linear analysis) and LS-DYNA for crashworthiness (non-linear). Both finite element models use the same chassis geometry that had been designed using a 2D CAD package. Creating a single model in Hypermesh significantly reduced the preparation time for analysis (i.e. reduced modelling time).

2.0 MODELLING

2.1 Introduction

The Leeds chassis is a hybrid semi-monocoque design, which consists of two Cr-Mo steel sub-frames being attached to a monocoque 'tub'. The monocoque is formed by scoring and bending a flat honeycomb sandwich panel into shape around the sub-frames. The joins are then re-bonded and reinforced using strips of carbon fibre pre-preg. The steel sub-frames are used to distribute point loads from the suspension and engine into the sandwich material and are bolted and bonded into the tub. The sub-frames also ensure compliance with FSAE roll over protection rules [1].

There are no steel tubes between the front and rear sub-frames, all loads being taken by the honeycomb panels. Sidepods are formed in a similar manner to the tub and bonded to the chassis. These provide both additional stiffness and side impact crash protection and also contain ground effect venturis to reduce lift at high speed. Both the engine and differential carrier ('diff box') are stressed members of the chassis. They bolt onto hardpoints on the rear sub-frame. The weight of the complete chassis without engine or diff box is less than 20 kg.

Figure 1: University of Leeds 2000 Car

2.2 Common HyperMesh Model

As described previously, it was felt that there was a significant advantage in creating a model that could be used for both torsional and crash analyses. By using HyperMesh as the pre-processor the resulting model could be exported to both ANSYS and LS-DYNA using the built-in data interfaces.
The model was created using the drawing functions in HyperMesh. In order to reduce the complexity of the model, discrete element approximations were used where possible. For example, the honeycomb material is represented by shell elements and the steel tubing of the sub-frames is represented by beam elements. Use was made of ‘collectors’ in HyperMesh in order to simplify material property specification and to allow easy editing of the model at a later date. The various parts chassis were linked using rigid elements.

Although both models were based on the same geometry, there were several differences due to the requirements of the analyses. This meant that the common model would need to be customised to suit the two loading scenarios. The torsional analysis requires little modification, the only item added was a stiff beam to allow the structure to be loaded.

The crash analysis required the common model to be modified by adding masses representing the wheels, engine and driver. Additionally it has been found from previous work [2] that beam elements are not sufficiently accurate to represent the steel tubing of the chassis in non-linear analysis: for this reason the beam elements were replaced by shell elements. Finally, a model of the impact-absorbing fibreglass nosecone was added to the crash model for use in frontal impacts.

The customisation of the common model to suit the two analyses is summarised in the Figure 2.

Figure 2: Use of a Common Chassis Model for Both Torsional and Crash Analysis
The use of a common model had been attempted previously by Butler et al. [2] but he was unable to successfully export the HyperMesh model to ANSYS. To ensure that this would be possible for the year 2000 car, a series of simple models was created to act as confidence tests to prove the validity of the interface.

2.3 HyperMesh-ANSYS Data Interface

HyperMesh exports models to ANSYS in the form of ‘.prp’ files which are read in and converted to the native format. The ‘.prp’ file is in a human readable format which consists of a number of blocks of elements. Each block contains a header describing the element, material, and real constant numbers, a list of co-ordinates defining the positions of the nodes forming each element and a footer with the material number.

As the chassis uses honeycomb sandwich panels extensively in its construction it was desirable to use ANSYS’ SHELL 91 multi-layer element type. Although HyperMesh version 3.1 does not directly support this element type it was possible to use another 8-node shell element type within HyperMesh and substitute the SHELL 91 in the element set-up within ANSYS. Transferring shell elements between HyperMesh and ANSYS was straightforward, requiring only minor modification to ensure that the element specifications of the collectors matched the element configuration within ANSYS.

There was some difficulty in transferring beam elements between packages. On examining the ‘.prp’ file it was found that the header was missing from each beam element block. This problem was easily solved by cutting and pasting headers from other element blocks.

Figure 3: HyperMesh Finite Element Model of Chassis.
3.0 ANALYSIS

3.1 Material Testing

To complement the research another project involved performing physical tests on specimens of the materials to determine their physical properties (Table 1). These results were used in two ways. For the torsional analysis, they were used to validate material models developed using physical properties from manufacturers’ datasheets. The crash analysis used the test data directly to produce the material model used for the shell elements in the chassis.

<table>
<thead>
<tr>
<th>Material</th>
<th>Test conducted</th>
<th>Quantity of result</th>
<th>Value</th>
<th>Application to FEA analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honeycomb sandwich panel</td>
<td>Tensile test</td>
<td>Young's modulus</td>
<td>E = 1.06 GPa</td>
<td>DYNA crashworthiness analysis</td>
</tr>
<tr>
<td>Honeycomb sandwich panel</td>
<td>Four point bend</td>
<td>Load curve</td>
<td>---</td>
<td>ANSYS torsional simulation</td>
</tr>
<tr>
<td>Honeycomb sandwich panel</td>
<td>Four point bend</td>
<td>Max load before failure</td>
<td>P_{\text{max}} = 2.6 kN</td>
<td>DYNA crashworthiness analysis</td>
</tr>
<tr>
<td>Polyurethane foam</td>
<td>Compression test</td>
<td>Mass density and Bulk modulus</td>
<td>\rho = 50.7 kg/m^3 and K = 0.63 GPa</td>
<td>DYNA crashworthiness analysis</td>
</tr>
<tr>
<td>Polyurethane foam</td>
<td>Compression test</td>
<td>Load curve</td>
<td>---</td>
<td>DYNA crashworthiness analysis</td>
</tr>
<tr>
<td>Fibre glass samples</td>
<td>Tensile test</td>
<td>Young's modulus and fracture stress</td>
<td>E = 7.29 GPa and \sigma_f = 231 MPa</td>
<td>DYNA crashworthiness analysis</td>
</tr>
</tbody>
</table>

Table 1: Physical Material Test Results and Applications

3.1 Torsional Analysis & Optimisation

High torsional stiffness is a desirable attribute for a racecar design as it allows the handling of the car to be accurately controlled by varying the suspension parameters. A flexible chassis reduces the ability of the race engineer to translate a change in front to rear roll stiffness ratio into a change in front to rear load transfer distribution [3]. Thus the vehicle’s handling balance becomes more difficult to tune.

Clearly any level of stiffness may be achieved when designing a chassis simply by adding more material to the more highly stressed areas of the structure. This is not good practice for a racing car, as extra weight will have a detrimental effect on its performance. For this reason, a better measure of a chassis' torsional performance is the stiffness to weight ratio (specific stiffness), calculated by dividing the torsional stiffness by the structure mass.
The finished chassis model represents the ‘as built’ state and is referred to as the ‘baseline’ chassis configuration. This was analysed using ANSYS and the model was refined to overcome any errors in the model that had been identified. The stiffness of the baseline chassis was 880 Nm/degree while the specific stiffness was 44.6 Nm/degree/kg.

The baseline model was then modified to create a number of design iterations (Figure 4). These iterations were analysed in the same manner as before and the results were compared to the baseline model to identify the most promising modifications for future chassis designs.

The results of the analysis are summarised in (Figure 4). The greatest increases in specific stiffness would come from increasing the thickness of the honeycomb and replacing the aluminium outer skin with carbon fibre.

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![Figure 4: Results of Different Design Iterations.](image)

3.2 Crashworthiness Analysis

Racing cars are designed to be driven near the limit of adhesion at all times and are therefore prone to be involved in accidents, the most likely scenarios being a frontal or side impact. In order to validate the overall performance of the vehicle, both of these scenarios were simulated using the non-linear finite element analysis package, LS-DYNA.

The competition rules [1] have a comprehensive section covering safety parameters, which specify the minimum requirements for a spaceframe chassis. Due to the composite construction of the Leeds chassis, energy absorbent structures are used to provide equivalent protection. These structures are the nosecone for frontal impacts and the sidepods for side impacts and are more than adequate when compared to the minimum requirements specified by the rules.

Previous work by O’Rourke [4] in conjunction with the Williams Formula 1 team and current FIA Formula 1 rules [5] quote suitable levels of deceleration that drivers can
undergo without high levels of injury. The mean deceleration rate should be lower than 40g and the peak value should not exceed 60g for more than 3ms.

In the frontal impact scenario, the vehicle is simulated hitting a rigid wall, head on at 30mph. In the side impact scenario, the vehicle hits a rigid cylinder (representing a lamppost) at a lateral velocity of 30mph, mid way along the car.

**Frontal Impact**

Figure 5 shows the average deceleration of all the nodes positioned at the driver’s centre of gravity. It can be seen that the average deceleration of the driver is approximately 0.4 mm/(ms)² (40g), with a peak for more than 3ms of 0.75 mm/(ms)² (75g). This is above the target set to avoid injury ([4] and [5]) and is due to the relatively high speed of the impact. Due to the nature of the competition (low cornering speeds) and the track design (open car park with no rigid walls and track marked by cones), the speed of the vehicle would be much lower in an accident at this type of competition. As well, the formula SAE regulations [1] only require a relatively small crush zone compared with the F1 regulations ([4] and [5]).

Another contributing factor to the high deceleration rates measured, is because the restraint system is not modelled and the nodes simulating the driver’s mass are rigidly attached to the chassis. Also the chassis structure itself was not damaged showing that the nosecone acted as a sacrificial structure as planned.

![Figure 5 – Average Deceleration, of the Driver Nodes (in frontal direction), Time History for Frontal Impact of Chassis Structure.](image)

**Side Impact**

In a side impact collision the main consideration, with respect to driver injury, is cockpit intrusion. The main method of energy dissipation in this scenario is the deformation of the sidepods. The simulation results showed that the cockpit suffers no intrusions due to the deformation of the sidepods which absorbed the impact energy and the stiffness of the
cockpit sides. The average deceleration of the driver was found to be 30g and the peak value which lasted for more than 3ms was 57g. This is within the target set to avoid driver injury and again the restraint system is not modelled and the nodes simulating the driver’s mass are rigidly attached to the chassis.

4.0 CONCLUSION

This paper has described how HyperMesh was used to create a common model for the torsional and crashworthiness analysis of the University of Leeds 2000 Formula SAE racecar.

It has shown the modelling techniques used, how the common model was modified to suit the needs of the two analyses and how the data interface between HyperMesh and ANSYS was proven. The results of the analyses have been described and the routes for optimising the chassis identified. A more detailed account of the results may be found in a paper which will be presented at the upcoming 2000 SAE Motorsports conference.

These analyses represent just some of the analytical work undertaken by students in the design of the Leeds formula SAE racing car. This work contributed to the team winning the Altair Engineering Best Use of Optimisation in Design Award at the 2000 Formula SAE competition, which was the third year running that the team had won the prize.

5.0 REFERENCES


