Cambridge University Eco Racing: Design and Analysis of a Solar Electric Vehicle

Charlie Watt, Martin McBrien, Kento Taoka

Department of Engineering, University of Cambridge

A technical overview of the solar electric vehicle 'Orion', developed by Cambridge University Eco Racing (CUER), is presented here. The vehicle is the second built by the team, and will be raced across Australia in the World Solar Challenge in October 2009. The paper gives particular reference to the use of Abaqus in simulation and optimisation of the structural performance of the vehicle chassis, shell and wheel motor.

1. Introduction

Cambridge University Eco Racing (CUER) are currently designing and manufacturing a solar electric vehicle, 'Orion' to race across the Australian continent as part of the World Solar Challenge (WSC) in October 2009. The World Solar Challenge is a 3000km race along public roads through the outback, from Darwin to Adelaide. The solar powered cars must complete the entire journey using only energy directly derived from the sun.

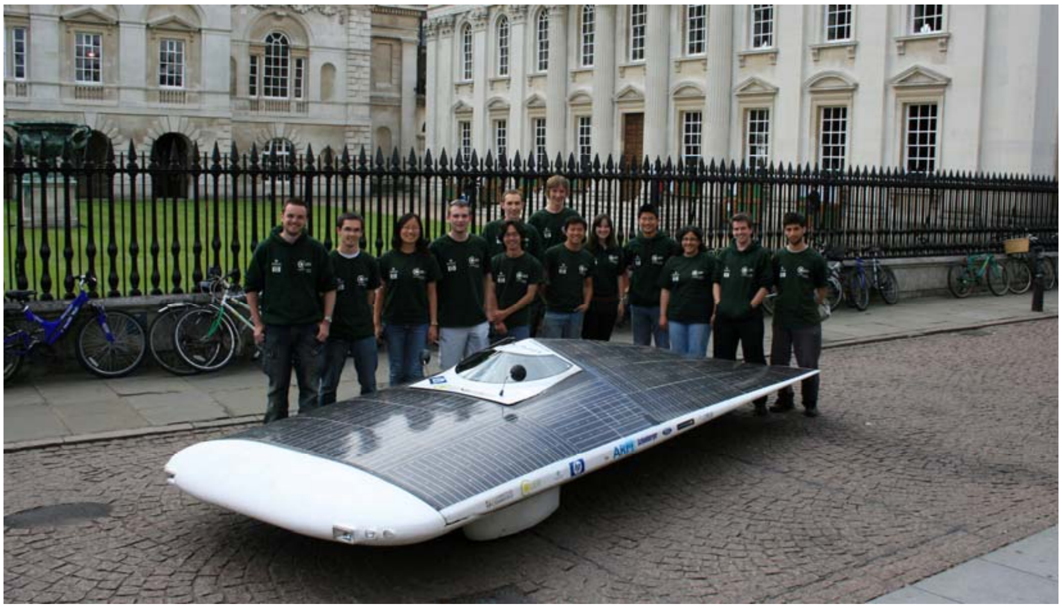

Figure 1. Affinity and CUER team, June 2008

In 2007/2008, the team developed a prototype vehicle, 'Affinity' (Figure 1). Affinity was designed to be road legal in the UK, and was driven from Land's End to John O'Groats as part of an 'End to End' tour that combined outreach visits at schools and public attractions with road testing and data collection. This experience has fed into the design of the WSC race-vehicle currently in development, and discussed in this report is how Abaqus has been used to optimise an already weight-efficient vehicle design to meet an ambitious weight target of 160kg.

2. Technical overview

A high-level technical overview of a solar electric vehicle system as a whole is presented here, followed by a more detailed look at each system in turn. The performance of CUER's vehicles Affinity and Orion, and how they are optimised to be as efficient as possible, is then discussed.

2.1 System

Figure 2 shows a cutaway diagram of Affinity, highlighting the main vehicle systems. The main mechanical structure consists of a space frame chassis supporting the driver and component loads, taking these to the wheels through the vehicle suspension. The aerodynamic shell, also supported by the chassis, is a composite construction with a honeycomb core, giving high stiffness at minimum weight. Mounted onto this shell are the solar cells, which cover the entire top surface of the car.

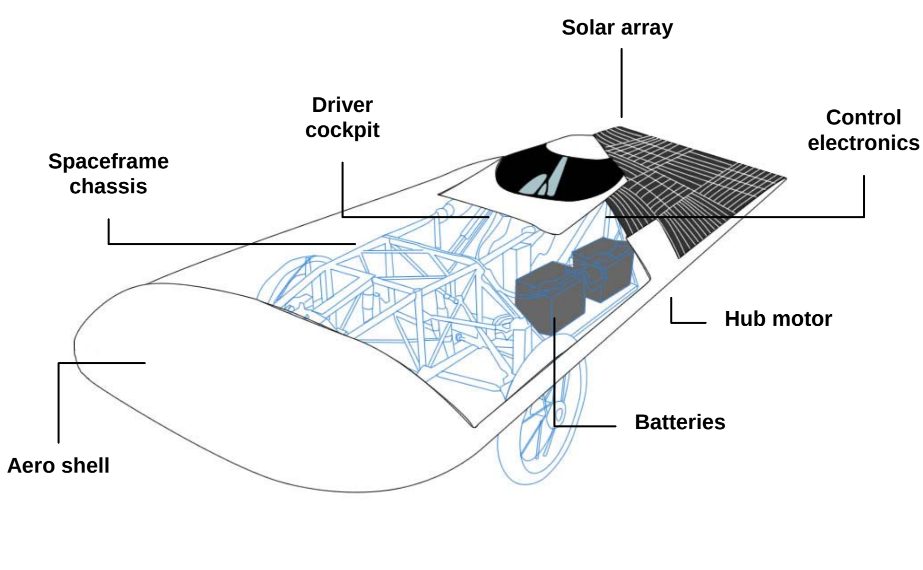

Figure 2. Schematic of prototype vehicle, Affinity

The electrical energy generated by these solar cells is stored in batteries, which act as a buffer in variable environmental conditions. A very efficient hub motor, mounted inside the rear wheel, drives the car forwards with no need for a drive-train. The whole electrical system is monitored and controlled by a sophisticated telemetry system, which can communicate with support vehicles while driving. This allows real-time monitoring of the car and modelling of future conditions to derive a strategy that ensures the car is driven in the most efficient way possible.

2.2 Aerodynamics

Aerodynamic drag will account for around two thirds of energy used at cruising speeds of 60mph, so optimisation in this area is important in developing a competitive vehicle. Most vehicles take a flat shape to ensure the solar array, mounted on the top surface, is oriented favourably towards the sun. As far as is possible, the outer shell has no protrusions and the wheels are fully faired to ensure minimum drag.

Based on the results of testing of Affinity and Computational Fluid Dynamics (CFD) simulation, CUER’s WSC vehicle Orion has changed shape significantly. The wheel configuration has been switched to a tricycle configuration, with the driver seated within the front fairing. The blended canopy from Affinity, while more aerodynamically efficient, has been switched for a bubble canopy to improve solar efficiency. Figure 3 shows the aerodynamic design for Orion.

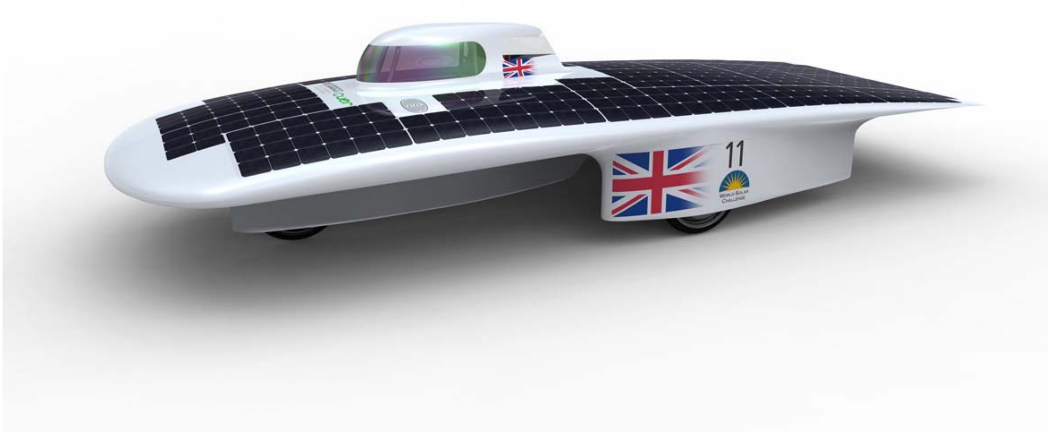

Figure 3. Aerodynamic design of ‘Orion’

2.3 Mechanical systems

With aerodynamic drag accounting for two thirds of motive power, rolling resistance accounts for almost all of the remaining third. As such, a lightweight mechanical design that is robust enough to complete the arduous route is the second key component to a successful vehicle. Figure 4 shows Orion's mechanical design.

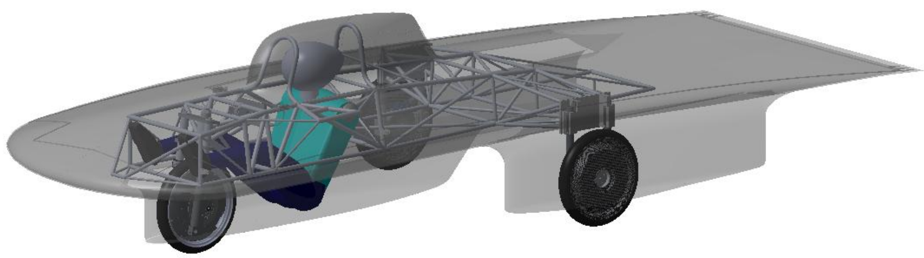

Figure 4. Orion mechanical design

A space-frame chassis is the backbone of the car, with all components attached to it. While Affinity used a steel space-frame, Orion has switched to aluminium with optimisation aided by structural performance simulation using Abaqus. Similarly, the carbon fibre composite shell and aluminium motor housing have also been analysed using Abaqus. This is discussed in more detail in Section 3.

The car has a three-wheeled configuration to reduce mass and simplify drive-train, and careful analysis has been carried out to ensure stability in cross winds and during cornering. Suspension is used to reduce shock loading and vibration, but is sprung relatively stiffly as energy is absorbed through tyre scrub and in the dampers during suspension motion.

2.4 Electrical systems

A solar electric vehicle is a unique class of transportation because it can produce its own energy from the sun, giving an effectively infinite range in the right environmental conditions. Without the solar array, it is simply a highly efficient electric vehicle, with many technologies in common with modern commercial electric cars.

The solar array itself, measuring $6m^2$ in area on Orion, is made up of high efficiency (22%) monocrystalline silicon solar cells arranged in five parallel strings of series cells. Each string has its output controlled by a maximum power point tracker (MPPT) which varies the string voltage to extract maximum power in differing conditions.

The MPPTs output power onto a high voltage DC bus, in parallel with a battery pack that absorbs excess energy in sunny conditions and provides extra energy to the motor when required. The battery pack is made up of high energy density lithium polymer cells, and a battery management system ensures protection against over-charge, etc. A brushless DC hub motor is used, with a specially designed motor controller allowing for energy recovery through regenerative braking.

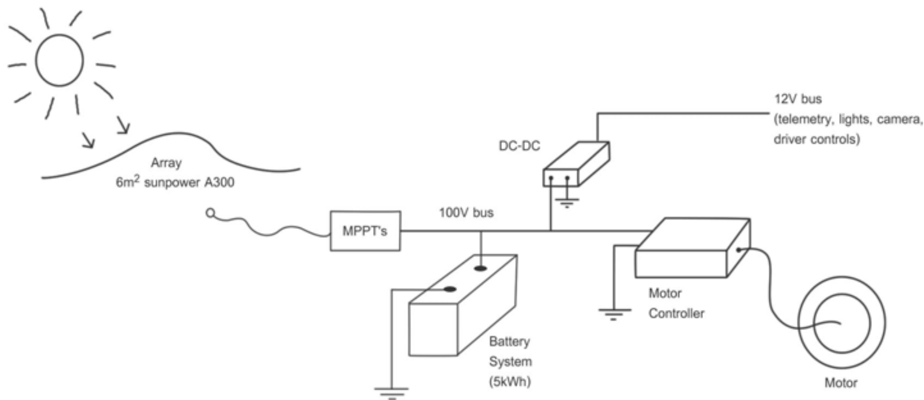

Figure 5. Electrical system

2.5 Strategy

All of the vehicles systems are monitored via a communication system, and performance data is constantly relayed back to a chase vehicle. This information is fed into a model which takes account of anticipated future conditions (road gradients and condition, and weather predictions), and this allows an optimum race strategy to be computed. This is an exciting aspect to the project that can potentially give CUER the edge in the race.

The strategy system also acts a diagnostic tool, allowing the support team to know in real time when the vehicle is not performing as it should, and, in some cases, to even diagnose and fix the problem without stopping.

2.6 Vehicle Performance

The interaction of the vehicles systems can be modelled by looking at the energy flows around the car. Figure 6 shows the expected relative energy spending for Orion at a cruise speed of 60mph.

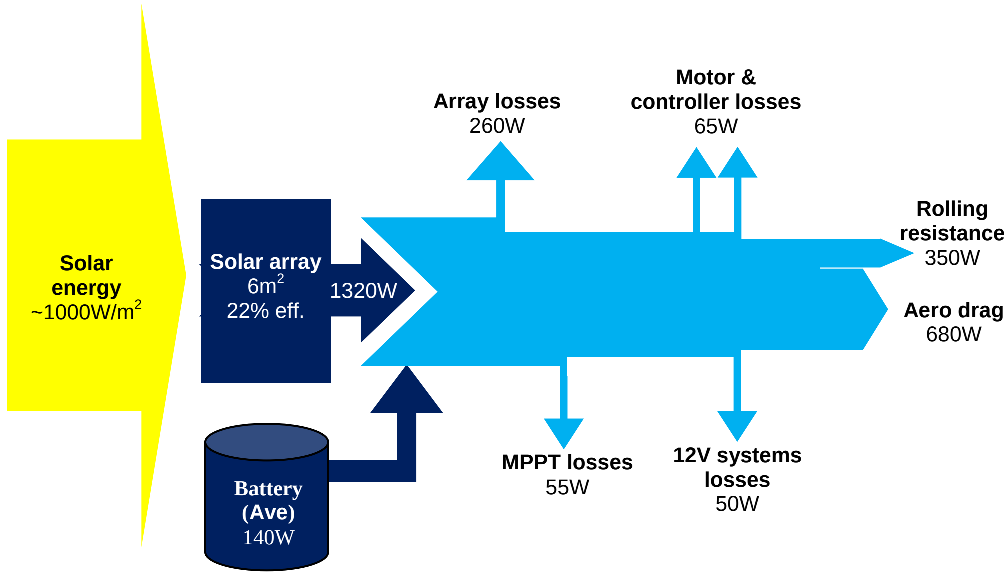

Figure 6. Typical energy 'spending'

The World Solar Challenge is held in the Australian spring, when incident solar energy will be of the order 1000W/m^2. The solar cells on Orion convert this solar energy to useful electrical energy with an efficiency of 22%. However, due to the curved surface of Orion, not all the cells are oriented to be incident to the sun's rays at any one time and so a geometrical efficiency of the array can be defined. For Orion, this geometric efficiency is approximately 80% in Australia in October. Therefore around 260W of the possible array power is lost. CFD modelling has determined that the aerodynamic gain from Orion's curved shape outweighs this lost array power.

Energy is lost through the car's electrical systems; the Maximum Power Point Trackers are around 96% efficient, and the motor and motor controller have a combined efficiency of around 94%. Finally, energy is also lost in the 12V system, which encompasses all of the control electronics, telemetry and communications.

The remainder of the energy is used to drive the vehicle forward, overcoming aerodynamic drag, rolling resistance, and the effects of any road gradients (neglected in this simplified scenario). At Orion's cruise speed of 60mph, aero drag accounts for around two thirds of the mechanical power at the wheel, while rolling resistance accounts for the remaining third.

The energy flow model discussed in this section includes consideration of vehicle weight through rolling resistance, but neglects the effects of acceleration and of gradients. When these effects are modelled for the World Solar Challenge route, it has been estimated that power consumption can be reduced by 2-3W for each kilogram of mass removed. A target weight of 160kg, not including the driver, has been set for Orion (~100kg less than the prototype, Affinity). Careful design of the space frame chassis and composite shell will be important in meeting this target.

3. Structural Design

This section looks specifically at some of the structural aspects of the design of our race vehicle, and discusses the use of Abaqus in the design and optimisation of three particular components; the chassis, the motor, and the composite shell.

3.1 Space Frame chassis

An initial study looked at various chassis material and geometry concepts, and a detailed consideration of the feasibility of using natural materials, and specifically bamboo or plywood, is ongoing. The hope is that a low energy-footprint and lightweight vehicle structure can be developed for a future car. Abaqus is being used here to look at the expected performance of these concepts, and particularly at the performance of joints, which are the difficult part of the design.

Driven by the tight time-scale of the design phase of the project and the requirement of a reliable structure, an Aluminium space-frame structure is proposed for the race vehicle. This is further justified by the experience and understanding gained through designing, building and testing a steel space-frame chassis for the prototype vehicle Affinity.

The design (shown Figure 7) has been developed by considering the constraints imposed by the aero shell, driver position and ergonomics and other vehicle systems. Initial member sizing was done using very simple loading and boundary condition assumptions and using a truss analysis. A simple beam model has been run for several static load-cases representing worst case dynamic load situations to check the global response of the structure. The aluminium chassis structure is expected to weigh 18kg, 7kg lighter than the equivalent structure in the prototype vehicle.

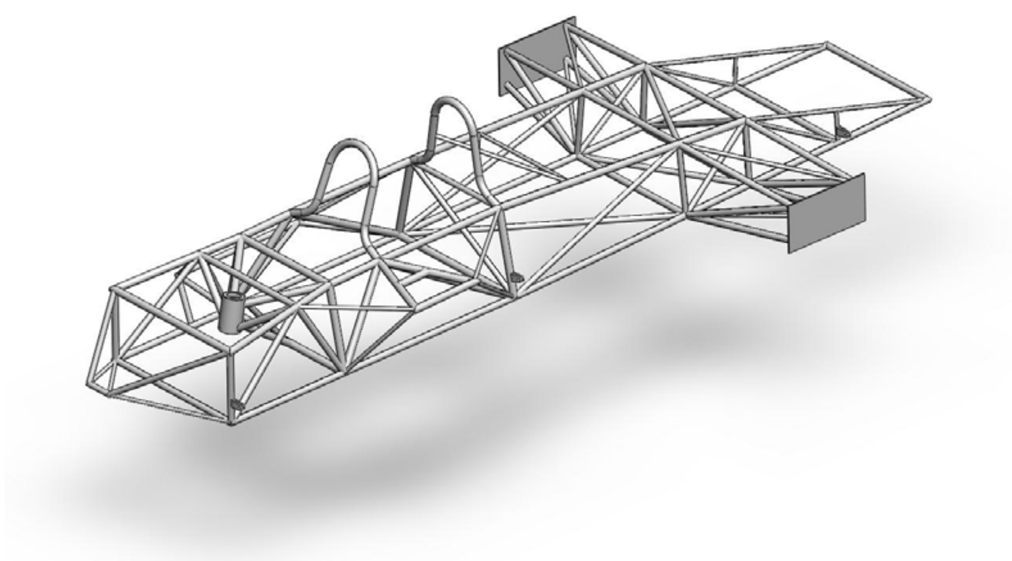

Figure 7. Space-frame geometry

Further to the beam model, checks are being carried out on the local response of certain critical parts of the structure. For example, a shell model of the roll-bars is being developed to check the local plastic response of the joints in the structure for the case of vehicle roll-over (Figure 8).

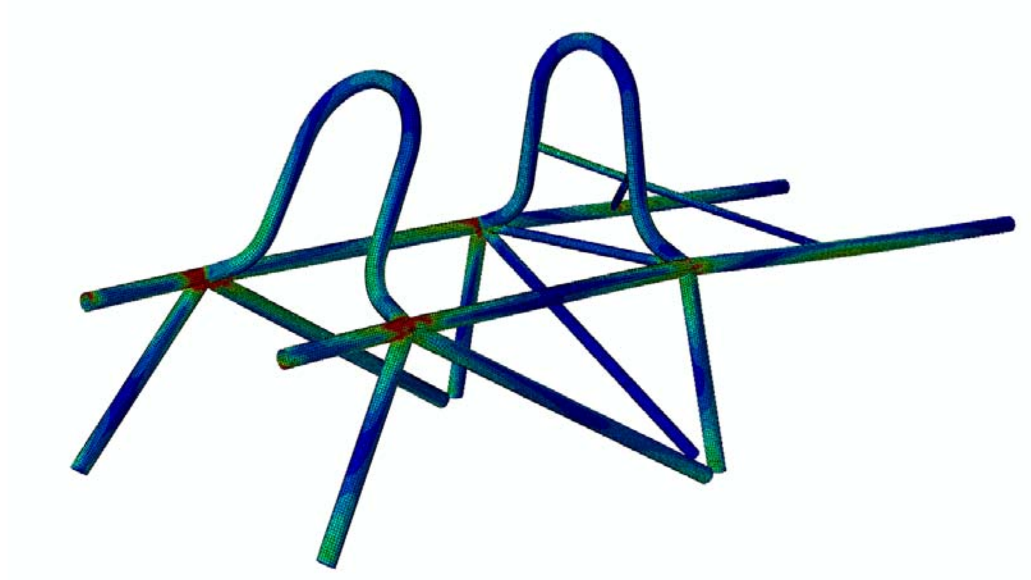

Figure 8. roll-bar shell model

3.2 Wheel motor

An in-wheel brushless DC motor is being built by the team. The design incorporates a high performance electromagnetics kit provided by CSIRO and is based on a structural design provided. The structural design has been adapted to allow for a few required geometric changes, and to allow for simplified machining. An analysis looking at the structural performance of the motor frame is ongoing.

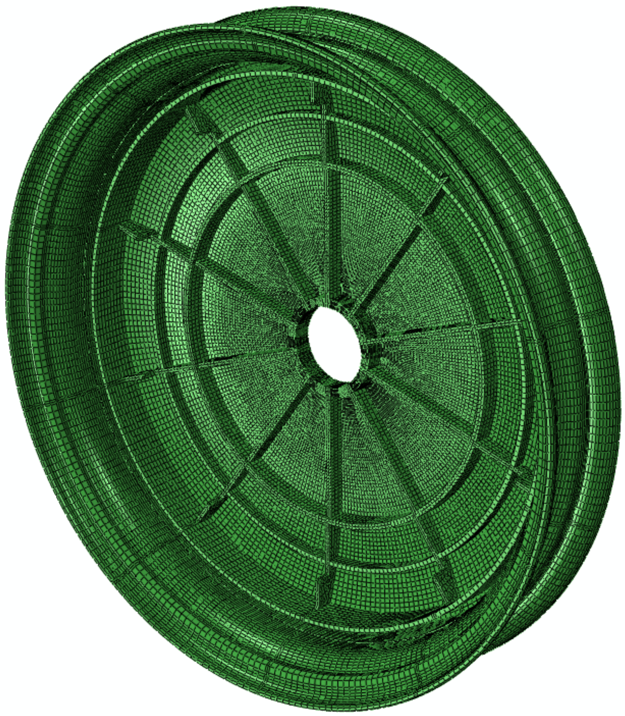

Figure 9. Wheel motor structural-frame geometry and mesh

The load-cases that control for radial, bending and torque response of the wheel are those for fatigue in dynamic vertical load, cornering and braking loading respectively. An impact load-case should also be checked according to BS AU50. The wheel motor structure is tested by assuming equivalent static loads, and using a solid continuum element model (Figure 9).

3.3 Composite shell

Key to hitting our ambitious weight target is a lightweight composite shell. The shell provides the aerodynamic form, and the area required to place the PV cells. It is not a structural component, but supports its own weight, spanning off the chassis.

The shell section is a carbon fibre weave either side of a honeycomb sandwich core. Simulations have looked at the effect of core thickness and weave weight on stiffness and ply stress under static loading representing worst-case 'bump' loads. This has been modelled using the composite layup tools in Abaqus, as a three-ply stack with averaged material properties associated with the two weaves and the honeycomb core.

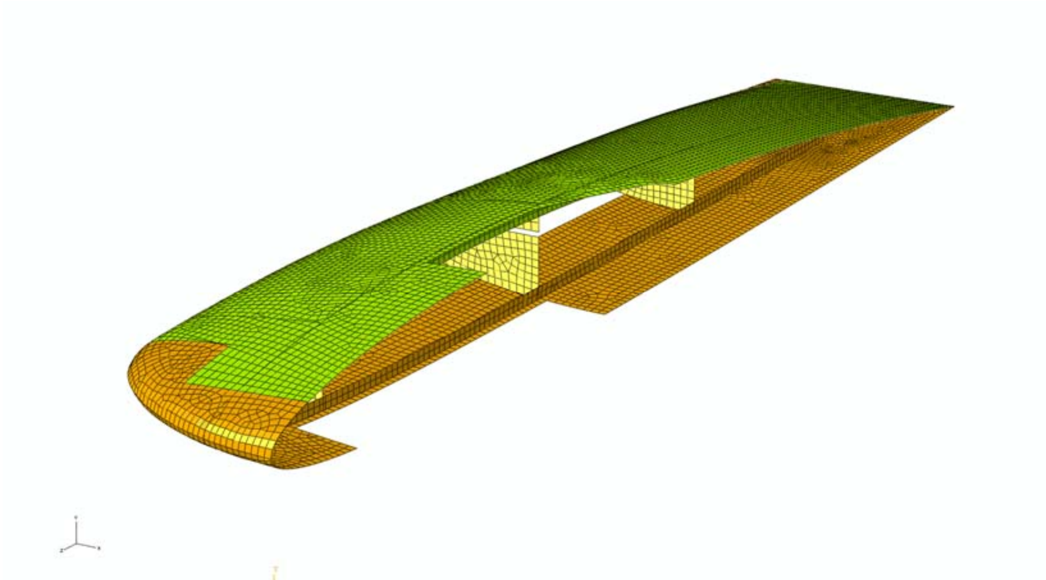

Figure 10. Half-shell assembly (showing mesh)

4. Conclusion

A technical overview of CUER’s new race vehicle has been presented, and the development of a prototype vehicle discussed. A brief outline of the ongoing structural analysis, with particular reference to the use of Abaqus, on the race vehicle has also been presented.

5. Acknowledgements

CUER are very grateful of the continuing support of all of our sponsors. In particular to Simulia, who have supported parts of the structural design through helping with Abaqus simulations.