MODELING AND DESIGN OPTIMIZATION OF A FORMULA STUDENT RACE CAR

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Formula Student, FEM Modeling, Components design, Optimization

ABSTRACT –
Formula Student Series is a competition where teams from universities around the world design and construct a single-seater race car to participate in related international events. Teams have to conform to a set of rules imposing restrictions at the general specifications of the car, such as the dimensions, the engine capacity and the safety. The paper presents a series of case studies from the use of Finite Element Method (FEM) modeling and design optimization of various components from the current race car of the Aristotle Racing Team (ART), investigated with the aid of ANSA and μETA software packages. More specifically, various structural parts were modeled and analyzed to reduce weight and deformation, given the restrictions imposed by materials' mechanical and physical properties. Moreover, extensive Computational Fluid Dynamics (CFD) analysis of the intake manifold was performed for optimizing the air flow to obtain a better engine performance. Additionally, multiple crash analyses of the front part of the car were carried out for reducing the number of the experiments, thus minimizing cost and development time of the car impact attenuator. The use of optimization tools in several components, led to a significant reduction of weight without compromising in structural stiffness.

1. INTRODUCTION

Aristotle Racing Team "ART" was created in 2006 at the Mechanical Engineering Department of the Aristotle University of Thessaloniki. Since then, ART has successfully developed two race-cars, which have competed in several European FSAE events. Based on the team's experience from previous years, ART started the design of its third vehicle in September 2011 (see Figure 1). The

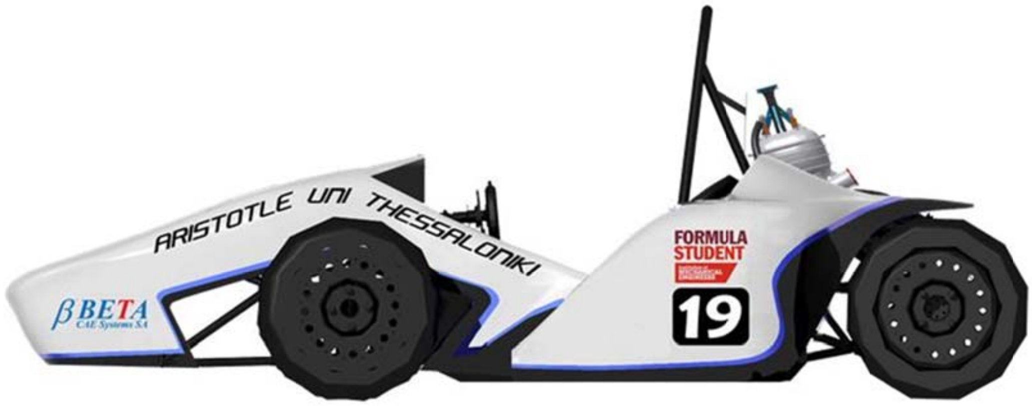

Figure 1 – ART13 single-seater race car, in the frame of Formula Student.

aim was to remain competitive while completing the project within a tight time-frame of 8 months. The feedback from the judges in 2 Formula Student participations in 2012, contributed to a further evolution of the vehicle.

The basic design objectives of ART13 were to:

- Lower the centre of gravity (CG) by at least 25% compared to the team's previous car and reduce weight.
- Improve vehicle ergonomics and driveability.
- Increase engine performance and efficiency.

The present paper describes the design aspects of several parts and components of ART13 race car, with reference to modelling solutions facilitated by software packages of BETA-CAE Systems.

2. Carbon Drive-shaft

In the concept of weight reduction, ART converted the drive-shaft for the drive-train system (see Figure 2) from steel tube to a carbon fibre one. Removing weight from the drive-shaft reduces rotating mass which is beneficial for acceleration and deceleration performance. The use of carbon fibre leads to a weight saving of more than 400 gr from each drive-shaft.

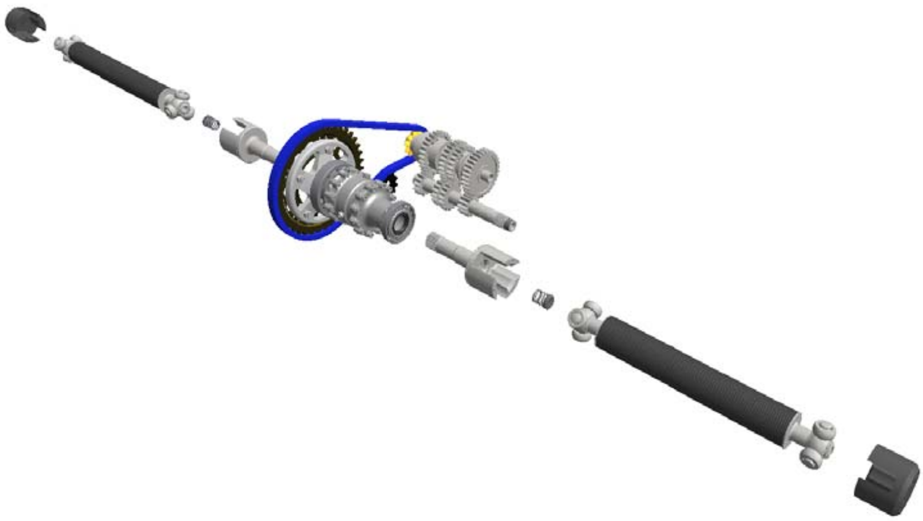

Figure 2 - 3D view of drive-train system

Design and Technical requirements

Maximum torque was calculated to 700 Nm by considering 1.3 g longitudinal acceleration to the system and by applying a safety factor of 2. The length of each tube is 308 mm long, with an inner diameter of 45 mm and wall thickness of 2.95 mm. Under these design constraints it was tried to model carbon fibre tubes using for main material orientation ±45^0.

F.E. Analysis and Model Comparison

The type of analysis applied was static structural and the objectives were to increase the torsional stiffness and reduce weight. Shell elements were used for the carbon fibre tube and a transversely orthotropic material was defined with the use of material matrix MAT8.

First, an approximation model with the use of laminate tool was made, trying to achieve a filament winding model. The thickness of the layers was in the range of 0.3 mm to 0.5 mm. The first layer has a thickness of 0.5 mm and orientation 5^0 as described from Brazier effect. The rest layers have a thickness in the range of 0.3 mm to 0.4 mm and orientation ±45^0. The mechanical properties used in the model are given in Table 1.

Table 1 – Mechanical properties of the laminated material.

Symbols	E_1	E_2	v_{12}	G_{12}	RHO
Units	GPa	GPa	-	GPa	g/cc
Value	135	10	0.3	5	1.60

The maximum rotational displacement of the carbon fibre tube is 0.047 rad, distributed as presented in Figure 3.

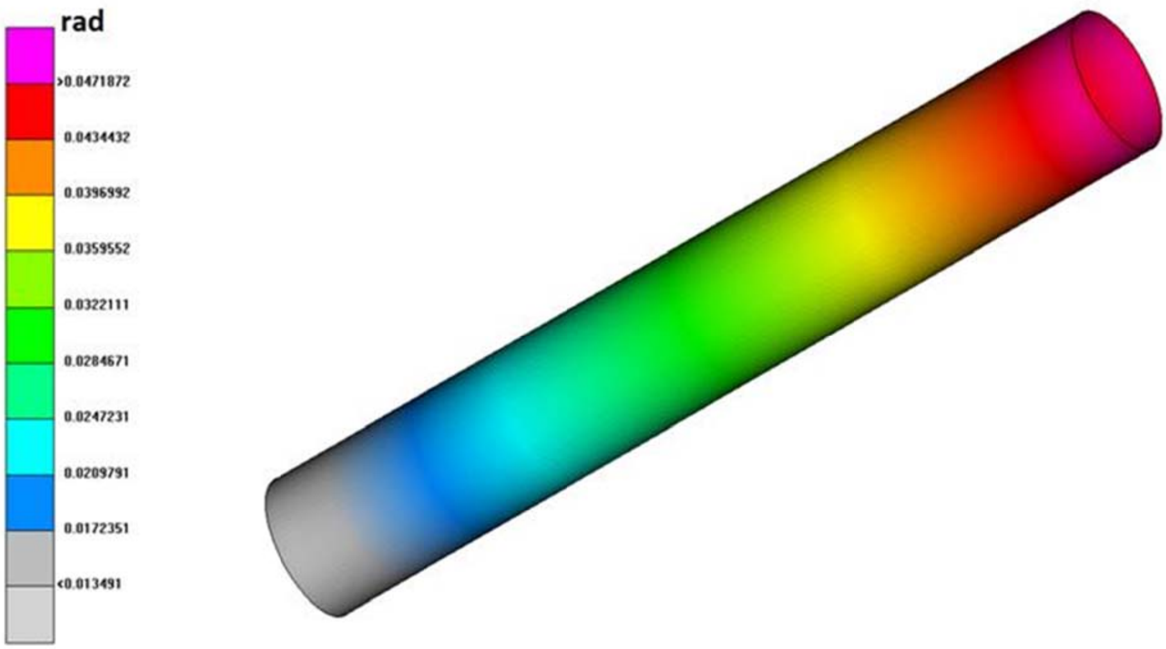

Figure 3 - Rotational displacement (rad)

3. Pedal Box and Brake Pedal Analysis

One of the upgrades that the team decided to add in the car was a hand clutch system that would allow the driver to change gears faster, improving driveability and thus lap times. In this context, the pedal box had to be redesigned from a three-pedal concept, to a two-pedal one, used just for throttling and braking. A further evolution would be to have an adjustable pedal box, allowing a freedom of positioning to accommodate drivers of different height.

Design and Technical requirements

Making an adjustable pedal box would require greater width and thus greater volume and weight, so the minimization of the volume of the pedal box was necessary. A pedal box is essential to conform to the FSAE technical requirements, which imply that it should be able to withstand a force from the driver up to 2000 N. Thus, the brake pedal must be able to withstand this force at a minimum deformation, for that case a maximum displacement of 1 mm was deemed necessary. The same constrains apply to the pedal box, which distributes the forces from the pedal to the frame.

F.E. Analysis and Optimization Process

The first objective was the proper set-up of a good quality mesh and a correct simulation that would yield reliable results. Based on that, the ultimate goal would be to design a stiffer and lighter

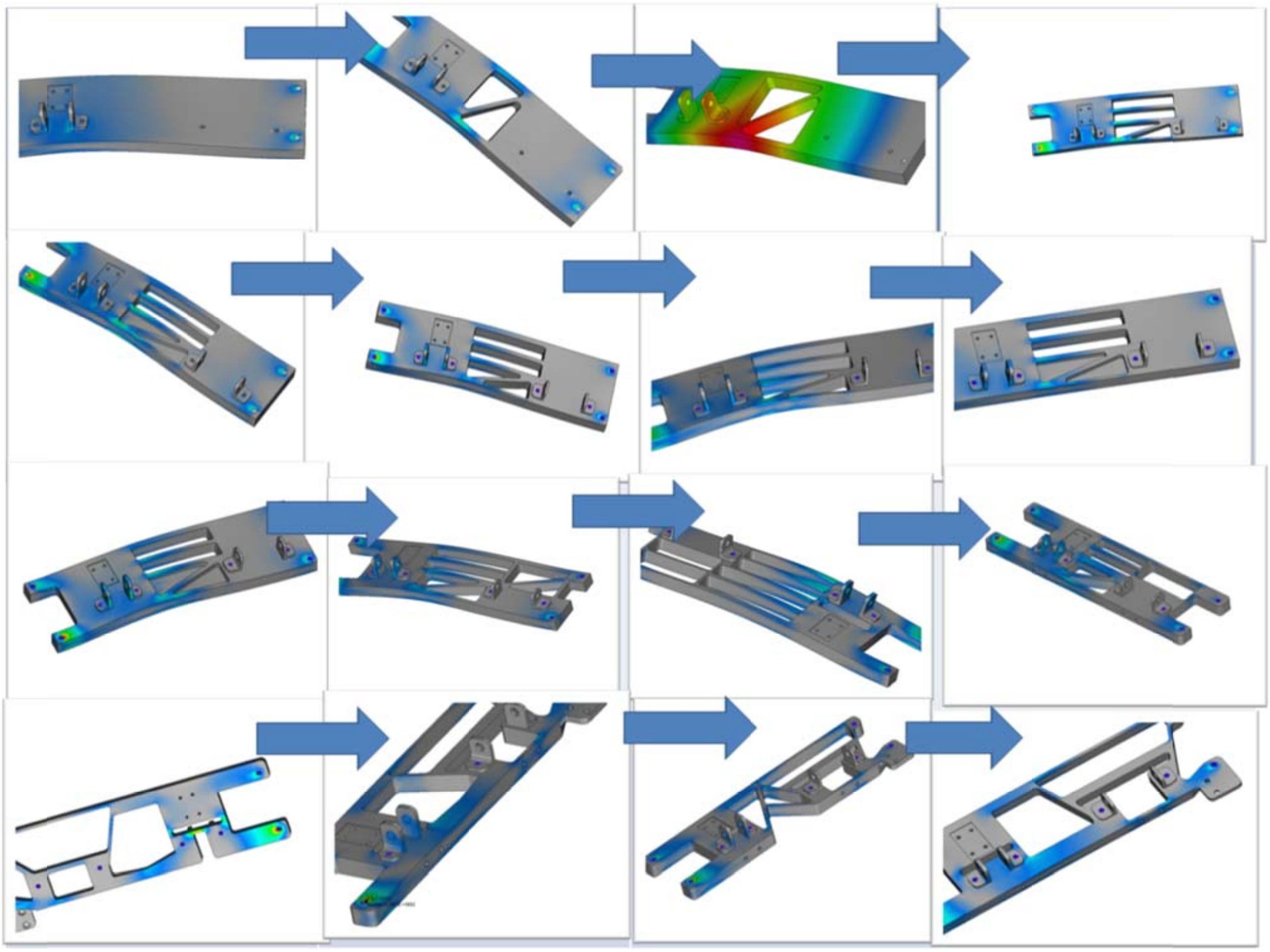

Figure 4 – Design optimization of the pedal box, manually and software assisted (bottom right).

pedal box. The process consisted of an initial design of the new pedal box, which was imposed to the described analysis. Subsequent versions were designed to adjust stiffness, checking whether that would add volume if the part was not stiff enough, or reduce volume if the deformation and strains were inside the defined parameters. This loop (see Figure 4) was repeated several times. The same process was also followed on the brake and throttle pedals but with fewer iterations because there was less space for improvement.

After several optimization loops, the new designs were not converging to the targeted weight that was initially set. Thus it was decided to integrate a topology optimization program in the design phase so that it would deliver the best results within the above-mentioned restrictions, in the least amount of time. The software package used was TOSCA Structure topology optimizer, due to its compatibility with the ANSA pre-processor platform. The model was set-up and after adjusting the key parameters and configurations an optimal result was finally reached.

The optimized solution had to be redesigned to ensure an easy manufacturing, and after few more calculation runs, the final design of the components was ready for manufacturing.

Results

The final design was at half the weight of the initial one and was even lighter than the non adjustable pedal box, that was used in the previous car. The overall result was a lighter, equally stiff and adjustable pedal box that conforms with FSAE regulations (see Figure 5).

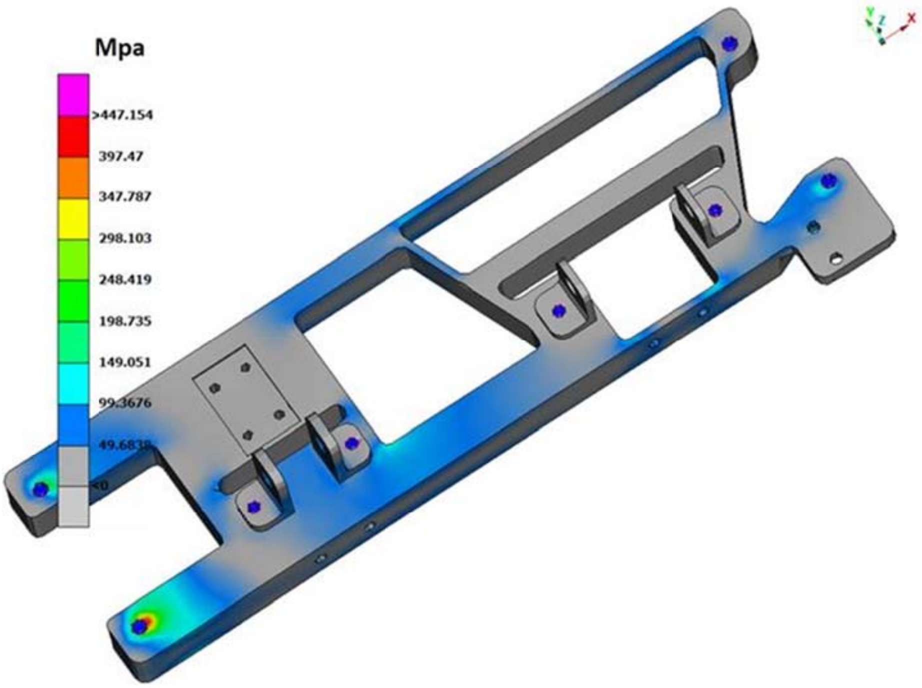

Figure 5 - von Mises stress distribution in the adjustable pedal box, as defined for the optimum pedal box design.

4. CFD in Formula Student

Computational Fluid Dynamics plays an increasingly important role in the field of motor sports engineering both in the design and analysis of external vehicle aerodynamics, as well as in that of several vehicle's sub-components. This also holds true for Formula Student race-cars, which, though relatively low-speed compared to other motor sport classes, benefit greatly from optimizing the air flow both around the vehicle and inside the engine. An example of ART13 newly designed intake manifold is given in Figure 6.

Figure 6 - 3D view of the new intake manifold.

Design and Technical requirements

One of the main applications of CFD in Formula Student racing, apart from external aerodynamics, is the improvement of the air flow through the intake manifold, which greatly contributed to the engine's performance. A typical FSAE intake manifold consists of the following parts: A) the throttle system, which in the case of a Formula student car is a butterfly valve, B) the Ø 19 mm air restrictor, according to the regulations, which limits the amount of air entering the engine and thus provides a physical limit to its power, C) the diffuser, to regain air pressure loss from the restrictor, D) the plenum, the volume where air coming from the diffuser is stabilized and E) the runners, which are the tubes that connect the plenum to the engine.

Design goals

The FSAE intake systems are limited by regulations with a Ø19 mm restrictor. Forcing all the air to pass through such a small diameter causes massive static pressure losses. To account for these losses, a diffuser is always used downstream of the restrictor. Hence, our first design goal was to minimize these pressure losses by improving the diffuser profile through CFD analysis.
Another part that required attention was the intake plenum where it was necessary to avoid further aerodynamic losses due to secondary flow, as these account for about 20% of the intake's performance. Thus, the second design goal was to minimize these areas of recirculating flow as much as possible and avoid boundary layer detachment.

Results

After analysing the flow through the restrictor- diffuser assembly of the team's previous intake, flow separation was detected at high air velocities (Mach>0.5) which led us to a new diffuser profile designed to operate at velocities up to Mach 1 with minimal separation resulting to higher pressure recovery at the end of the diffuser (Figure 7).

a) b)

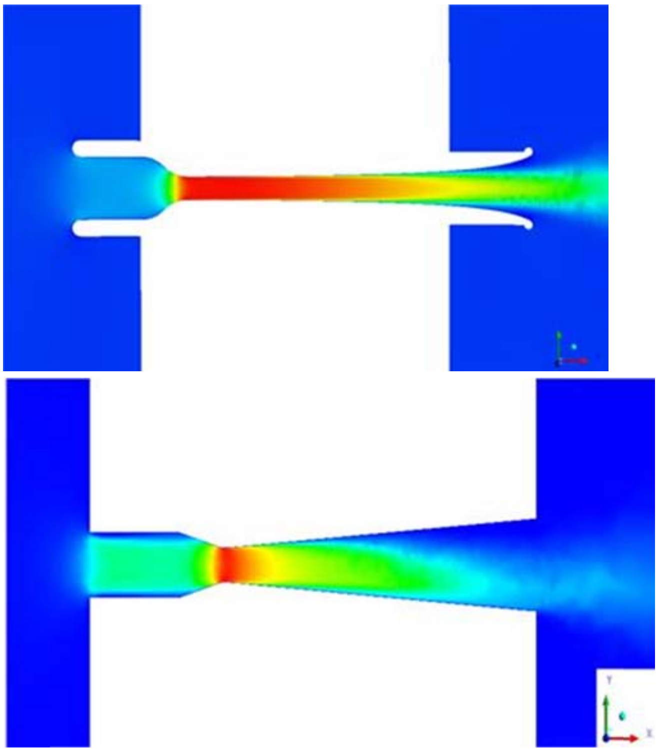

Figure 7 – (a) ART9 intake diffuser, (b) ART13 intake diffuser.

As for the plenum design, the initial concept was to place the runners in a symmetrical pattern around the diffuser instead of the more typical in-line arrangement. This leads to the minimum divergence of the flow profile for each runner resulting in a smoother engine operation. Moreover, the plenum walls were designed to guide the air flow to each runner without separation occurring along the route. Finally, during the design process several areas of recirculation were detected and were summarily corrected by testing each design version using CFD analysis (Figure 8).

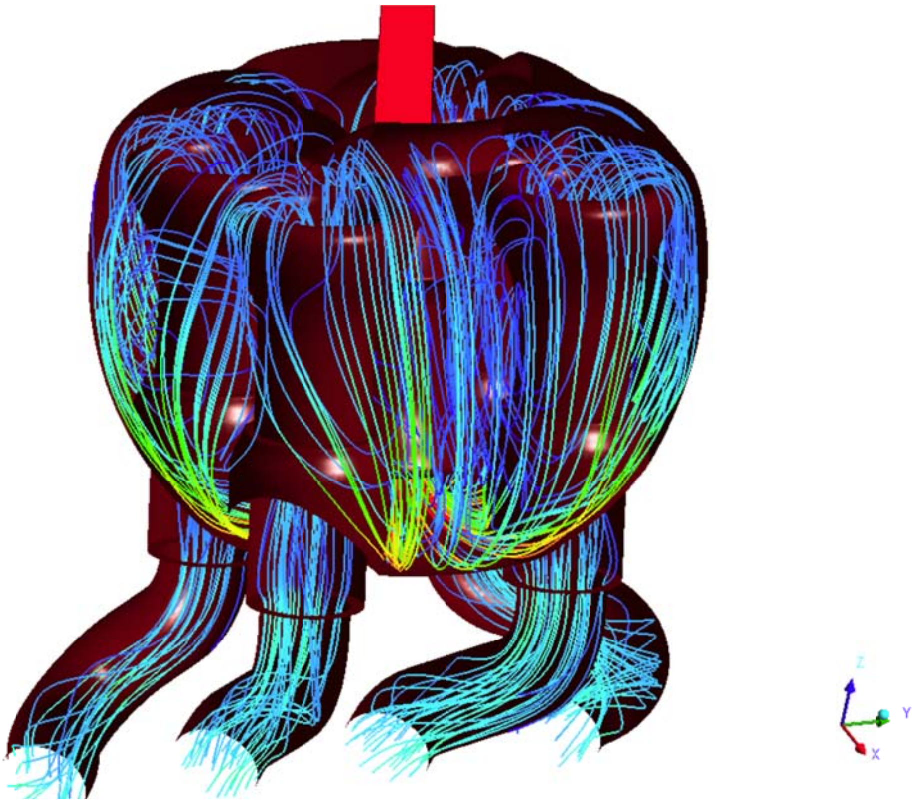

Figure 8 – Visualised result of CFD analysis of the intake plenum.

5. Crash analysis – Impact attenuator

A Finite Element analysis of the car's impact attenuator is necessary towards minimizing the number of required dynamic tests to reach the desired goal.

Design and Technical Requirements

Impact Attenuator’s length reduction was the main goal in order to have a vehicle that is much more manoeuvrable, given that the length of this structure defines the length of the front part of the vehicle. Also according to the competition’s rules, which mainly aim to the safety of the driver, it must be an energy-absorbing structure that should absorb at least 7350 J. Basically , this converts to a total mass of 300 kg running into a stationary object with a velocity of impact of 7.0 m/s. Also, the deformation should be such as providing a maximum average deceleration of less than 20g, with a peak deceleration of less than or equal to 40g. On the other hand, no part of the anti-intrusion plate (which in our case is a 2 mm solid steel plate) should permanently deflect by more than 25.4 mm (1 inch) after the test. Rohacell 110 IG (PMI) foam was the material chosen for this application.

F.E. Analysis and Models

Experimental tests with the material had been performed prior to conducting the crash analysis. Therefore, a a model had to be built that would lead to the same performance as the experimental results. Basically this means that the strain reached in the experimental tests has to be reproduced by the model. Also the model should predict the acceleration function of time and the damping of the Anti-Intrusion Plate. For the purpose of such analysis, Finite Element code Ls-Dyna was used. It should be added that this solver requires much care with many aspects in the model, such as the contacts – the element type – the material type/database etc.

So a model was developed as shown below (Figure 9). Also it should be added that the strain throughout the loading is similar to the experiments.

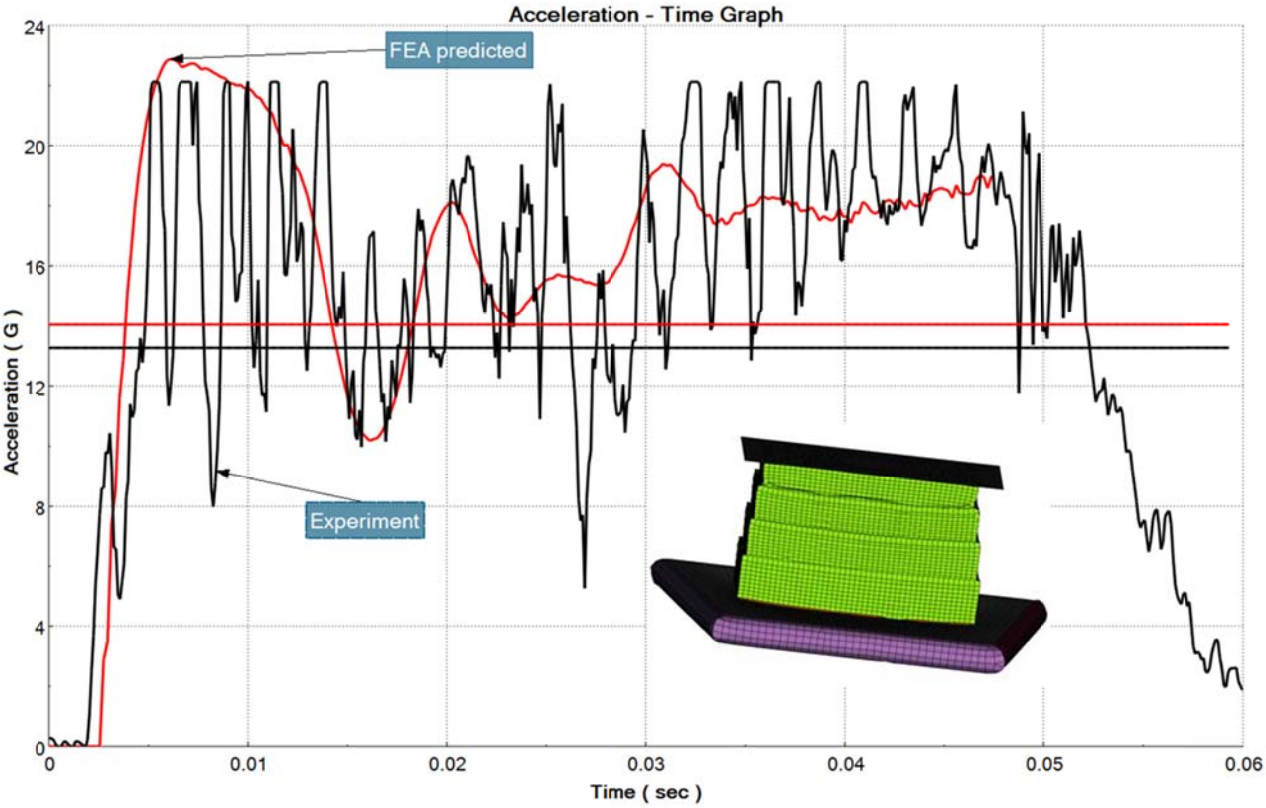

Figure 9 – Impact attenuator dynamic simulation model and acceleration graph – comparison with the tested acceleration.

A major problem though with this model is that it cannot predict accurately the damping of the Anti-Intrusion Plate. Some improvements for this model would be:

- To use a PID for the material that would permit Failure Index is highly recommended.
- To reach a more precise strain output in the model.

6. Conclusions

A series of case studies with the use of FEM modelling and design optimization of various components of the current race car of the Aristotle Racing Team were investigated with the aid of ANSA and μETA software packages. Various structural parts were modelled and analyzed to reduce weight and deformation, given the restrictions imposed by the mechanical and physical properties of the materials used. Moreover, extensive CFD analysis of the intake manifold was performed for optimizing the air flow to obtain a better engine performance. Multiple crash simulations of the front part of the car were carried out for reducing the number of the experiments, thus minimizing cost and development time of the car impact attenuator. Also, the use of optimization tools in the design of several components, led to a significant reduction of weight without compromising in structural stiffness.

7. Acknowledgements

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8. References

1. Formula SAE Rules, *SAE International*, 2013.