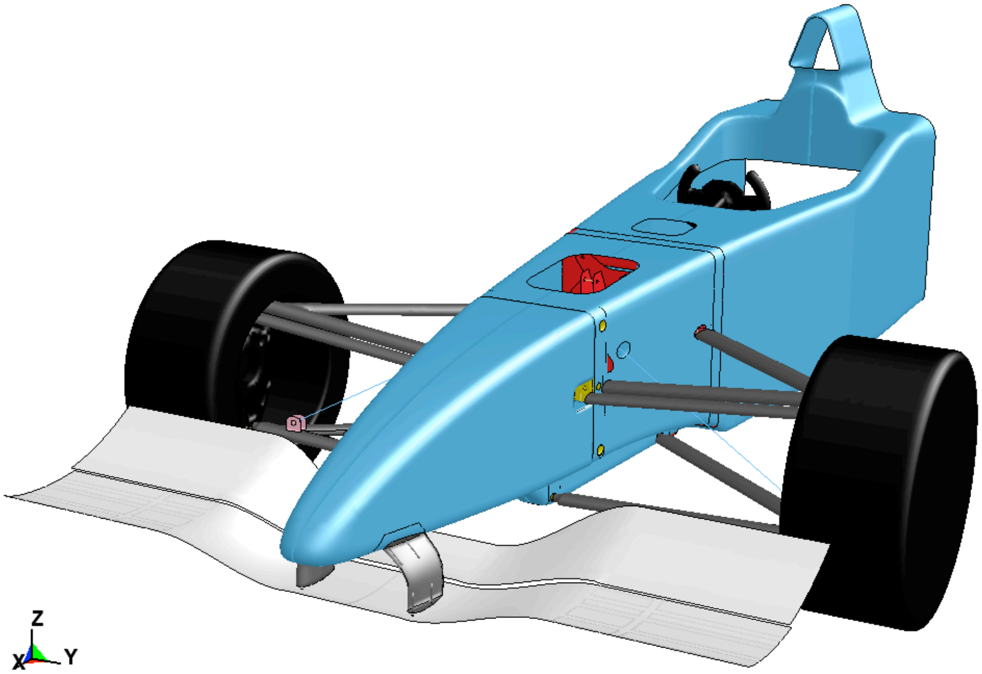
F1 PACE CAR: CRASH ANALYSIS



4/21/2010

Crash Analysis Using LS-DYNA

This report contains a list of all the modeled features, creation of the LS-DYNA model, results obtained from the analysis, and future suggestions to improve the current model.

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INTRODUCTION

Vehicle crash analysis has historically been the postmortem physical test that caused engineers and manufacturers to launch a flurry of product modifications and redesign, engineering change orders, and even the eventual demise of a car model. One need only think of the Ford Pinto or Chevy Corvair as examples of models that were designed, manufactured, and sold long before the automotive industry knew how unsafe some of their cars really were. In the early 60's a number of analysis codes were developed to assist engineering in the a priori investigation of designs to better predict when a given part or assembly would fail in real life. However little was done until the mid 70's when Dr. John O. Hallquist developed the first analysis code that attempted to analyze the impact between two bodies. This early DYNA has matured into a widely used crash analysis tool that today catches many design flaws long before the first prototype is ever realized. Today, the correct use of this tool is credited with saving millions in development costs, reducing untold numbers of vehicle recalls and ultimately saving un-numbered lives by empowering engineers with the ability to virtually crash their design until they arrive at an optimally safe survival cell for the occupants.

This report will focus on work done collaboratively by BYU Mechanical Engineering and LS-DYNA engineering creating a crash simulation on the Pace F1 race car. From February to April 2010, BYU students met with industry expert Suri Bala to create a best possible frontal impact simulation. Students worked on the model 6-10 hours a week with a one-hour coaching session from Suri each week. The results of this work are enlisted below with a detailed description of the methodology adopted, plan of action and finally, the progress that was made.

COLLABORATION TOOLS

As all interactions between BYU Mechanical Engineering students and LSTC engineer Suri Bala were done remotely, certain collaboration tools were very useful in organizing the projects work and results.

D3View

D3VIEW, an online collaboration tool for LS-DYNA projects, was used as a repository for all work done. Using D3VIEW made it easy for BYU students to share current progress on the model, information about the car, media (photographs and videos on the car) that abetted functioning of various components, and other questions easily with Suri Bala. The version control feature of D3VIEW was particularly useful in backing up and logging the progression of the car model. The milestone and tasks features were also useful in helping everyone working on the project, know specifically the tasks that needed to be completed by each student each week and also when weekly meetings would be held. Once the LS-DYNA simulation results were available, D3VIEW was used extensively to review model information, time-history plots and media files such as images and movies generated from D3PLOTs and BINOUTs files.

Cisco Webex

For review of the each week's work, and for instruction, Cisco Webex, an online desktop sharing application, was used to share desktops between BYU students and Suri Bala. This tool proved extremely useful in allowing Suri to review the student's work, and use other instructional material to teach the BYU students about LS-DYNA and the modeling process. Additionally, modifications could be made spontaneously which helped to quicken the overall process of model creation, as described below.

MODEL CREATION

Discretization Process

Creating a discretized model of the PACE car began with identifying the most basic structural components of the car and meshing them. Functionality of those basic structural components and how they connected with various other components was additionally important. For example, modeling the suspension required a detailed comprehension of its mechanics and dynamic movements, as discussed later in this section. The components which were first meshed include the front wing, nose cone, nose/wing connection pieces, structural bulkheads, and the monocoque body (See Appendix A for a detailed list of each part). The meshing process began by cleaning the part geometry in NX. Several features and geometrical constructions were inaccurate and inconsistent to the actual part produced: inconsistent in that they were either not the same as the actual component with regards to geometry or shape, or had CAD features that would not allow correct meshing. De-featuring the geometry and exporting it to a STEP file in NX was the next step. The STEP files were then imported into Hypermesh and meshed using a 2D shell mesh for the thinner/ hollow parts (nose cone, front wing, monocoque body) and a 3D solid tetramesh for the bulkier parts (bulkheads, nose/wing connection pieces). The mesh was then checked and refined in several iterations throughout the project to get rid of any misshapen elements. Mesh quality was an important part of obtaining accurate results – mesh element size and variables such as interior angle and warpage were kept under control within a range of acceptable values. Staying within that range increased the accuracy and quality of the mesh which in turn produced more realistic results. Mesh quality is discussed in short below.

Subsequent to meshing the main structural components, we focused on adding more detailed components to the model. The wheel assemblies along with beam elements representing the suspension struts were similarly meshed and added to the assembly. We then meshed several of the suspension and steering components of the car keeping in mind which components would prove structurally effective (in the core sense and which would be addendums to the structure (provide structure but do not enhance structural integrity by much). As important as meshing these various components were, was the task of connecting the components as they were connected in the car and then modeling these connections for crash analysis. The accomplishment of this task was done using LS PrePost. The meshed geometry from Hypermesh was imported into LS PrePost as an LS DYNA keyword file and then saved as a keyword file within LS PrePost (Note: Some components were not meshed in Hypermesh but were directly imported into LS PrePost and meshed therein). Within LS PrePost nodes were created for the type of joint/feature connecting these components. These components and their motion were modeled using several different connection methods which will be discussed in the "Part to Part Connections" section of this report. The fixed and revolving brackets were meshed as 2D shell elements and their quality was checked within LS PrePost. The suspension was modeled by attaching spring elements to the revolving and fixed brackets through revolute joints, then connecting the small revolving bracket to the large fixed bracket and rigid strut element through additional revolute joints. These connections allow the modeled pieces to as closely as possible behave like the actual components which are installed on the car, but at the same time are not modeled only for the purpose of correct representation with the car. Because there is load transfer between these components and that they enable deflection (hence absorption), these connections were quintessential to accurate modeling.

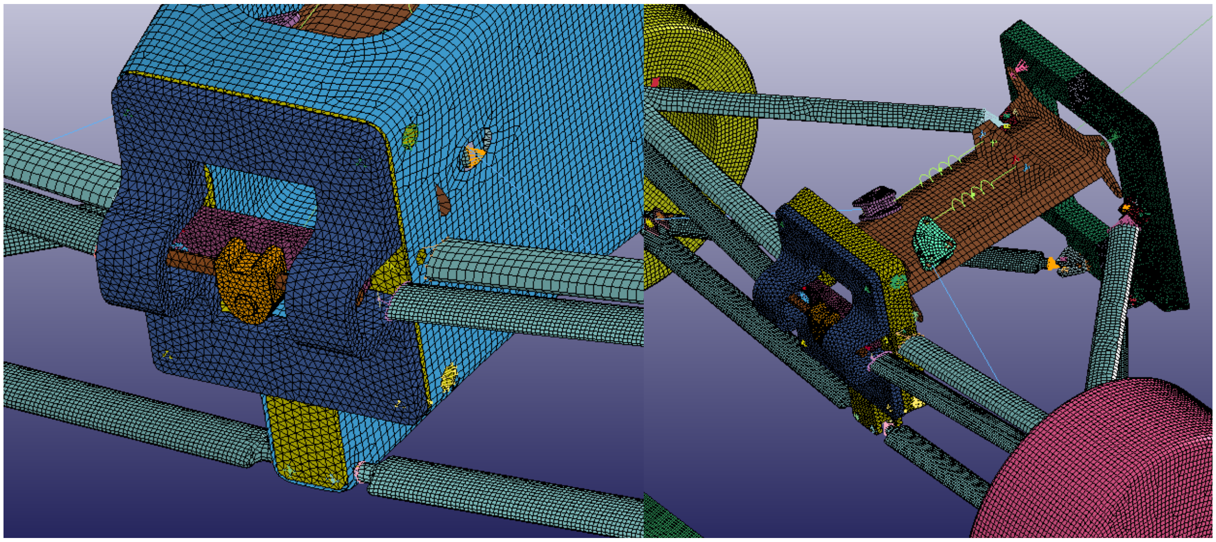


FIGURE 1 – RACK AND PINION JOINT / SUSPENSION COMPONENTS WITH JOINTS

Missing Components

To simplify the model, several of the components of the car were not modeled, but rather were represented as point masses and rigid bodies. Since we were dealing with a linear direct impact, model geometry was less important – rather component properties and meshing were crucial. The components acted mainly in series progressing from the front of the car to the middle, all interconnected to each other. This component representation was done to preserve the inertial properties of these components, which would be very important to create an accurate impact simulation of the car. These point masses were created in LS-DYNA by creating a single node, adding a mass and inertial properties to it with the LS-DYNA keywords *PART_INERTIA and

*CONTRAINED_NODAL_RIGID_BODY_INERTIA. Point masses were at both of the front wheels to represent the mass of the wheel and brake component assembly. Both the tire and steering wheel mesh were only added for visualization purposes. Additionally one very large point mass (accounting for roughly 85% of the total mass of the simulation) was attached to the rear of the monocoque body to represent the mass of all components behind the monocoque including the engine, transmission, rear wheels and suspension, and other miscellaneous components. The rear portion was not meshed since it was not directly involved with impact but inertial properties were included to give the system representative momentum.

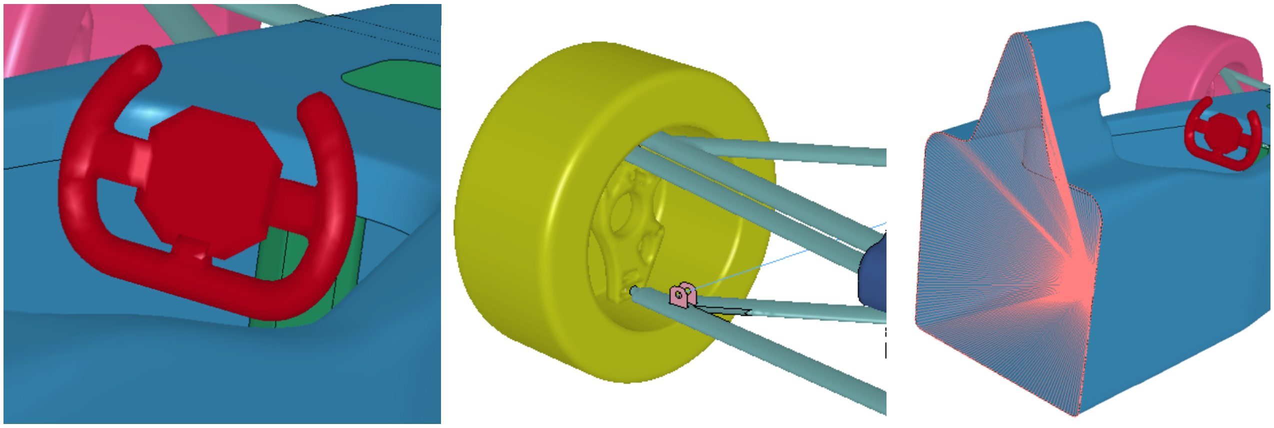


FIGURE 2 - STEERING WHEEL, TIRE AND REAR-CAR REPRESENTED USING RIGID BODIES WITH INERTIA PROPERTIES

Mesh Quality

Obtaining accurate results meant having a good mesh. Hypermesh was used mainly to check mesh quality. Intersection and penetration of elements created by meshing, with each other, were checked for to avoid overlap of the elements. Intersection and penetration checks ensure that elemental boundaries were of the same type i.e. no finely discretized element boundary was in contact with a coarsely discretized element boundary: here discretized refers to element size). Warpage was kept under 5.000 and the interior angle was kept within 45.000° (degrees). The Jacobian parameter allowed the distance between elemental boundaries to be within a certain fixed range. And finally a check was done to make sure every side of the component had been meshed and had discretized elements - a common mistake that goes un-noticed.

Part To Part Connections

All bolts, screws, and fastener connections were modeled using nodal rigid bodies. These connections were used for the screws connecting the front wing to the nose, the nose to the body, and a number of brackets to the bulkhead. The nodal rigid bodies work by constraining all nodes that would be adjacent to the fastener into a single body. Surface to surface contacts which connected the bulkheads to the carbon fiber body and nose were modeled using the LS-DYNA keyword CONTACT_TIED_NODES_TO_SURFACE.

To fully simulate the effects of the crash on the front of the car, several joints were modeled using LS-DYNA keywords. These joints include the rack and pinion steering joint, and the universal joint which connects the rack and pinion to the steering column. Additionally several revolute joints were used to connect the suspension struts to the body and the wheel upright. The revolute joints were made first by creating a NODE SET. The NODE SET consisted of nodes upon or in the part. The created NODE SET was then made into a rigid body using the CONSTRAINED_NODAL_RIGID_BODY keyword – this allotted the node set rigid body characteristics. For the creation of a revolute joint four nodes (each pair co-incident) were created between the two parts where the revolution occurs and these four nodes were defined with respect to the rigid body created above as CONSTRAINED_EXTRA_NODES. The four nodes were defined in relation to themselves by the CONSTRAINED_REVOLUTE_JOINT keyword. As can be observed this process was but short. Based on the model building effort, we found that the joint creation process was laborious and time consuming. Upon Suri Bala's suggestion to ease the joint creation process, Dr. John Hallquist implemented a new option named *CONSTRAINED_JOINT_COOR_{JOINT_TYPE} that eliminates the need to define and follow the difficult process of *CONSTRAINED_EXTRA_{OPTION} as LS-DYNA internally creates all necessary nodes to define the joint axes. This option is available in LS-DYNA version 971 r5 released after March 25th.

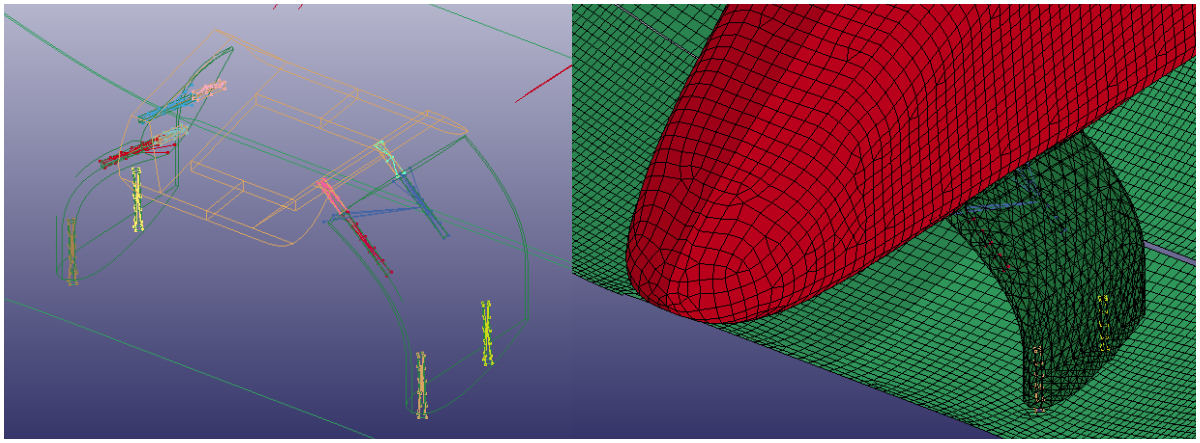


FIGURE 3 – NODAL RIGID BODY CONNECTIONS IN THE NOSE CONE

MODEL VERIFICATION

Eigenvalue Calculations

As in any new model development, the verification and validation of connections is important. LS-DYNA's built-in IMPLICIT functionality was used to compute the eigenvalues and eigenmodes to identify missed connections and to verify existing connections.

Shakedown

Simulation shakedown is a process by which a fully-assembled model is run with no loads and boundary conditions for a fixed 1000 cycles with a minimum 100 time history outputs points. The expected behavior from such a simulation is zero energy and forces. Any non-zero energy present was investigated and fixed prior to running impact simulations.

ASSUMPTIONS

Several assumptions were made throughout the modeling procedure for the sake of efficient calculations and fairly accurate calculations. A majority of the assumptions were made with respect to the NX model and amongst them, most significantly was material properties. Lack of information about the material type of various components in the entire car posed as an obstacle to correct and full model representation. We had information on several components and their material types that we obtained from PACE Partners, however were not complete in the list of materials. There was more information on the front of the car than on the rear and hence material assumptions had to be made for the rear of the car. Observation of the produced car revealed that most of the components were made of aluminum and steel, with aluminum being more predominant in occurrence. Hence, 75% of the rear of the car was assigned aluminum material properties and the remaining steel properties. Additionally it was unknown what alloy of aluminum and steel were used and hence a further assumption had to be made (Aluminum 6061 was chosen along with Stainless Steel in NX).

The second assumption was the stiffness of the car suspensions. The manufacturer rating was not available and so calculation of the spring stiffness was done both mathematically through equation solving and also through comparison with typical stiffness values for race cars. An equation relating the number of turns of coil to the thickness of the coil and material properties of the spring coil was solved to get the stiffness of the suspension spring. The spring was then modeled in Hypermesh as a spring element and connected to the brackets and the rest of the car by revolute joints as described above.

Assignment of which component should be a rigid body and which other should be flexible was also a matter of judgment and assumption. For example the wheel components (wheel, wheel rotor disk, brake caliper and brake pad) were made as rigid bodies with assigned masses and combined inertial properties within the upright bar connecting the wheel to the central portion of the car. This was an educated judgment but was at the same time a simplification or assumption.

RESULTS

The results were as expected with the body collapsing sequentially. The beam elements (struts) that connect the wheel to the main core body deflected inwards upon the wheel hitting the solid rigid wall hence transferring the forces to the nose cone and monocoque of the car. Analysis of the crash simulations conducted by Suri Bala reveal that the crash produces a high inward movement of the car i.e. high fringe levels. The deflection of the beam/struts pull the wheels inward as the struts progress further into the monocoque and nose cone area. A key event that occurs is between the frontal nose cone and the monocoque: these two components are bounded by a bulkhead (a piece of solid material providing critical structural support). Upon impact the nose cone crumbles due to transfer of impact from the nose cone tip and the beams connected to the wheels. The force proceeds to the bulkhead which merely transfers the load to the monocoque. The monocoque, being hollow and made of sheet metal, crumbles upon itself due to the inertia of the rear of the car and also the forward transfer impact coming from the frontal bulkhead. This in a way creates a crushing load – trying to compress a soda can from both sides leads to crumbling. Crumbling of the monocoque is highly undesired simply because the most important element of the car resides in the monocoque: the driver. Nonetheless correct distribution of effective stresses in and around the nose cone conclude that the car has been designed to take as much impact as possible in the frontal portions, leaving little to transfer to the mid and rear ends of the car.

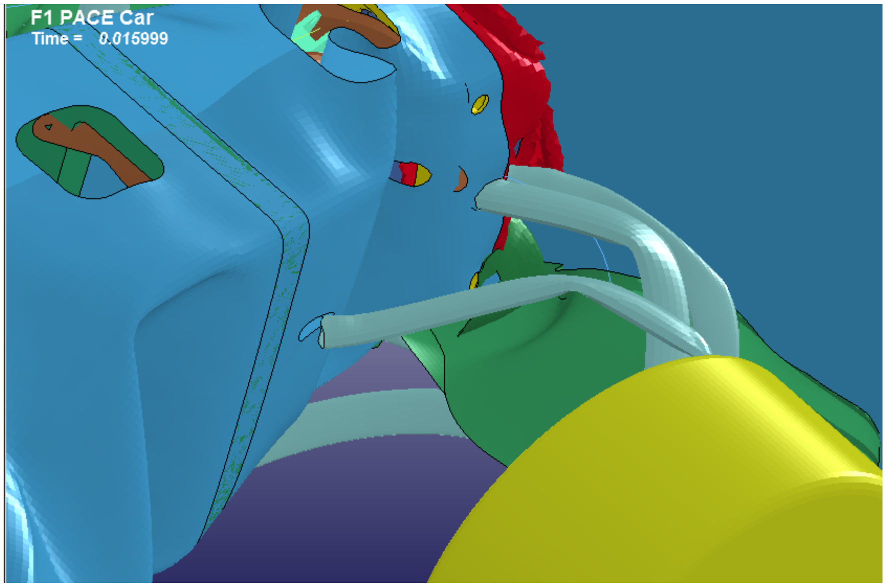


FIGURE 4 – CRUMBLING STRUTS

Our analysis suggests that at high speeds the transfer of loads would proceed through the mid portion of the car causing major injury to the human driver and hence at this stage has not passed the safety criterion required for a high speed formula one race car. We come to this conclusion based on the simulation results and also intuitive understanding of the monocoque and nose body which are primarily hollow that the car is not deemed safe for high speeds. We suggest adding additional structural members to the frontal portion of the car to prevent transfer of high velocity loads to the driver. This would mean additional weight and lower speeds (given the current engine) but a balance would have to be attained between safety and efficiency.

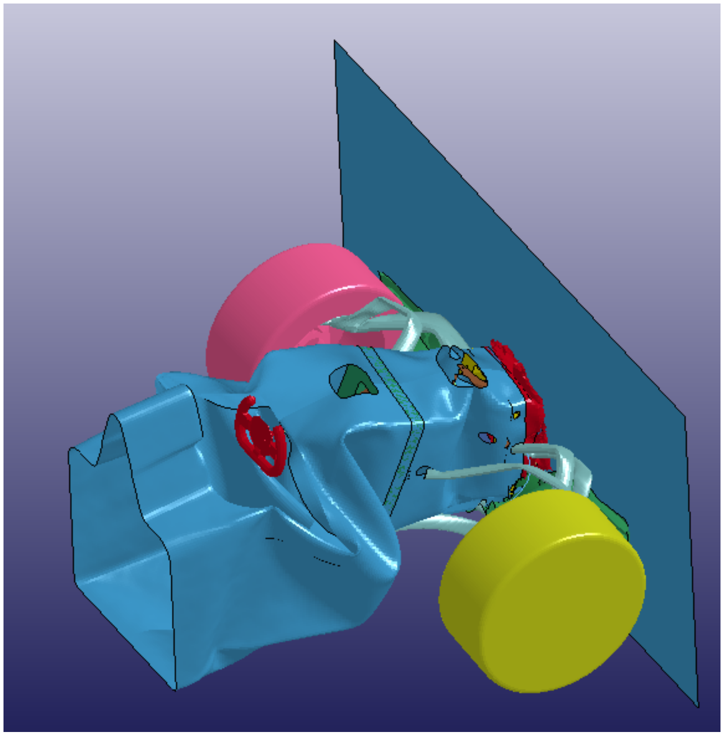


FIGURE 5 – CRUSHED MONOCOQUE BODY

RECOMMENDATIONS FOR FUTURE WORK

The model created in this design iteration is great, but there is much that could be done to expand and improve it. A list of possible future work could include:

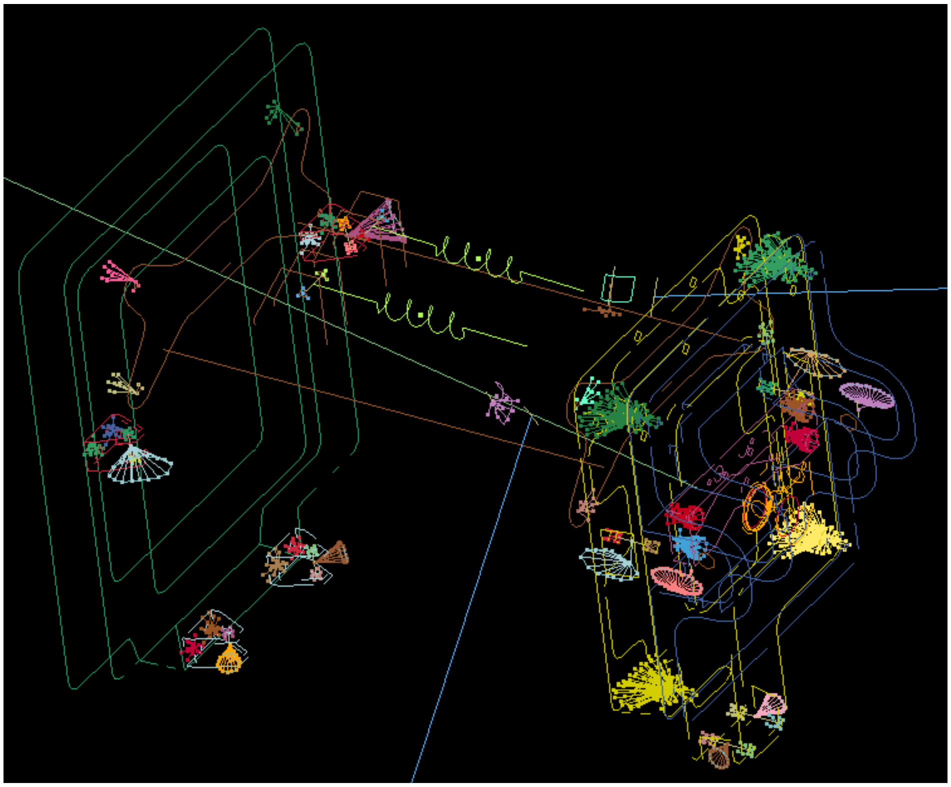
1. Meshing and adding the front wing tips.
2. Adding the most up to date version of the suspension brackets.
3. Creating a better model of the suspension with more accurate spring values.
4. Researching and obtaining more accurate material property and failure values for the nose and monocoque body carbon fiber pieces. Getting more accurate thickness values for the shell elements such as the monocoque, nose cone, etc could also improve the model's accuracy.
5. Meshing and adding the engine cover.
6. Adding more of the components in the rear of the car such as the suspension, wheels, rear bulkhead, etc.
7. Gathering more accurate mass and inertia information about the point mass representations.
8. Adding in the seat, seatbelt restraints, and a "crash test dummy".
9. Getting the most up to date NX CAD model of the PACE car (or updating the current model) with all the components that the currently car actually contains. This would

really streamline the crash analysis project allowing engineers to quickly export and mesh parts.

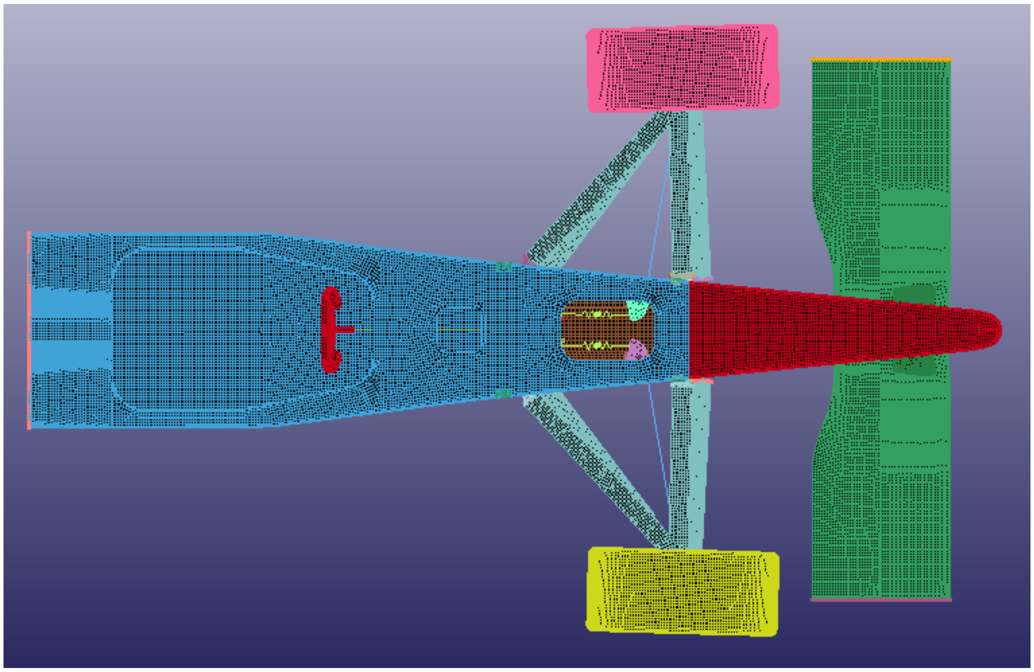
APPENDIX A: PART LIST

Assembly Name	Part Name	Element Type	Thickness	Material
Structural				
	Monocoque Body	2D Shell Quad	6mm	Carbon Fiber 1
	Front Bulkhead	3D Tetra4		Aluminum
	Rear Bulkhead + Brackets	3d Tetra4		Aluminum
Nose				
	Nose Cone	2D Shell Quad	3mm	Carbon Fiber 2
	Nose Connection Pieces	3D Tetra4		Alumold 500
	Front Wing	2D Shell Quad	12/6 mm	Aluminum
	Wing Connection Pieces	3D Tetra4		Aluminum
Wheel				
	Wheel Uprights	2D Shell Quad		Rigid
	Tire	2D Shell Quad		Rigid
	Suspension Struts	2D Shell Quad	3mm	Mild Steel
Steering				
	Steering Wheel	2D Shell Quad		Rigid
	Steering Shaft	1D Beam		Rigid
	Steering Bracket	3D Tetra4		Aluminum
	Rack	3D Tetra4		Aluminum
	Rack Guide	3D Tetra4		Aluminum
	Pinion	3D Tetra4		Aluminum
Suspension				
	Suspension Springs	Spring		Spring Elements
	Swiveling Brackets	3D Tetra4		Aluminum
	Large Suspension Bracket	2D Shell Quad	15mm	Aluminum
	Suspension Strut	1D Beam		Rigid

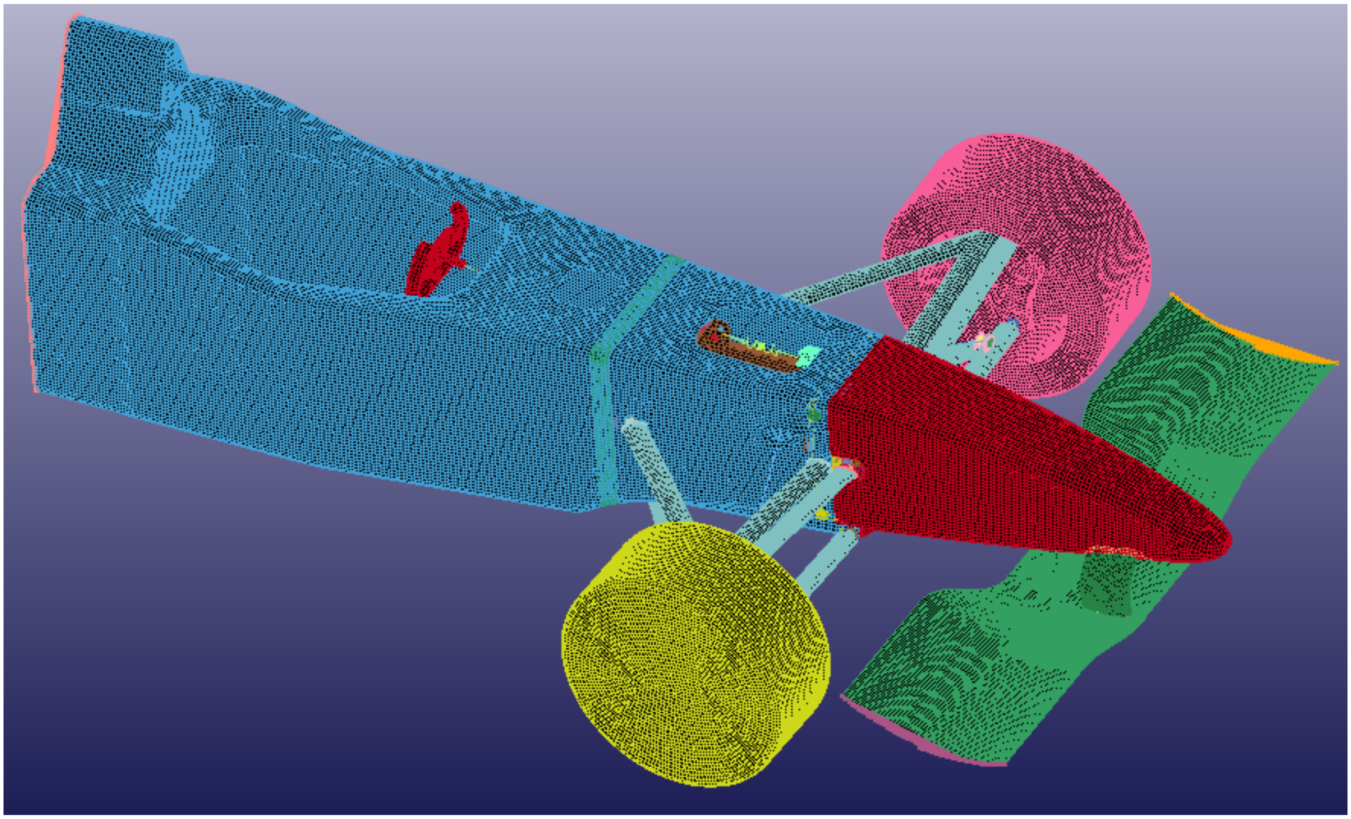
APPENDIX B: ADDITIONAL PICTURES



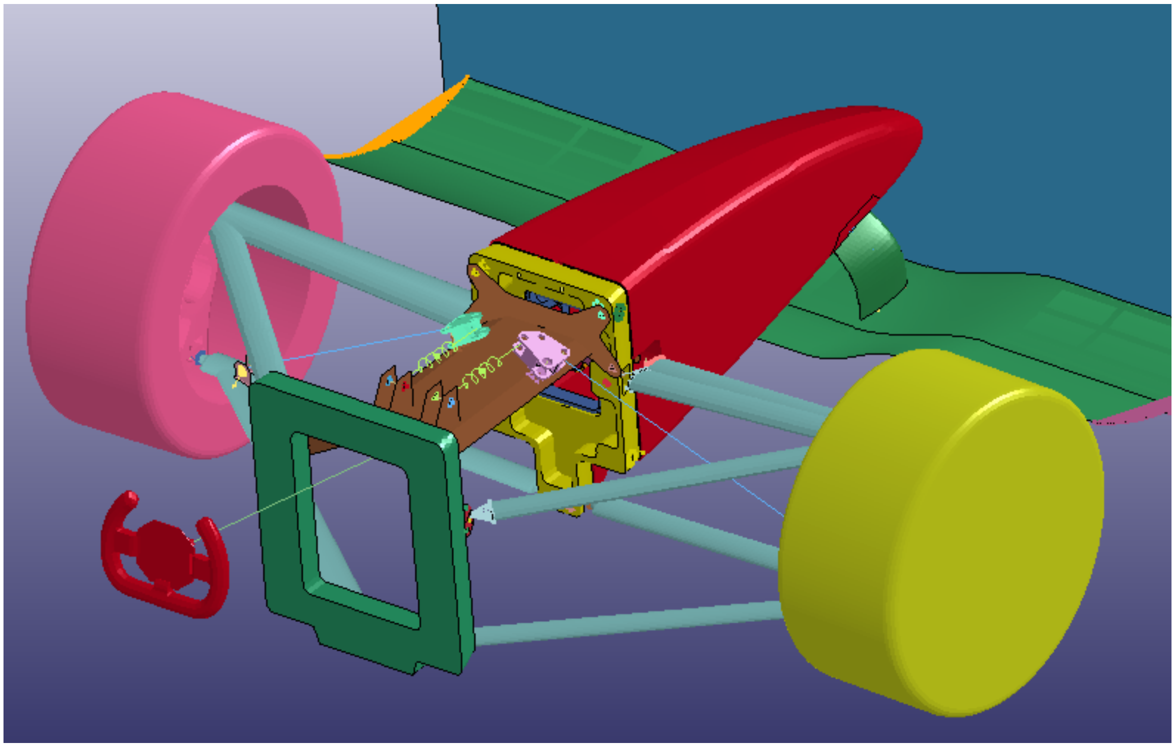
VISUALIZATION OF ALL NODAL RIGID BODIES AND CONNECTION COMPONENTS



TOP VIEW OF MESHED CAR

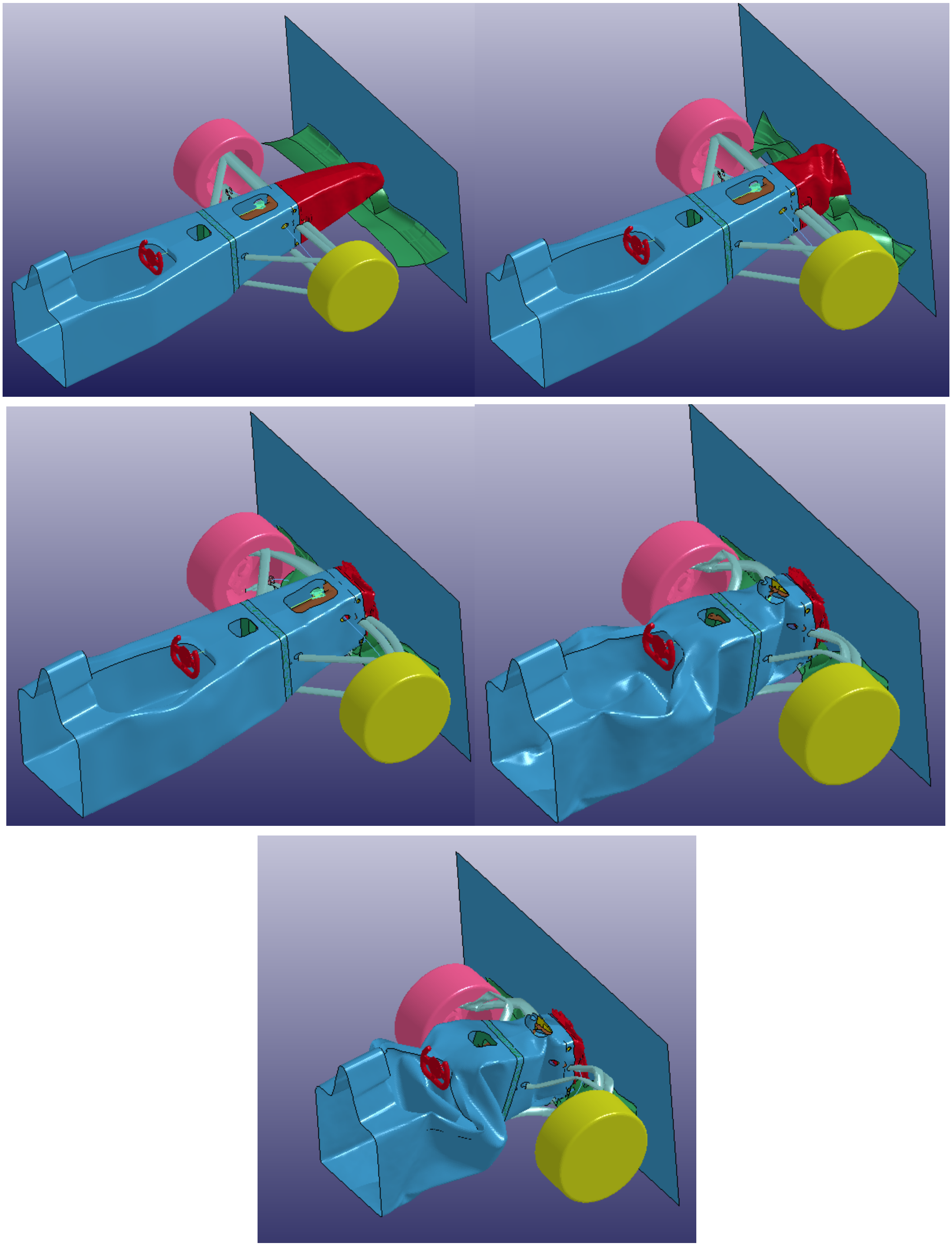


ISO VIEW OF MESHED CAR



VIEW OF SUSPENSION AND CONNECTION STRUTS

Visualization of Car Impact



Name(id)	Element	Material	Density	Modulus	Thickness	NIP	OPTT	Formulation	Mass
Nose (1)	shell	other (54)	1.2000E-09		3.00	2.0	0.00	2	0.38183543E-02
Monocoque Body (2)	shell	other (22)	1.8000E-09		3.00	2.0	0.00	2	0.23599463E-01
front wing attachment (3)	solid	elastic-plastic (3)	2.000E-09	7.00000E+04			0.00	10	0.13924737E-02
front bulk head (4)	solid	elastic-plastic (3)	2.2000E-09	7.00000E+04			0.00	10	0.46870857E-02
Pinion (5)	solid	rigid (20)	7.8900E-09	2.10000E+05			0.00	10	Merged Rigid Body
Rack (6)	solid	rigid (20)	7.8900E-09	2.10000E+05			0.00	10	Merged Rigid Body
auto created (7)	solid	elastic-plastic (3)	2.2000E-09	7.00000E+04			0.00	10	0.47266232E-02
front wing (8)	shell	elastic-plastic (3)	2.2000E-09	7.00000E+04	12.00	2.0	0.00	2	0.21226065E-01
front wing (9)	shell	other (22)	1.8000E-09		6.00	2.0	0.00	2	0.00000000E+00
auto created (10)	beam	elastic-plastic (3)	7.890E-09	2.10000E+05			0.00	1	0.00000000E+00
auto created (11)	solid	other (22)	1.800E-09				0.00	10	0.96869262E-04
auto created (12)	solid	elastic-plastic (3)	7.890E-09	2.10000E+05			0.00	10	0.42108085E-03
auto created (13)	solid	elastic-plastic (3)	2.200E-09	7.00000E+04			0.00	10	0.13362790E-01
upright (left) (14)	shell	rigid (20)	7.8900E-09	2.10000E+05	1.00	2.0	0.00	2	0.23000000E-01
auto created (15)	solid	elastic-plastic (3)	2.200E-09	7.00000E+04			0.00	10	0.74714096E-03
auto created (16)	solid	elastic-plastic (3)	2.2000E-09	7.00000E+04			0.00	10	0.47654728E-03
auto created (17)	solid	rigid (20)	2.2000E-09	7.00000E+04			0.00	10	0.11913689E-02
strut (18)	shell	elastic-plastic (3)	7.8900E-09	2.10000E+05	3.00	5.0	0.00	2	0.00000000E+00
unknown (19)	shell	other (22)	1.8000E-09		1.00	2.0	0.00	2	0.00000000E+00
Steering Shaft (20)	beam	elastic-plastic (3)	7.8900E-09	2.10000E+05			0.00	1	0.00000000E+00
suspension bracket (21)	shell	elastic-plastic (3)	2.20000E-09	7.00000E+04	15.00	2.0	0.00	2	0.62542255E-02
suspension bracket connector (left) (22)	shell	rigid (20)	7.8900E-09	2.10000E+05	1.00	2.0	0.00	2	0.27569706E-03
Revolute Joint Beam (23)	beam	elastic (1)	7.89000E-09	2.10000E+05			0.00	2	0.25106838E-03
suspension bracket (24)	shell	elastic-plastic (3)	7.8900E-09	2.10000E+05	3.00	2.0	0.00	2	0.21837382E-01
bottom strut bracket (25)	shell	elastic-plastic (3)	7.8900E-09	2.10000E+05	10.00	2.0	0.00	2	0.48241628E-03
suspension spring (26)	beam	null (9)	1.000E-10	0.00000E+00			0.00	3	0.23522109E-09
suspension rod to lower strut (27)	beam	elastic-plastic (3)	7.8900E-09	2.10000E+05			0.00	1	0.86107489E-03
upright (right) (28)	shell	rigid (20)	7.8900E-09	2.10000E+05	1.00	2.0	0.00	2	0.23000000E-01
suspension bracket connector (right) (29)	shell	rigid (20)	7.8900E-09	2.10000E+05	1.00	2.0	0.00	2	0.27569706E-03
steering wheel (30)	shell	rigid (20)	7.8900E-09	2.10000E+05	1.00	2.0	0.00	2	0.20000001E-02
null shells for visualization (31)	shell	null (9)	1.3000E-13	0.00000E+00	0.00	2.0	0.00	2	0.35236375E-15

APPENDIX C: Material Properties