Crashworthiness of a Jet Dragster

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Abstract

An analysis on a Larsen Motorsports (LMS) Generation-6 jet dragster chassis has been conducted to determine the crashworthiness of the frame and to identify problematic areas which need to be addressed in order to project the driver from injury in the event of a crash. This analysis was conducted in conjunction with specialized graduate coursework in Automotive Engineering, particularly Crashworthiness, at the Florida Institute of Technology. The foundation of key concepts, such as crash mechanics, trauma biomechanics, and computer simulation of high-speed impacts in LS-DYNA, were introduced in the course and complemented the jet dragster research that built upon these concepts. Static and dynamic crash analysis has been conducted using ANSYS and LS-DYNA, simulating a variety of crash scenarios – frontal and angled impacts at varying speeds. Static structural simulations conducted in ANSYS are used as a baseline to compare the results of the dynamic simulations conducted in LS-DYNA. Reduced complexity of the model affected realistic behavior of the dragster in the dynamic simulations. Additionally, because the Gen-6 car is brand new and does not have any performance or crash data, additional sources of crash data for similar high-performance vehicles will need to be researched in order to validate the simulation results. Recommendations for energy-absorbing foam locations in the car will then be made and implemented to improve driver safety.

Introduction

Florida Institute of Technology (FIT) is Florida's second-highest ranked private National University in Florida and was founded in 1958 as a graduate school offering educational opportunities to NASA scientists, engineers, and technicians. Florida Tech currently offers nine different disciplined degrees in engineering, with Mechanical Engineering being the most popular major for 2015 graduates, making up 13% of the student population. [1] The Mechanical Engineering Master's of Science degree program offers multiples areas of specialization: Automotive Engineering, Dynamic Systems, Robotics, and Controls, Hydrogen and Fuel Cell Technology, Structures, Solid Mechanics and Materials, and Thermal-Fluid Sciences.

Graduate engineering students have the opportunity to enroll in specialized courses, which complement and build upon thesis research in these fields. Crashworthiness, a class offered in the Automotive Engineering program, has introduced key concepts and software skills needed for the development of thesis work focused on the crashworthiness of a vehicle, such as a jet dragster. Crashworthiness covers multiple disciplines in this field of study and the class description is as follows:

"Introduces the design of vehicles to protect occupants during collision. Includes trauma biomechanics, crash mechanics, structural crashworthiness, computer simulation of occupant motion on dynamic structural behavior. Draws examples from aeronautical and automotive applications." [2]

Florida Tech has partnered with Larsen Motorsports, a major affiliate of the university, to apply and validate research into jet dragsters. Larsen Motorsports (LMS) is the leading professional multi-team exhibition jet racing company in the world. LMS is owned and operated by Chris and Elaine Larsen, who started the company in 1994. A LMS jet dragster typically reaches speeds of 270-280 mph in a standing quarter mile in approximately 5.6 seconds. A jet dragster has an extremely high power-to-weight ratio, producing approximately 5000 pounds of thrust, with the engine and afterburner, and weighing roughly 1400 pounds in total, with the driver and fuel. A jet dragster accelerates from 0-60 mph in just over one second and 0-275 mph in 5.6 seconds.

Jet dragster racing is truly a one-of-a-kind motorsport. With the acceleration forces these cars are capable of producing and the speeds the dragsters reach, jet dragster racing can be especially dangerous. Throughout Elaine Larsen's fifteen year jet racing career, she has suffered from a subdural hematoma, broken kneecaps, shattered teeth, and cracked ribs, to name a few of her more serious injuries. Racing accidents cannot be completely prevented and jet racing accidents tend to be more serious than typical street car accidents due to the speeds involved. To investigate the dangers of jet racing and to obtain a better understanding of the safety of these high-powered vehicles, research and simulations have been conducted on jet dragster accidents in conjunction with the Crashworthiness course work.

Literature Review

Crash Mechanics

Understanding the basic concepts of crash mechanics builds the foundation upon which both crash models will be developed on. To describe an automotive crash scenario, and impulse model is used. There are various phases in the case of an accident. First, there is prior to the collision ($t < t_1$) and then, there is after the collision ($t > t_2$). The details happening during the impact ($t_1 < t < t_2$) are typically most important in understanding the structural crashworthiness and occupant injury aspects, and is usually less than 100 ms [3]. During this time frame the forces on the car are extremely large and act as an impulse. When considering the impulse of a crash event, the external forces can be neglected because they are small compared to the collision forces. As a result, momentum is conserved but energy is not. Because it is a high-speed nonlinear impact event, inelastic behavior will occur and energy will not be conserved [3].

Material Modeling

The jet dragster chassis is made of 4130 Normalized Chromoly. For the static structural analysis, the properties input into ANSYS for simulation are Young's Modulus, Poisson's Ratio, Density, and Yield Strength. For a dynamic simulation, the jet dragster will undergo plastic deformation, which is an irreversible and unrecoverable reorganization of the internal structure of the metal [4]. Because steel also deforms differently under different strain rates, both plasticity and strain-rate effects must be accounted for when modeling chromoly in a crash simulation [5]. Viscoplasticity is the theory used to describe this rate-dependent and inelastic behavior seen in metals. The material model most commonly used in LS-DYNA to model automotive impacts that can account for viscoplasticity is Material Type 24, *MAT_PIECEWISE_LINEAR_PLASTICITY. This material type can be defined with an arbitrary stress-strain curve and an arbitrary strain-rate dependency. To produce an accurate stress distribution, the rate-dependent effects must be accounted for in the stress-strain curve inputted into LS-DYNA. To account for strain-rate dependency, the Cowper-Symonds model is used [5].

Static Structural Simulation Set-up

Static analysis in ANSYS is used as a preliminary analysis and should complement the results produced in the dynamic simulation in LS-DYNA. A frontal crash scenario is a basic simulation that can be initiated, prior to the angled impact scenarios, to produce baseline results. To set-up the vehicle to accurately simulate a frontal impact, the bottom back end of the frame should be fixed and should be constrained so that it does not deflect horizontally [5]. The magnitude of the impact force should be calculated using principles of conservation of momentum and should be applied to the front of the vehicle [5]. In the case of an angled impact, the impact force should be distributed into components accordingly.

Total deformation and maximum stress are two values that should be monitored throughout the simulation to evaluate impact severity.

Contact Modeling

The most common issue in LS-DYNA large deformation problems is contact treatment. Accurately modeling the contact between interfaces is crucial in determining how the vehicle will perform in a finite element crash simulation [6]. There are a variety of contact types in the LS-DYNA library, some for specific situations and others for general use. According to LS-DYNA support, in LS-DYNA, a contact is defined by identifying (via parts, part sets, segment sets, and/or node sets) what locations are to be checked for potential penetration of a slave node through a master segment [6]. When considering a vehicular impact with a concrete barrier, contact and friction is typically specified for steel-to-steel contact, steel-to-roadway contact, tire-to-barrier contact, and barrier-to-barrier contact [7]. The frictional coefficient, μ, is defined in the contact card and can be defined as a fixed constant value or as a function of the velocity at which the surfaces slide past one another [7]. To maintain simplicity throughout the dragster simulation, a fixed constant value is used.

Methodology

The Larsen Motorsports new Generation 6 jet dragster was modeled for the crash analysis. This car was designed and fabricated in-house at Larsen Motorsports and was modeled in Solidworks using actual measurements taken from the developed chassis. Only the chassis was modeled for the finite element simulation, as opposed to the entire vehicle, to reduce the complexity and computation time of the high-speed crash model. Because the back half of the chassis has not been built yet, the back half of another Larsen Motorsports jet dragster, closely resembling the design of the Gen 6 concept, was modeled and modified to fit the new front half.

The chassis was modeled using the 3-D sketch tool, sketching a series of nodes and lines for the frame. The chassis model was then imported to ANSYS by inputting the nodal coordinates of the model and connecting the nodes with lines, creating the same frame that was modeled in Solidworks. Tubular cross sections were applied to each line according to the size of the tubes. The tubes ranged in size from 0.75 inch diameter to 1.625 inch diameter with a 0.095 inch wall thickness for the roll cage and 0.058 inch wall thickness for the rest of the chassis. The chassis built at LMS are built with splice joints used in crush zones. Spliced tubes are typically used in a chassis to strengthen the chassis structurally in critical areas in order to create crush zones designed to deform and absorb energy in the event of a crash. To reduce the model's complexity and address the contact issues, the spliced tubes were simplified in the model of the chassis. These tubes were treated as a single tube with a larger wall thickness, as opposed to one tube inside another.

There are two types of integration methods used in finite element simulations: implicit integration and explicit integration [8]. Both integration methods were used for the analysis of the crashworthiness of a jet dragster. Implicit methods are suitable for most transient simulations, excluding highly non-linear and high-speed impact scenarios. Although a high-speed jet dragster crash impact is a non-linear dynamic event, a preliminary linear elastic analysis was conducted on the chassis using implicit integration in ANSYS to obtain baseline results that can be compared to the dynamic simulation. To model the non-linearity of a jet dragster crash, simulations were also conducted in LS-DYNA, which utilizes explicit integration methods and small time steps to capture the resolution of a high-speed impact. Although LS-DYNA is capable of performing both implicit and explicit simulations, ANSYS was selected to perform the implicit analysis because this best complemented what was learned and applied in the engineering coursework.

A. Static Structural Simulation

Although a frontal impact is not a likely crash scenario for a jet dragster, a frontal impact was simulated to begin the initial crash analysis. A frontal impact crash is the simplest case and can be used as a baseline to compare the results produced in ANSYS to the results produced in LS-DYNA.

The magnitude of the impact force used in the static analysis was estimated using the principles of linear impulse and momentum, principles both covered and applied to vehicular accidents in the Crashworthiness course. Impulse and momentum are both conserved during an impact. The conservation of energy principle was not used because in the case of a high-speed impact, it is expected that there will be inelastic material behavior, therefore kinetic energy is not conserved. Because the internal forces between the vehicle and the wall exceed the magnitude of the external forces, such as friction with the ground, the external impulse is small and it can be assumed that momentum is conserved [3]. Impulse is the integral of force over some period of time, and equals the change in momentum. The impulse focuses on the impact event – the time interval over which the force is applied during an accident. It is assumed that the impulse occurs over a very small time, typically 100 ms or less, which simplifies the application of the force during the impact [3]. Using this principle, the average impact force during the collision can be calculated for this simulation.

To perform a static structural simulation for a frontal crash on a jet dragster, the calculated force was applied to the front of the car, directed toward the rear and a fixed support was applied to the chassis, at the lowest, most rear part of the chassis. Figure 1 shows a single simulation of a static structural impact analysis.

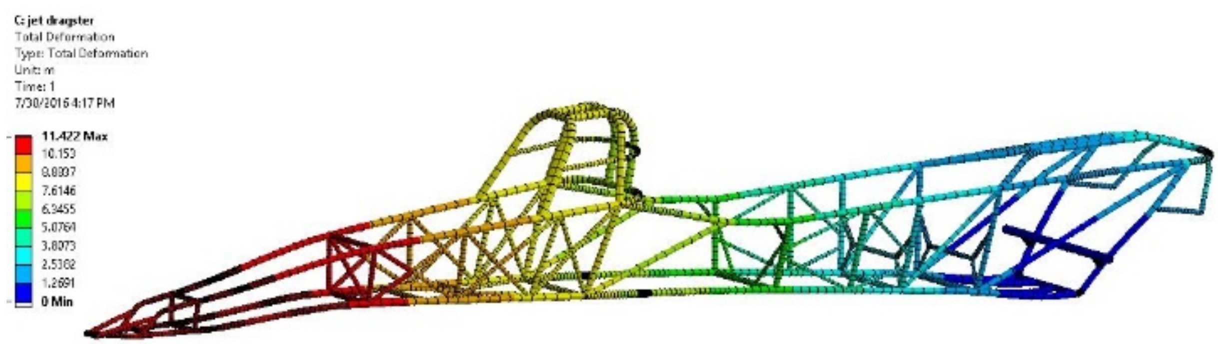

Figure 1: Static structural simulation of jet dragster impact

B. Dynamic Simulations

In addition to impulse and momentum principles, the concepts of finite element analysis theory and contact modeling in LS-DYNA were introduced in the Crashworthiness class. The theory of implicit versus explicit integration, simulation stability, and hourglassing were all topics discussed and needed in the approach of a finite element model in LS-DYNA. Additionally, key operational LS-DYNA functions were discussed in the course, such as keyword input file editing, processing data in LS-PrePost, correctly modeling contact, and the coupling of ANSYS and LS-DYNA. These concepts, along with the introduction of basic LS-DYNA tutorials and simulations in the class, were used to aid in the development of the jet dragster LS-DYNA simulation.

A bogie model, a simple frame on wheels modeled and provided by the National Crash Analysis Center, was used in an impact simulation to become familiar with editing keycards within the keyword file, especially *RIGIDWALL_PLANAR, monitoring contact forces, and performing both frontal and angled impacts. Additional simulations were conducted to begin learning key LS-DYNA concepts. These simulations were completed to learn how to edit material properties in the LS-DYNA keyword file, to create different types of elements in LS-PrePost, to introduce element editing, to learn how to position a dummy in a model, to introduce seat belt fitting, to calculate occupant injury criterion, and to introduce post-processing tools. These are all critical skills need for the simulation of a jet dragster, but were completed at a very basic level. Figures 2 and 3 show screen shots from a couple of these simulations.

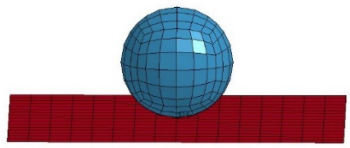

Figure 2: Ball impacting plate

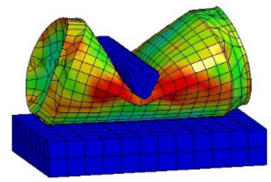

Figure 3: Soda can crush [9]

To model a realistic representation of a jet dragster crash, two different contact regions were defined: contact between the chassis tubes and contact between the vehicle and the barrier. Within each contact card, friction coefficients were defined for steel-to-steel contact and steel-to-concrete contact. Frictional forces between the contact surfaces are critical in a crash simulation because they can change the vehicle's behavior and response during impact. Two critical contacts that are not represented in this model are the contact between the tires and the pavement and the contact between the tires and the barrier. As the model develops and more components are added to the dragster, these contacts need to be added to improve simulation accuracy

A typical barrier used at a dragstrip is a rigid, three-foot concrete barrier. In the event of an accident, the barrier minimally deforms and typically experiences little damage [10]. The barrier is modeled using solid elements and a rigid material card, with concrete material properties, and is constrained in all directions to prevent it from moving during impact. The simulation was run with four different wall angles: 15, 30, 45, and 60 degrees. An initial velocity of 125 m/s (280 mph) was used for the jet dragster in the analysis. The meshed model consisted of 10,770 nodes and 6066 elements. Beam elements were used for the dragster and solid elements were used for the barrier.

The main goal of the jet dragster simulation is to show how different impact angles affect crash severity and to identify critical parts of the vehicle in an oblique impact. Because multiple sources of drag, such as the tires, vehicle components, and ground friction, are neglected in the model, the behavior of the vehicle post-impact will not be realistic enough for accurate analysis. Therefore, the analysis should focus on the short interval of impact. Drag forces during this interval are negligible compared to the other forces involved.

Results

The variations in impact severity for the different angled walls were apparent in all four simulations. As the angle of impact increased, the dragster experienced substantially more damage, as expected, and is shown in Figures 4-7.

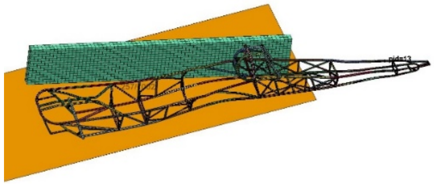

Figure 4: 15 degree impact

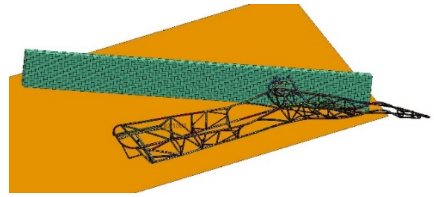

Figure 5: 30 degree impact

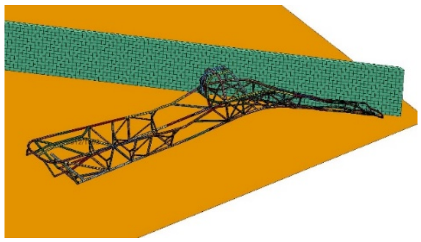

Figure 6: 45 degree impact

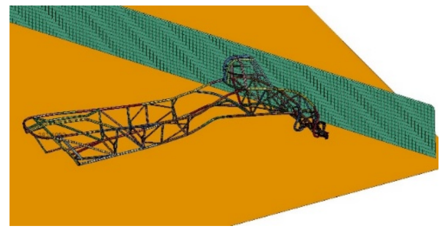

Figure 7: 60 degree impact

The resultant forces of the dragster and barrier during impact were plotted and are shown in the Figures 8-11.

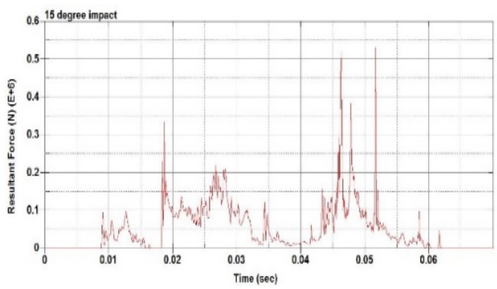

Figure 8: 15 degree impact resultant forces

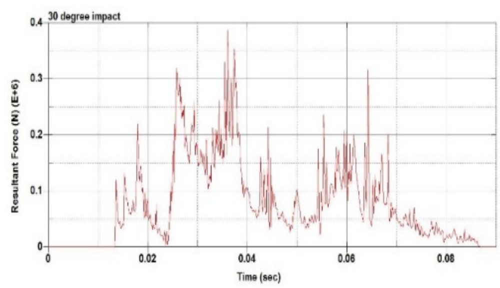

Figure 9: 30 degree impact resultant forces

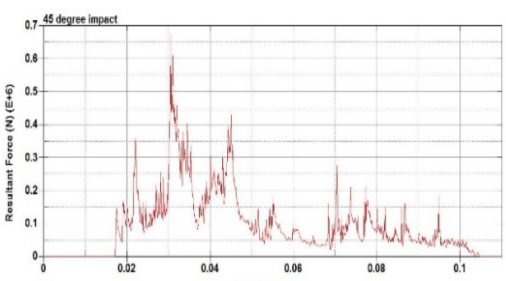

Figure 10: 45 degree impact resultant forces

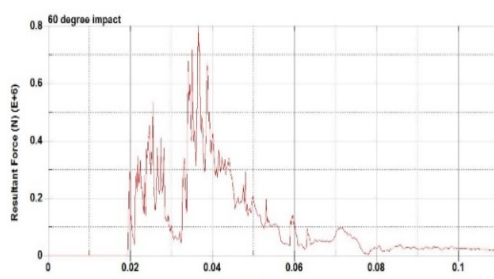

Figure 11: 60 degree impact resultant forces

The 60-degree impact showed the highest peak force during wall impact, while the 30-degree impact showed the smallest peak force, but had a longer sustained impact with the wall compared to the other three crash scenarios. The most critical crash scenario is a high impact force over a small time interval, which usually results in high loads and severe injuries to the driver. To improve the safety of the driver's compartment in the case of an impact, the simulation results will be used in designing custom foam cushioning in the driver's compartment, which will reduce the loads and lengthen the duration of vehicle's impact to allow the safety equipment and energy absorbing foam to protect the driver.

Although these results provide insight to the behavior of a jet dragster during a high-speed impact, the magnitudes of the forces cannot be taken at face value because of the exclusion of key components in the simulation. The current simulation uses the bare jet dragster chassis for analysis. To get a more complete model, mass blocks should be added to the chassis to represent the different parts of the car. Adding additional weight to the vehicle in the appropriate areas will allow for the weight distribution and center of gravity of the vehicle to accurately portray the real jet dragster.

Additionally, there are also components on the dragster that directly affect its behavior during impact. The tires absorb energy when they impact the wall, and the friction between the tires and pavement and the tires and the barrier can significantly change the car’s response. Additionally, the fuel tanks on the sides of the vehicle are designed to be energy absorbing structures in the case of an impact. The front wing and nose are the first components to hit the barrier, and are also designed to absorb energy. In the driver’s compartment, the dash, the driver’s seat, and the pedal assembly are all components that prevent the compartment from collapsing, left to right, during an impact.

Lastly, the results of the dynamic simulation did not closely align with the results from the static simulation model. The application of the force on the dragster during the static simulation needs to be adjusted to more closely align with the angled impacts conducted in the dynamic analysis for a more direct comparison.

Section 5: Conclusions

The foundation developed in the automotive engineering Crashworthiness course played a key role in the advances made in the jet dragster simulation. As basic concepts were developed throughout the course, the research conducted for automotive thesis work, focused on jet dragster crashworthiness, built upon these concepts and took them to another level through the application of a high-speed impact dragster simulation.

As multiple dynamic simulations were conducted, it was evident that the angle of impact had a significant effect on the plastic deformation of the chassis. Because key components were excluded to simplify the model and reduce computation time, the chassis experienced excessive deformation that is not realistic of a typical crash scenario. Although the results from the current simulation are valuable for a comprehensive understanding of the overall crashworthiness, additional model developments will improve the reliability of the analysis and increase the validity of the overall review. Moving forward, the first step that should be taken in improving the model accuracy is the addition of mass blocks and select key components. As the dynamic model continues to be improved upon, the static simulation will also be refined in order to get an immediate result that can start being implemented to improve driver safety.

Lastly, after conducting a substantial amount of research on crash LS-DYNA crash simulations, significant emphasis was placed on developing crash models alongside full-scale crash test results to ensure model validity and accuracy. There are a variety of factors and variable that needs to be fine-tuned when building a crash simulation that can only be accomplished by comparing simulation results to real test results. Because this simulation is a new venture in the jet dragster industry, there is no previous test data, pictures, or videos available to assist in the development of the model. As a result, the information produced from the dragster simulations need to be validated using other methods.

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I am a second year Graduate Mechanical Engineering student at Florida Tech, with a focus in Automotive Engineering. I completed my Bachelors in Mechanical Engineering at Embry-Riddle Aeronautical University, where I began my work with Larsen Motorsports, the leading jet dragster race team in the world. I have held several roles on the team: Final Assembly Specialist, Jet Technology Center Co-host, and Crew Chief. My research is in the Crashworthiness of a Jet Dragster, which has introduced me to the field of Human Factors. Ultimately, I would like to continue to pursue the field of Human Factors for a career, while participating in STEM outreach programs to encourage and motivate the younger generation in this industry.

Dr. Matthew Jensen

Dr. Matthew J. Jensen received his bachelor's degree in Mechanical Engineering from Rose-Hulman Institute of Technology in 2006. Matthew received his doctorate from Clemson University in 2011 in Mechanical Engineering, focused primarily on automotive control systems and dynamics. He is currently an Assistant Professor of Mechanical Engineering, the ProTrack Co-Op Coordinator and Chair of the General Engineering Program at Florida Institute of Technology. His research interests include applications in automotive/transportation safety, electro-mechanical systems, data analysis strategies and techniques, dynamic modeling and analysis, and engineering education.

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