COMPARISON OF STRUCTURAL DAMAGE AND OCCUPANT INJURIES CORRESPONDING TO A VEHICLE COLLISION ONTO A POLE VERSUS A FLAT BARRIER

A Thesis by

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Karachi, Pakistan, 2002

Submitted to the Department of Mechanical Engineering
and the faculty of Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

December 2005

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The following faculty members have examined the final copy of this thesis for form and content and recommended that it to be accepted in partial fulfillment of the requirement for the degree of Master of Science, with a major in Mechanical Engineering.

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AKNOWLEDGEMENT

I would like to take this opportunity to sincerely thank my advisor Dr. Hamid M. Lankarani, for his continuous support during my stay at Wichita State University. He has constantly encouraged me during the course of my thesis for which I am grateful. I would also like to thank my committee members Dr. Ramazan Asmutulu and Dr. Krishna K. Krishnan for their time and effort in reviewing this report.

I would also like to thank my parents who were always there for me with their support, love and continuous encouragement. Lastly, I would like to thank all of my friends at the Computational Mechanics Laboratory at the National Institution for Aviation Research (NIAR) for their kind cooperation during my studies at Wichita State University.

ABSTRACT

Vehicle safety is of great value to the automobile manufacturer. During the recent past, great measures have been taken in improving the safety of passenger cars/vehicles; however, continuous effort is still needed to design safer vehicle in frontal impact/collisions. Recently new modeling techniques have been developed to design more crashworthy vehicles. In this study a typical mid-size sedan is analyzed in a front-on full-width as small as an offset impact/collision simulation.

This thesis describes the structural damage on a vehicle colliding with a rigid pole as compared to the same vehicle colliding with a flat barrier. A rigid pole is to consider the worst case impact scenario. The National Highway Traffic Safety Administration (NHTSA) has specifications for barrier crashes. It does not have any standards for pole crashes. In reality, there are many pole related vehicle crashes every year. Pole crashes involve vehicles colliding with utility and traffic light poles, trees, etc. The purpose of this study was to study the intrusion and injury values for the pole test and compare it with the barrier testing method of NHTSA. The analyses are performed using the guidance set forth under the New Car Assessment Program (NCAP) and the Insurance Institute for Highway Safety (IIHS). The analyses are run using LS-DYNA software. The crash barrier and the rigid pole are modeled in MSC/PATRAN. The accelerations at various points are recorded. The occupant compartment intrusions are compared between the pole and barrier.

To study the response of the occupant a MADYMO model is used. An average size US male is represented by a Hybrid III 50th percentile male dummy model is used to study the passenger injury response. The dummy is placed inside the car using the extended coupling method. Extended coupling is a software technique in which the passenger/occupant model is placed inside the main compartment on the driver's seat.The acceleration values are plotted and injury values are evaluated. The lower body injury during the collision/crash test as a result of the intrusions in the main cabin of the car is calculated using the Tibia Index and forces. The barrier and the pole test results are compared, which indicates that the intrusions and injury values are more severe in the case of pole impact and in off-set crash test and that there might be severe leg injury.

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CHAPTER ONE

INTRODUCTION

1.1 Objective

These days most automobiles are equipped with more safety features than previously designed automobiles. However, most of the passenger vehicle occupants of frontal crashes still die. A recent survey showed that more than 30,000 people die in crashes in USA every year. Motor vehicle crashes are the leading cause of death for children greater than three years of age. Automobile accidents are one of the major sources of deaths in the country. More people die from automobile accidents compared to other medical diseases like cancer and heart related diseases. Although automobile accidents data includes accidents involving driving under the influence (DUI) or driving while intoxicated (DWI). [2]

The crash worthiness of an automobile can be defined as the ability of the automobile to absorb energy from an impact/collision in case of an accident and to protect occupants sitting inside the cabin of the automobile and prevent injuries. These days the automobiles are becoming good and crashworthiness day by day but there is still need for further improvement and good crashworthiness design. There is still plenty of room to design the front structure of an automobile which can perform better in the case of a frontal impact/collision. Furthermore the main cabin safety can also be improved by keeping the cabin intact in case of an accident and therefore preventing the crash forces to penetrate inside the main cabin. This will prevent severe injuries to the occupants sitting inside the main cabin.

Out of several safety related issues involving automobile crashes front-on collision is of top importance. The purpose of this research is to study and compare the crash results for full width and offset collision of a Ford Taurus with a barrier and the same with a rigid pole.

In recent times, cars have become more equipped with safety devices such as airbags, seatbelts and improved structural design which absorbs more energy during the crash. Much of it has to do with the

National Traffic and Motor Vehicle Safety Act 1, which was first introduced in 1961. It states that the manufacturers of passenger cars and all different types of vehicles must conform to certain safety standards.[7]

Under the direction from the department of transportation, the national highway safety traffic administration (NHTSA) regulates the manufacturers of automobiles to comply with federal motor vehicle safety standards (FMVSS). The law defines FMVSS as a minimum standard for motor vehicle performance. This regulation states that the vehicle should meet or exceed the safety standards set forth by the Department Of Transportation (DOT) that the passengers inside the vehicle are not exposed to any undue risks in the case of an accident. The regulations are very comprehensive in nature and they detail every single thing about a vehicle ranging from pollution standards to crash worthiness requirements.

Manufacturers have to make sure that every vehicle has to pass all the FMVSS crash requirements at 35 miles per hour (mph). The article 208 of FMVSS is designed to protect passengers in a vehicle in frontal collisions/impacts.[7] This was introduced to improve the occupant/passenger safety in a frontal collision/impact and to minimize the magnitude of injuries. This regulation requires all auto mobile manufacturers to test a representative dummy in frontal crashes using appropriate restraining system and calculate injury parameters.

The Federal New Car Assessment Program (NCAP) tests new passenger cars at 35 mph in frontal crashes into rigid barriers. These crashes involve the full width of the vehicle's front end and thus distribute the impact of the crash along the vehicle's frame structure, which absorbs most of the impact and often collapses in doing so. Thus the integrity of occupant compartment is not compromised with a full width barrier test except at very high speeds.

NCAP has also involved in a 40 mph crash at an angle in to a collapsible or deformable barrier that means the barrier absorbs more energy during the crash, unlike a rigid barrier. Since the smaller area of the vehicle’s front end must absorb the entire impact of the crash, it is crushed more than in a frontal crash and damage or deformation of the passenger compartment is more likely.

However there are no tests for the car crashing in to a pole. The purpose of this research is to compare the results of crash analysis of a Ford Taurus crashing in to a rigid barrier with the crash analysis of a car hitting a pole, using simulation software.

1.2 Background

As more cars were manufactured and came on the roads, there was a need to protect and prevent traffic accidents. During early 1930’s motor vehicle safety act was implemented. This act helped developed the FMVSS.

This regulation is meant as a minimum safety requirement for car safety in crashes in the event of a frontal collision/impact. This regulation is meant to protect the occupants of the car/vehicle against accidents, minimizing injuries, reducing deaths, reducing the magnitude of injuries. This regulation also tests the structural integrity of the critical components in the main cabin of the car/vehicle. After the introduction of this regulation/law automobile manufacturers have paid more attention in the development of a safer car. This development is not limited to just adding restraining systems to the car but has also lead the automobile manufacturer in the development a car which is more safe, meaning the car structure has improved absorbing more energy during an impact. This regulation has significantly helped in improving restraint systems. Therefore reducing the number of deaths over a period of years. This has also led in designing a car structure which can absorb more energy during a front on collision/impact and therefore leading to minimum compartment intrusions which ultimately save lives.

The federal new car assessment program tests new passenger cars in 35 mph frontal crashes into rigid barriers. This test involves the full width of the vehicle’s frame structure, which absorbs much of the impact and often collapses in similar fashion. Such tests put huge pressure on passenger restraint system and have resulted in substantial improvements in these systems for the last 15 years.

The institute's test also involved a 40 mph offset crash at an angle into a collapsible or deformable barrier (meaning the barrier absorbs some of the energy of the crash, unlike a rigid barrier). Since a smaller area of the vehicle's front end must absorb the entire impact of the crash, it is crushed more than in a frontal crash meaning the intrusions are more in offset impact compared to full frontal impact and the damage or deformation of the passenger compartment is more likely. This test is similar to vehicle to vehicle crashes. The stiff structures of one car are unlikely to align with those of the other vehicle and are thus less likely to crush in a straight axial direction. Instead, they will bend or buckle sideways, absorbing much less energy of the impact than in a frontal accident and permitting a correspondingly grater portion of the impact to flow through to the passenger compartment. Using a deformable barrier approximates these real time conditions.

No tests have been carried out to see the intrusions, injury values and deformations when a passenger car is crashed in to a rigid pole. The main purpose of this research was to perform crash analysis of a typical sedan (Ford Taurus) with a rigid pole which was designed in MSC Patron and imported in LS-Dyna. The crashworthiness of the car hitting a pole was performed in LS-Dyna. Occupant compartment intrusion refers to deformation of a vehicle in a crash that intrudes into an occupant's survival space. The crash results showed higher intrusions and deformations values as in the case of car hitting a pole compared to the crash analysis of a barrier. Also the head injury value was higher in the case of a pole when compared to the barrier.

In case of automobile collisions the most critical injury which can lead to the death of an occupant is the injury to the head. Therefore the head injury analysis are considered one of the most important features in crash testing. The head injury measurement is defined later in this section. The head injury is simply a measure of acceleration and force with respect to time integration. The most common way the brain can be injured is by acceleration; resulting in a closed head injury. This is because usually there is no break of the skin or an open wound. The head injuries are caused because of rapid change of motion and direction in case of an accident. This can cause skull fracture and also traumatic injuries to the brain which can lead to immediate death. This report will present the head injury values involving a typical mid size sedan with a rigid barrier and a rigid pole.

The Head Injury Criteria (HIC) is defined with the following equation [4]:

$$\mathrm{HIC} = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\,dt \right]_{\max}^{2.5} (t_2 - t_1)$$

The HIC formula is evaluated in the event that the anthropomorphic test dummy (ATD) head strikes some part of the compartment or adjacent structure, or other items in the cabin. The time interval is defined as the time during which the ATD head is in contact with some part of the main compartment.

1.3 Research Goals

The purpose of this research is to analyze the difference in results for frontal crash of a Ford Taurus when it is crashed with a barrier under FMVSS/NCAP rules and regulations to the car when it hits the pole under similar conditions and speed. The idea was to compare the deformation, damages, intrusion values and injury values to that of the frontal impact with a barrier; as the pole impact is somewhat different from that of a barrier. The crash analysis is done using non-linear finite element software LS-DYNA and the occupant responses are taken when the MADYMO dummy model was imported in LS-DYNA using extended coupling to see the real time response of the dummy with the crash.

This report uses a finite element model of a typical mid size Sedan. This FE model is to be tested in a frontal impact with a barrier and also with a pole using LS-DYNA3D crash code. A full scale crash test of a Ford Taurus impacting a barrier at 35 mph and an offset deformable and an offset barrier at 40 mph is to be analyzed. Similarly a full scale test of the same model is to be carried out with frontal impact with a rigid pole at 35 mph and with an offset at 40 mph. The occupant dynamic responses and injury criteria are to be evaluated using MADYMO coupled with LS-DYNA to see the real time response of the occupant in a crash. The study of an occupant injury in a compartment intrusion is to be done.

CHAPTER TWO

CRASH TESTING PROCEDURES AND SIMULATION SOFTWARE

2.1 NHTSA and Crashworthiness

Every year the NHTSA does crash testing of brand new cars. The testing is performed to satisfy different parameters as defined in Federal Motor Vehicle Standards (FMVSS) involving different types of collision. These types may be front, side or rear end collision. This testing is also done for roll over collisions. Then the crash results are rated on a scale form one to five star, one being the least.

Federal law requires all passenger cars to pass a 30 mph frontal crash test. Instrumented dummies wearing safety belts measure the force of impact to the chest, head and legs in this test. These readings are the basis of the five star rating. The test vehicles are chosen from those models that are new, potentially popular, redesigned with structural changes or have improved safety equipment such as an airbag. The vehicles are bought from the dealers and not directly from the manufacturers and only one of each model is tested. The test program deals only with crashworthiness. The results tell us how well a car will protect one in a frontal crash, but give no indication of the car's ability to avoid a collision. This is affected by such characteristics as anti-lock brakes, maneuverability, rapid acceleration, and good driver visibility.

2.2 FMVSS 208

The Department of Transportation directed the National Highway Traffic Safety Administration (NHTSA) to introduce safety regulations to improve passenger safety in front impact/collision of vehicle. This regulation is known as FMVSS 208. This regulation is intended to minimize road accident, deaths and injuries arising from road side accidents. This regulation was taken into effect in the mid 1960's. This regulation requires all automobile manufacturers to show compliance with this regulation. This law mandates all automobile manufacturers to be in compliance with FMVSS 208. This regulation sets forth requirements for automobile performance and automobile equipment performance meeting all the FMVSS 208 safety standards and also give information on how to perform crash tests. The main purpose of this regulation is to protect the occupants from injuries in the event of an accident from the structural model design and manufacturing of an automobile.

This FMVSS 208 regulation is primarily designed to protect occupants sitting in the front seats of the car/vehicles in the event of frontal collision/impact. This regulation covers the safety requirement for the protection of passengers inside the vehicle in an accident. The main motive of this regulation is to minimize deaths in car crashes and the magnitude of injuries. This is done through the use of star rating associated with each automobile. The greater the star rating safer the automobile is in a frontal collision accident. The star rating system is advancement from the old force and acceleration measurement system implemented earlier in the 1960's. This regulation also details the safety equipment requirements for passengers in the front driver and passenger seat.

This regulation initially also regulates the type of passenger safety restrain system needed to be installed in an automobile. This regulation has been amended to regulate large passenger vehicles, buses and trucks and also identifies the importance of using a supplemental restraint safety system also known as passive restraint system. The active restraint system normally includes shoulder and lap belts which are user operated while the passive restraint system includes driver and passenger side airbags which are not user operated and are deployed automatically using automated sensor equipments. By implementing these types of safety standards, through this regulation helps improving the crash worthiness of the passenger cars/vehicles and it also identifies the requirement for continuous passenger safety equipments which includes development of safer lap and shoulder belts and air bags.

The passive safety requirements were introduced in 1986. In 1991 it was mandated that all vehicles should be certified at 30 mph frontal crash test. In the year 1996, it was mandated by the NHTSA that all cars should have front driver and passenger side airbags. During the recent past, in addition to the rigid barrier test be conducted at 30 mph, in the beginning of 2003 the NHTSA required that the front barrier test should also be conducted at 25 mph with a 5th percentile adult female and a 50th percentile adult male without the seat belts fastened. This test is in addition to both the dummy tests to be performed at 30 mph using both dummy models with their seat belts fastened. By doing so the certification requirements were increased from the use of 50th dummy model to include the 5th percentile female dummy model and also child dummy model.

There were some conflicts between the NCAP and NHTSA regulations. For example, in NCAP testing the automobile manufacturers were allowed to use safety restraint system protecting the occupant in a frontal accident while in NHTSA regulation the safety restraint system were not used. This allowed the automobile manufacturers to get a higher star rating in terms of the safety of the car. Efforts have been made to reduce these conflicts. This regulation has further evolved over the years to increase the safe inflation of the air bags. For instance this regulation requires the automobile manufacturers to design a sensor system integrated with the car's central computer crash system to detect if an adult is sitting in the front seat. The purpose is to have the air bags inflate when an adult is sitting in the front seat of the car while it prevents from inflating when a small child is sitting in front seat of the car.

2.3 Testing Methods

Two crash testing methods are discussed here as part of evaluating the crashworthiness of a passenger vehicle.

2.3.1 NCAP test method

In 1978 the US NHTSA began crash-testing popular vehicle models in the country. Their protocol, FMVSS 208 involved running vehicles head-on in to a fixed barrier at 35 mph test results were published for the information of consumers, as they aim of the international New Car Assessment Program (NCAP) figure below shows the setup for the NCAP testing method. A mid size car is used as a test article.

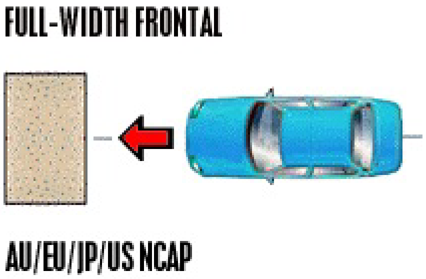


Figure 2.1 Full-width frontal crash [8,11]

This test involved placing the dummies in the two front seats. The test article is tested by crashing the test article against a rigid barrier. The velocity of the test article is 35 MPH. The results from the crash test are measured, the occupant dummy models injuries are also noted. The critical area of the dummy model is checked. These critical areas are head, neck and lower torso. This method is very helpful in the evaluation of the occupant injuries and cabin restraint systems. This test doesn't evaluate the structural integrity of the test article.

Over the years NHTSA has been working to improve passenger safety. In the mid 1990's NHTSA introduced a star rating based system for frontal crashes. This is a better rating system and more user friendly system instead of using all those numerical values, NHTSA converted to a five-star rating system.

2.3.2 IIHSS Test Method

The IIHS, realizing the limitations of the full width frontal crash test by NHTSA, uses a frontal offset crash test similar to tests carried out in Europe. Offset test is more challenging to the vehicle's structure more than the full frontal tests do, providing more information on passenger safety in the most common kinds of collisions. The figure below shows the IIHS testing method.

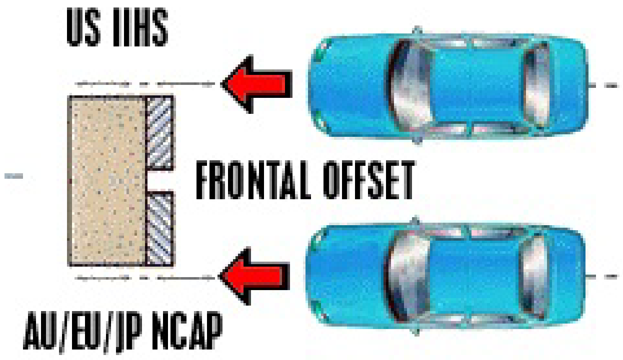


Figure 2.2 offset frontal crash test [8, 11]

The IIHS first used this test in 1995 at 40% offset at a speed of 40 mph. They made four categories depending on the amount of protection from serious injury. In this test 40% of the total width of vehicle strikes a barrier on the driver side. To account for a real life scenario the barrier can be made from a composite material. By modeling the barrier with composite material, the crash testing of the car/vehicle to the composite barrier creates impulses comparable to the impulses generated during a car collision of same class. This means that the test results can be compared only among vehicles of similar weight. Like full width crash test results, the test results of IIHSS cannot be used to compare vehicle performance across weight classes. The following figure shows the setup for the offset crash testing method.

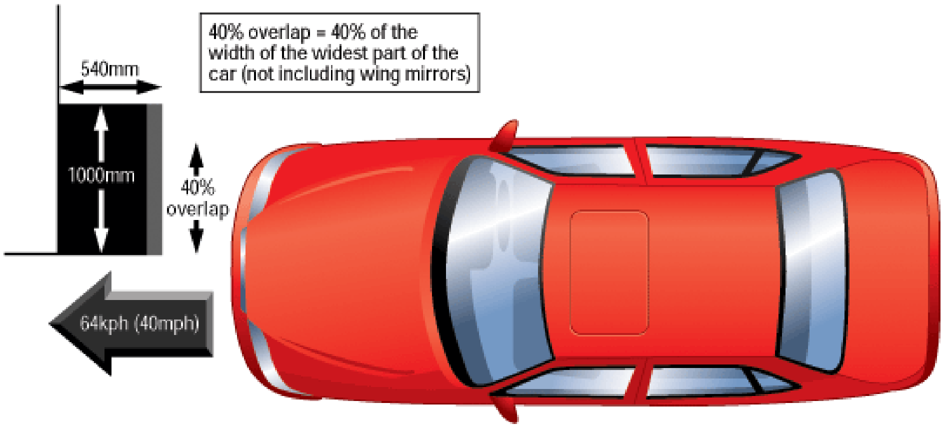


Figure 2.3 Vehicle overlap with deformable barrier [13]

2.4 Simulation and Analysis Software

This section presents the various CAD, finite element analysis and occupant safety simulation utilized in the analysis of frontal crash of Ford Taurus FE model

2.4.1 LS-DYNA

LS-DYNA is a general purpose, explicit finite element program used to analyze the non-linear dynamic response of three dimensional inelastic structures. LS-DYNA has a built in fully developed collision analysis features. This software also has built in features to check for errors in defining the surface contacts between mating surfaces. These features and options make this software very user friendly and easy to use to run all type of crash analysis.

Typical finite element software uses iterative integration procedures to compute the results. These results are generated using an output file which may be of .txt extension or some other type of graphical representation. There are normally two types of of integration method used in the programming of the software. These are explicit time stepping method (ETSM) and implicit time stepping method (ITSM) [10]:

$$\text{ETSM} = y\ (t+\Delta t) = F\ (Y\ (t))$$

$$\text{ITSM} = G\ ((t),\ Y\ (t+\ (\Delta t))=0$$

It is clear from the above equations that implicit method requires more time compared to the explicit method, therefore explicit method is preferred over implicit method where time is of value. Since explicit requires less time to analyze and it saves a lot of hard disk storage space. This allows complex models to be analyzed with a lot of finite elements inside at with results producing significant deflections in a reasonable amount of time. From the above equation it can be seen that the ITSM requires more calculations compared to the ETSM, thus requiring more time to analyze. This is the reason why when it comes to running models with complex geometry ETSM can be used more efficiently.

LS-DYNA has built in material libraries, which range from several hundred metallic and non-metallic resources. We can also define material properties in the software. These material library resources ranges from elastic material, glass material, linear foam material, elasticplastic material, fiber glass composite material, carbon fiber composite material and many more. This built in data base of material resources gives added advantage to LS-DYNA over other competitive crash analysis software packages.

Software provided contact commands can be used to define surface contacts between different items. One can also define multiple contact surfaces. LS-DYNA software has a built in contact analysis scheme which is fairly user friendly and can be checked easily for errors. LS-DYNA has built in algorithms which defines the contact between the mating surfaces/parts. There are many different ways to define contact in LS-DYNA. Contact cards from the DYNA reference user manual can be seen for further details. These contact algorithms includes rigid to rigid body contact, edge to edge contact, surface to surface contact, deformable body to rigid body contact and many more. These are all real life contact conditions which can be used directly to evaluate real time simulations. This can be used in heavy industries, in oil drilling or in smaller applications such as defining contact between drilling/milling tooling to the work piece. These contact options are used extensively in automobile industry. By using these contact options, it saves the manufacturer a lot of time and money in developing an actual prototype to test. Initial results can be obtained by using the contact methods provided in LS-DYNA software. These results can later be verified by using the actual prototype testing methods.

LS-DYNA has a vast application, few of them are listed below:

- Crash analysis for cars/vehicles, passenger and military air crafts, trains, ships.
- Passenger safety restraint system analysis.
- Bird strike analysis.

LS-DYNA requires LINUX/UNIX platforms to execute and analyze. LS-DYNA runs well on super computers and MPP machines. The computer memory requirement depends on the size of the file used.

Typically if the mesh size is more than 2 million elements, it can use upto 7 GB of disc space. To receive better result it is highly recommended that LS-DYNA needs to be run on super computers. This increases the efficiency of the software and accuracy of the result. The figure below shows a typical finite element model of a mid size sedan. This model will be used for simulation/analysis.

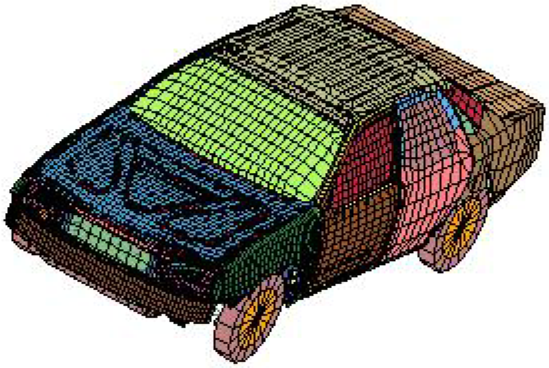


Figure 2.4 Finite element typical mid size sedan LS-DYNA model [10]

2.4.2 MADYMO PROGRAM

MADYMO is software developed to use to study the occupant injury response in the event of a crash analysis. There are several MADYMO human dummy models developed for the purpose of reducing the actual prototype testing and test setup. This reduces the testing and certification cost of a vehicle which automobile manufacturers have to suffer during the developing stages of a new product. Since it minimizes the use of actual testing in the initial stages of the product development. If there is a discrepancy in the design of the new model it can be detected early using the MADYMO model therefore reducing huge amount of initial cost towards product development and safety. It has a unique combination of fully integrated multi-body and finite element techniques. Figure below shows a typical MADYMO working model. The software uses the explicit time stepping method which is the second time derivative of the degree of freedom in explicit model. To obtain an accurate and efficient algorithm for multiple body system, the computer operation should be linear with the number of bodies provided all joints in the model have the same degree of freedom.

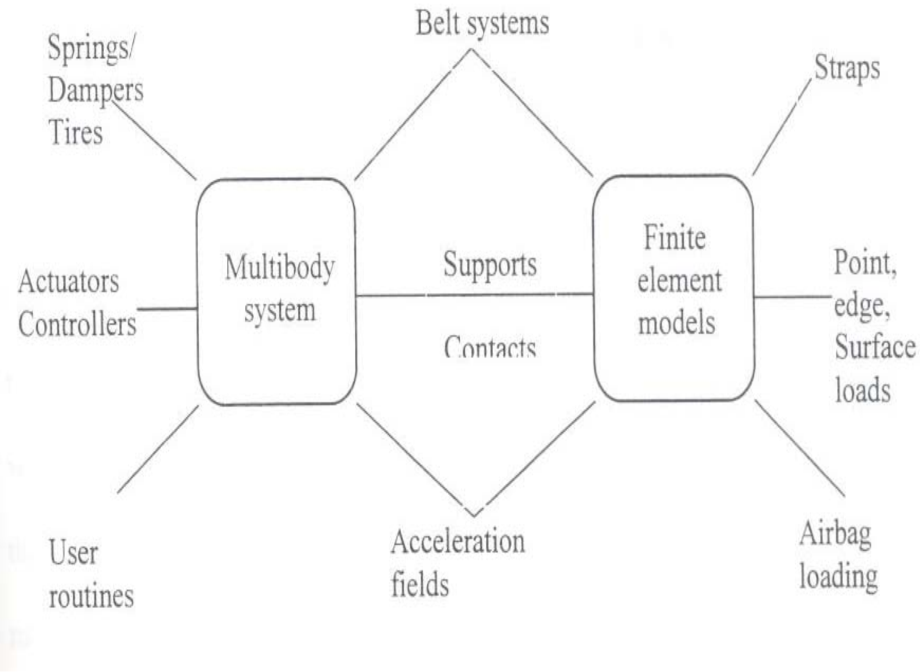


Figure 2.5 MADYMO working model [15]

There is a wide variety of MADYMO models generated for use of impact/collision analysis. there are some differences between these models depending upon the type of impact/collision analysis required. The differences are for occupant models for example there is a walking/standing pedestrian dummy model, also there is a detail FE model. For this analysis an occupant human dummy ellipsoidal model is selected. This occupant human dummy model is a multi dimensional model an it can be used in a vast range of impact/collision analysis. These analyses can range from front impact, side impact, rear impact and more complex accidents simulations like a vehicle rollover accident.

The skeleton of the human dummy model used for this analysis is selected from the MADYMO database. This human dummy model is composed of links/series of rigid bodies joined together by kinematic joints. There are kinematic joints built inside the model which can be used. The ellipsoidal model used in this analysis is made from MADYMO rigid body modeling techniques. The internal characteristics are defined within the rigid bodies of the model. Since this is an ellipsoidal model, the outer profile of the dummy model is made up of cylinders, planes and ellipsoid.

To account for the displacement or buckling bending of soft tissues in the human dummy model like skin and flesh is defined by force based contact which is a specification for the ellipsoidal model. These properties are very important as they relate how the dummy is going to interact with its surrounding atmosphere. This is of great importance, as this report analysis the occupant response in the frontal impact/collision. The reason for choosing the ellipsoidal dummy model over the finite element model and facet model is the fact that the ellipsoidal model is more time efficient and gives more accurate results for this type of analysis.

The manner in which the bodies modeled relate and communicate with their surroundings permits the use of different integration techniques as governed by the laws of motions. All techniques are known to be stable and thus confines the time stepping to allow to be performed. In the event that, there was a need to perform an analysis with FE model in it, the analysis can be run with finite element using various time steps for each individual module.

To bring the MADYMO model inside the LS-DYNA structural car model, required a special method called extended coupling. This extended coupling method allows the user to review real time results and interaction of the dummy model with a main cabin interior of the car. It also let the user see the real time response of the main cabin compartment intrusions and its affect on the occupant sitting on the front seat of the car. The other option, to avoid extended coupling could be to take the acceleration impulses from the LS-DYNA crash software and manually input in the MADYMO occupant dummy model to get the injury responses. The use of extended coupling is a fast emerging technique as it permits the analysis to be run with the occupant dummy model sitting inside the car permitting the user to run the analysis simultaneously with the car model. By doing so, the damage to the car structure and occupant injury response can be evaluated in a single run of software.

The typical method involved in extended coupling is to develop two input files, one file for the LS-DYNA model and one file for the MADYMO model. After making these input files, the task is to make these files communicate with each other. For details about how to interact these two input files, referred to the LS-DYNA and MADYMO reference user manual. The coupling cards are added to define and control coupling. By adding the MADYMO and LS-DYNA coupling cards the software will exchange information during the simulation. The very important part of this extended coupling technique is to develop the contact between the occupant dummy model and its LS-DYNA surrounding atmosphere, which is in this case is the main cabin interior of the car. There are special commands available to do this job, for example the user can define the master mating surface and the slave mating surface and this will limit the type of desired contact. Attention should be made to make sure that before running the analysis that the units are in the same system for both software, by doing so it will not create any scaling errors in the output files.

When the software is executed the coupling will form two set of output files for LS-DYNA and MADYMO output files. An animation file will also be generated in the result section. The coupling technique is very useful and it enables the researcher to combine the two individual systems, in this case the occupant dummy model and a typical mid size sedan model. The coupling method is used widely in the industry these days for certification and product development.

The seat belt model is also included to make the analysis more closer to real life scenario. Since the occupant sitting on the front seat of the car is required by law to wear a seat belt while driving. The seat belt model used in this analysis is a typical seat belt finite model used in MADYMO data base. The seat belt is attached to the car model at three points representing the actual seat belt attachments in an actual car. The seat belt model is modeled with a slack belt and pre tension consideration.

The output results computed by the MADYMO/ DYNA provides detail injury parameters. These injury parameters include viscous injury response (VC), femur and tibia loads, head injury criteria (HIC), Thoracic Trauma Index (TTI), Gadd Severity Index (GSI) and other user defined injury values. If there is requirement for specific injury parameter calculation, it can be done by editing the output options and defining a new injury parameter in the output file. The injury values can be obtained in tabular form or in graphical form. After setting up the crash model analysis using DYNA and MADYMO, the user can easily manipulate the selection and criteria for injury responses. For example the user can reduce the magnitude of occupant injuries by editing by editing the special options available inside the software or by modifying the design conditions. This enables the MADYMO software very user friendly in vehicle crash safety tests.

A typical system in inertia coordinate system is shown in the following figure.

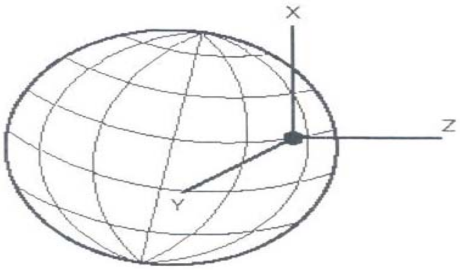


Figure 2.6 Coordinate System [14]

Contact Surfaces such as planes and ellipsoids, restraint systems, spring-damper elements as well as nodes of finite elements structures in MADYMO can be attached to the inertial space.

Null system: Several systems with known motion can be defined, for instance to represent a vehicle for which the motion is known from experimental data, as shown in Figure 2.7. However, the preferred way to model this is using a system of one body with a prescribed motion [14].

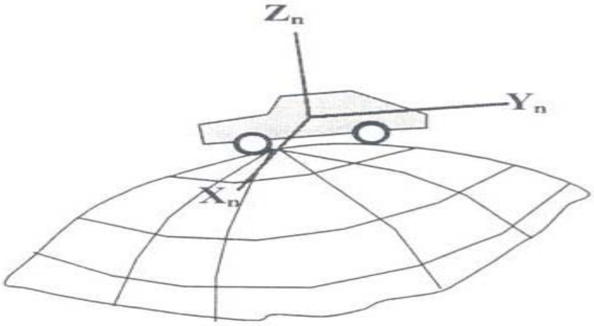


Figure 2.7 Null System Coordinate System [14]

The motion of a null system coordinate system relative to the inertial coordinate system must be specified as a function of time. This motion is defined by the coordinates of the null system origin O and quantities that define the orientation of the null system coordinate system.

The time points at which the position of the origin O is defined can differ from the time points for which the orientation is specified. This can be useful, for instance, in case the orientation of the null system changes only slightly. Then the orientation can be specified at less time points than the position of the origin in order to reduce the amount of input data.

Multiple System of bodies:

It is a system which can be defined in which bodies (pair or couple) within a same system are joined together using kinematic joints. A kinematic joint constrains the relative motion of the pair of bodies which can be translational joint and it allows only the relative translation.

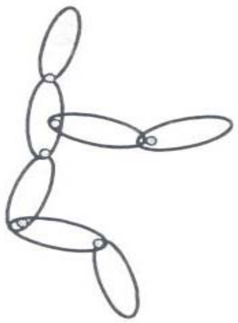


Figure 2.8 Examples of single and multi-body systems with tree structures [14]

A kinematical joint restricts motion of the two bodies it connects. The MADYMO software is equipped with several joint features. These joint features include translational joint, revolute joint, universal joint etc. This allows ease of modeling in the software. Figure 2.9 shows the different types of joints. The way a specific type of kinematic joint constrains the relative motion of two bodies is characteristic for that type of joint. The relative motion allowed by a joint is described by quantities called joint degrees of freedom. The number depends on the type of joint.

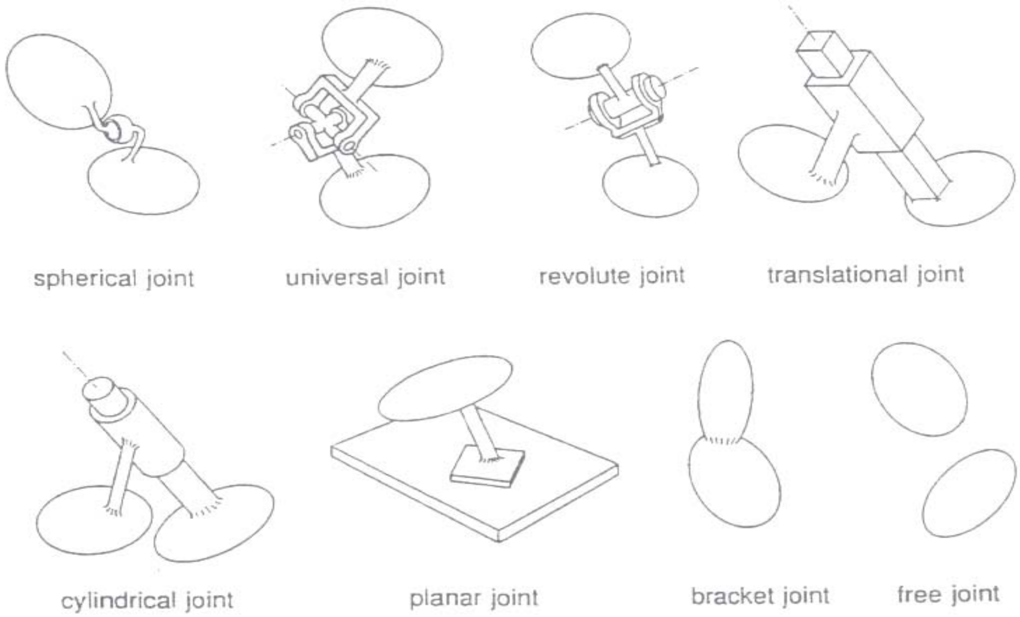


Figure 2.9 Joint Types [16]

A system of bodies is defined by the specification of which bodies are connected by kinematic joints, the type of kinematic joints, the geometry. These joints represent the attachment of the mechanical bodies using a mechanical constraint. In addition, he shape of bodies may be needed for contact calculations or post-processing purposes. Applied loads on bodies can be modeled with the force models described in subsequent chapters.

Kinematic Joints: A kinematic joint constrains the relative motion of this pair of bodies, e.g. a translational joint allows only relative translation. A kinematic joint is referred to by the number of child body of the two bodies connected by the joint. The constraint load is applied on the kinematic joints. The load is placed on the interconnected bodies through kinematic joints.

From the classical laws of Physics the summation of forces should always be equal to zero or the loads applied and the reactions generated will be equal and opposite. Therefore the load on the constraint will be equal in magnitude but opposite in direction.

The following figure, which is 2.10 shows the constraint load in a spherical joint in the vector coordinate system where i and j represent the direction of the force vector. The joint strength can be determined with the use of constraint load.

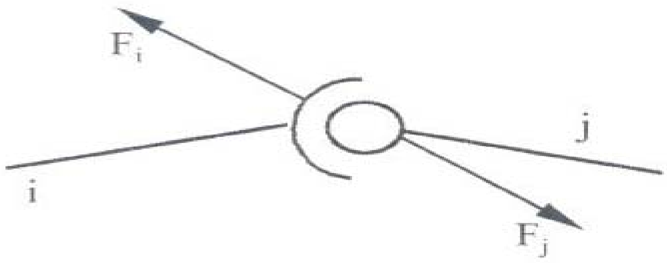


Figure 2.10 Typical Constraint Load in Spherical Joint [14]

The injury parameters are defined as the response of the human body or a dummy model, in this case when subjected to mechanical loads. The response of the dummy model (human body) with respect to time leads to a injury criterion. In response to a mechanical load, a body's specific region will undergo mechanical and physiological changes. This is called the biomechanical response. If an irreversible deformation occurs in a dummy model or a system under investigation, the system is said to be injured or the injury has occurred to the dummy model. This can result in damage to anatomical structures, therefore altering normal function.

The mechanism involved is called the injury mechanism; the severity of the resulting injury is indicated by the expression injury severity. The scale or magnitude of the injury is a physical quantity which can be measured. Many schemes have been proposed for ranking and quantifying injuries. To calculate the injury in terms of numbers, researchers have developed Anatomical scales which can measure the injury with respect to the anatomical position, the nature of injury and its magnitude. These scales rate the actual injuries rather than the consequences of the injuries. The commonly used type of scale is known as the Abbreviated Injury Scale (AIS). Although originally intended for impact injuries in motor vehicle accidents, the updates of the AIS allow its application now also for other injuries like burns and penetrating injuries.

2.4.3 Injury Parameters

As discussed earlier the injury criterion is a measure of the displacement of the particular point with respect to time, therefore almost all injury criteria originate from accelerations, relative velocities or displacements, or joint constraint forces. Most injury criteria need some mathematical evaluation of a time history signal. MADYMO performs these injury parameter calculations.

The following injury parameter calculations are available:

1. Head Injury Criterion (HIC)
2. 3 ms Criterion (3 MS) (Chest)
3. Thoracic Trauma Index (TTI)
4. Tibia Index (TI)

The injury parameter calculations are carried out on the linear acceleration signal of a selected body. The TTI calculation is carried out on the linear acceleration signals of two selected bodies [3, 4, 5]:

$$\mathrm{HIC} = \left[\frac{1}{t_2 \bullet t_1} \overset{t_2}{\underset{t_1}{\bullet}} a(t)dt \right]_{\max}^{2.5} (t_2 \bullet t_1)$$

Tibia Index measures the magnitude of injury to the Tibia bone. The Tibia Index calculation is given by the following [3, 4, 5]:

$$\mathrm{TI} = | F_Z / (F_C)_Z | + | M_R / (M_C)_R |$$

Where F_Z = Compressive axial force

$(F_C)_Z$ = critical compressive force with a value of 35.9 kN

M_X = Bending moment about the joining axis

M_Y = bending moment about the joint η–axis

$M_R = ((M_X)^2 + (M_Y)^2)^{½}$

The Tibia Index can be calculated for the top and bottom of each tibia. For each joint, the corresponding axial force F_Z is used. The limiting value tibia index under FMVSS 208 is one.

Viscous Criterion (V*C) is defined as the product of sternum deflection, normalized by chest depth and sternum deflection rate. The limiting value for viscous criterion under FMVSS 208 is 1.3 m/s.

The Thoracic Trauma index is given by the following equation:

TTI(d) = [T12 + max(LURY or LLRY)

Where T12 = peak lateral acceleration in g's

LURY is the left upper rib Y acceleration in g's and LLRY is the left lower rib acceleration in g's.

2.4.4 MSC/PATRAN

MSC/PATRAN is a useful designing/modeling computer program. It can be used to simulate product performance and manufacturing processes early in the deign-to-manufacture process. MSC/PATRAN includes a pre and post processor with analysis modeling, analysis data integration, analysis simulation, and results evaluation capabilities.

MSC/PATRAN provides direct access to the geometry. MSC/PATRAN is very user friendly when it comes to exporting the geometry including geometrical tolerances to analysis software. The export file contains detailed geometric information of the solid model and is compatible with most analysis software. This MSC/PATRAN software has a wide variety of options available in its database. It has options to generate the geometric model, to edit an existing geometric model or to import the model to other software for analysis.

MSC/PATRAN can be used for meshing the solid model as well. This software allows the user to either do a solid surface meshing or node meshing. It also let the user edit the meshing. The loads can be applied with appropriate boundary conditions as requires with the design geometry. The post processor is very powerful and can locate and identify the errors with relative ease, this enable the user to increase the productivity of the model file.

The result section of this software can enable the user to read and interpret useful output information with relative ease. The output information can be plotted as graphical or tabular values. Furthermore the greatest and the lowest corresponding values can also be reported easily.

The use of color, grouping and animation with high speed database access allow you to interpret analysis data with new understanding.

MSC/PATRAN also provides a customized interface for many analysis solvers through MSC's unique preference capability. By preference, it means that the software has special features for solvers like creating an import file which can be read directly by the solving software like LS-DYNA, NASTRAN or ABAQUS. The software package of MSC/PATRAN may come with the analysis feature which may include analysis types ranging from thermal analysis, structural analysis to composite analysis.

Using the powerful capabilities of the MSC/PATRAN PCL tool kit, you can customize all of these functions to your requirements. Providing unmatched programmability, flexibility and opportunity for customization, PCL is the core MSC/PATRAN component that delivers and open CAE environment.

CHAPTER THREE

CRASH ANALYSIS OF A FORD TAURUS

3.1 Study of the FE model

The FE model is developed by EASi Engineering for National Highway Traffic safety Administration (NHTSA). Figure 3.1 depicts a finite element model of a typical mid size sedan.

The model of the typical mid size sedan used in this analysis is very well defined in the front section. The analysis presented in this report is also based on a front on collision therefore this model satisfies the need for this analysis. The centre and back part of the car model being not very well defined will not affect the efficiency and accuracy of the simulation nor it will have any negative affect on the results because in frontal impact the centre or rear part of the vehicle does not undergo any significant deformation.

3.1.1 Finite element model description

The vehicle model is divided in to 134 parts. These parts represent the components of the vehicle. Out of the 134 parts, 104 parts are used with the shell elements to model the sheet metal components. Eighteen parts are assigned beam elements to represent the steel bars in the vehicle and one part is modeled with brick elements to represent the radiator. This FE car model uses shell elements. Typical shell elements are model in triangular form also some quadrilateral elements are used. The material model assigned to these shell elements is a general isotropic elastic-plastic material. The stress strain relation for the isotropic elastic-plastic material is defined with eight stresses versus strain points. The beam elements use the isotropic elastic material model. The solid elements are assigned material type, metallic honey comb, and use the constant stress solid element formulation. The parts of the model which is being analyzed are attached to gather with special commands called spot welding and also using attachment constraint defined in LS-DYNA3D.

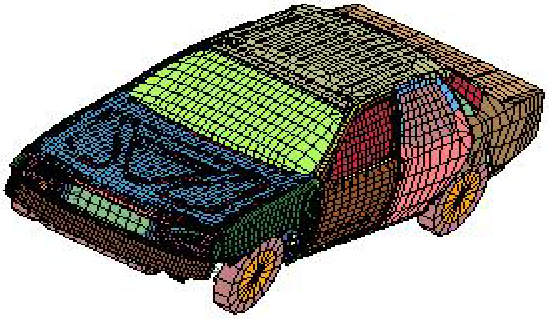


Figure 3.1 Mid Size Sedan FEA model [10]

Table 3.1 Vehicle model summary

Total parts	134
Total nodes	27329
Total shell elements	29325
Total solid elements	331
Total beam elements	120

The contact and friction between the components are modeled with one single surface sliding interface also known as automatic contact for beam, shell and solid elements with arbitrary segment orientation. A summary of the FE vehicle model is listed in the table.

3.2 Model Validation

The accuracy of the simulation can be evaluated comparing the simulation results with the test data. The evaluation focuses on the comparisons of acceleration profile taken at the various positions of the vehicle for two different impact velocities. The simulation of the frontal crash of the Ford Taurus model for an impact velocity of 30 mph is compared with the full scale test data. Figure 3.2 shows the simulations. The acceleration profile comparisons of engine top, left and right rear seats are shown in the figure. All of them show excellent agreement with the test with respect to peak values and timing of the curves.

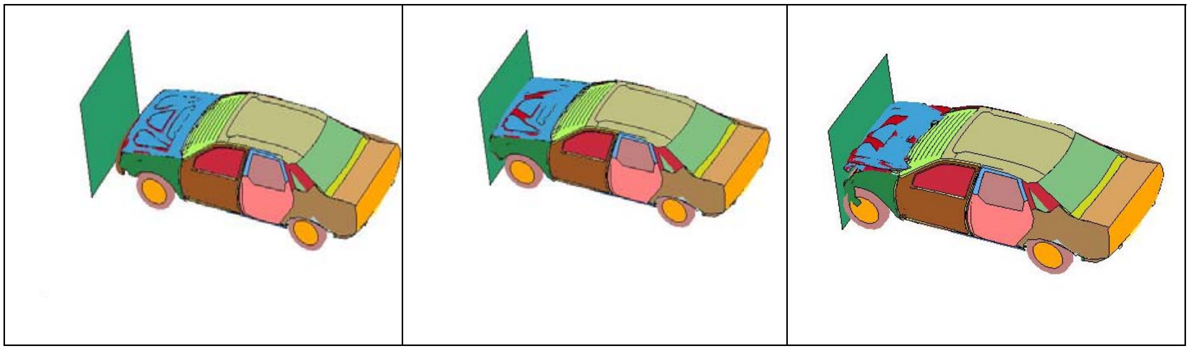


Figure 3.2 Simulation of 30 mph crash against a rigid barrier

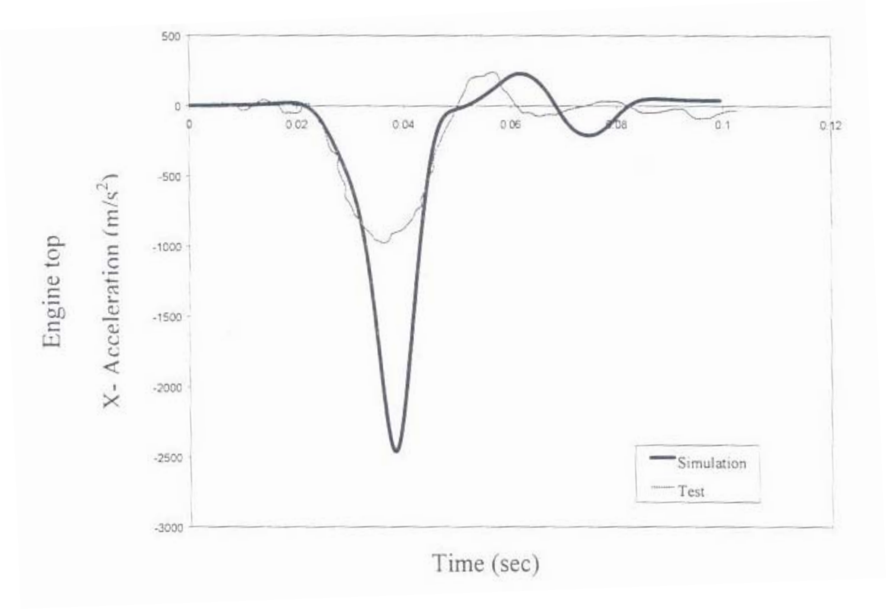


Figure 3.3 Comparison between test and simulation for engine top for 30 mph

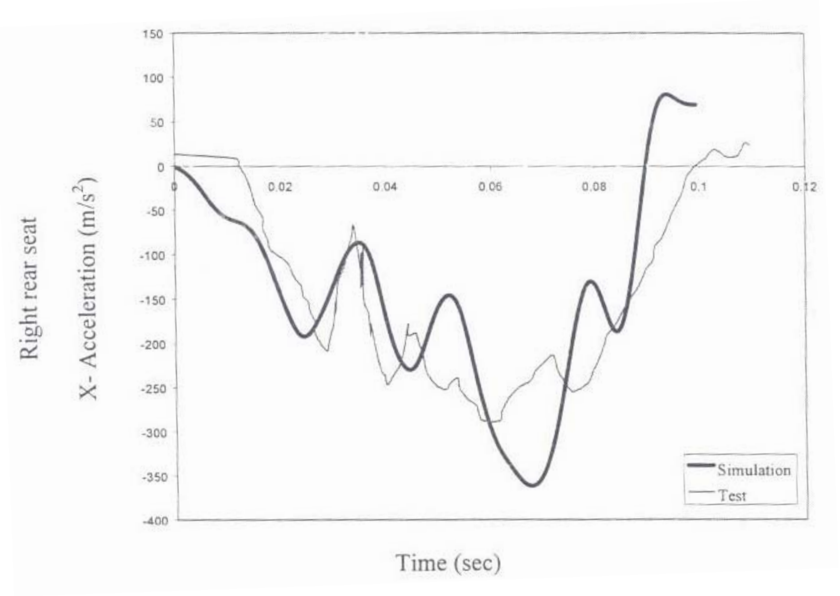


Figure 3.4 Comparison between test and simulation for right rear seat for 30mph

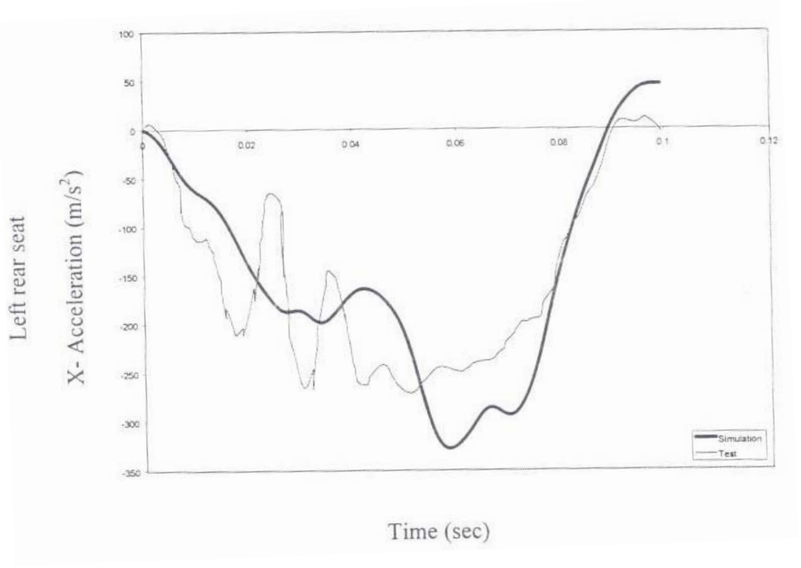


Figure 3.5 Comparison between test and simulation for the left rear seat

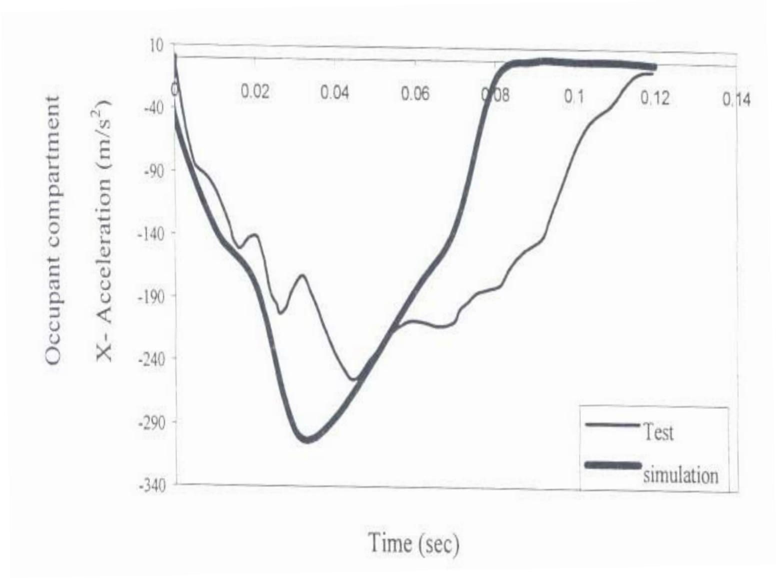


Figure 3.6 Comparison of occupant compartment acceleration for the actual test and simulation

3.3 Full-width Frontal Crash

The detailed finite element model of the Ford Taurus is crashed with a rigid barrier full-width at 35 mph according to NCAP regulations. The barrier is developed in MSC/PATRAN and it is rigid.

3.3.1 LS-DYNA simulation

The simulation was run for 115 milliseconds of simulation time with a time step of 10 milliseconds. The total computational time required for the run was around nine hours. The simulation is done using a rigid barrier. Contacts are given between the front part of the car and barrier as hot surface to surface. The car model comes in contact with the barrier at 5 ms; the hood starts to deform at 28 ms; the front structure gets crushed against the barrier. Maximum crush of the front structure occurs at 85 ms. Figure below shows the different stages of deformation of the car during simulation.

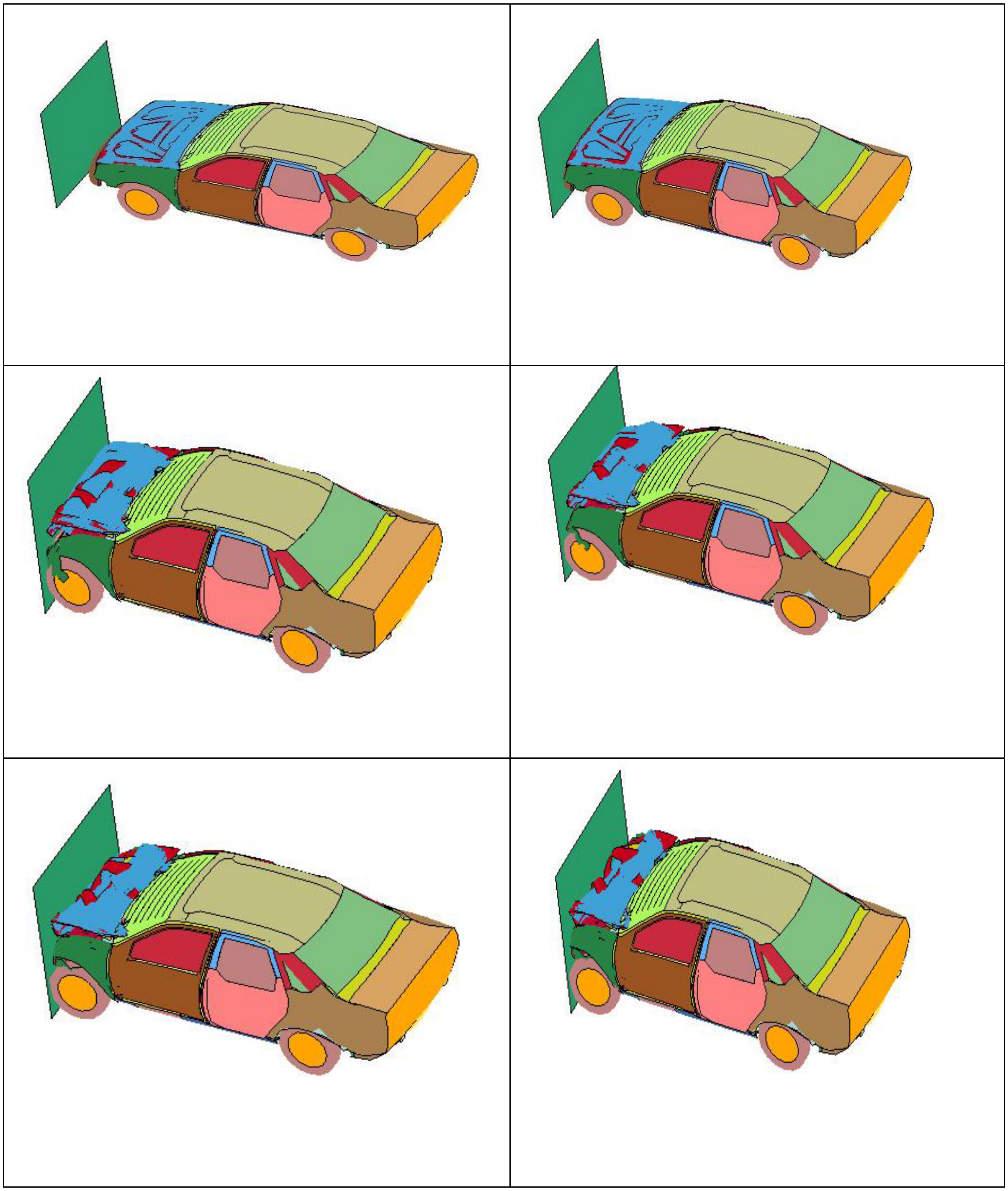


Figure 3.7 Animation sequence of full-width frontal crash with rigid barrier

3.4 Rigid Barrier

A rigid barrier is used in the full-width frontal crash. The barrier is modeled in PATRAN with solid elements. The properties are assigned as rigid to make it behave like a rigid barrier. Then the model is saved as a DYNA format file in PATRAN so that it can be imported in DYNA as a key file.

3.4.1 Time history records

The acceleration time histories at different locations in the car model are recorded. The peak values in the time history records for the engine top and bottom are high when compared to the tires as the engine parts are more rigid. The acceleration values on the instrument panel and the occupant compartment are relatively low since most of the crush energy is absorbed by the front structure. The maximum deceleration in the engine is 217 g while in the cabin it is 52 g.

The off-set crash test has low peaks when compared to the full-width. The left front tire has very high peak when compared to the right one since crash are in left front structure. The occupant compartment decelerations are low when compared to the full-width. With front on collision with pole the deceleration is higher when compared to the barrier. Same is the case with off-set testing the left tire has higher peak values than the off-set barrier test which shows that pole impact is more severe than a barrier impact.

3.4.2 Rigid pole

In the full width frontal crash a rigid pole is to be used the pole is modeled in PATRAN. The diameter of the pole is 250 mm and the properties are assigned as rigid. Then the pole model is imported in DYNA as a key file.

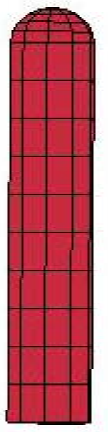


Figure 3.8 Rigid pole

The acceleration time histories at different locations in the car model are recorded. Nodes are picked at different locations on the vehicles and acceleration values are recorded.

3.5 Offset Frontal crash based on IIHS

Offset barrier crash tests are conducted at 40 mph and 40 percent overlap. The test vehicle is aligned with the deformable barrier such that the right edge of the barrier face is offset to the left of the vehicle centerline by 10 percent of the vehicle's width as shown in the figure.

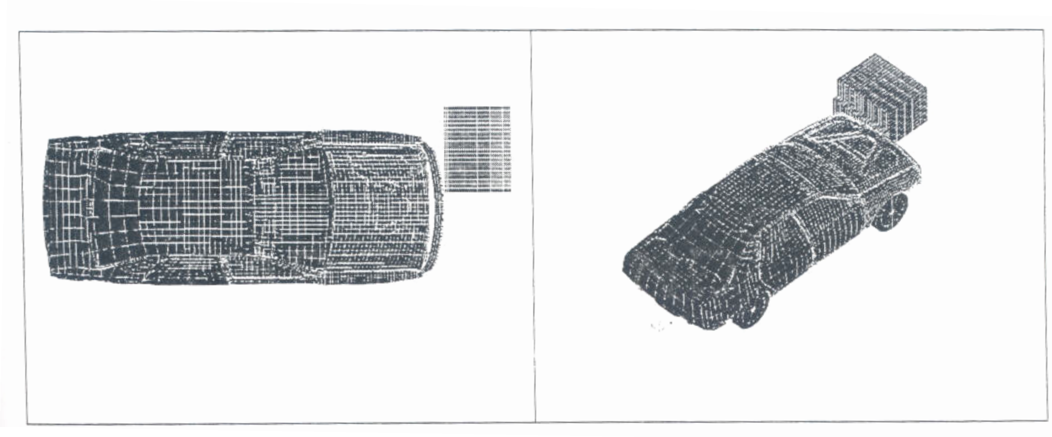


Figure 3.9 Initial setup for offset frontal crash

3.5.1 Offset deformable barrier

The barrier is composed of two elements, base unit and deformable face. The base unit is 650 mm high, 1000 mm wide and 300 mm deep. The deformable face is 1 m wide and 450 mm thick attached to a base of 90 mm thick, the deformable face is made of bumper element of aluminum honey comb. The deformable barrier is placed at a height of 20 cm from the ground. The profile of the deformable face is shown in this figure.

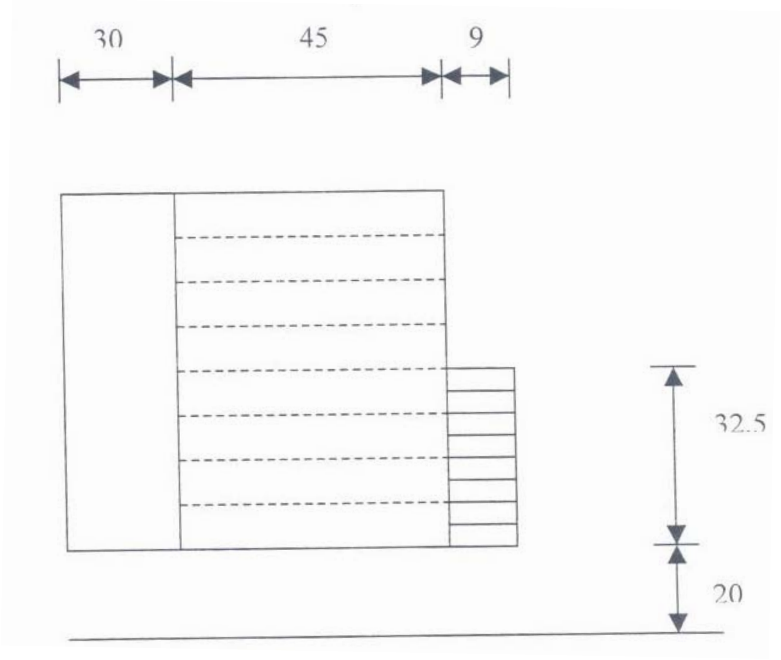


Figure 3.10 Profile of Deformable Face

3.6 Crash profile

The frontal offset/pole test simulated crash test of the Ford Taurus model is done using LS-DYNA. The simulation is run for 150 milliseconds with a time step of 10 milliseconds. The hood starts deforming at 40 ms. In the case of offset crash the front portion of the barrier also deforms but not in the case of pole and rigid barrier. At 80 ms left end of the deformable face is crushed completely. At 100 ms the vehicle starts pulling towards right. Figure below shows the simulation results for the offset barrier testing.

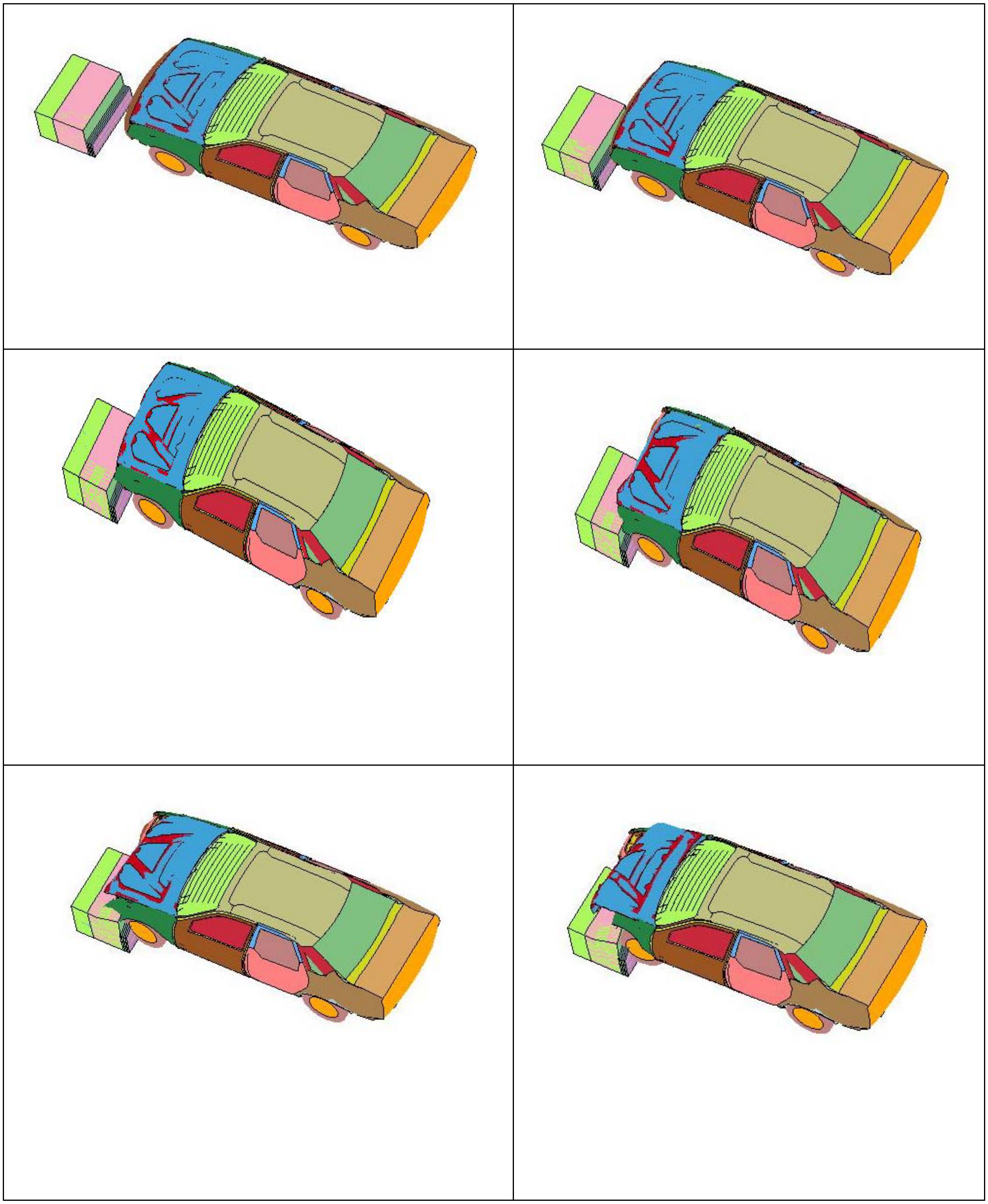


Figure 3.11 Animation Sequence of offset frontal crash

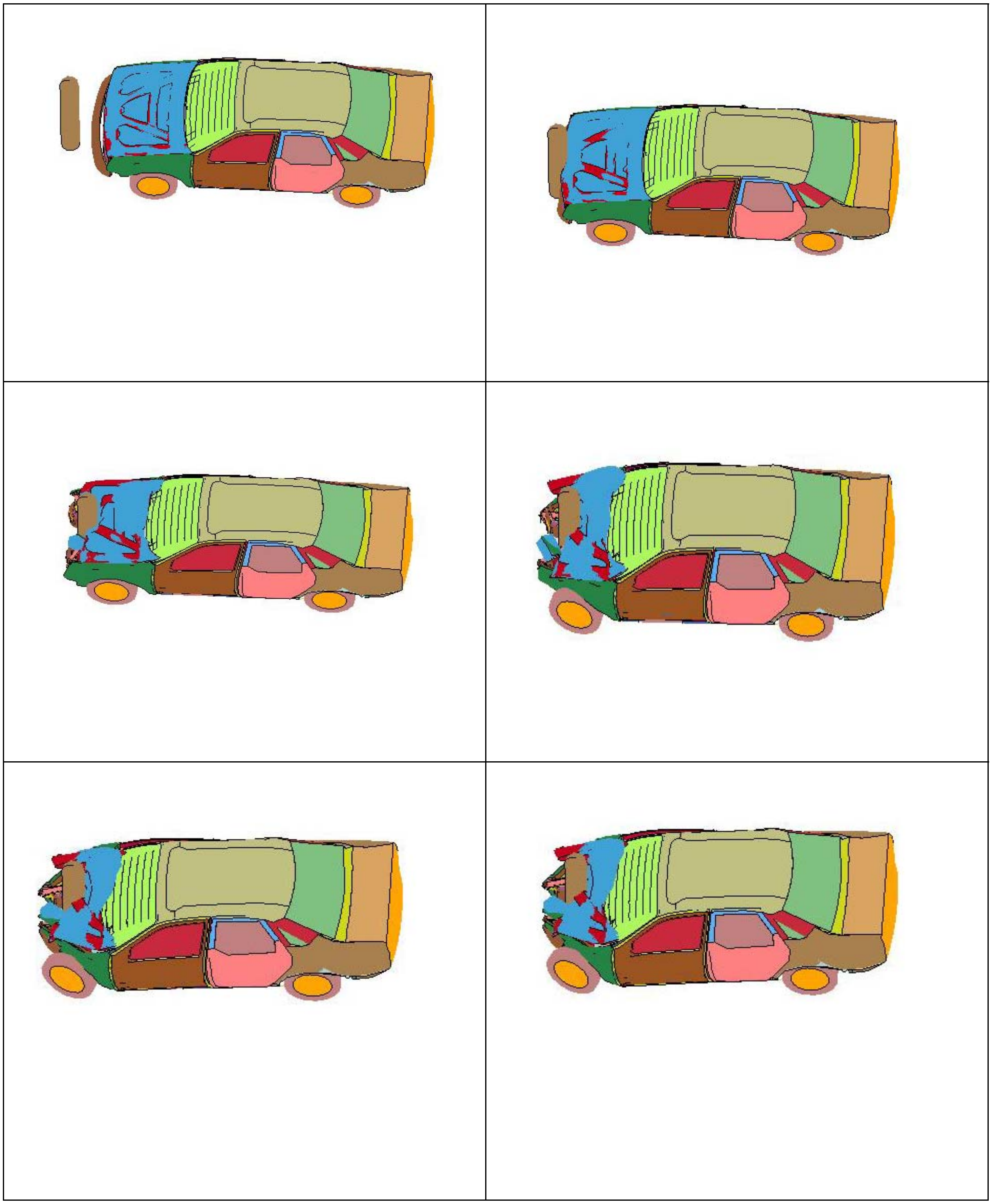


Figure 3.12 Animation sequence of pole frontal crash

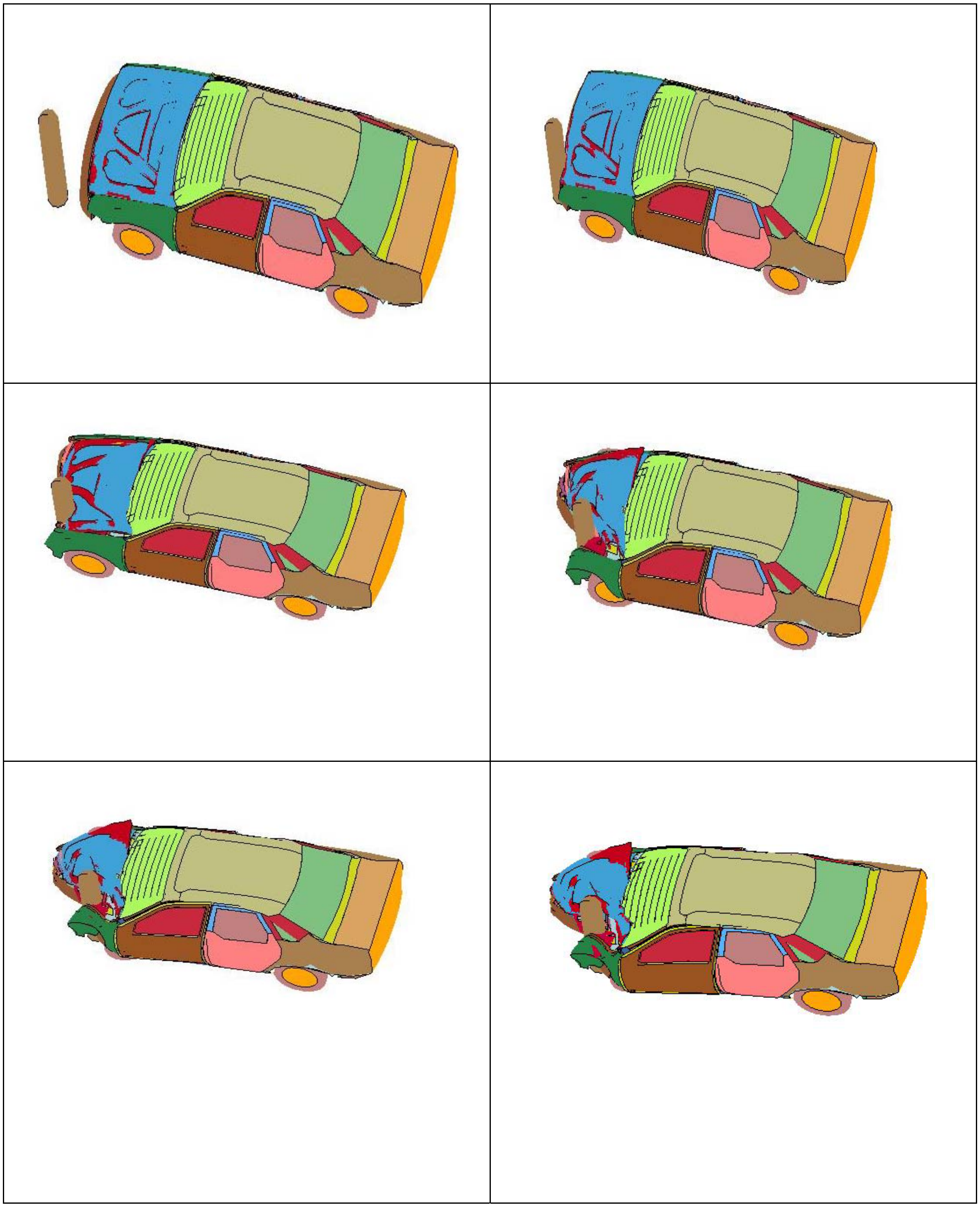


Figure 3.13 Animation sequence of pole offset crash

3.7 Comparative study

When we compare full width barrier test with the pole (full width pole) test, the crash results suggest that the intrusion and injury values are much higher in the case of the pole test because of the point impact since the point load are more severe as compared when the car hits a barrier in which there is much bigger area which comes in contact with the car hence maximizing energy absorption. Similarly in the case of offset collision when we compare the intrusion values and injury values the between pole and barrier the intrusion values are greater in comparison of the barrier because of the same reason.

3.8 Occupant compartment Intrusion

As mentioned above the intrusion values are more in the offset crash, the frontal structure of the car does not absorb the crash energy as in the case of full-width crash. So the offset tests are more demanding of structure. In the offset crash the car model tends to move around the barrier or pole, where the sides of the passenger compartment slides around the engine compartment resulting in substantial firewall and dash intrusions at the height of crash. Front suspension mechanism is typically located forward of the foot rest area where brakes and gas pedals are located and right on top of the main floor. The suspension mechanisms is considered rigid in length wise direction and during a vehicle crash of the front of the vehicle will try to penetrate the attaching locations back in to the toepan (location of brake and gas pedal). In a full width crash the whole front suspension is acted upon while in the offset crash force acts upon the left side of the front structure.

Observations on occupant compartment intrusions are shown in the following tables.

Table 3.2 Occupant compartment intrusion for the car hitting a barrier

Intruding Component	Full-width(mm)	Offset(mm)
Footboard/Toepan	102	183
Firewall	89	125
Floor	4	24
Left A-pillar	9	54
Instrument panel	9	64

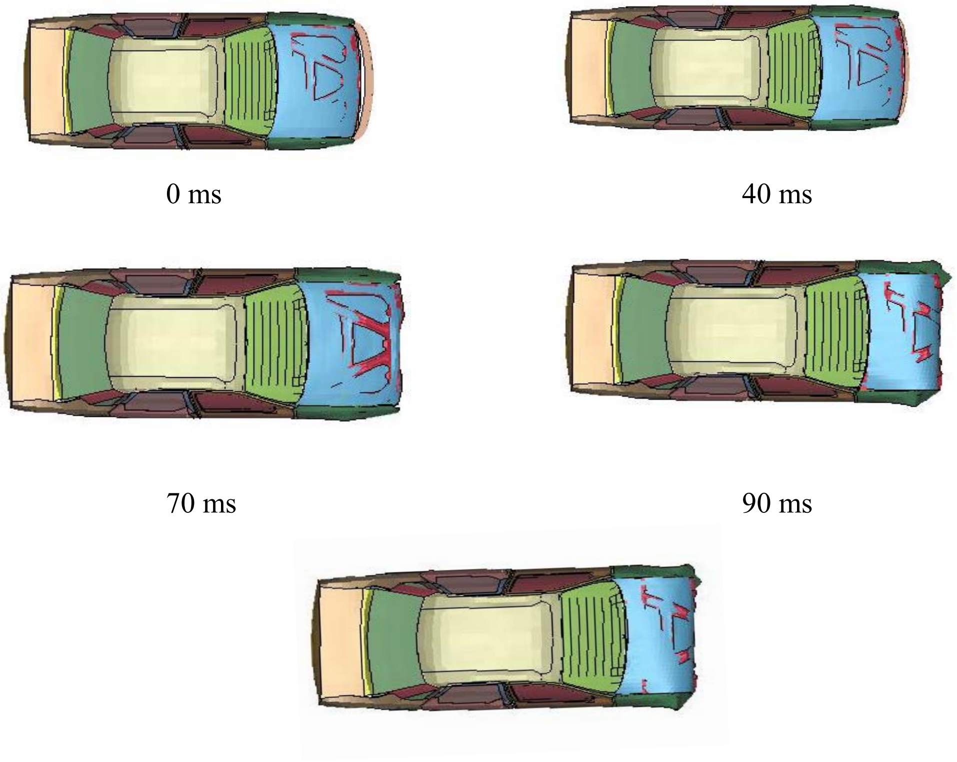
Table 3.3 Occupant compartment intrusions for the car hitting a pole

Intruding component	Full-width(mm)	Offset(mm)
Footboard/Toepan	118	253
Firewall	93	129
Floor	14	31
Left A-pillar	12	95
Instrument panel	12	70

The intrusion estimates are based on the rearward movement of the A-pillar, instrument panel and the toe board/floor board. For the toe-board six nodes on two straight lines are selected. For each of the nodes the displacement n X, Y, Z directions is noted. A reference node is taken at the rear bumper in order to separate the vehicle motion from the intrusion and the displacements are takes with reference to that node. The maximum displacement between the displacement of reference node and the selected nodes determines the intrusion.

3.9 Crash energy absorption

Crashing the full width of a vehicle in to a rigid barrier maximizes the energy absorption and the intrusions in the occupant compartment are not high; however, crashing the vehicle into pole results in higher intrusion values because of the fact that not the full face of the car comes in contact with the pole resulting in point impact and higher intrusion and injury values. Same is the case with offset crash when we compare the offset barrier test with the offset pole test it is noted that the deformation in the car's front structure is more resulting in higher intrusion values and injury values.



0 ms

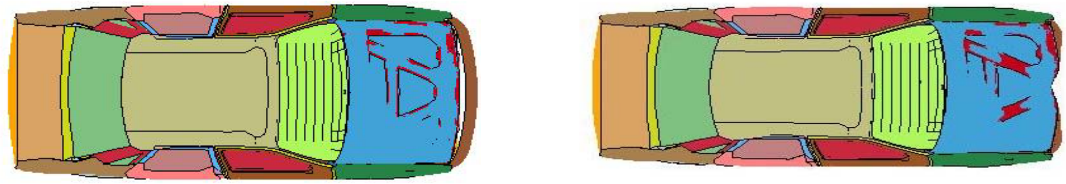
40 ms

70 ms

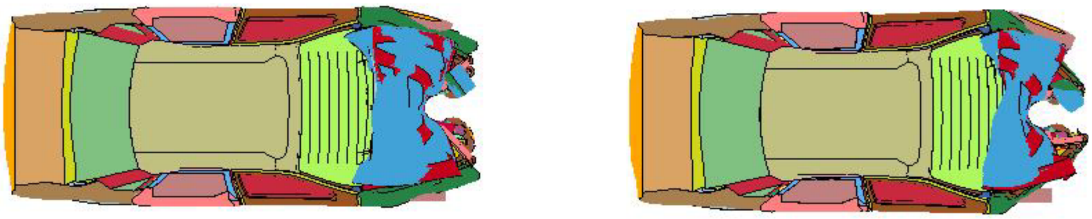
90 ms

115 ms

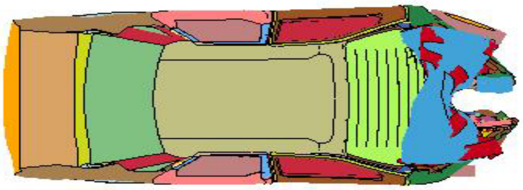
Figure 3.14 Deformation of the front structure in the full width barrier crash



0 ms 40 ms

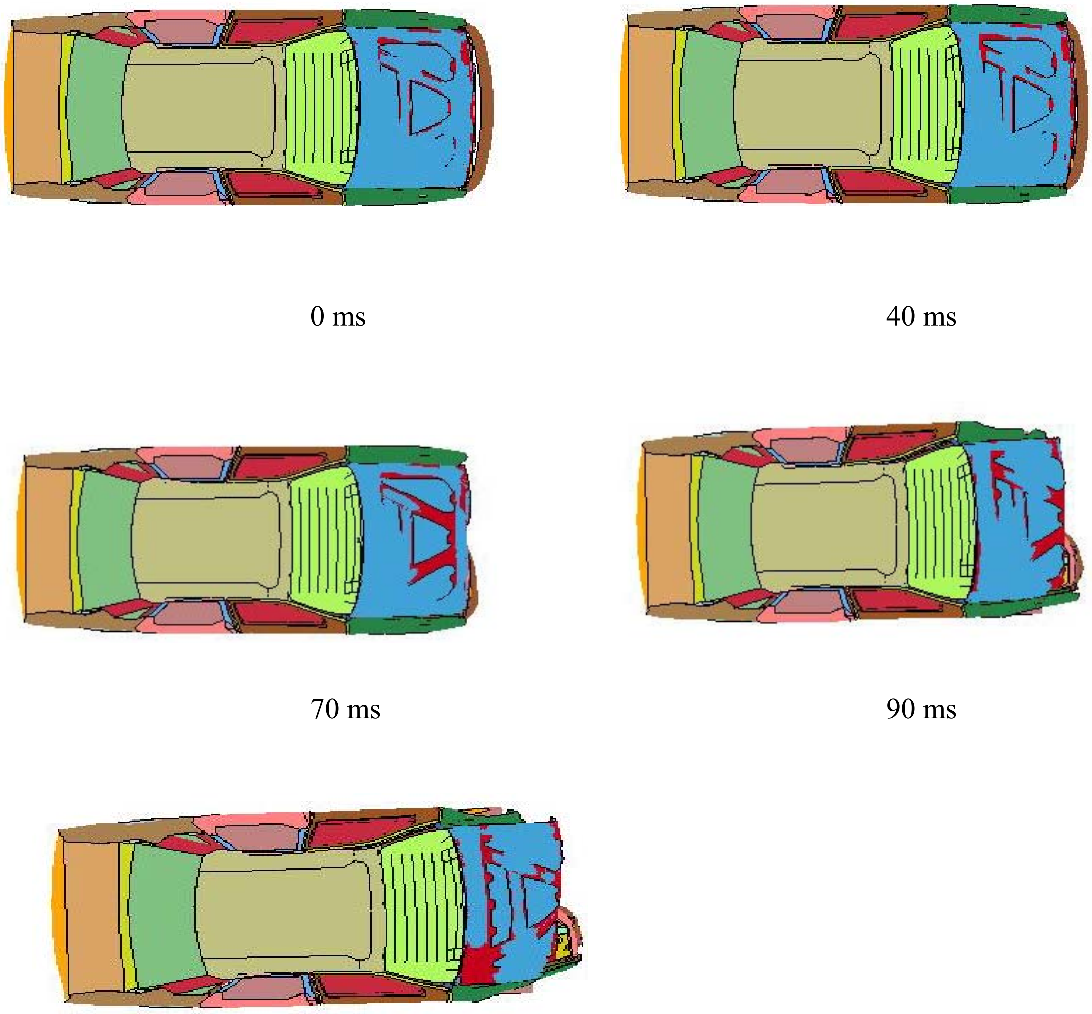


70 ms 90 ms



115ms

Figure 3.15 Deformation of the front structure in full width pole crash



0 ms

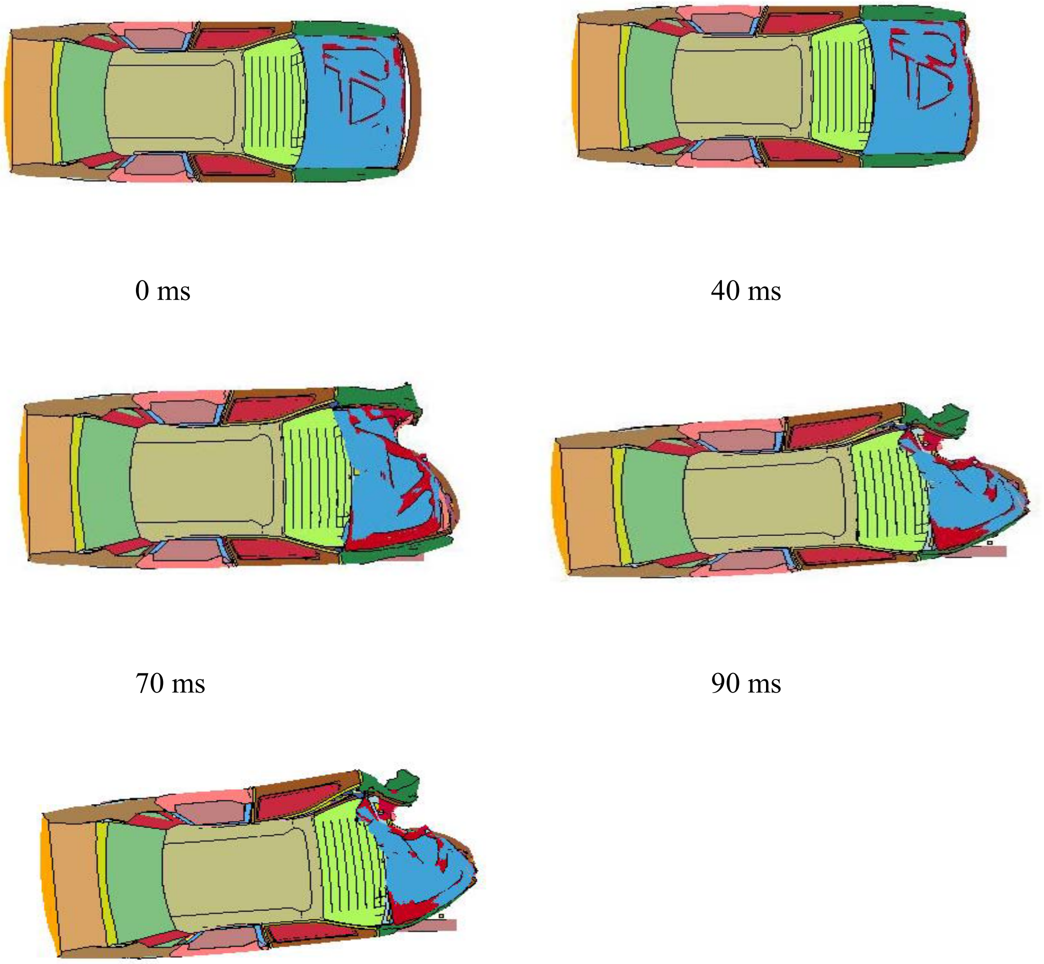
40 ms

70 ms

90 ms

115 ms

Figure 3.16 Deformation of the front structure of the car in offset barrier crash



0 ms

40 ms

70 ms

90 ms

115 ms

Figure 3.17 Deformation of the front structure of the vehicle in an offset pole crash test

CHAPTER FOUR

OCCUPANT IMPACT RESPONSE

4.1 Dummy Database

The hybrid III is the most widely applied dummy for frontal impact. There are two types of hybrid III dummy models available. One is the 50th percentile dummy model and the other is 95th percentile dummy model. The 50th percentile is a five feet six inch dummy model with a weight of 170 lbs. the 95th percentile dummy model is six feet two inches with a weight of 223 lbs. for this analysis a 50th percentile male dummy model is used. Recently 5th percentile female dummy model and three children dummy models of 3, 6 and 10 years old have also been introduced.

The detail of the dummy model can be found in the MADYMO user manual [15]. The dummy model consists of head which weighs approximately 10 lbs, a neck weighing almost 3.4 lbs, the upper torso 38 lbs, the lower torso 38 lbs, arms 10 lbs and legs 30 lbs. The neck and spine are joined. A flexible torsion restraint joint model is considered. The dummy model used in the analysis is shown below. The dummy model permits the user to change the dimensions like height, length of the dummy if required to achieve a more realistic contact.

Figure 4.1 Hybrid III dummy model [15]

4.2 Importing the Dummy to LS-DYNA

The dummy model is imported from MADYMO to LS-DYNA by writing coupling cards in the key file of the ford Taurus model enabling it to place it on the driver seat of the car. By doing that we can get to see the responses of the dummy and interactions with the compartment and injury values. All of this is done by using extended coupling.

4.3 Belt Model

For the modeling the seat belt a combination of MADYMO seat belt segments and finite elements are used. Both the lap and shoulder belts are modeled using these segments. The parts of the belts which contact the dummy are modeled with membrane elements. Figure below shows the dummy with seatbelt

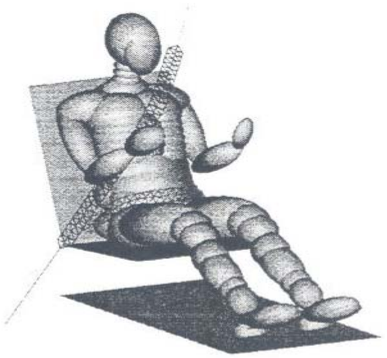


Figure 4.2 Seat belt model

4.3.1Finite element lap and shoulder belts

The finite element lap and shoulder belts are connected by MADYMO segments at their end nodes. The finite element segments are modeled by using membrane elements. Nylon is the material assigned to these belts. The seat belts dimensions are of a typical car seat belt which is approximately 1.6 inches wide and 0.04 inches thick. The contact between the FE belts and the 50th percentile dummy is governed by ellipsoid-node contact interactions. The FE belt section of the shoulder belt is in contact with the right clavicle, the right upper arm, the neck and the collar, the left and right upper torso, the ribs, the sternum and the abdomen. The belt section of the lap belt is in contact with the hips, abdomen, the bottom ribs and the lower torso of the dummy. Friction between ellipsoids and planes and finite element nodes is taken in to account. Figure 4.3 below shows the finite element seat belts.

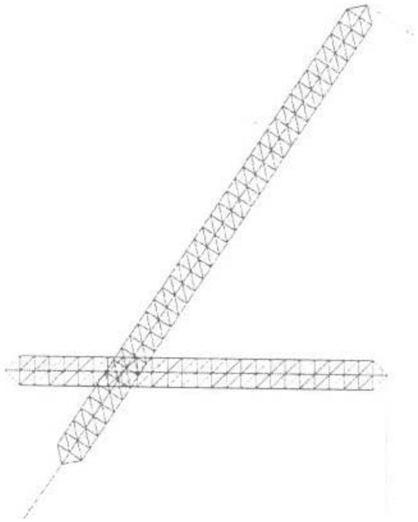


Figure 4.3 Finite element lap and shoulder belt

4.4 Study of the Occupant Kinematics During Impact

The occupant response in full-width and offset crash of both pole and barrier are analyzed. Since the dummy is coupled with ls-dyna so we can view the pulses in ECM and we don’t have to take the pulses and feed it to dummy to obtain the acceleration pulses. In doing so, we can also get the dummy interactions with the car. The full width test is based on NCAP test method and offset crash test is based on IIHSS method. Occupant responses are evaluated by using the injury criteria as given in the MADYMO software. The head injury value can be found in the peak file of the program. The chest and pelvis injuries can also be found in the peak file of the program. The tibia index is a measure of leg/foot injury criterion.

4.5 Occupant Injury Response

The HIC and chest accelerations results for 35 mph frontal crash test for both pole and barrier is compared in the following table. The HIC exceeding 1000 is an unacceptably very high head injury according to FMVSS. As it is clear from the following table that both HIC and chest accelerations values are higher in pole test in comparison to the barrier test, therefore there should be some standards for pole testing too like the barrier test which they have right now.

Table 4.1 Full-Width comparison

Injury Parameter	Limiting Value for FMVSS 208	Full-Width (Barrier)	Full Width (Pole)
HIC	1000	427	598
3MS Max	80 (g)	34 (g)	38 (g)

Similarly in case of the offset test, results show similar pattern.

Table 4.2 Off-set Comparison

Injury Parameter	Limiting Value for FMVSS 208	Off-set (Barrier)	Off-set (Pole)
HIC	1000	460	610
3MS Max	80 (g)	36 (g)	41 (g)

4.5.1 Calculation of HIC

The HIC value is calculated for a 36 ms window. The HIC value for frontal crash for barrier is 427 and for pole is 598, HIC value for off-set crash for the barrier is 460 and for pole are 610.

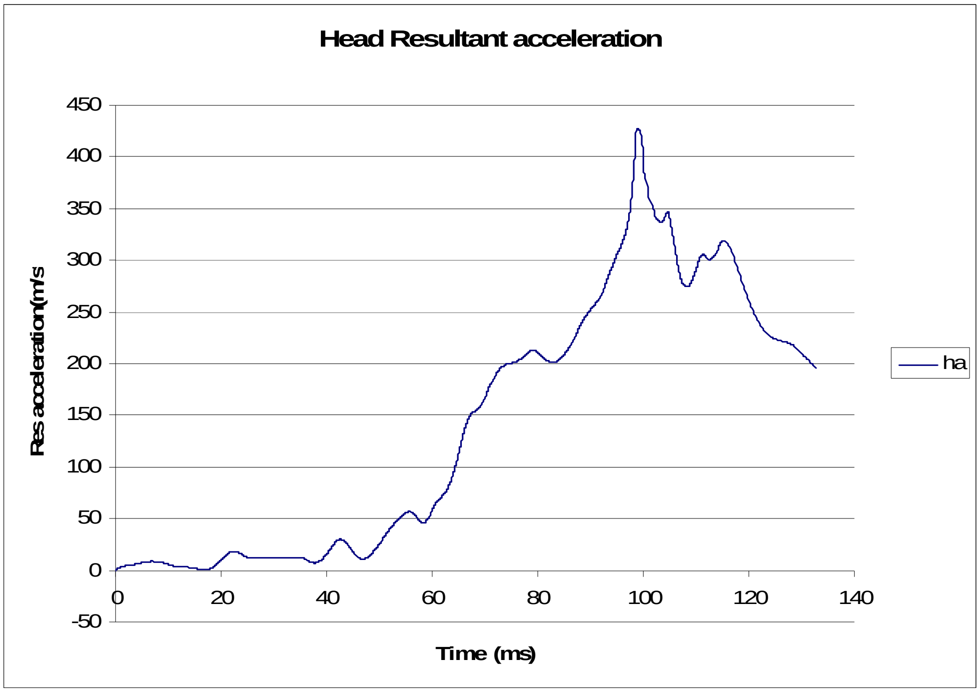


Figure 4.4 HIC window for full-width barrier crash test

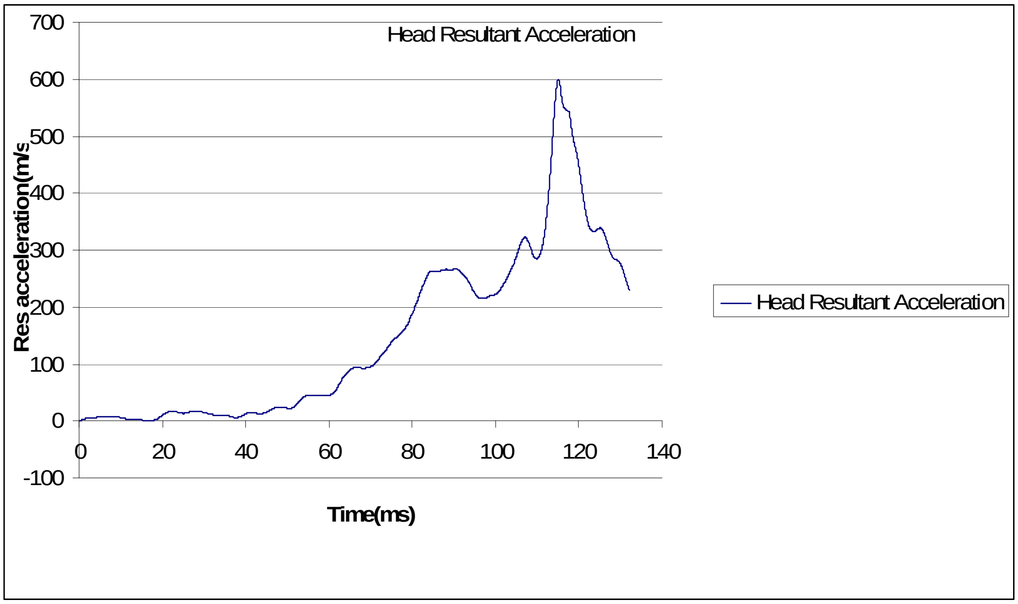


Figure 4.5 HIC window for full-width pole crash test

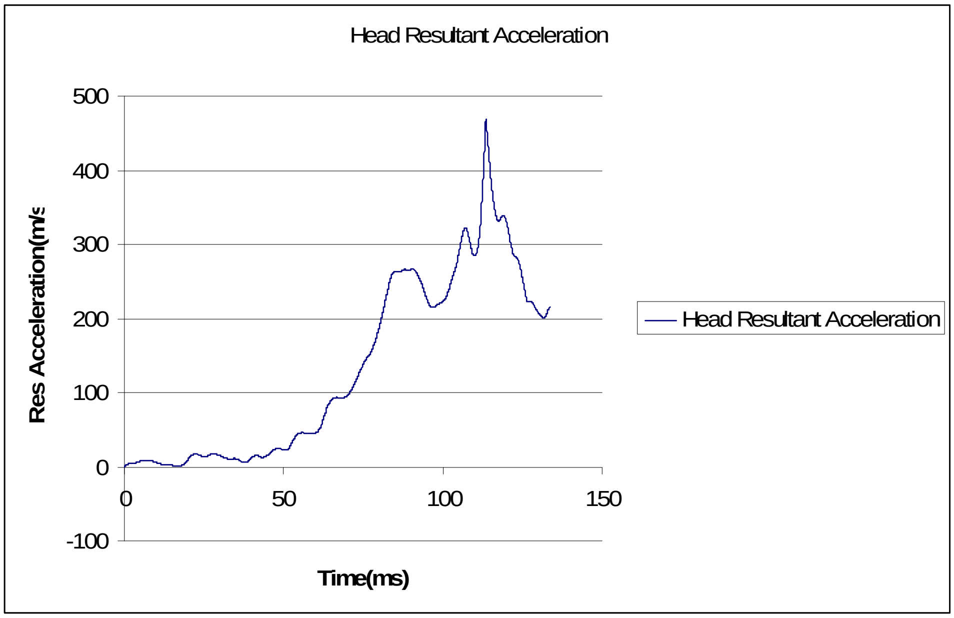


Figure 4.6 HIC window for off-set barrier crash pulse

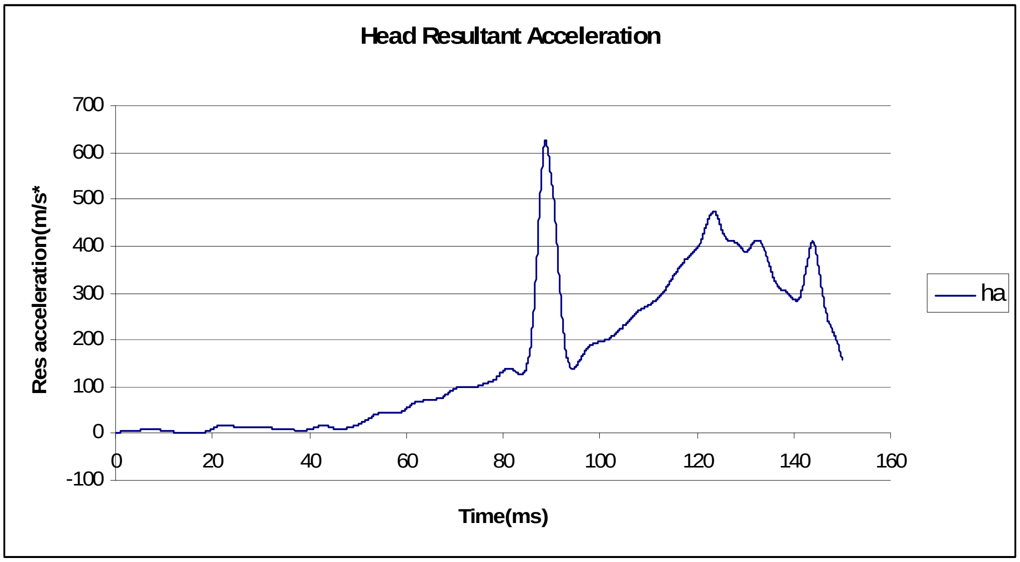


Figure 4.7 HIC window for off-set pole crash pulse

4.5.2Other injury parameters

The values for injury parameters for the full-width crashes are given in the following table

Table 4.3 Full-width occupant injury responses

			Barrier	Pole
Injury Parameter	Element	Limiting value for FMVSS 208	Numerical Value	
V*C	Upper Torso	1.3 (m/s)	0.16 (m/s)	0.563 (m/s)
Left Femur Force	Left Femur	10000 (N)	1156 (N)	2014 (N)
Right Femur Force	Right Femur	10000 (N)	1145 (N)	1890 (N)
3MS Max	Chest	80 (g)	34 (g)	38 (g)

Viscous Criterion (V*C) is defined as the product of sternum deflection, normalized by chest depth and sternum deflection rate.

Table 4.4 Peak values of acceleration and the time at which they occur for a full width 35 mph test

Body	Peak Acceleration (g)							
	X Comp	Time (ms)	Y Comp	Time (ms)	Z comp	Time (ms)	Res.	Time (ms)
Lower Torso	30	130	5	97	16	146	34	92
Upper Torso	38	142	5	36	13	102	35	105
Head	57	8	6	134	29	101	63	92

Table 4.5 Peak values for a full-width pole test

Body	Peak Acceleration (g)							
	X Comp	Time (ms)	Y Comp	Time (ms)	Z comp	Time (ms)	Res.	Time (ms)
Lower Torso	33	120	6	91	16	130	34	94
Upper Torso	37	140	5	34	13	110	36	93
Head	58	9	5	130	34	99	65	90

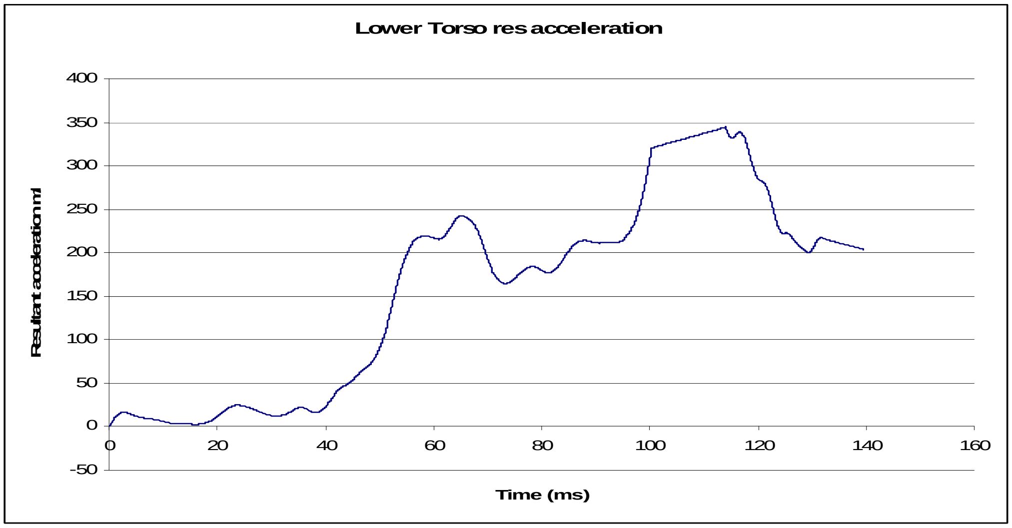


Figure 4.8 Lower torso resultant acceleration for barrier front

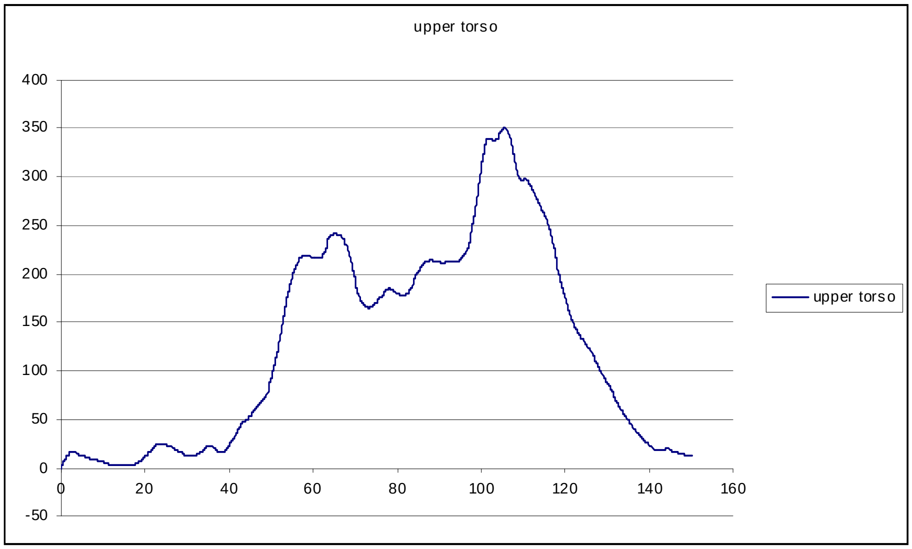


Figure 4.9 Upper torso resultant acceleration for barrier front

The lower and upper torso acceleration profiles are shown in the following figure.

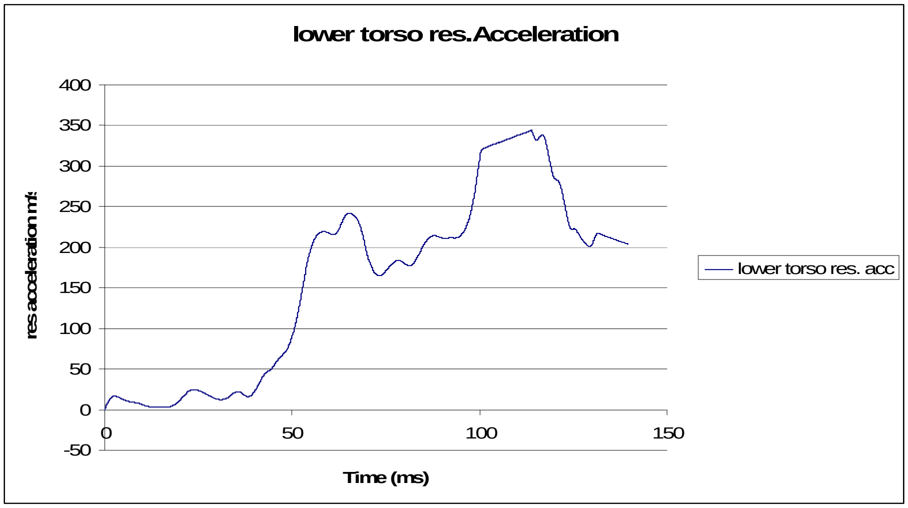


Figure 4.10 Lower Torso resultant acceleration pole front

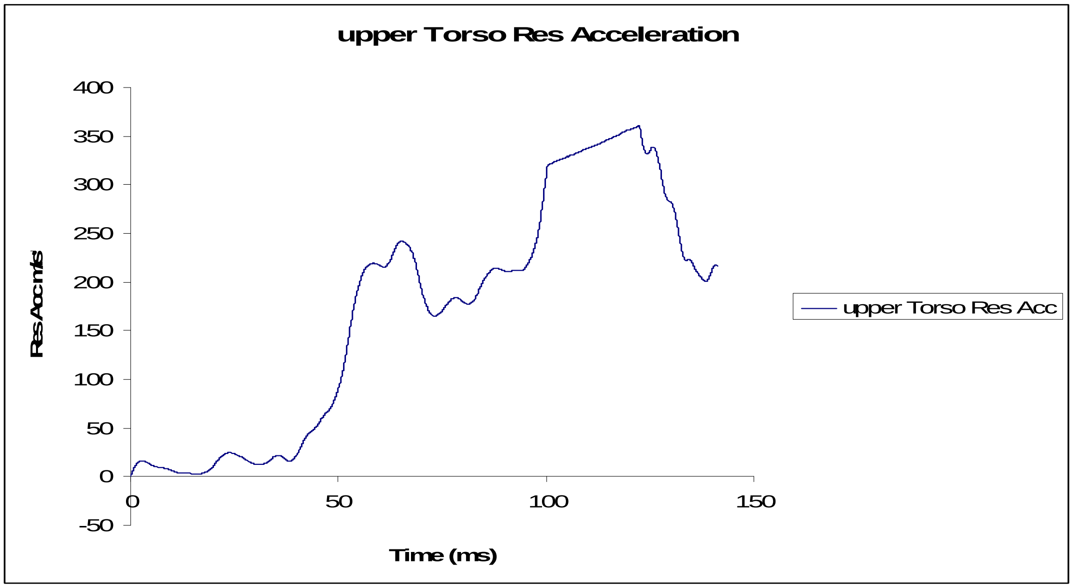


Figure 4.11 Upper torso resultant acceleration pole front

Table 4.6 Peak value of acceleration and the time at which they occur for an offset (barrier) at 40 mph test

Body	Peak Acceleration (g)							
	X Comp	Time (ms)	Y Comp	Time (ms)	Z comp	Time (ms)	Res.	Time (ms)
Lower Torso	28	10	5	142	21	65	33	134
Upper Torso	38	11	4	54	8	147	31	132
Head	50	16	4	175	32	130	58	130

Table 4.7 Peak value of acceleration and the time at which they occur for an offset (pole) at 40 mph test

Body	Peak Acceleration (g)							
	X Comp	Time (ms)	Y Comp	Time (ms)	Z comp	Time (ms)	Res.	Time (ms)
Lower Torso	33	120	6	91	16	130	34	94
Upper Torso	37	140	5	34	13	110	36	93
Head	58	9	5	130	34	99	65	90

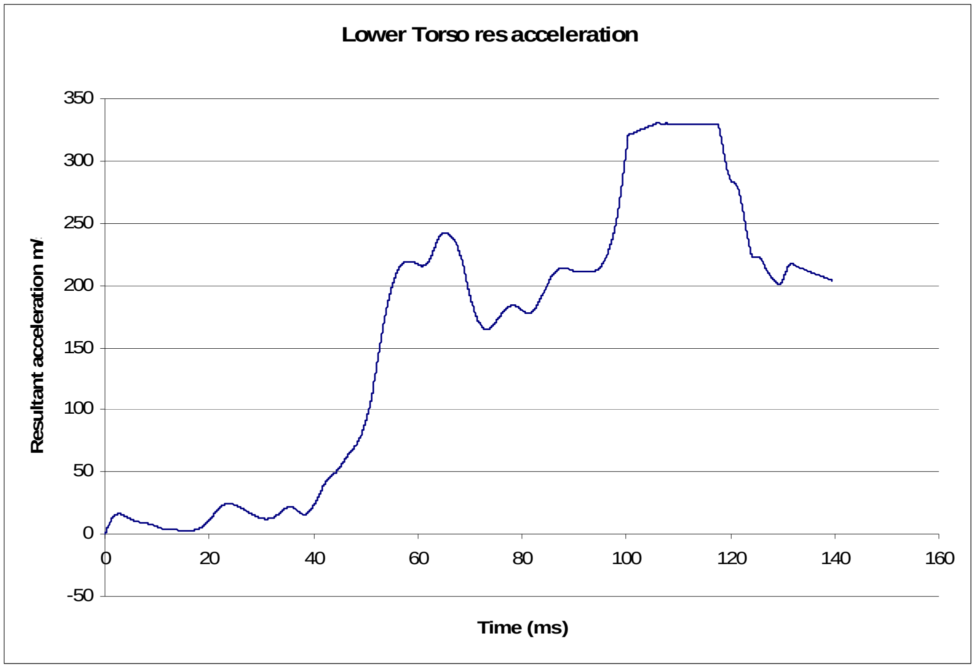


Figure 4.12 lower torso acceleration barrier off-set

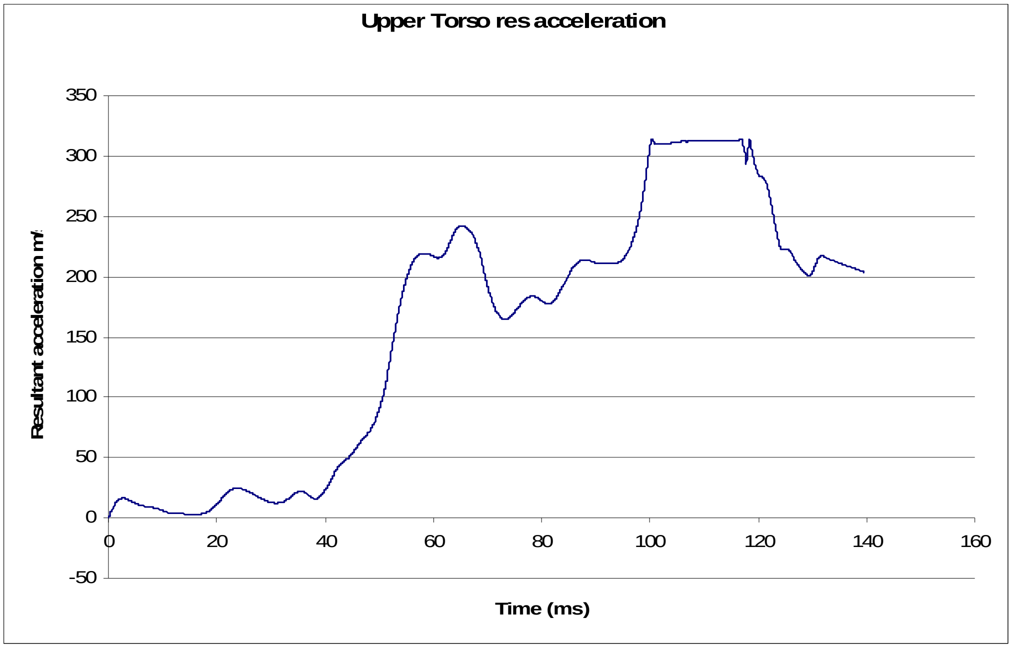


Figure 4.13 Upper torso acceleration for barrier off-set

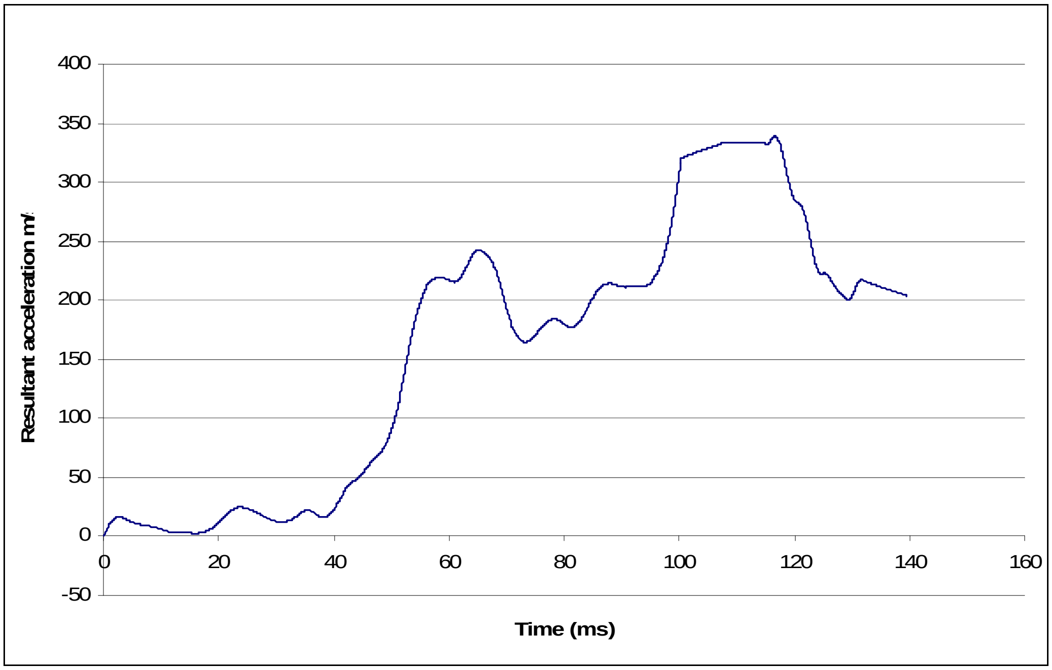


Figure 4.14 Lower torso acceleration for the pole offset crash test

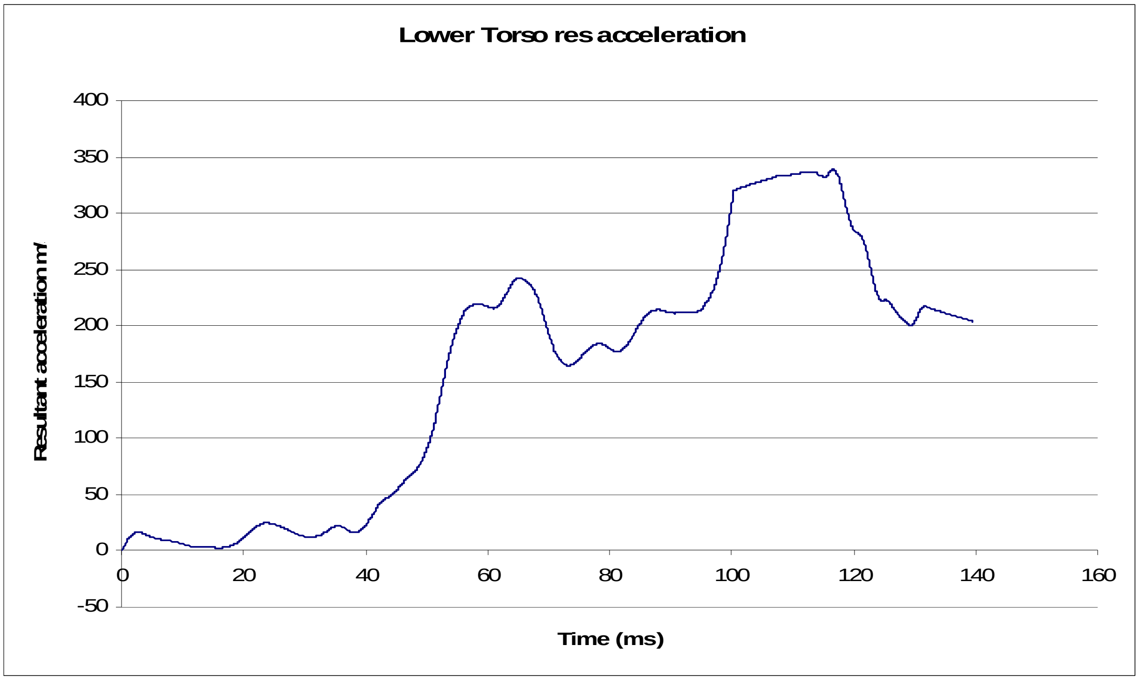


Figure 4.15 Upper torso acceleration for the pole offset crash test

Table 4.8 The values for the offset crash are given in the following table

			Barrier	Pole
Injury Parameter	Element	Limiting value for FMVSS 208	Numerical Value	
V*C	Upper Torso	1.3 (m/s)	0.15 (m/s)	0.59 (m/s)
Left Femur Force	Left Femur	10000 (N)	1467 (N)	2560 (N)
Right Femur Force	Right Femur	10000 (N)	1372 (N)	1685 (N)
3MS Max	Chest	80 (g)	35 (g)	39 (g)

4.5.3 The injury response

The tibia index measures combined bending and compression forces on the lower leg and an index reading of 1 or more represent an unacceptably high risk of tibia fracture. The tibia forces and tibia index values for the full width test are given in the table:

Table 4.9 Tibia forces and Tibia index in a full width frontal crash

Element	Tibia Forces (N)	Tibia index
Lower Right Tibia	1285	0.127
Lower Left Tibia	2390	0.262
Upper Right Tibia	851	0.354
Upper Left Tibia	1870	0.537

Table 4.10 Tibia forces and tibia index values for pole crash test, full-width

Element	Tibia Forces (N)	Tibia index
Lower Right Tibia	1301	0.187
Lower Left Tibia	2395	0.273
Upper Right Tibia	878	0.410
Upper Left Tibia	1898	0.621

Table 4.11 The tibia forces and tibia index values for the offset crash pulse (barrier)

Element	Tibia Force (N)	Tibia index
Lower Right Tibia	2580	0.91
Lower Left Tibia	2703	0.795
Upper Right Tibia	1865	0.342
Upper Left Tibia	2010	0.451

Table 4.12 The tibia forces and tibia index values for the offset crash pulse (pole)

Element	Tibia Force (N)	Tibia index
Lower Right Tibia	2661	1.06
Lower Left Tibia	2719	0.805
Upper Right Tibia	1883	0.35
Upper Left Tibia	2094	0.463

As it can be observed that injury to the lower left and lower right are more in the offset crash test method. Moreover the injury becomes more severe when it comes to pole test when compared to the barrier test. The lower tibias of both the legs have high injury risk in pole test when compared to the barrier test.

CHAPTER FIVE

CONCLUSIONS AND RECOMENDATIONS

5.1 Conclusions

The full-width and off-set crash analysis simulations were performed on the finite element model of a Ford Taurus and the results were compared. In the frontal impact mode, where the vehicle crashes in to a flat rigid barrier at 35 mph using LS-DYNA, the deformation is spread across the parts from one side to the other. Whereas when the vehicle crashes in to a pole, the deformation is more localized. This results in higher intrusion and injury values to the occupant. The pole impact resembles a point impact and hence the deformation of the front structure is larger. As a result to this, the occupant is at higher risk to potential injuries.

The integrity of the occupant compartment can be maintained while crashing the full-width of a vehicle into a rigid barrier that maximizes energy absorption. During a crash, the main cabin of the car should withstand the impact forces and retain the structural integrity. The pillar of the car, dashboard and other main cabin compartment interior parts should not penetrate deeply inside the cabin, by doing so it reduces the occupant injury. The point impact can result in deeper intrusions compared to the barrier impact.

The off-set crash test which was done at 40 mph and 40% off-set using LS-DYNA and the corresponding responses were recorded in MADYMO. The deformation pattern is different from that in the full-width crash test, since the impact area is smaller. Hence, the resulting crash energy needs to be absorbed by the 40% frontal area of the vehicle. The impulse generated as a result of the crash causes the front structure of the car to undergo deformation.

There were two different scenarios for offset testing, one with the barrier and the second one with the pole. The overall deformations for the offset tests are more severe as compared to the front collisions for the aforementioned reasons above. As a result, the injury potential to the occupants are also higher. Off-set crash test results have increased intrusion values of the toe-board in to the occupant compartment, which in turn results in injuries to the lower extremities. The intrusion values of footboard, instrument pillar and left A-pillar are higher in the case of pole crash as compared to the off-set barrier testing.

The integrity of occupant component is maintained in barrier testing because the energy dissipation is distributed over a large area there by maximizing energy absorption, which is not the case for the pole testing. During the study of a typical frontal collision, the goal is to distribute the impact energy as much as possible on the front portion of the car. There is also an effort to absorb as much energy as possible and this will reduce the cabin intrusions dramatically.

The parameters that influence the outcome of a crash are typically the velocity, overlap and angle of impact, stiffness of the front-end structures, occupant restraint system characteristics, and stiffness properties of the interior components such as knee bolsters, seat cushion and steering wheel. With these models, any of these characteristics can be varied to perform a design of experiments study. The simulation results presented in this paper demonstrate the need that there should be some standards for pole testing similar to flat barrier testing of FMVSS 208.. Bringing in some new standards for pole testing will improve the safety standards of the vehicle and it can help making a safer car. Further improvement in the model will improve its fidelity and its ability to more accurately predict the behavior under various impact conditions.

The full-width crash test is especially demanding of the restraint systems but the integrity of the occupant compartment is maintained and the injury to the passenger totally depends on how well the restraint systems behave. In off-set test, as only part of the vehicle’s front structure comes in contact, the intrusion values are higher; therefore, the off-set testing is more demanding of the structure. The FE dummy was imported to the car itself to obtain real time dummy dynamic responses.

5.2 Recommendations

A modification of the vehicle's structure can be made from the baseline simulation in order to reduce the lower extremity injuries. A passenger side impact dummy can also be placed to obtain injury responses in other types of collisions, such as side impact. The movement of the steering wheel can also be taken in to account while performing a MADYMO analysis, which can give more realistic occupant injury responses. Occupant responses for a 95th percentile male adult and a 5th percentile female adult can also be utilized instead of 50th percentile. The Ford Taurus model can also be tested for other modes of impact which includes side and rear. The diameter of the pole can also be changed to check for intrusion and injury values. The material of the pole can also be varied to steel or any other kind of material. Poles of different cross sections beside circular can also be studied with the developed simulation methodology.

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