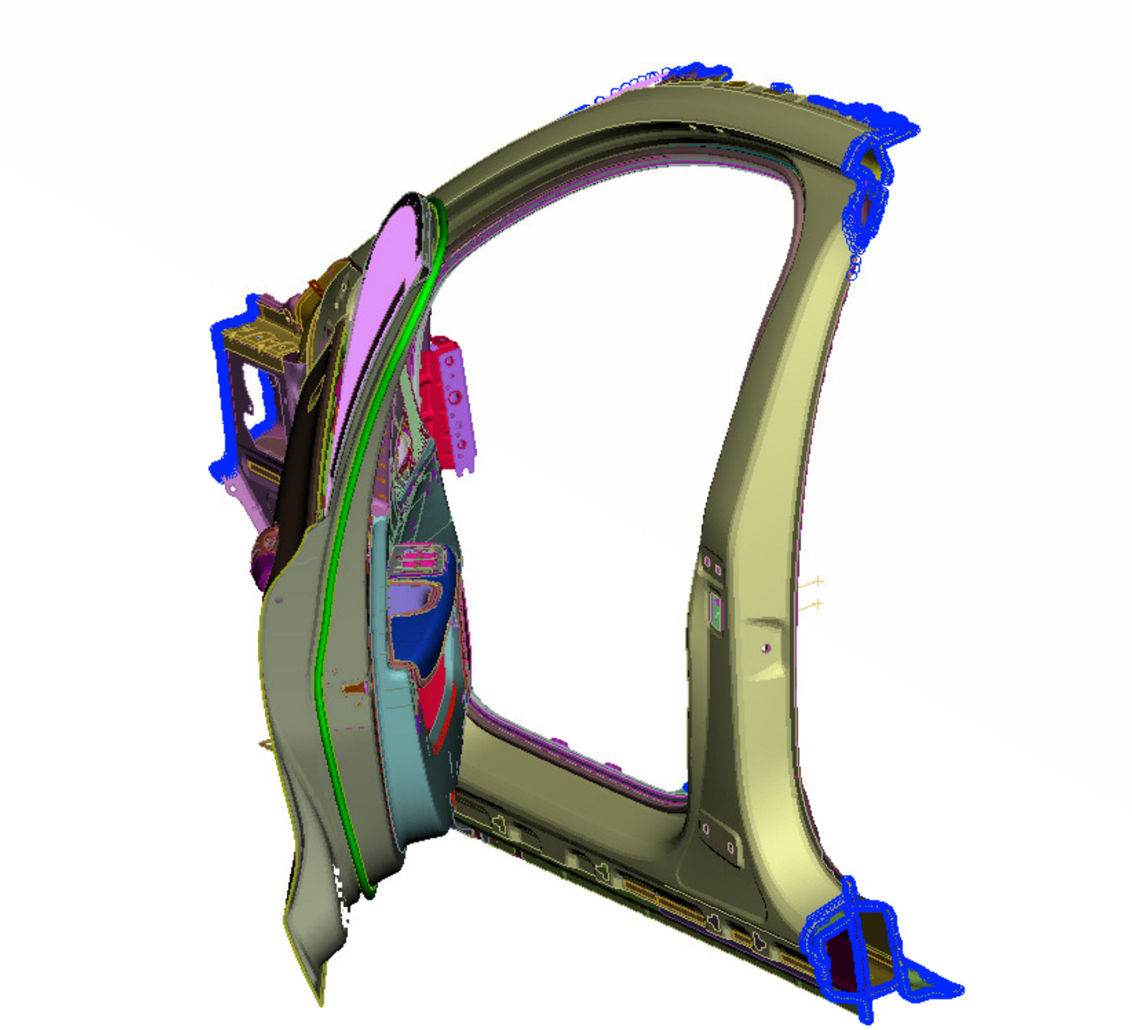
CHALMERS
UNIVERSITY OF TECHNOLOGY



Optimal analysis procedure for dynamic FE simulation of car door close cycle

Master's thesis in Applied Mechanics

Abdullah Tekcan
Viktor Keric

Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Master's thesis 2019

Optimal analysis procedure for dynamic FE simulation of car door close cycle

Abdullah Tekcan & Viktor Keric

Department of Industrial and Materials Science
Chalmers University of Technology
Gothenburg, Sweden 2019

Optimal analysis procedure for dynamic FE simulation of car door close cycle
Abdullah Tekcan & Viktor Keric

Supervisor: Mikael Almquist, Alten Sweden AB
Examiner: Lennart Josefson, Department of Industrial and Materials Science

Master's Thesis 2019
Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Optimal analysis procedure for dynamic FE simulation of car door close cycle
Abdullah Tekcan & Viktor Keric
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

The Durability Department of Volvo Cars (Gothenburg) is interested in modifying its approach to the finite element (FE) analysis of the door sealing system. The sealing system is a complex and important component in a door closing event. Volvo Cars currently uses an implicit FE solver in a model in which nonlinear spring elements describe the relationship between the forces and displacements in the sealing system. Volvo Cars has proposed to switch to using LS-Dyna which has an explicit solver. Explicit solvers are more computationally effective than implicit solvers and it enables Volvo Cars to use the same FE-software for the analysis of different loading situations, and also to be able to use a better geometric and material model for the sealing system. Volvo Cars has expressed that with the use of LS-Dyna, dependency on the physical testing could be reduced.

The development of a working explicit model of a Volvo car door that captures the static and dynamic behaviour of the sealing system during a door closing event is presented. It is developed for LS-Dyna based on existing knowledge from the implicit solution and data received from the implicit model. To model the rubber sealing system in an explicit solver, both the static and dynamic behavior of the sealing system are needed.

The static behaviour for the rubber sealing is estimated using a hyper-elastic material with Yeoh material model. Three material constants in the Yeoh material model (C_{10}, C_{20} and C_{30}) that affect the stiffness of the sealing system are determined using a quasi-static simulation of a section of the sealing with a prescribed motion of the door closing event. The constants are selected using a curve fit analysis.

To capture the dynamic behaviour of the sealing system an existing LS-Dyna airbag model is used. The airbag model made it was possible to estimate the evacuation of the airflow out from the sealing system during the closing event. The unknown parameter that had to be established in the airbag model was the shape factor. The shape factors will be determined by comparing the measured acceleration signals provided by Volvo Cars to the simulated acceleration signals. By comparing the acceleration signals it is possible to determine which values of the shape factors gives the best signal correlation.

Finally, it is concluded that the evacuation of air from the sealing system during a door closing event can be estimated by the working explicit model of a Volvo car door. It is recommended that additional studies be carried to determine the applicability of the model to a variety of doors and sealing geometries.

Acknowledgements

This is a Master's Thesis at the Department of Industrial and Materials Science at Chalmers University of Technology written by Abdullah Tekcan and Viktor Keric.

It was carried out during the first half of the year 2019 at Alten Sweden AB in cooperation with Volvo Cars. During the thesis we were faced with both exciting and challenging problems, which contributed to the work become more interesting to us.

We would like to thank Alten Sweden AB and Volvo Cars for given the opportunity to do the Master's thesis, for the trust and the support we received during the work. We would also thank the staff of the Alten Sweden AB and Volvo Cars who contributed with much help during the work and shared their knowledge and time during the project and directed us in the right direction with their experience in the field.

Finally, we would like to thank our supervisor and examiner from Chalmers University of Technology professor Lennart Josefson, for his support and expert advising along the way.

The simulation work performed during this project was completed utilizing the Volvo Cars resources. We hope that this thesis can help Volvo Cars in their future work.

Abdullah Tekcan & Viktor Keric, Gothenburg, 2019

Contents

List of Figures

List of Tables

1
Introduction

This chapter aims to present the background and how this master's thesis came about. It will also present the objectives taken in this thesis.

1.1 Background

Computer Aided Engineering (CAE) is widely used in many industries today, especially in the automotive industry where quality has long been a major focus area. The CAE software in calculation-driven product development provides a comprehensive set of tools that helps reducing costs and time to be reduced significantly. Continuous development of the analysis procedures is important to keep up with the competition and customer expectations [1].

Volvo Cars is a common user of different softwares in calculation-driven product development to ensure that the quality and safety of their cars fulfills their Big Hairy Audacious Goal (BHAG) "Vision 2020" from year 2008, where they stated the goal: zero fatalities or serious injuries in traffic accidents in a new Volvo car by 2020 [2].

To ensure that the doors of a Volvo car have high quality, durability and safety Volvo Cars performs different required calculations to evaluate the strength and durability of the door. The analysis carried out are; door intrusion resistance, the dynamic behavior of a closing door (hard closing, weak closing and cyclic closing) and strength calculations. To perform these calculations Volvo Cars uses three different softwar: MSC Nastran for door closing, LS-Dyna for door intrusion resistance and Abaqus FEA for strength calculations.

The Finite Element (FE) software MSC Nastran with transient implicit analysis is used by Volvo Cars to simulate the event of closing a car door. The complex parts of the model such as the sealings and the latch are modeled as nonlinear spring elements. The properties for these spring elements are provided by the sealing supplier and from physical prototype testing. In order to change to a non-testing dependent method, the durability department at Volvo Cars would instead like to use the FE software LS-Dyna with transient explicit analysis to analyse the door closing. By using the FE software LS-Dyna it will be possible to model the sealings and latch with a realistic geometry and material behavior, thus it is possible to simulate the door with a high or low force and velocity. The purpose of this simulation in LS-Dyna will be to predict the stress distribution, displacements and contact forces at certain points of interest on the door. By being able to predict the behaviour, the development phase will be shortened. This change in FE software will also contribute to Volvo Cars using two different software (Abaqus FEA and LS-Dyna) instead of three to evaluate the strength and durability calculation on their doors. A previous report also indicates that switching from a transient implicit analysis to a transient explicit analysis for similar simulation of a hood results in a decrease of computational time [3].

1.2 Purpose

The purpose of this thesis is to develop and evaluate the possibility to simulate closing car door by using the FE software LS-Dyna with a transient explicit analysis.

1.3 Limitation

- The car door will be modeled with all material components included; plastic, glass and sheet, but the friction of hinges and the check strap of the door will not be modeled as their effect on the response can be considered negligible. This is due to the fact that the physical closing time for the door is so small.

1.4 Research questions

- Is it possible to model the complex parts in LS-Dyna with a realistic geometry and a material behavior?
- Will the output data from LS-Dyna correlate with the corresponding data from the MSC Nastran solver and acceleration signals?
- Will this method in LS-Dyna work for all doors of Volvo car models?

2
Theory

This chapter of the thesis includes a description of theory relevant for this thesis project. Understanding the theory is of high importance because it will be useful later to identify the complex parts that will be designed and simulated.

2.1 Literature study

There are no previous studies or projects for dynamic FE simulations of closing a car door in LS-Dyna published. Previous studies have been done of the event of a hood slamming in LS-Dyna. A literature study was carried out to identify important observation that will be relevant to this thesis work.

A master's thesis carried out by two students from Chalmers University of Technology at Volvo Cars studied an explicit FE modeling of hood closing in LS-Dyna [3]. The assignment was to set up a model of a car front in LS-Dyna to analyze the displacements of the hood and its contacts to the surrounding components during hood closing. The results obtained from the new LS-Dyna model were compared with the results from both the current MSC Nastran model used at Volvo Cars and to test data from Volvo Cars. Finally the LS-Dyna model was implemented in a Volvo S90 model in order to validate that the method will work on other Volvo Cars models. According to the study they successfully generated a methodology good enough to apply for different car models. Although the methodology was deemed reliable, some concerns for future work were voted. One concern was with the hood sealing and a suggestion was made to further investigate the model with a foam/soft rubbers. More investigations were suggested to find more sophisticated airbag models and also to investigate a model with closed sealing cavity.

At Ford Motor Co a nonlinear damping model for sealing compression load deflection behaviour in one- and two- dimensional versions from first physical principles [3]. This model incorporates the effects of sealing damping response due to air flow through the ventilation holes, were air flow produces a damping force in addition to the force that occurs due to nonlinear elastic compression load deflection behaviour of the sealing. The damping force is directly affected by the rate at which the sealing is being compressed between the closing door and the car body, but also the door closing effort depends on the spacing and the size of the ventilation holes.

2.2 Car door components

A car door consist of eleven main sub-assemblies, door frame, hinges, power system, mirror and speaker system, inner panel, window system, door mechanism and sealing system.

The door frame consists of the inner and outer panel. There is also an anti-intrusion beam for side crash protection, see figure 2.1.

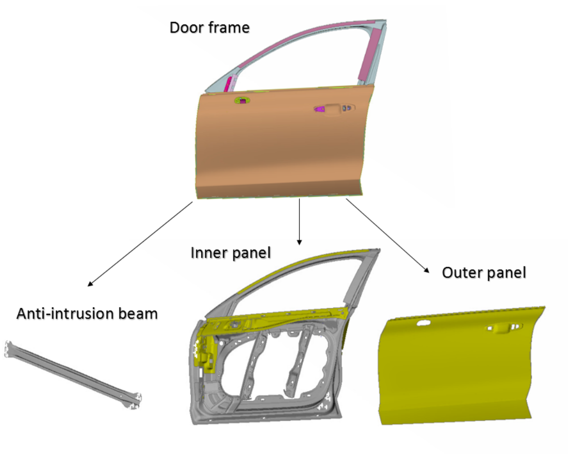


Figure 2.1: Door frame- exploded view

The check strap and the hinges make the door movable and are situated on the part of the door connected to the car body. The power system is made up of the wiring harness and is also included in mirror and speaker system. The Mirror system consists of the mirror glass, the frame, attaching plate, and all the insulation, whereas the speaker system includes the speaker, and the connection wiring to the car. Figure 2.2 shows the inner panel that includes the handle, the armrest and the speaker grid etc.

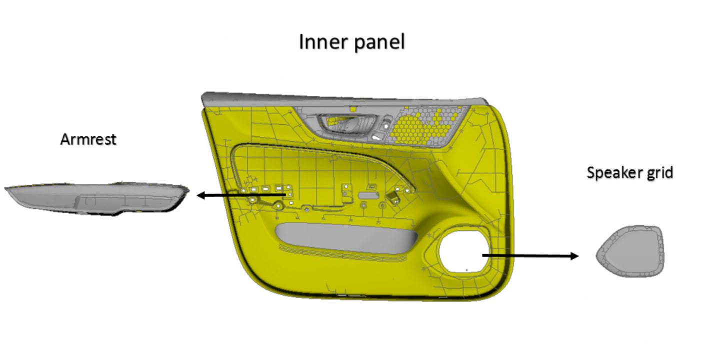


Figure 2.2: Inner panel- exploded view

The window system includes the window motor, the regulator and the glass. Last, the door mechanism consists of the door lock and latching mechanism. The sealing system is divided between the sealings attached on the car body, respectively on the door, and includes all weather strips and moldings that provide insulation from sound and weather. In the following subchapters the components that concern this thesis are further described.

2.2.1 Sealing system

The sealing system covers all the moldings that provide insulation from sound and external impact to weather strips. A complete sealing system is mainly divided in to two parts: the sealing that is attached to the door and the sealing that is attached to the car body. These parts are divided in various sections since the static and dynamic behaviour are different at different sections. The different behaviour in the sections occur because the door hits the sealings with various angles.

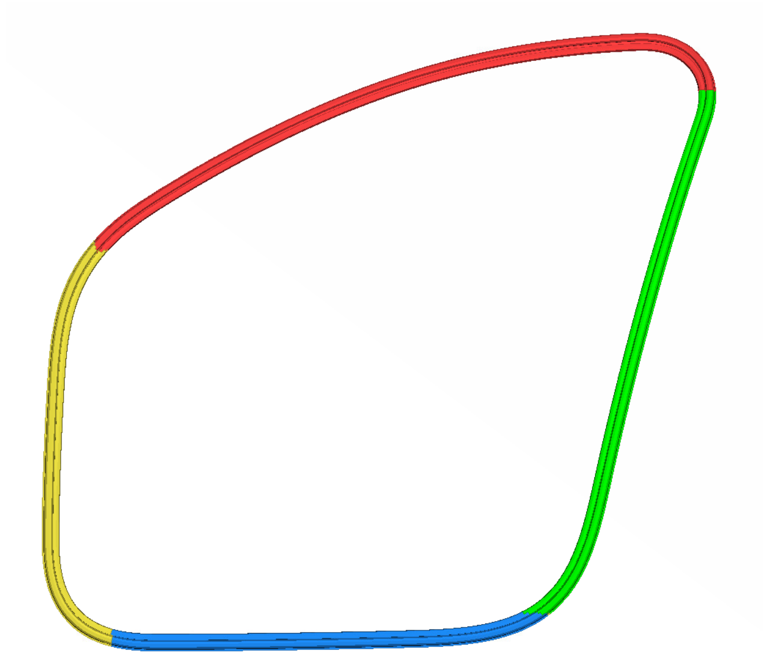


Figure 2.3: Sealing divided in different sections

The types of sealings that are used in these areas are hollow with vent holes, see figure 2.4 and 2.5. Just before the door is closed the sealing system is filled with air, when the sealing system is being compressed the air inside the sealing system starts to flow out from the vent holes, together with the door being closed. The sealings attached to the door and to the car act as dampers during door closings. The material used in these sealing system are a type of synthetic rubber called EPDM (ethylene propylene diene monomer rubber). EPDM has a wide range of properties depending on the manufacturing process. EPDM is assumed to be hyperelastic and isotropic incompressible.

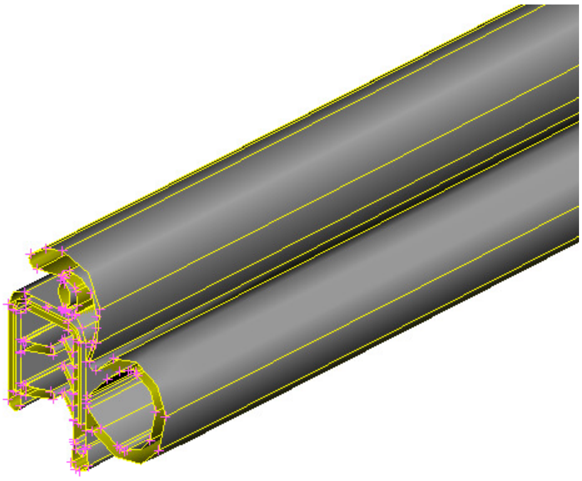


Figure 2.4: Cross section geometry of body mounted sealing

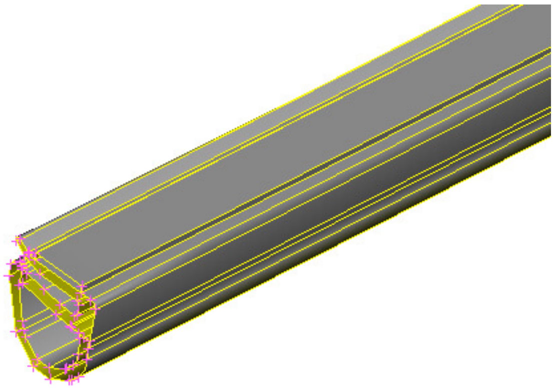


Figure 2.5: Cross section geometry of door mounted sealing

2.2.2 Door latching mechanism

To ensure that a car is secured and to prevent unauthorized entry to the vehicle each door of a car is equipped with a latch which makes it possible to lock the door to the body in the closed position. Locking the door is not the only task that the latch system has, it is also suppose to perform to a specific level during a car accident so the possibility of occupants to eject during a crash will be minimum. It is required to have a minimum strength of door in a longitudinal, respectively in lateral direction, (parallel, respectively perpendicular to the car direction of travel) to enforce that the occupants do not eject. To lock the door there is a door striker placed on the car body where the latch locks by hooking to that [5].

2.3 Current analysis method

The current available analysis method at the durability department of Volvo Cars is to analyse the door closing with transient implicit solution in Nastran. The complex parts of the model, such as the sealing system and the latch, are modeled as nonlinear spring elements, see figure 2.6, which makes it hard to make changes in the sealing geometry and the latch mechanism. Further, since contacts are the Nastran model is in general not modeled the actual contact forces are disregarded.

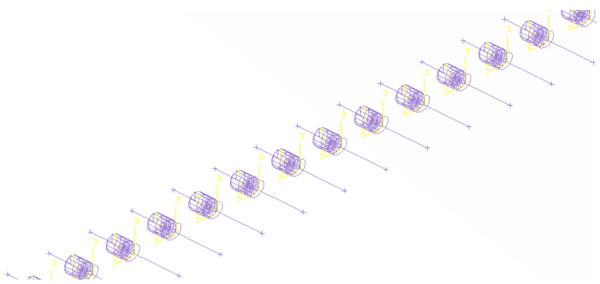


Figure 2.6: Nonlinear spring elements

2.3.1 Physical test data

In order to model the nonlinear spring elements, physical tests must be performed. The physical tests are experimented tests performed on the sealing system. The physical tests data represent both the static and the dynamic behaviour. The sealing supplier sets up experimented tests for different section of the sealing system.

As mentioned in section 2.2.1 the sealing that is attached to the door, respectively to the car body is divided in different sections. Since the static and dynamic behaviour are different at different sections. This is due to the different impact angle of the door on the sealing. The material model of the sealing used in Nastran is correlated with the physical tests data obtained from the provider.

2.3.2 Current static and dynamic behaviour

The static and the dynamic behaviour of the sealing system are taken from physical tests and are set up with nonlinear spring elements in Nastran. The static data is set up with a force vs a displacement relation. The force is in Newton and is calculate for every ten millimetres because in the Nastran model the nonlinear spring elements are ten millimetres apart, as seen in figure 2.6. Figure 2.7 shows a typical static force-displacement curve representing a section of the sealing.

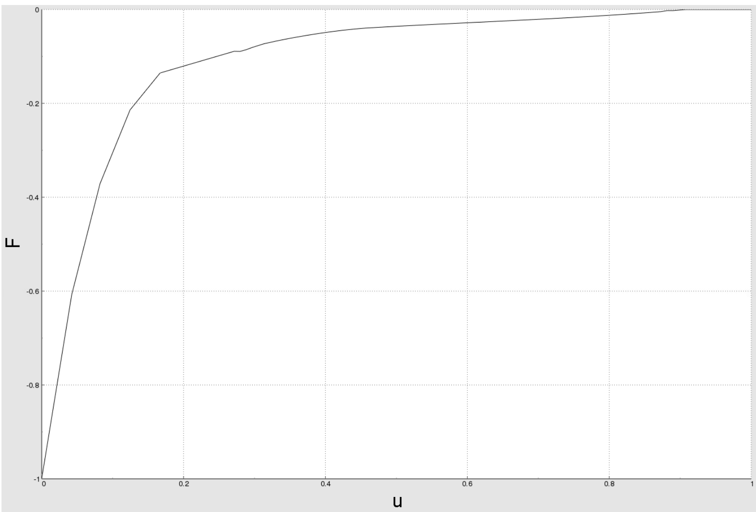


Figure 2.7: Normalized static data for a non-linear spring element in the Nastran model

To capture the dynamic behaviour for the sealing system, Volvo Cars proceeds from the static data and captures the dynamic behaviour with equation (2.1).

$$F_d = C_d|u|^{E_u}|v|^{E_v} \tag{2.1}$$

Where C_d is a scale factor, E_u is the compression exponent and E_v is the velocity exponent. The values for these constants are provided from the sealing supplier. With a given velocity it is possible to calculate the dynamic force over the displacement for each data point. The data from both the static and the dynamic forces are used as properties for the nonlinear spring elements.

2.4 Analysis method

Transient problems are in structure dynamics solved by using time step schemes. There are two different schemes to use, either implicit or explicit. These solving method are described in details below.

2.4.1 Implicit analysis

For implicit analysis it is possible to estimate the discretization in time by studying the equations of motion at time t_{n+1}.

$$\boldsymbol{M\ddot{U}} + \boldsymbol{C\dot{U}} + \boldsymbol{KU} = \boldsymbol{F} \tag{2.2}$$

Each term represents different states of a particle. The first term ($\boldsymbol{M\ddot{U}}$) describes the inertial forces based on the acceleration, second term ($\boldsymbol{C\dot{U}}$) describes the internal damping based on velocity, third term ($\boldsymbol{KU}$) describes the internal stiffness based on the displacement and fourth, $\boldsymbol{F}$, the external force.

In order to solve the discretization in time, an integration is done using a step-by-step method. In implicit schemes, the discretized fields $\boldsymbol{U_{t+\Delta t}}$ are expressed in the fields at present times and earlier

$$\boldsymbol{U_{t+\Delta t} = f(\dot{U}_{t+\Delta t}, \ddot{U}_{t+\Delta t} U_t, ...)} \tag{2.3}$$

2.4.2 Explicit analysis

How the system moves over time require a discretization in both space and time [6]. Discretization is used to convert a continuous equation into a form that can be used to calculate numerical solutions. By studying the equations of motion at time t_{n+1} it is possible to estimate the discretization in time.

$$\boldsymbol{M\ddot{U}} + \boldsymbol{C\dot{U}} + \boldsymbol{KU} = \boldsymbol{F} \tag{2.4}$$

Each term represents different states of a particle and describes inertial forces based on the acceleration, internal damping based on velocity and internal stiffness based on displacement.

In order to solve the discretization in time, an integration is done using a step-by-step method. In this thesis an explicit solution will be performed. In explicit schemes the equation of motion is evaluated at the previous time U_t and $U_{t-\Delta t}$.

$$U_{t+\Delta t} = f(U_t, \dot{U}_t \ddot{U}_t, U_{t-\Delta t}, ...) \tag{2.5}$$

The time integration is approximated by the time step limit, in LS-Dyna the Central Dierence Method is used. To ensure that the simulation is conditionally stable, a critical time step Δt is designed as a stability limit. The time step is bounded by the largest natural frequency of the structure for each element. To estimate the critical time step equation 2.6 is used.

$$\Delta t_{critical} = 0.9 \frac{l_e}{c_e} \tag{2.6}$$

Where l_e is the smallest element length and c_e is the adiabatic sound of speed. In shell meshes the adiabatic sound speed can be expressed with Young's modulus (E), the specific mass density (ρ) and Poisson's ratio (ν)

$$c_e = \sqrt{\frac{E}{\rho(1-\nu^2)}} \tag{2.7}$$

2.5 Element formulation and shell element quality criteria

FE models are constructed with nodes and elements. Shell elements are assigned formulation to describe which shell theory is used. In LS-Dyna some element formulations are more accurate and more computationally costly than others. The characteristics of the elements are important since strains and stresses are calculated at the integration points in the element, while displacements, velocities and accelerations are evaluated at the nodes. Depending on what is important, LS-Dyna offers element formulations that are either under or fully integrated, see figure 2.8 [6].

Figure 2.8: Under respectively fully integrated shell element

For the sealing system only fully integrated elements is implemented. Fully integrated elements have four in-plane integration points and therefore are not subjected to hourglass modes. For fully integrated elements hourglass control is used to give the correct solution for warping [6].

Meshing is an important part of a FE model since it can influence the result's accuracy, but also dramatically influences the simulation time. In this sense element quality criteria is of high importance. The mesh criteria used is shown in table 2.1

Aspect ratio	Skewness	Warpage	Taper	Min length	Max length
3	30	7	0.5	3 mm	6 mm

Table 2.1: Table of the mesh critera

This mesh criteria is used by Volvo Cars for fully integrated shell elements and it is also used in the present work.

2.6 Rubber elasticity

The sealing system used for rubber material models are based on phenomenological theories, because the theories aim to construct mathematical framework to describe rubbery behavior without reference to the microscopic structure. The phenomenological theory used in this thesis is Yeoh model because the assumption was that the rubber was hyperelastic and isotropic incompressible [7].

2.6.1 Elasticity

The Yeoh model is derived from the strain energy function. The strain energy function relates the state of strain to the strain energy density.

$$W(\boldsymbol{B}) = W(\lambda_1, \lambda_2, \lambda_3, \boldsymbol{n_1}, \boldsymbol{n_2}, \boldsymbol{n_3}) \tag{2.8}$$

Where $\boldsymbol{B}$ is the left Cauchy-Green deformation tensors, $\boldsymbol{n_i}$ is material direction dependency and λ_i are the principle stretches. These principle stretches can be expressed in invariants I_i

$$I_1 = tr(\boldsymbol{B}) = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{2.9a}$$

$$I_2 = \frac{1}{2}(tr(\boldsymbol{B}^2) - tr(\boldsymbol{B}^2)) = \lambda_1^2\lambda_2^2 + \lambda_1^2\lambda_3^2 + \lambda_2^2\lambda_3^2 \tag{2.9b}$$

$$I_3 = det(\boldsymbol{B}) = \lambda_1^2\lambda_2^2\lambda_3^2 \tag{2.9c}$$

These invariants will be used in Yeoh model [7].

2.6.2 Yeoh model

The Yeoh model describes the behaviour of a hyperelastic, isotropic incompressible rubber material. The Yeoh model is assumed to be isotropic and thereby the directional dependency is excluded from the strain energy function (2.8) [7]

$$W(\boldsymbol{B}) = W(\lambda_1, \lambda_2, \lambda_3) \tag{2.10}$$

The strain energy function can be expressed in a polynomial form [8] [3]

$$W(\boldsymbol{B}) = W(I_1, I_2, I_3) = \sum_{i,j,k=0}^{\infty} C_{ijk}(I_1 - 3)^i + (I_2 - 3)^j(I_3 - 3)^k \tag{2.11}$$

As described before the material is assumed to be incompressible which makes the third invariant equal to $1(I_3 = 1)$.

$$W(I_1, I_2) = \sum_{i,j=0}^{\infty} C_{ij}(I_1 - 3)^i(I_2 - 3)^j \tag{2.12}$$

C_{ij} are material constants used in the model in order to fit the material data. Significant with the Yeoh model is that the dependency of the second invariant is far less than the first invariant thus the second invariant can be neglected ($j = 0$) while the first invariant is selected to three parameters ($i = 3$) that decides the material behaviour [8] [3]. With the equations 2.9a and 2.12 the Yeoh model can be written as

$$W = C_{10}(\frac{2}{\lambda} + \lambda^2 - 3) + C_{20}(\frac{2}{\lambda} + \lambda^2 - 3)^2 + C_{30}(\frac{2}{\lambda} + \lambda^2 - 3)^3 \tag{2.13}$$

2.7 Airbag

In an airbag the control volume and pressure are depended on each other, LS-Dyna relates these quantities from an equation of state. The equation of state is derived from the Gamma Law Gas where the pressure relates to the mediums density and the specific internal energy of the medium.

$$p = (k-1)\rho e \tag{2.14}$$

where p is the pressure, ρ is the density, e is the specific internal energy and k is defined as

$$k = \frac{c_p}{c_v} \tag{2.15}$$

where c_p and c_v are the heat capacity for the pressure respective volume.

To control the sealing cavity(vent holes and leakage) in airbags, LS-Dyna implemented the model from Wang and Nefske [9]. Wang and Nefske define the mass flow rate out of the bag by

$$\dot{m}_{out} = \dot{m}_{23} + \dot{m}'_{23} \tag{2.16}$$

where $\dot{m}_{23}$ is the vents and define by

$$\dot{m}_{23} = C_{23}A_{23}\frac{p_2}{R\sqrt{T_2}}Q^{\frac{1}{k}}\sqrt{2g_c\left(\frac{kR}{k-1}\right)\left(1-Q^{\frac{k-1}{k}}\right)} \tag{2.17}$$

and where $\dot{m}'_{23}$ is leakage and define by

$$\dot{m}'_{23} = C'_{23}A'_{23}\frac{p_2}{R\sqrt{T_2}}Q^{\frac{1}{k}}\sqrt{2g_c\left(\frac{kR}{k-1}\right)\left(1-Q^{\frac{k-1}{k}}\right)} \tag{2.18}$$

where C_{23}, A_{23}, C'_{23}, A'_{23} and g_c are the vent orifice coefficient, vent orifice area, the orifice coefficient for leakage, the area for leakage, and the gravitational conversion constant, respectively.

Shape factor is the bag characterization parameter and is defined by

$$\mu = \sqrt{g_c}(C_{23}A_{23} + C'_{23}A'_{23}) \tag{2.19}$$

because by assuming uniform temperature and pressure the perfect gas law can be applied

$$p_2V = m_2RT_2 \tag{2.20}$$

and with equations 2.16-2.20 it is possible to write the mass flow rate out like

$$\dot{m}_{out} = \mu\sqrt{2p_2\rho}\sqrt{\frac{k\left(Q^{\frac{1}{k}} - Q^{\frac{k+1}{k}}\right)}{k-1}} \tag{2.21}$$

2.8 Software

LS-Dyna is developed by *Livermore Software Technology Corporation (LSTC)* in 1976 by Dr.John O. Hallquist and is an advanced general-purpose finite element program. LS-Dyna has the capability to simulate real world mechanical problems and is widely used in different areas such as automotive, aerospace and construction. The program has its origins in highly nonlinear, transient dynamic finite element analysis using explicit time integration [10]. LS-Dyna uses different "cards" to define behaviours of a model, theses cards are required to do modal analysis in LS-Dyna. Cards for nodes, elements, material, boundary conditions, initial conditions and load conditions together make up the input file for LS-Dyna. In this thesis LS-Dyna is used to develop a simulation method for closing a car door by using a transient explicit analysis.

ANSA is an advanced CAE pre-processing software developed by *BETA CAE Systems* for full-model build up from CAD data to ready-to-run solver input files. CATIA V5, NX Pro/ENGINEER, SolidWorks, Inventor, JT and other file formats can be converted into ANSA files simply by using the available translators. The geometry input data can be cleaned up and then meshed by using ANSA to make the CAD data into ready-to-run solver input file. Batch meshing tool, completely integrated into ANSA, is a powerful tool for multilateral and controllable meshing with shell or volume elements and is also a very useful tool to generate perfect mesh easily and fast [11].

Nastran (NASA Structural Analysis) was developed by MacNeal-Schwendler Corporation (MSC) in 1965 for NASA is a finite element analysis (FEA) program. The software is multidisciplinary and it is used by engineers to perform static, dynamic and thermal analysis [12].

modeFRONTIER is a multidisciplinary design optimization (MDO) software and has its origin in the European research project on ”Design Optimization” called Frontier. This software allows the user to choose the optimization strategy based on the design space boundaries and hence aims to assist the design of coupled engineering systems through the use of numerical methods [13] [14].

3
Methods

This chapter includes a description of the methodology used in this thesis. Here the detailed explanation will be presented, with all the necessary steps, details and all assumptions needed to set up the LS-Dyna input file. It includes simplifing the model, setting up the geometry and mesh for the sealing system, attaching the sealing system to the doors, respectively the body. Determining the suitable material for the sealing system depending on the static and the dynamic behaviour.

3.1 Simplified body model

In order to avoid long computational time, the whole car body was not used during this thesis. Instead the body was cut into a smaller piece, where all the nodes that were joined with the whole body were constrained in all degrees of freedom, as seen in figure 3.1.

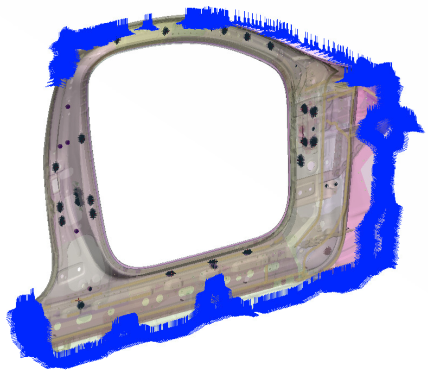


Figure 3.1: Simplified body model with the blue illustrating the free ends that are constrained in all degrees of freedom.

3.2 Open door and velocity

To decrease simulation time the door needs to be open just enough to make the sealing system undeformed. In order to close the door at the right speed, equation 3.1 was used.

$$\omega = \frac{v}{r} \tag{3.1}$$

where ω represent the angular velocity while v and r represent the initial velocity respectively the length of the car door.

3.3 Geometry clean up

The difference between the Nastran approach and the LS Dyna approach is in modelling the sealing. The sealing will go from being 2D nonlinear spring elements to 3D shell elements that will be obtained from the actual geometry of the sealing. It will make it possible to capture the behaviour of change in the seal geometry without extensive physical tests to derive the relation between forces and displacements.

The sealing system was developed in CAD tool and had to be converted into a calculation model, a finite elements model. By using the pre-processor ANSA (v19.0.0) it was possible to create FE models suitable for the LS-Dyna explicit solver. Modification in form of a geometry cleanup had to be implemented, while the geometry cleanup was performed some small sections of the sealing system were considered negligible as it was assumed to have no impact on the analysis. During the geometric cleanup, small parts and narrow angels were treated to avoid small elements. It was handled by carefully deciding whether if to remove or to compensate on the geometry will affect the analysis. Small mesh sizes affects the computational time and the stability of the analysis.

3.3.1 Body seal

Figure 3.2 shows the cross section of the CAD model for the seal mounted on the body. As visualised in the figure the sealing is made of seven parts. Three hollow rubber parts called sponges (grey, green and yellow), three solid rubbers called EPDM (red, light blue and purple parts) and a steel carrier (blue part).

The CAD model has a very detailed design and the geometry had to be to clean up to make the CAD data ready-to-run.

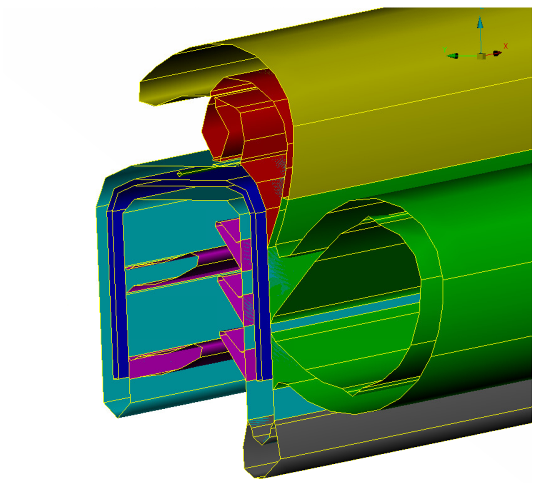


Figure 3.2: Cross section of the car mounted seal

Before meshing the model a mid surface operation was performed, this was done in order to create shell surfaces and not detailed volume cubes since it would make the the model more complex and thus increase the simulation time. Mid surface means that the thickness of the elements is assigned as half in one direction and half in other direction, see figure 3.3.

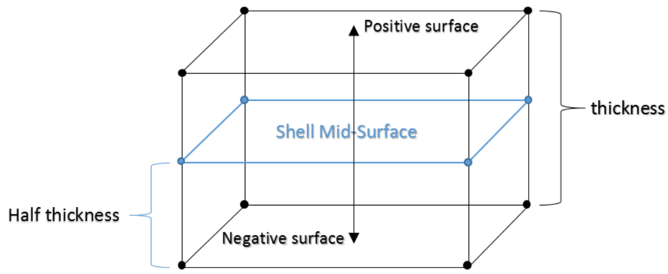


Figure 3.3: Mid surface operation

The mid surface operation is used where the thickness is small compared with the span length of the component. In this case the thickness was very small and in order to skip a detailed volume meshing a mid surface was created for the parts sponge_3 (yellow), sponge_1 (green), EPDM_1-4 (purple) and for EPDM_6 (purple).

EPDM_5 (red) has more complex geometry, see figure 3.4. The geometry was hard to capture with a mid surface, which led to the use of a different method. In essence, a manual mid surface is created where one surface is removed and the other is moved to half the direction of the middle line.

Figure 3.4: Cross section of EPDM_5

Figure 3.5 shows the EPDM_70 (light blue) and the steel carrier wrapped together. The steel carrier is inside the EPDM_70 and it was difficult to get EPDM_70 wrapped around the steel carrier using a mid surface operation. The solution was to remove the steel carrier from the model since the only contribution was to keep the whole seal at position without folding. The same method was used for EPDM_70 as for EPDM_5. To compensate the removed steel carrier, EPDM_70 was given a stiff and a static property.

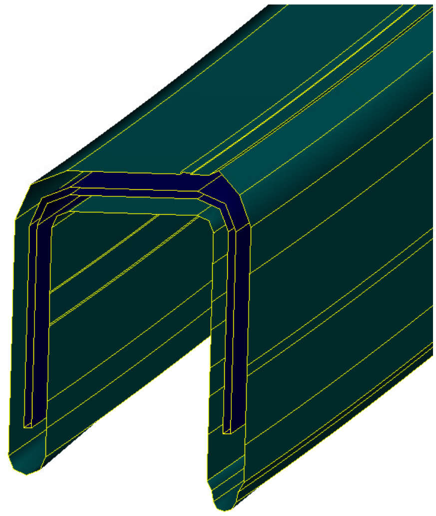


Figure 3.5: Cross section of EPDM_70

An observation made during the geometry cleanup was that the contact between the Sponge_2 (grey) and the door frame had very limited impact during the slamming moment. It was also difficult to mesh Sponge_2 (grey) because it was a small part and has a narrow angel. Therefore a decision was made to remove that part.

When the geometric cleanup was computed and shells had been created for all parts, these newly created surfaces were then meshed with fully integrated shell elements and was used the given mesh criteria, see table 2.1

3.3.2 Door seal

Figure 3.6 shows the cross section of the CAD model for the seal mounted on the door. As visualised in the figure the seal is made of three parts. A tape strip (blue part) and two rubber parts, one hollow rubber called sponges (green part) and one solid rubber (red part).

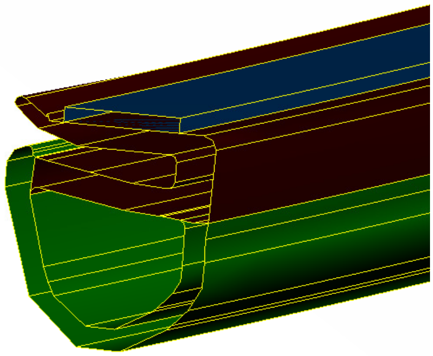


Figure 3.6: Cross section of the door mounted seal

The modification made on the door seal was to first remove the tape strip (blue part) because the tape strip served as adhesion. That will be later modelled as a contact. To make the solid CAD geometry into shell a mid surface operation was done on the remaining parts in order to create surfaces. The new created surfaces are then meshed according to the chosen criteria.

3.4 Contacts

In order to reflect the reality the contacts were setup different for the door mounted seal and the body mounted seal in LS-Dyna. The contact models are obtained from general 3D contact algorithms.

3.4.1 Door mounted seal

For the door mounted seal a contact was done to mimic the tape glue and also taking into account that tape strip was gone. The contact card chosen was **TIED_TO_SURFACE_CONTRAINED_OFFSET* because the tied contact mimicked the glue and kept the seal in position. The contact was constrained-based due to different mesh size between the door and the seal, the offset variable was given to take into account that tape strip was gone, see figure 3.7

To capture the contact between the seal and the body the **CONTACT_AUTOMATIC_SURFACE_TO_SURFACE* contact card was used. The contact was done between the hollow rubber (green part in figure 3.6) and the body, see figure 3.8

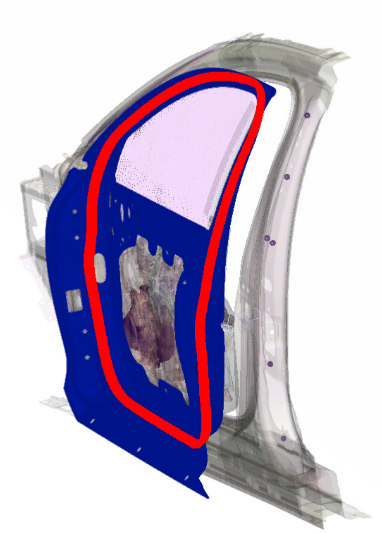


Figure 3.7: Tied contact between the door and the seal

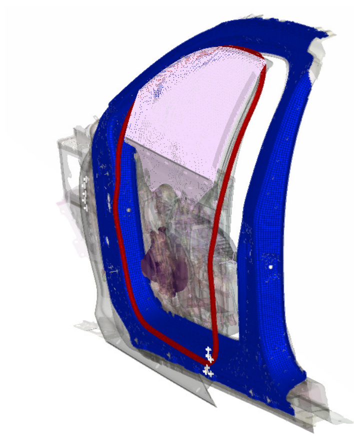


Figure 3.8: Contact between the body and the seal

3.4.2 Body mounted seal

For the body mounted seal a contact card,**CONTACT_AUTOMATIC_SINGLE_SURFACE* was used between the seal and the body to mimic that the seal is fixed to the body.The contact was done for the body and the whole seal expect for sponge_2. Sponge_2 was used instead used to capture the contact between the door and the seal, where the **CONTACT_AUTOMATIC_SURFACE_TO_SURFACE* contact card was used. The contact was done between the sponge_2 and the door, see figure 3.9. This is done in order to not over-constrain the contacts.

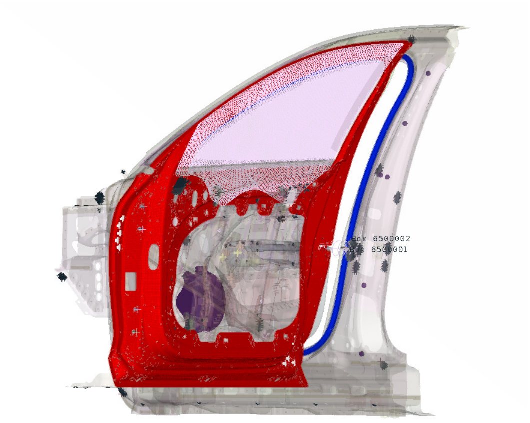


Figure 3.9: Contact between the door and the seal.

3.5 Material

In order to capture the static behaviour for the rubber a hyperelastic material with Yeoh material model was used. Yeoh material model is used since it captures the behaviour of rubber with large deformations. In Yeoh material model there are three parameters, C_{10}, C_{20} and C_{30} that affect the stiffness of the sealing system. A quasi-static simulation was setup to determine the sealing system stiffness.

3.5.1 Body cut for quasi-static behaviour

In order to capture the quasi-static behaviour the simplified body model, see section 3.1 was cut in even smaller piece together with the sealing system and the door, see figure 3.10. This further simplification was done to minimize the simulation time, since keeping the time minimum in this stage is important because in the parameter optimization stage a lot of simulations were carried out. As mentioned in section 2.2.1 and in section 2.3.1 the sealing system is divided in small sections with different attack angles. The cut of the body seal and door seal was done with these in mind and is further described in section 3.5.2 .

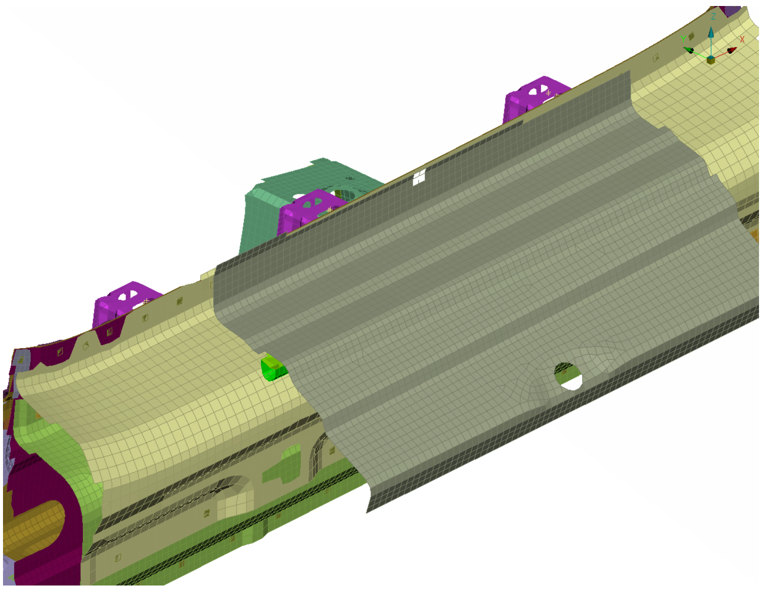


Figure 3.10: Quasi-static simulation setup with a rotational movement in positive y-direction. The white dot represents the node that is used to evaluate the simulation

3.5.2 Quasi-static simulation

In order to tune in the three material constants that is used in Yeoh model quasi-static simulations had to be done in LS-Dyna. The static data in Nastran is different in different sections of the seal. That is because the sealings impact angles are different depending on the position on the door. The static data from Nastran was obtained for different sections of the sealing.

When the quasi-static simulation was set up, the impact angle had to taken into account. Therefore the data were selected into a specific section and the model in LS-Dyna was designed for that particular section only. Because of the uncertainties with how the test was performed another arrangement was done in LS-Dyna to set up similar angle of attacks. It was done by having a constant angular motion around the hinges for the specific section. In order to set up a constant angular motion a prescribed motion of a rigid part had be done. To get this rigid part to rotate around the hinges, a local coordinate system was made in the hinges and then the rigid part's centre of gravity was moved to the rotational axis. This rotational movement is in positive y-direction, seen in figure 3.10. The door seal was mounted to the rigid part with constrained nodes and the body seal was mounted to the body with a Single Surface contact. A single Surface means every part is in contact with itself and each other.

To control a quasi-static analysis was performed an eye was kept on the kinetic energy in the system, because the kinetic energy must remain small in comparison to the internal energy. This verifies that the inertial effects in the system is minimized and the system acts quasi-static.

In order to fit the curves it had to be taken into account that the force in Nastran was for every 10 millimetre described in section 2.3.2. LS-Dyna provides the force in kilonewtons and displacement in millimetres. To be able to target the Nastran curve, the units in LS-Dyna and Nastran had to be the same. It was done by converting kilonewtons to Newtons and dividing the force with the specimen length multiplying with ten to get the force for every ten millimetres.

With the set up for a quasi-static simulation in LS-Dyna and a target curve from Nastran a curve fit analysis was done in modeFrontier to optimize the material constants in Yeoh material model.

3.5.3 Material constant optimization strategy

In modeFrontier a scheme was done to run several simulations with different material constants, see figure 3.11. Before the scheme was setup, the material constants in Yeoh model had to be parameterized in order to make the program change the constants to the desired values. After each simulation a set of data points were produced, these data points were compared to the data points collected from Nastran. The output from this comparison came in form of Mean square errors.

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2 \tag{3.2}$$

As seen in equation 3.2, only the Y-values were consider, the Y-values representing the force. Therefore when the model was setup, the displacement in LS-Dyna had to be equal to the data from Nastran. In order to accuratley determine the starting position in LS-Dyna, a node had to be chosen. By knowing the position on a closed door it is possible to determine how many degrees the door has to open in order to get the node's position to correlate with Nastran starting position. How the node was selected was based on the position and length of the sealing section. The node is highlighted in figure 3.10 as a white dot.

Evaluation of the lowest Mean square error value gave the most accurate fit.

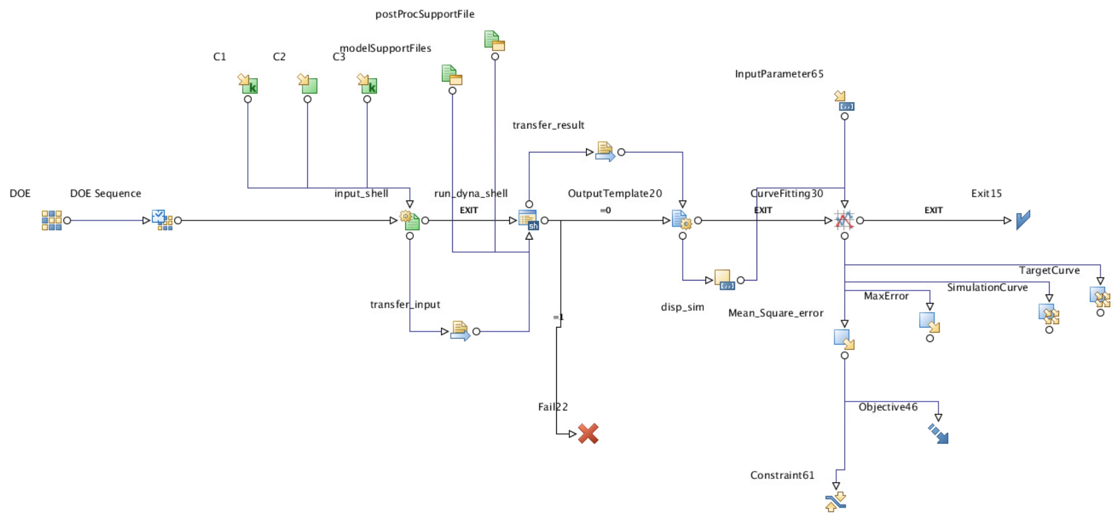


Figure 3.11: modeFrontier scheme to run several simulations with different material constants

3.6 Locking mechanism

The approach in this thesis was to focus on the sealing system, but due to the impact of the locking mechanism in the slamming moment, that had to be considered. In order to capture the impact of the slamming force a nonlinear spring element was constructed. The non linear element was setup between the striker and the door. The behaviour for the element was taken from the data in the Nastran model where a nonlinear spring is also used. Based on the data, a discrete element was created with a material that has a prescribed force over displacement.

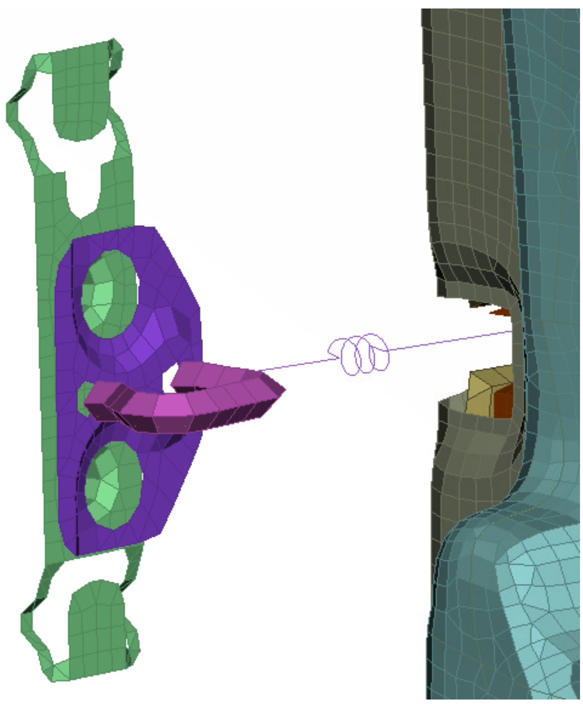


Figure 3.12: Nonlinear spring element with prescribed force over displacement

3.7 Airbag

To capture the dynamic behaviour in LS-Dyna, an airbag model was used. The airbag model chosen is $^*AIRBAG\_SIMPLE\_AIRBAG\_MODEL$. It was chosen because it satisfies the demands on establishing a control volume with vents and leakage. This airbag model was applied on the door and the body sealing separately. A nominal area was assumed for the vent holes.

In $^*AIRBAG\_SIMPLE\_AIRBAG\_MODEL$ it was also only one unknown parameter because an assumption of dry airbag in the seal was made. The unknown parameter describe the vents and leakage is the shape factor μ. The shape factor was the parameter to investigate. It was done in the complete model and is described further in section 3.7.1

3.7.1 Complete model

The quasi-static test setup was done on a smaller model to fit the material constants, because the data that was available represents a section of the seal and therefore it made sense to do the simulation on a selected section. To capture the dynamic behaviour equation 2.1 can be used on the static data, however the data for the dynamic behaviour is also available for the whole door, in terms of measured acceleration signals provided from Volvo Cars. The accelerometers are placed on the door's anti-intrusion beam and they are placed at the front and the upper position on the beam, respectively at the rear and the lower position on the beam, see figure 3.13

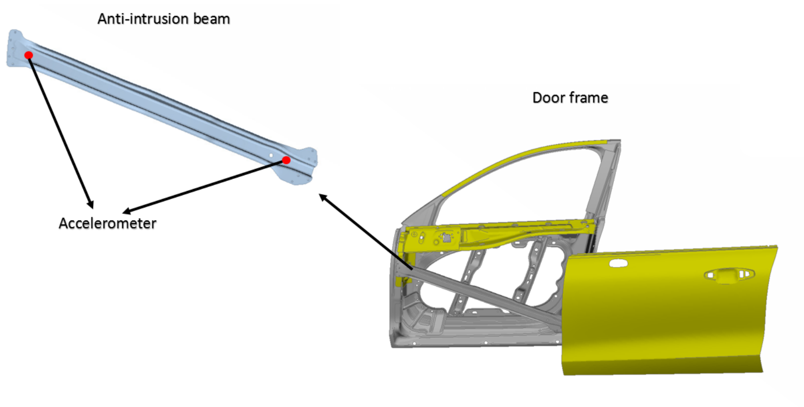


Figure 3.13: Location of accelerometers on the door anti-intrusion beam

In order to differentiate the noise from the shock, it was decided to only evaluate the acceleration signal at the rear and lower position on the anti-intrusion beam. The reason for evaluating the signal at the rear and the lower position is that it presented a much clearer shock compared to front and upper position and consequently made the evaluation process more obvious. Hence the best approach to tune in the airbag parameters in LS-Dyna was to examine the behaviour in the complete model.

As mentioned in section 3.7 the unknown parameter to tune is the shape factor for each of the sealings. The combination of different shape factor for each sealing gave different simulated acceleration signals, these simulated acceleration signals were compared with the measured acceleration signals provided from Volvo Cars.

The door was closed at "normal" speed with the velocity of 1.5 m/s. The approach to reach the best fit for the two shape factors was a sample selection of parameters for each seal. The white dot in figure 3.10 represents the node that is used for the evaluation. The shape factor range from zero to one. After the samples were simulated, the acceleration signals had a lot of noise, see figure 3.14. To ease the comparison, a filtration was done for the simulated acceleration signals which lead to a filtration on the measured signals. The filtration used for this case was Ideal Band Pass at 0-120 frequency interval, see figure 3.15.

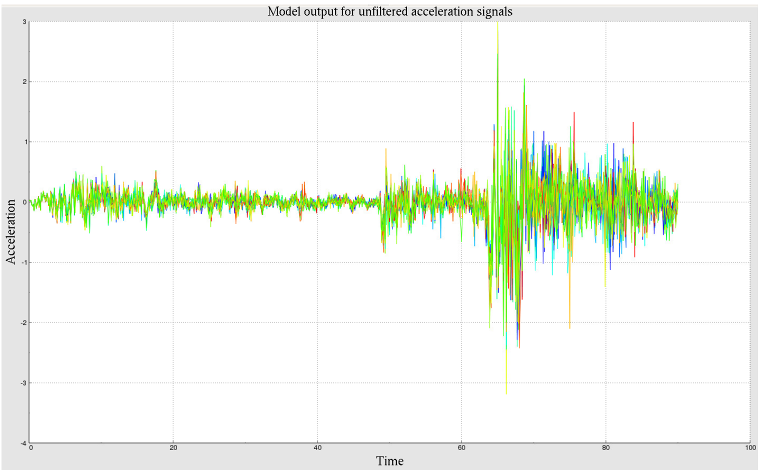


Figure 3.14: Model output for node shown in Fig 3.10 for different values for the shape factors with unfiltered acceleration signal

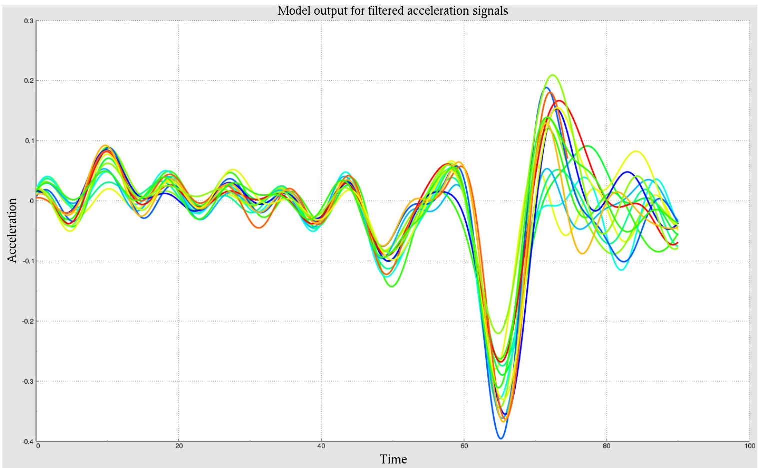


Figure 3.15: Model output for node shown in Fig 3.10 for different values for the shape factors with filtered acceleration signal

These sample size gave an indication of which value on the shape factor is a good fit and narrows it down to an interval of parameters. Some more simulations were done in that interval. Then a selection was made based on which combination of shape factors for the sealing system had the most similar peak and behavior after the peak. To evaluate the acceleration signals the comparison was made by examining the peaks in each signals.

4
Results

This chapter of the thesis presents the results.

4.1 Geometry clean up

Figures 4.1 and 4.2 shows the meshed versions of the seals that is used in the analysis.

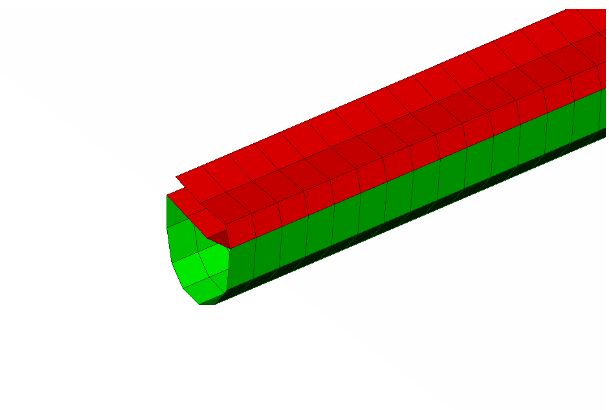


Figure 4.1: Meshed cross section of the door mounted seal meshed

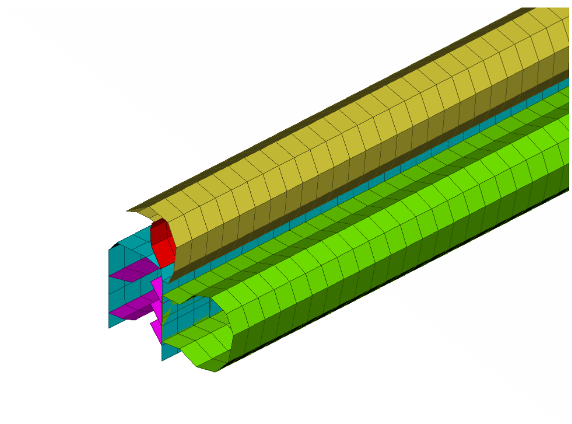


Figure 4.2: Meshed cross section of the body mounted seal meshed

4.2 Quasi-static simulation

The best suited material constants were determined by a quasi-static setup processed in modeFrontier. The white dot in figure 3.10 represents the node that is used to evaluate the simulation. Evaluation of the lowest Mean square error value along with visual check gave the most accurate fit.

To control that the quasi-static analysis was performed correctly an eye was kept on the kinetic energy in the system, because the kinetic energy must remain small in comparison to the internal energy. This verifies that the inertial effects in the system were minimized and the system acts in a quasi-static way.

To control that a quasi-static analysis was performed correctly and validate that the inertial effects didn't affect the result, the energies in the system were examined.

4.2.1 Door mounted seal

The highest MSE value is $3.3154 \cdot 10^{-2}$ compared to the lowest MSE value reached is $4.8768 \cdot 10^{-4}$. The lowest MSE results in the material constants

$$C_{10} = 3 \cdot 10^{-4}\, GPa,\; C_{20} = 0\, GPa,\; C_{30} = 7 \cdot 10^{-4}\, GPa$$

The energies in the system for the door sealing quasi-static simulation simulation.

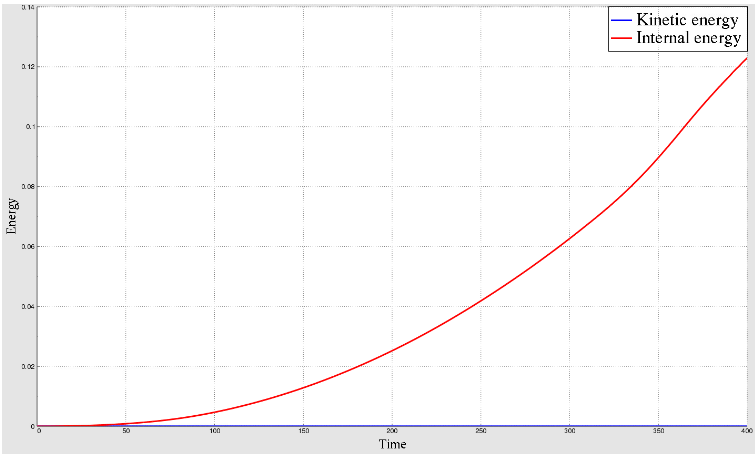


Figure 4.3: Internal energy vs Kinetic energy for the quasi static on the door seal

As seen in figure 4.3 the internal energy is much higher than the kinetic energy which indicates that the inertial effect has a minimal affect.
A comparison between the quasi-static simulation in LS-Dyna with the given material constants and a target curve from Nastran is visualised in the graph 4.4

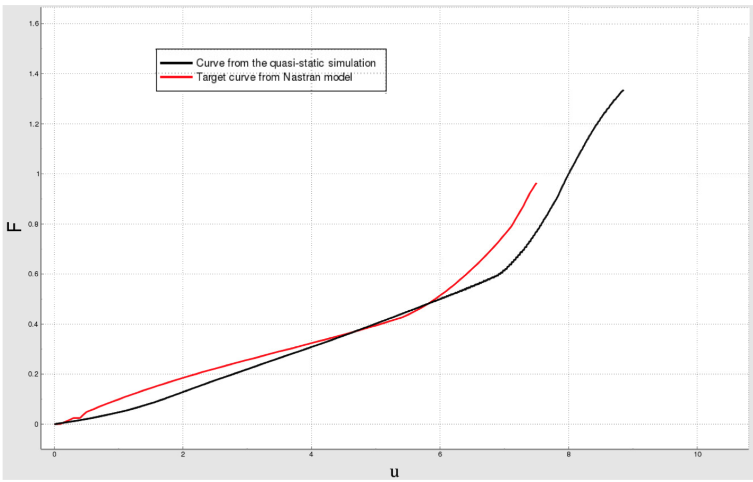


Figure 4.4: Comparison between the target curve and the curve with the given material constants. The force represents the reaction force from the sealing section and displacement represent the node shown in fig 3.10

The result is considered to be good enough to proceed with the project.

4.2.2 Body mounted seal

The highest MSE value is $1.5665 \cdot 10^{-}1$ compared to the lowest MSE value reached is $7.3887 \cdot 10^{-2}$. The lowest MSE results in the material constants

$$C_{10} = 2.75 \cdot 10^{-4}\ GPa,\ C_{20} = 5.60 \cdot 10^{-5}\ GPa,\ C_{30} = 2.7 \cdot 10^{-4}\ GPa$$

The energies in the system for the body sealing quasi-static simulation.

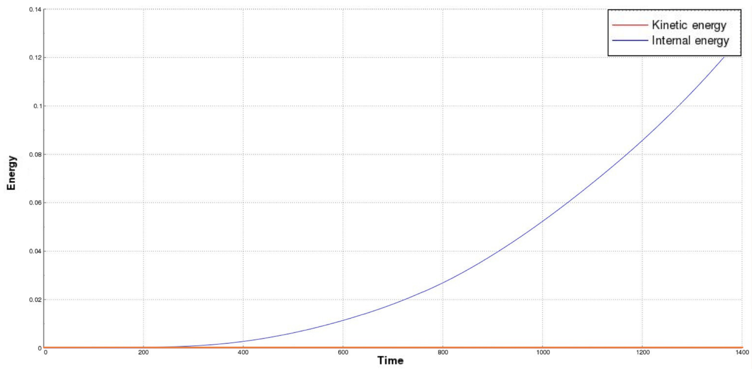


Figure 4.5: Internal energy vs Kinetic energy for the quasi static on the body seal

Figure 4.5 shows that the internal energy is much higher than the kinetic energy which indicates that the inertial effect has a minimal affect.
A comparison between the quasi-static simulation in LS-Dyna with the given material constants and a target curve from Nastran is visualised in the graph 4.4

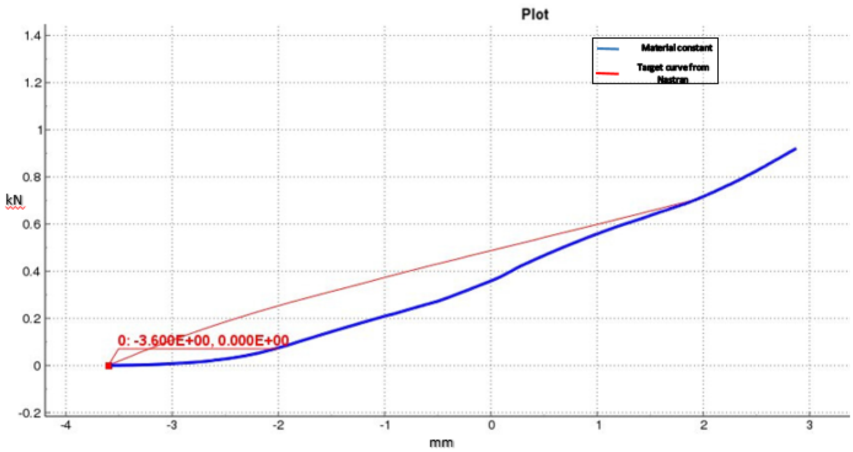


Figure 4.6: Comparison between the target curve and the curve with the given material constants. The force represents the reaction force from the sealing section and displacement represent the node shown in fig 3.10

4.3 Airbag

In order to compare the filtered test result with the filtered simulated results, the signals had to the moved on the time axis where the peaks were set at time zero. The black curve represent the measured acceleration signal while the other coloured curves represent different acceleration signals with different shape factor.

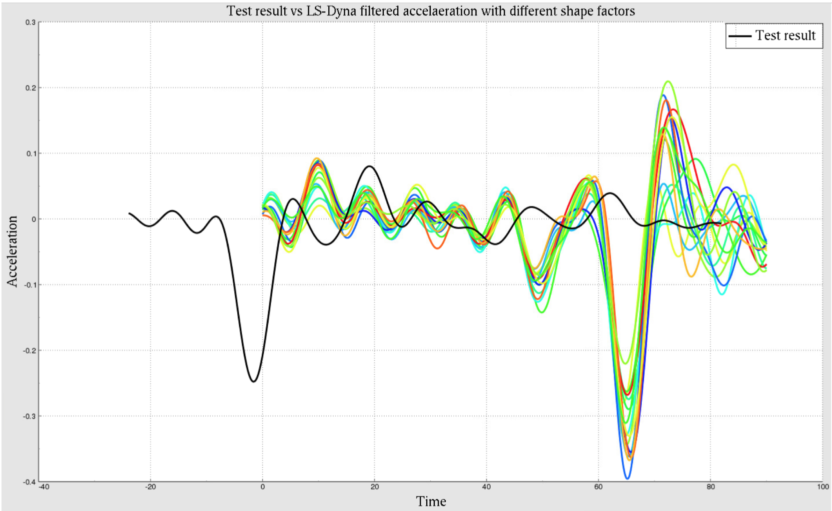


Figure 4.7: Filtered acceleration for both the test results and the simulated result for the node shown in Fig 3.10. Black indicate the test result and the others colours represent the simulated results with different shape factor

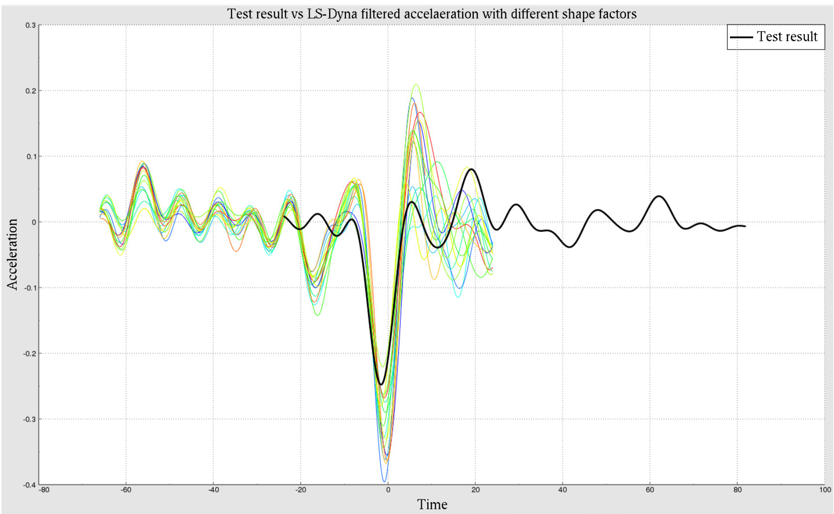


Figure 4.8: Filtered acceleration for both the test results and the simulated result for the node shown in Fig 3.10. Black indicate the test result and the others colours represent the simulated results with different shape factor. All peaks are moved to time zero

From the figure 4.7 and 4.8 it is shown the best fits from the model output compared with the test result.

The best fit is

Shape factor on the body, μ	0.1
Shape factor on the door, μ	0.1

Table 4.1: Value on the shape factor for the body mounted seal, respectively for the door mounted seal

Figure 4.9 visualises the test results and an airbag model with the shape factor 0.1 for the body, respectively 0.1 for door.

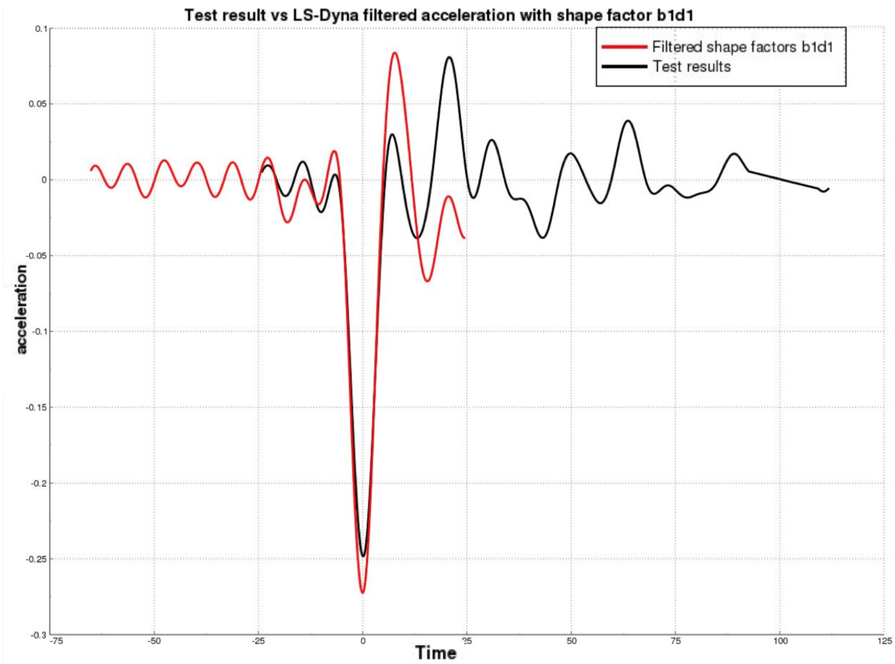


Figure 4.9: Filtered acceleration for both test results and model output for the node shown in Fig 3.10. Black indicate the test result and the other indicate the output from the model. The test results and the output from model all moved at time zero

To check that the peak of the acceleration signal occurs at impact, figure 4.11 is used to verify it.

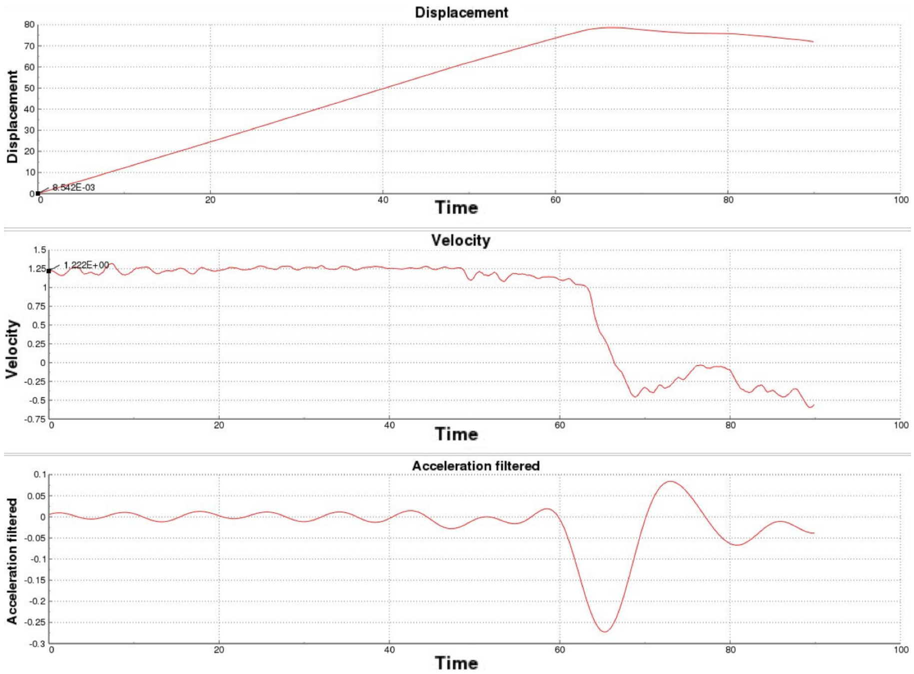


Figure 4.10: Sequence of motion in displacement, velocity and acceleration for the node shown in Fig 3.10

As shown in the figure 4.11 the change in the displacement, velocity and acceleration appears at the same time step which indicates that the data for the acceleration is reliable.

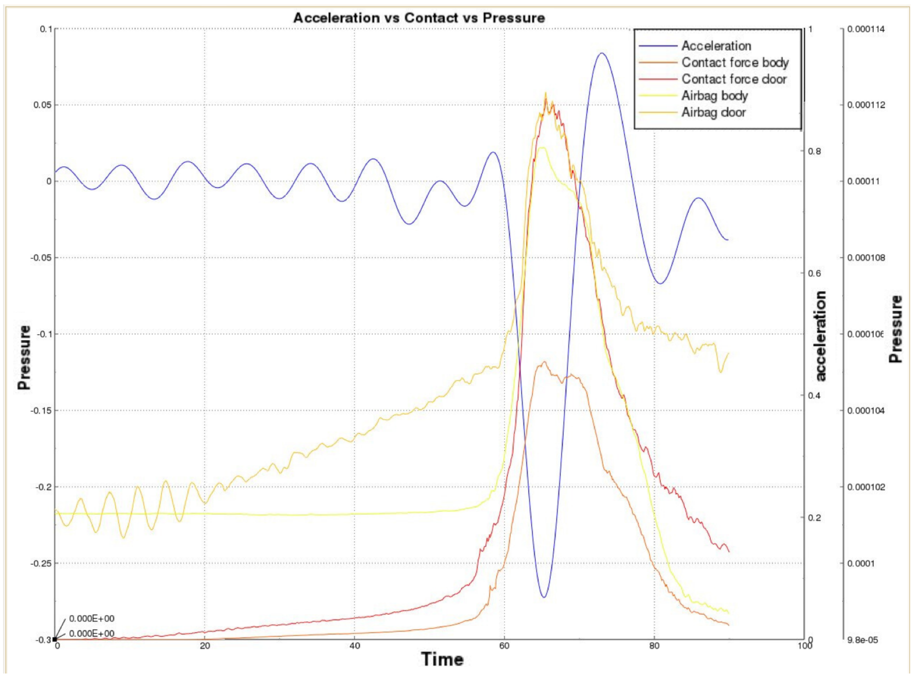


Figure 4.11: Sequence of Acceleration vs Contact vs Pressure for the node shown in Fig 3.10

5

Conclusion and Discussion

5.1 Material model

As we can see in section 4.2, the same rubber material gives different material behaviour for the body sealing and for the door sealing, due to different cross section geometry. Before the quasi-static simulations were made, in theory the behaviour were assumed to be the same but with different impact angels. After the quasi-static simulation results show that different cross sections geometry give different behaviour. This indicates that the cross section geometry has a big influence on the material behaviour so with new geometry there is the need for new physical tests to verify the material behaviour in LS-Dyna.

Figure 5.1 shows zoomed in part of figure 4.4 where it is obvious that the breaks (B_1 and B_2) do not occur at the same location. This error is assumed to occur because the geometry difference between the CAD data provided from Volvo Cars and the geometry cleaned up data, see section 3.3. Further, as seen in figure 5.1 it is obvious that the quasi-static simulation captures the material behaviour compared with the test data.

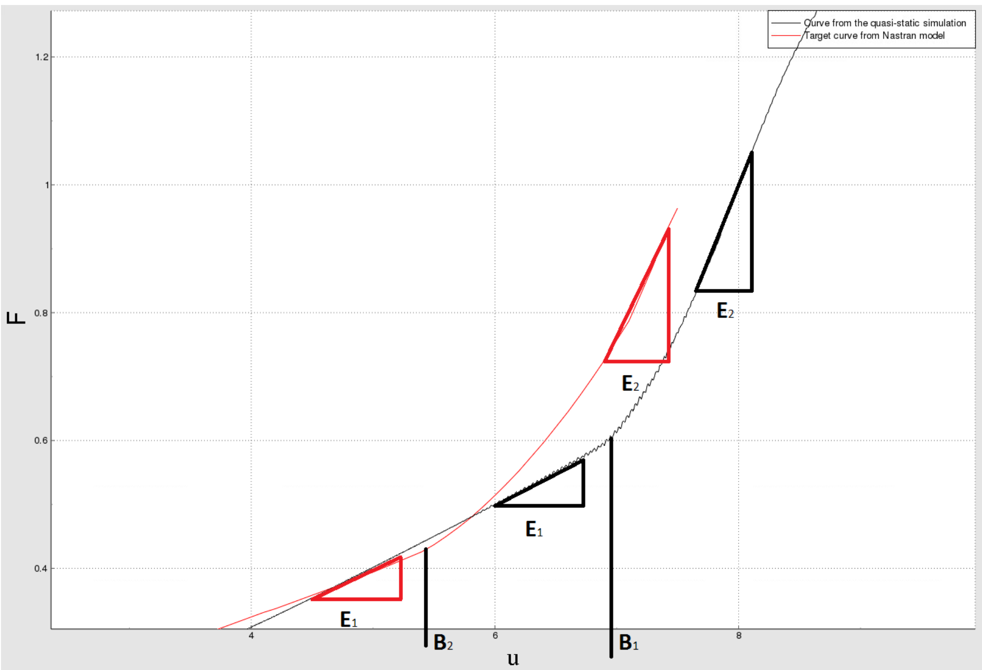


Figure 5.1: Zoomed in comparison between target curve and simulated curve with lowest MSE. The force represents the reaction force from the sealing section and displacement represent the node shown in Fig 3.10

In figure 5.2 it is shown where the error occurs when the quasi-static simulation is compared to the target curve for the body mounted sealing. Every simulation with different material constants that was made during the material constant optimization, see section 3.5.3 shows the same error. This error is also assumed to occur because of the geometry difference between the CAD data provided from Volvo Cars and the geometry cleaned up data, see section 3.3. As seen in figure 5.2 it is obvious that the quasi-static simulation captures the material behaviour compared with the test data.

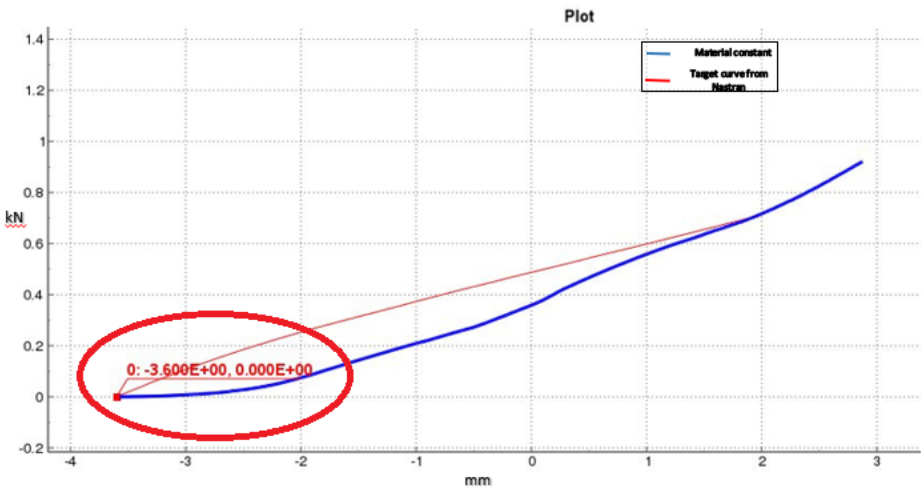


Figure 5.2: Comparison between target curve and simulated curve where the error is highlighted. The force represents the reaction force from the sealing section and displacement represent the node shown in Fig 3.10

To avoid the error that occurs during the quasi static simulation, the mid surface operation that was made during the geometry clean up could be skipped. If the simulations were made in this way so the sealing geometry made of solid instead of shell elements the simulation time should increase significantly. Further another factor that is assumed to affect the error is the uncertainty in how the quasi static test was setup and performed by the sealing supplier. If the setup for the tests are known it could be replicated and in this way avoid any confusing material constants. During the quasi-static simulation performed in LS-Dyna, see section 4.2, the simulation was setup like a door closing event and the impact angle was taken into account, due to minimize the set up error as much as possible. Even if all this mentioned factors that can affect the curve output from quasi-static simulation performed in LS-Dyna is identical to the psychical test this does not mean that the final acceleration comparison would be good enough. A better way to catch a good curve fitting between the acceleration signals will be discussed in the next section.

5.2 Complete model

A complete model with all the necessary parts is used to compare the acceleration signals provided by Volvo Cars and the acceleration signals from LS-Dyna simulations. The air inside the sealings has a big influence to this acceleration signals and as mentioned in section 3.7 to capture the dynamic behaviour and illustrate the air inside the sealing system in LS-Dyna, an airbag model was used. Figure 5.3 shows that the airbag model has a damping role similar to reality. The pressure increases while the volume decreases at impact. After the impact the pressure and the volume will be incorrect and the reason for that is that the air flow into the sealing system is set to zero. It is obvious that the pressure, contact force and acceleration increases during impact which indicates that the data for the acceleration is reliable.

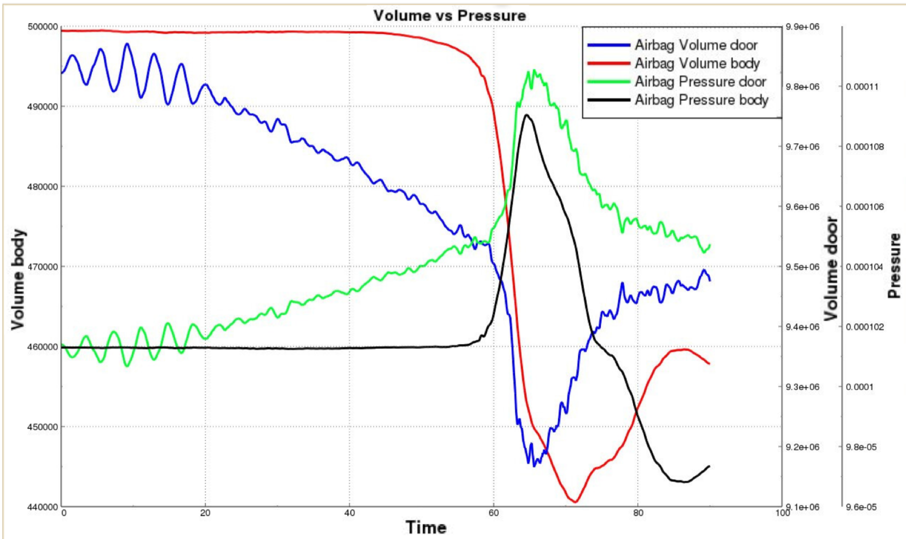


Figure 5.3: Sequence of volume vs pressure for the complete model with the shape factor 0.1 for the body, respectively 0.1 for door

As seen in the marked area in figure 5.4 acceleration signals do not damp out as rubber assumed would behave. Some uncertainties occur due to the oscillations in the acceleration signal that may been caused by other components in the door. This can be explained section 3.7.1 where its describe that the data for the dynamic behaviour is available for the whole door, in terms of measured acceleration signals. When Volvo Cars measured the acceleration signals, the accelerometers were placed on the anti-intrusion beam, which has interfering noises between the sealing system and the measuring point.

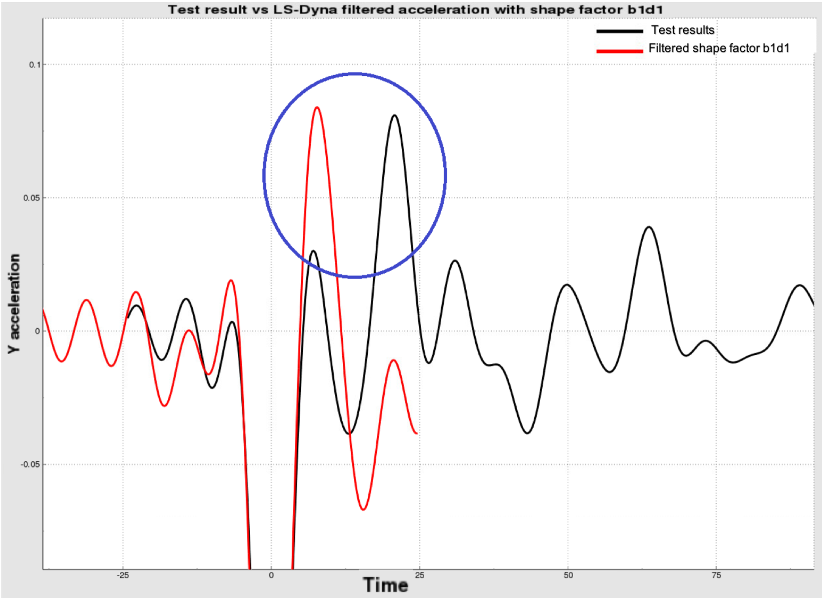


Figure 5.4: Comparison between measured acceleration signal and simulated acceleration signal where the error is highlighted

Using an airbag model to capture the dynamic behaviour has it flaws. The theory for the airbag model and for the mass flow out cannot be connected to a mechanical model for the sealing system. To estimate the outflow of the air, the shape factor had to be determined and with each the vent holes were summed up in a total area. This method to determine the outflow of the air creates limitation in accurately establishing the sealing dimension.

The conclusions from this master's thesis are that it is possible to model complex parts such as the sealing system with realistic material behavior and geometry. It is also possible to estimate the evacuation of air from the sealing system during a door closing event by the working explicit model of a Volvo car door. The output data from the working explicit model correlates good enough to use this particular Volvo car door. However, it is recommended that additional studies should be carried out to determine the applicability of the model to a variety of door and sealing geometries. It is also recommended to evaluate the airbag model with the dynamic equation from section 2.3.2 and compare the difference with this methodology.

References

[1] Computer Aided Engineering In Automotive Industry
https://automotivecae.wordpress.com/
Accessed 2019-01-25

[2] Volvo Car Corporation
https://group.volvocars.com/company/vision
Accessed 2019-01-25

[3] Peter Lagervall & Mattias Rundqwist (2016), Master's Thesis at the Department of Industrial and Materials Science at Chalmers, Explicit Finite Element Modeling of Hood Closing

[4] Yuksel Gur, Kenneth N.Morman (1997). Modelling the Dissipative Effect of Seal Air Hole Spacing and Size on Door Closing Effort. Ford Motor Co.
https://saemobilus-sae-org.proxy.lib.chalmers.se/content/971901/abstract
Accessed 2019-05-07

[5] Maurizio Mozzone (2013), Master's thesis, Study of the Door Closing Performance of an Aluminum Door, Department of Applied Science, University of Windsor

[6] DYNAmore Nordic (2019), Ls-Dyna Introductory Course, Linköping

[7] Viktor Sandell (2017), Master's thesis at Luleå University of Technology at the Department of Engineering Sciences and Mathematics, Extraction of material parameters for static and dynamic modeling of carbon black filled natural rubbers

[8] Oscar J. Centeno G. (2016), Master's thesis at Lund University at the Department of Construction Sciences, Finite element modeling of rubber bushing for crash simulation

[9] Livermore Software Technology Corporation (2019), LS-DYNA Theory Manuel

[10] Livermore Software Technology Corporation
http://www.lstc.com/products/ls-dyna
Accessed 2019-05-06

[11] BETA CAE International AG (2018), Brochure, ANSA-The advanced CAE preprocessing software for complete model build up.
https://www.beta-cae.com/brochure/ansa_brochure.pdf
Accessed 2019-05-07

[12] MSC Software
https://www.mscsoftware.com/product/msc-nastran
Accessed 2019-05-07

[13] Enginsoft, Brochure, modeFRONTIER-The innovative integration platform for multi-objective and multi-disciplinary optimization.
https://www.enginsoft.com/bootstrap3/images/products/mF/modefrontier.pdf
Accessed 2019-05-07

[14] Multidisciplinary Design Optimization Laboratory
http : //mdolab.engin.umich.edu/
Accessed 2019-05-07