Development Process of Seamless Airbag Covers

Description of tools and generation of material properties using high strain rate tensile testing.

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Abstract

Over the last decade, safety restraint systems in automobiles have progressively gained attention. Federal, national, and international safety regulations have become increasingly severe, with consumer awareness of safety issues at an all time high. Various institutes and organizations research and test the safety of vehicles and provide results in the form of crash star ratings. With that, there is a movement in the marketing of vehicle safety in which selling arguments and negotiation tactics are focused around the crash star rating of the vehicle. Based on this trend, vehicle manufacturers are continually working on applying new technologies and refining their restraint systems.

One area of restraints with a focus on refinement is inflatable systems, known as airbags. This report will describe two distinct developments related to the passenger airbag, which is an inflatable system mounted directly behind the instrument panel on the passenger side of the vehicle. A comprehensive assessment of instrument panel and plastics technology related to these developments will be reviewed.
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Chapter 1

Introduction

Automotive manufacturers are endlessly looking for ways to make their cars safer, lighter weight and more cost effective. As restraint and safety systems get more sophisticated, the new advanced systems are expected to be incorporated without affecting the overall cost of a vehicle. Therefore, constant improvement in the efficiency of restraint systems is necessary.

General Electric is a supplier of engineering thermoplastics that can be used for various applications throughout the automotive industry. Due to their enhanced material properties, engineering thermoplastics can be positioned in applications where commodity plastics will not suffice.

During my internship with General Electric I supported the Instrument Panel team. The key assignment was to compare and contrast two unique airbag systems. Within this report, this airbag assignment as well as an introductory project will be reviewed. After a short description of the automotive industry and GE’s role herein, an explanation of instrument panels will be described before continuing with the actual Airbag projects.

In the automotive industry, two types of instrument panels, further referred to as IP’s, are utilized: hard and soft. While a hard IP is hard to the touch, a soft IP is covered with a layer of foam and skin, which gives it a soft feel. A current trend throughout the industry is the use of seamless airbags in which the airbag door is invisible. In soft IP’s, the airbag door can easily be hidden behind the layers of foam and skin. In hard IP’s, seamless technology requires a sophisticated tear seam in the material. In both cases the airbag breaks through the material by its own inflation pressure. In this study both a soft seamless airbag system and hard seamless system are investigated.

Key to both seamless system investigations are correlation studies involving material properties and computer simulations. The generation and application of material data for impact events such as airbag deployments, is critical to computer simulated Finite Element Analysis, further referred to as FEA. Due to the sensitivity of data generation and interpretation of this data, care has to be taken to ensure appropriate correlation to actual safety related events.

To obtain good understanding of the problems encountered in the assignments, an intermezzo describing material behavior of thermoplastics, has been added.

1.1 General Electric Company

Before discussing the actual assignments, it is good to get a feeling for the structure of the automotive industry and the structure of General Electric also with regard to...
function of a co-op.
On top of the automotive pyramid are the car manufacturers, or OEM’s. OEM stands for Original Equipment Manufacturer and is an acronym used throughout the industry. After that come the tiers. They supply semi-manufactures or complete substructures. Distinction is made between tier one, two etc. A tier one directly delivers to the OEM, a tier two to the tier one, etc. Material suppliers deliver the materials used by the tiers or directly used by the OEM’s. They use the raw materials supplied by the raw material suppliers.

![Diagram of automotive pyramid](image)

**Figure 1.1:** Different businesses of the General Electric Company. Plastics is a division of advanced materials and is a material supplier for the automotive industry.

With 315,000 employees GE is one of the largest companies in the world with revenue of about 134 billion and earnings of about 16 billion dollar. One of the four key areas to drive business growth is technology; with 2.7 billion dollar spend on R&D annually.

The Automotive Application Development Center houses businesses from GE Plastics, Silicones and Finance to serve the OEM’s and Tiers with technical support for the use of GE products and to work on new technologies that drive growth in the industry. The Plastics team is divided in different teams such as Lighting, Under The Hood, Components and IP/ Structures.

During my internship I worked for the IP/ Structures team. Aim was to gain as much knowledge as possible about instrument panels and plastics, to be able to work with the team on applications and technologies. GE’s philosophy is to give the co-op some freedom in determining the assignments according to interest and profession. This resulted in two assignments on seamless airbags, with an emphasis on material data for computer simulation programs.
Chapter 2

IP Specifications

For every part used in a vehicle, extensive requirements exist. These requirements apply to the design as well as the material, performance, life cycle, safety etc. Every OEM works with its own requirements and standardization is almost never seen. Larger problem however, is that most OEM's do not share their requirements as easily with the tiers and the suppliers as expected. Instead, the tier or OEM is given a few requirements during a project, but the complete list is never given. Reason for this is that an OEM does not want others to be able to compare their requirements to those of other OEM’s enabling them to say something about the quality of their products.

GE Plastics is always working on pro-actively looking for better design solutions and with assessing the market for new opportunities. Therefore it is necessary to have access to the different design and test requirements of every OEM, to be able to determine if the product is suitable for the application under investigation.

The IP team has a large demand for the design and test specifications for instrument panels and the first assignment was to obtain this data for the most import OEM’s in the US, such as Ford, GM, DCX, Toyota and Nissan.

Sometimes access is granted easily, for example, Ford shared all their requirements all at once, but sometimes nothing has been shared by the OEM’s at all. Creative solutions have to be found to obtain the data, such as retrieval from persons that have been working in projects with the OEM in the past within GE, or by trading the information with a tier. For example Mitsubishi does not supply any information at all. Collins&Aikman is a tier one for Mitsubishi and has access to all the requirements and there is no confidentiality agreement. Access to the data has been gained by giving them some data about gloss measurements from a colleague within the structures team.

Most important part of the assignment is to get familiar with plastics used in instrument panels and to learn about CTQ’s. CTQ stands for Critical To Quality and defines the requirements for a product and outlines the demands to make a product best in class.

The following paragraphs will present some basics about IP’s, the most important CTQ’s for instrument panels, some safety requirements, materials used and some basic material properties of thermoplastics.

2.1 IP Basics

The main function of the instrument panel is to act as vehicle-driver interface. It houses steering, power train- and transmission controls, instrumentation, signaling and visibility control and it integrates comfort, convenience and safety features. Besides that, the instrument panel forms the partition between cabin and engine compartment.
Therefore, noise-reducing features are also included. The cross car structure, which provides dimensional stability of the vehicle and plays a major role in rigidity of the vehicle during side impacts, is noted to be a part of the IP as well. The instrument panel consists of several basic components as shown in figure 2.1. These components will be discussed in the next section.

2.2 Components

As the name suggests, the retainer forms the basis of the IP to which most of the other components are attached. It is a hard plastic structure that defines the basic shape of the IP. A soft IP is a retainer covered by a layer of foam and skin to provide a soft touch surface. The retainer can also be the first surface in the case of a hard instrument panel. It can be either painted or molded in color. Because retainers are large and often fairly thin-wall parts, they require a material with good flow and high heat resistance.

The structure is the component that provides dimensional stability and structural integrity during an impact. It consists of the cross car beam, which, in most cases, is still a steel tube, but effort is being put into manufacturing this part totally or partly out of plastic. The center stack and the steering column support are part of the structure, as well as the energy absorbers for knee impact.

These energy-absorbing features can have different shapes but all share the same purpose; in case of an impact they absorb the energy transferred by femur and knees, thus reducing the maximal load on these parts of the human body. Additionally they have the purpose of holding the occupant in place as much as possible and to prevent the body from submarining. Submarining happens when the passenger slides from under the seatbelt and disappears under the dash. Figure 2.2(a) shows an energy absorber commonly used nowadays, and Figure 2.2(b) shows a study done by GE according to energy absorbers with a longer and more stable deformation length, thus optimizing the amount of energy absorbed and reducing the femur load. The energy absorbers on the driver’s side are attached to the steering column support and covered by a plate called the knee bolster. On the passenger side they are positioned directly next to the
glove compartment where the glove box door often covers the absorbers. The knee bolster and the glove box door therefore play a very important role in energy transfer and their design plays a major role in the effectiveness of the energy absorbers.

![Figure 2.2: Energy Absorbers.](image)

(a) One piece mold&fold knee bolster reinforcement with energy absorbers.  
(b) GE patent knee energy absorbers.

The glove box assembly is a part that looks very simple but, in fact is rather complex. The requirements a glove box has to meet are extensive, as said, it must provide good energy absorbing or transferring properties during knee impact, remain closed under all circumstances during impact and manufacturing this part must be kept as simple as possible. Other separate components are the defroster grill that must be extremely weather resistant and low gloss, the trim bezels and the center console.

### 2.3 CTQ’s

Within GE, requirements for a product, design or technology are generally referred to as CTQ’s, or Critical to Quality. They describe the main demands that determine the success of the application. For Instrument Panels there are basically five different classes of CTQ’s.

#### 2.3.1 Structural Integrity and Durability.

CTQ’s in this class are related to stiffness, strength and fatigue, so no deformation under all driving conditions and normal use by occupants. It is important that the IP gives a robust impression and keeps its shape under all circumstances. For weatherability and high heat resistance, the instrument panel is divided in different zones (figure 2.3) that must be able to withstand certain degrees of heat and humidity aging. The temperature in a vehicle can be significantly high and plastics can lose a lot of their properties under high heat and/or humidity conditions. The upper surface of the IP, being a low gloss, often dark surface, directly below the windshield must especially withstand high heat. The IP must retain its shape, color and touch after sufficient time of exposure to cycles of humid and heat environments, followed by cold and dry situations. This is referred to as thermal cycling. A very common phenomenon in plastics is creep. Internal stresses cause the material
to deform over time, a process that is enhanced by high heat conditions. Resistance against this phenomena is also a key CTQ. Another big threat is the use of chemicals in and around the vehicle. The selected plastics are required to have resistance against these chemicals, to keep its color and to have no physical degradation. Therefore chemical resistance tests are performed, not only by just application of the different chemicals, but also by researching the behavior of the material in a tensile test with application of the chemicals. In case of an accident, severe impact loading on the retainer can occur, either by the occupant hitting the dash or by the deployment of the airbag. Therefore the material must be tough, and capable of withstanding the energy of the loading.

Figure 2.3: The IP is divided in different zones for heat and impact requirements.

2.3.2 Safety

The behavior of the IP during an incident is very important and several institutions have regulations for safety performance. The most important regulations in the US are the Federal Motor Vehicle Safety Standards (FMVSS), the New Car Assessment Program (NCAP) and Lateral Impact (LINCAP), and the Insurance Institute for Highway Safety (IIHS) ratings. Cars that might be sold in other parts of the world have to meet other standards as well. In general, one can say that care is taken to meet all the most severe requirements. More attention is given to the FMVSS regulations in section 2.4.

2.3.3 Dimensional

Dimensional requirements contain fit and finish behavior such as gap control, robustness and resistance against noise, squeak and rattle. Packaging is a requirement that describes a given volume in which the part needs to fit.

2.3.4 Cost, Mass and Environmental

Federal Cumulative Average Fuel Efficiency (CAFE) requirements demand a lightweight construction and efficient use of materials. Over the last few years also more stringent regulations according to recycle ability and odor emissions have been introduced, which also have to be taken into account.
CHAPTER 2. IP SPECIFICATIONS

2.3.5 Human Factors

Human factors are things as aesthetics, ergonomics, functionality and smell. A smooth finishing is required. In the case of a hard instrument panel it is necessary that reflections of sunlight and other sources are suppressed as much as possible. Therefore one of the key material requirements is low gloss. Purpose is to create an IP that looks like a high cost material like leather or wood rather then cheap plastic.

2.4 FMVSS Requirements and Tests

The most important safety requirements IP’s have to meet are the FMVSS requirements. In order to meet these requirements, both structural analysis and physical tests have to be performed. The FMVSS requirements are the FMVSS 201 for head impact, the FMVSS 208 for frontal impact and the FMVSS 214 for side impact. A very brief description of each standard will be presented, followed by an explanation of related testing procedures.

The FMVSS 201 specifies the performance requirements to provide head impact protection for occupants. These requirements apply to instrument panels, seat backs, sun visors, arm rests and upper interior components such as pillars. It also states that interior compartment doors, such as the glove compartment, must remain closed during a crash.

The IP head impact test consists of firing a 6.8kg, 165mm rigid hemispherical impactor with a speed of 19 or 24 km/hr at the IP (figure 2.4(a)). The acceleration is recorded, as well as time and cracking of the material.

The requirement is that the deceleration is less then 80 \( G \) for 3ms and the \( HIC_{36} < 1000 \). According to more severe requirements, valid from 2007, the \( HIC_{15} \) should remain below 700. A structural analysis is always performed of this test beforehand to optimize the design by adding or replacing ribbing, to review the influence of foam and to see the influence of the retainer material and thickness.

The HIC, or head injury criterion, is determined by using the following formula with the recorded data for acceleration in a predetermined time interval as inputs.

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

The FMVSS 201/S5.3 states that all compartment doors must remain closed during the following three test procedures.

The first procedure is a combined 10G horizontal and vertical acceleration, the second one is a full vehicle impact at 48 km/hr, and the last one is a 30G longitudinal deceleration. The PPDC, the Polymer Processing and Development Center in Pittsfield, Massachusetts, has the capability of performing a horizontal sled test, which is only done if requested by the OEM. FEA as well is only performed for these procedures, if the OEM requires this.

The FMVSS 201u, or upper head impact requirement, is only performed by structural analysis. The same head form is fired at the part under investigation (figure 2.4(b)) at the same speed as in the IP head impact test. The peak g-force is determined as well as the HIC value. Design of pillar trim and headliner is observed and countermeasures for compliance can be taken well in advance.

The FMVSS 208 specifies the performance requirements for test dummies seated in the front seats. The purpose of the standard is to reduce the number of fatalities and the
number and severity of injuries to occupants involved in frontal crashes. Current procedure is to impact a vehicle with a speed of 48 or 56 km/hr at a rigid wall. The wall orientation ranges from \(-30^\circ\) to \(+30^\circ\) to the line of velocity of the test vehicle. The current ruling requires unbelted passengers up to 40 km/hr. From the year 2011, wearing seatbelts is mandatory in all states and from that moment only belted tests will be performed. Suppliers never perform the actual test, but a structural analysis is done in most cases. In an FEA femur loads, intrusion of the occupant, the rebound energy, full vehicle dummy injury data and occupant kinematics are determined. The simulation is performed for the 5th percent adult female and the 50th percent adult male. Injury criteria are a femur load of less then 10 kN (6805 N for 5th pf), \(HIC_{15} < 700\), chest acceleration less then 60\(G\), and sternum compression less then 63 mm (52 mm for 5th pf).

Sometimes, in addition, a FEA of other FMVSS 208 requirements can be done as well. These include 40% offset deformable barrier at 40 km/hr, an out of position static PSIR deployment, chin on PSIR and chin on the steering wheel rim. Other dummies can be used as well, such as the 95th percentile male, 12 month old infant and 3 and 6 year old child dummies.

There are certain ways to tune the IP assembly to achieve the targets. Modifying the energy absorbing brackets and the stiffness of the knee bolsters and glove box for transferring the load can do this. Also, the influence of the stiffness of the steering column mounting structure and the position of the PSIR can be investigated.

The FMVSS 214 specifies the performance requirements for the protection of occupants in side impact crashes. A moveable deformable barrier hits the test vehicle at 54 km/hr on either side. Occupants are positioned in both the front and rear seats. The finite element study of this event by GE is not used to determine occupant injury, but rather to evaluate the structural performance. The role of the cross car beam is especially important for the structural integrity of the vehicle. The force transmitted through the system and the intrusion in the full vehicle are measured. Features to achieve these targets are design of the position of the weakest section in the beam for part stack-up and further buckling.

2.5 Material Portfolio

One of the first things necessary to understand when working with IP’s is which particular materials are used and the reason for this. In this section, an overview of the
most commonly used GE materials in IP applications will be presented. Later on, a
more general understanding of material properties of thermoplastics will be presented
to complete the knowledge necessary to be able to determine what material should be
used in a certain application.

One of the most familiar resins used in IP’s is the Lexan® Resin. It is a polycarbonate
amorphous engineering thermoplastic. Lexan® offers high impact strength, heat resis-
tance and high dimensional stability at elevated temperatures. It is flame resistant, can
be made UV stable and offers good processability and high flow, which is important in
huge (up to 5 kg) parts like retainers.

However, the chemical resistance can be low, especially against lubricants, which can
be a major problem in automotive applications. Besides that the high heat resistance
in combination with high humidity is not that good. After a long period of aging the
material can become brittle, thus being a major disadvantage.

To compensate this shortcoming, GE offers a derivative of Lexan®, Lexan® EXL.
It is also a polycarbonate-based material, with an additive named siloxane. This is a
silicone-based material that improves the low temperature ductility drastically, even
after long heat aging or exposure to sunlight. The material remains ductile at temper-
atures up to 30°C lower then for the normal Lexan® resins. Furthermore, it possesses
enduring aesthetics, thus providing a nice surface appearance and is very recyclable.

A new version of Lexan® EXL has been launched on the market by the end of Jan-
uary 2004 with even better low temperature ductility and excellent resistance against
heat and humidity aging. An application of this material in a hard IP retainer will be
discussed in this report.

Another resin developed to enhance the material properties from Lexan® is Cycoloy®.
It is a blend of polycarbonate and an acrylonitrile-butadiene-styrene terpolymer, or
ABS. The PC/ABS features an optimum balance of performance, process-ability and
cost. This resin is widely known for its very good flow and is therefore often chosen
in large parts such as instrument panels. Impact resistance is maintained until −30°C
while heat resistance can go up to 135°C. The UV stability, flame resistance and low
emissions make it a popular material for interior applications.

Where a lower cost solution is desired with good chemical resistance, hardness, rigidity
and melt strength, but impact and thermal requirements are not as stringent, Cycolac®
resin is often chosen. This is an ABS resin, modified with an elastomeric copolymer,
with good low temperature ductility and impact resistance. The high gloss of the ma-
terial makes it inapplicable for unpainted hard IP’s.
Noryl® is a resin based on polyphenylene ether (PPE) and polystyrene (PS). In combination with additives, it provides a wide range of physical and thermo-mechanical properties. General characteristics include high heat resistance, excellent electrical properties, hydrolytic stability, dimensional stability, low mold shrinkage and low creep behavior. Therefore it exhibits very good heat and humidity aging resistance. To enhance strength and dimensional stability, a glass filled version is often used, though processability decreases.

Cytra® is a PC/ABS/PBT blend, developed especially for applications such as IP’s because of its long flow length, high scratch resistance and very low gloss. In addition to these characteristics it has good impact behavior and good dimensional stability.

2.6 Material properties of thermoplastics

Working in this environment requires a basic understanding of material properties of thermoplastics; basic structure of the material must be understood in order to do a prediction about the behavior in a particular application. Understanding of the relationship between materials morphology and its mechanical properties greatly facilitates the understanding of the behavior of plastics. Therefore some basic polymer science will be presented.

Most basic difference in polymers is made between thermoplastics and thermosets. Thermosets cannot be re-melted due to their chemical structure. When reheating they undergo a chemical alteration and the material changes. Thermoplastics on the contrary can be re-melted, when doing so, their structural properties change. Only thermoplastics will be considered here.

One can distinguish two major categories within thermoplastics, the semi-crystalline and the amorphous thermoplastics. Semi-crystalline thermoplastics have a more ordered molecular structure and shorter polymer chains. Because the polymer chains have a length that is approximately equal for all chains, the melting point is well defined. The resistance against solvents is good, better then for amorphous thermoplastics but they tend to shrink more and are more likely to warp due to anisotropic shrinkage because the crystalline structure can cause an anisotropic structure.

Because of the shorter chains compared to amorphous thermoplastics, the melt viscosity is low and they posses very little melt strength. The mechanical properties are more temperature dependent.

Amorphous thermoplastics have randomly oriented polymer chains, there is no ordered molecular structure and the length of the chains is non-uniform. Therefore the molecular weight is higher. The long chains form physical entanglements, which provide some structural integrity.

Amorphous plastics are said to undergo second order transition. This means that there is no well-defined melting point; instead there is a melting trajectory. The second order is the fase where parts of the polymer start melting and the plastic becomes weak. Because of the melting trajectory, the cooling process during processing is more uniform; therefore there is more uniform and less shrinkage and less warp. Because of the long chains, the melt viscosity can be high.

Secondary bonds between the chains make the plastic more susceptible for chemical attack. Some amorphous thermoplastics can be optical transparent, like Lexan®.

Semi-crystalline and amorphous polymers can be blended to get an optimal mix of properties of both categories. Especially temperature dependent properties can be enhanced.
2.6.1 Fillers and Additives

In order to enhance the basic material properties and to tune the material according to the desired specifications, reinforcements, fillers and additives are used. The following are the most well known fillers.

Short glass fibers usually have the function to reinforce the material and to increase strength and stiffness. The creep, temperature and fatigue resistance increases and because of the brittleness of the glass, the failure strain, ductility and impact resistance decreases. Also the shrinkage and the coefficient of thermal expansion decrease. Negative effects are reduced flow and increased viscosity, thus making the material harder to process and more important, the wear of the tools increases drastically. Glass fibers have the tendency to align, causing anisotropic effects such as warpage. The fibers also cause a reduced surface finish, reduced gloss and an increase in density.

Fillers as minerals, glass spheres, inorganic flakes (mica) have the function of improving mechanical properties (stiffness, creep resistance, temperature resistance). They also improve electrical properties, reduce shrinkage and the coefficient of thermal expansion and can make the material flame retardant. However the down site is again a decrease in ductility and impact resistance, decrease in flow and aesthetics. Major advantage is the reduced warp.

Other commonly used additives are Coloring agents, UV stabilizers, processing aids, flame retardants, antistatic agents.
Chapter 3

Intermezzo

The contents of this intermezzo are not really a part of one of the assignments, but necessary to understand the problems encountered. Here some basics about the deformation behavior of thermoplastics and constitutive relations will be discussed. Last subject of this chapter will be an extensive explanation of high strain rate testing and the problems that occur during data generation, interpretation and the usefulness for FEA.

3.1 Deformation

3.1.1 Small strain Behavior

The mechanical behavior of a material below the yield strain is often referred to as small strain behavior. Different types of test methods can be identified to determine mechanical properties of polymers: uniaxial tension, uniaxial compression, plane strain compression, and simple shear are common used ways of testing materials to obtain mechanical properties.

The modulus is the key indicator of stiffness or rigidity and quantifies the resistance of the material against deformation. Three major types of moduli are described: Young’s modulus \( E \) is the resistance against uniaxial tension, the Bulk modulus \( B \) is the resistance to isotropic compression and the shear modulus \( G \) is the resistance to simple shear deformation or simply said, twisting of the material. Each type of modulus is defined by the stress required to deform a specimen by a certain strain. For example:

\[
\sigma = E \cdot \varepsilon \tag{3.1}
\]

The compliance for any given mode of deformation is defined as the reciprocal of that modulus. \( D \) is the tensile compliance, \( \kappa \) the bulk and \( J \) the shear compliance given by:

\[
D = \frac{1}{E} \tag{3.2}
\]

\[
\kappa = \frac{1}{B} \tag{3.3}
\]

\[
J = \frac{1}{G} \tag{3.4}
\]

Poisson’s ratio \( \nu \) is defined by equation 3.5 for an isotropic, or unoriented specimen. It describes the effect of the application of a deformation in one direction on the dimensions of the specimen in the other two directions perpendicular to the deformation. If
The value of $\nu$ provides the fundamental relationships given by equation 3.7 between the three types of moduli:

$$E = 2(1 + \nu)G = 3(1 - 2\nu)B.$$  \hspace{1cm} (3.7)

It is therefore necessary to know only one value of the moduli if the Poisson ratio is known. $E$, $G$, $B$ and $\nu$ are functions of both temperature and rate of the measurement and are often treated as complex dynamic properties. Stress/strain behavior depends on intrinsic material properties, preparation and processing conditions of the specimens and on test conditions.

A polymer softens drastically as its temperature is raised above $T_g$. Normally tensile and shear modulus decrease very slowly; around $T_g$ they decrease very rapidly over a narrow temperature range. (Figure 3.1) These changes in mechanical properties from glassy below $T_g$, to leathery around $T_g$ to rubbery above $T_g$, have a strong influence on the application of polymers. All mechanical properties depend on crystallinity, orientation and cross-linking.

### 3.1.2 Large strain behavior, failure mechanisms.

The usefulness of a polymer in many applications is largely determined by its predominant failure mechanism under the conditions of load application. It is therefore important to be able to predict the failure mechanism as a function of structure, processing conditions used in manufacturing and test conditions.

Factors that affect the failure behavior of polymers:
• chemical structures of repeat units
• details of molecular build
• cross linking
• supra molecular organization
• orientation
• thermal history
• variations in specimen geometry
• defects incorporated in the specimen during processing or use
• temperature and deformation rate
• mode of deformation

Three general modes of failure are identified in polymers; knowing brittle fracture, crazing and shear yielding.
In brittle fracture, failure is brittle in both microscopic (local) and macroscopic (bulk) level. Most familiar example is scattering of glass. Although most polymers are far less brittle then glass, they can be made to fail brittle under the right conditions. For example at very low temperatures, below $-100^\circ$C, most thermoplastics fail by brittle fracture just like glass.
When a specimen fails by brittle failure, primary (covalent) or secondary (van der Waals) bonds crossing the fracture surface, break. There is no plastic flow during the cleavage process since the mobility of the subunits is far too low. Defects in the material often act as stress concentrators and thus initiate failure by causing the local stress in their vicinity to exceed the strength of the material.

Three general modes of failure are identified in polymers; knowing brittle fracture, crazing and shear yielding.
In brittle fracture, failure is brittle in both microscopic (local) and macroscopic (bulk) level. Most familiar example is scattering of glass. Although most polymers are far less brittle then glass, they can be made to fail brittle under the right conditions. For example at very low temperatures, below $-100^\circ$C, most thermoplastics fail by brittle fracture just like glass.
When a specimen fails by brittle failure, primary (covalent) or secondary (van der Waals) bonds crossing the fracture surface, break. There is no plastic flow during the cleavage process since the mobility of the subunits is far too low. Defects in the material often act as stress concentrators and thus initiate failure by causing the local stress in their vicinity to exceed the strength of the material.

Figure 3.2: Process of Crazing; a) Formation of a localized plastic zone and buildup of significant lateral stresses. b) Nucleation of voids in the plastic zone, very often near the surface to release the triaxial state. c) coalescence of voids forming fibrils. d) wedge formed at the craze tip of deformed polymer [Bice2002].

Figure 3.3: The advance of the craze tip (from left to right) in which void fingers advance into the wedge of deformed polymer [Bice2002].

Crazing and shear yielding both require sufficient mobility of chain segments to allow plastic flow at molecular level. Both processes are therefore considered to be ductile at
Figure 3.4: The difference between a craze (left) and a crack (right). As the tip propagates, some craze fibrils start to breakdown. Crack propagation can occur if the stress is high enough and the craze has reached a critical size [Bice2002].

molecular level.
At macroscopic level however shear yielding is far more ductile then the process of failure by crazing. In crazing the following stages can be determined: cavitation, craze nucleation, propagation and breakdown and finally crack propagation (Figure 3.2 - 3.4). A sliding movement of atom layers along each other can explain the process of shear yielding. (Figure 3.5)

Figure 3.5: Simplification of the shear yield process [Bice2002].

The deformation mode affects the dominant failure mechanism by imposing different stress states on the specimen. For example the chance to fail by brittle failure under plane tension is much greater than under simple shear.
The specimen geometry affects the failure mechanism by causing different stress states in the specimen as well. For example thick specimens are much more likely to fail under brittle failure than thin films because of the tri-axial stress state that is created. Factors related to fabrication or end use affect the dominant failure mechanism by altering the specimen itself. For example, specimens manufactured by injection molding often show anisotropic behavior and exposure to harsh environments such as long high heat and humidity exposure can cause the material to degrade.
A rule of thumb is that, all other factors being equal, the polymer with the most ductile mode of failure will be the most useful one.

### 3.1.3 Stress strain curve

A typical stress strain curve can be seen in figure 3.6 for a ductile thermoplastic. Easy to distinguish are the elastic region with pre-yield, the yield point, post yield region and the point of fracture. More about this subject will be discussed in the next section.

GE has an extensive engineering data system. Two of its major tools contain a lot of material data necessary for the design process. First tool are the engineering datasheets. They are available for people inside as well as outside the company. They provide general material data such as yield stress, fracture
3.2 Constitutive Relations

In order to be able to perform a Finite Element Analysis, reasonable assumptions or simplifications have to be made to obtain a solution. This means discretization of the material continuum through finite elements, assumed loading and boundary conditions and it involves assumed material properties and material constitutive models that best describe material characteristics and failure criteria during an airbag deployment.

The last topic is the main point of interest of this section. Traditional FEA are built around simulating steel and other materials with metallic characteristics. Engineering thermoplastics have substantially greater viscoelastic and viscoplastic behavior than metals and this is not well reflected in the material models in most FEA solvers. Current methods involve performing uniaxial tensile stress-strain testing on material samples, converting these data to true stress-strain and placing the data in a mathematical representation developed for metals. Deficiencies occur in material testing, material database and mathematical formulations for constitutive equations.

Plastics show strong strain rate dependence for yield stress, flow curve, failure strain and modulus of elasticity. Additionally many polymers show softening (load drop) in the tensile stress-strain curves. Because of the load drop, locally very high strains can occur. These strains are hard to detect and the softening behavior often causes numerical problems in FEA.

The third difference between plastics and metals is the effect of the state of stress on yield. The yield stress of plastics not only depends on the deviatory, but also on the hydrostatic components of the stress tensor and therefore the Von Mises criterion is not suitable and should be modified.

A last difference is due to the low thermal conductivity and high ductility of plastics. Plastics experience significant adiabatic heating at relatively low strain rate. As a result, the stress-strain curves at different strain rates can cross each other. Typical thermoplastic behavior is an initial yield followed by a sudden load drop, then deforma-
Figure 3.7: Typical influence of temperature and strain rate on the stress/strain curve.

...tion continuously at lower stress until rupture as can be seen in figure 3.6. In literature, there are many discussions on the mechanisms associated with load drop. No theory is better than the other and they provide not so much insight. Therefore this project will focus more on the behavior itself then on the mechanisms. Three stages will be considered: elastic deformation and initial yield, post yield deformation and fracture. Hereby the emphasis will be on strain rate dependency in order to be able to use the data for an airbag deployment simulation.

3.2.1 Elastic deformation and initial yield

Young’s Modulus

The mechanism of small strain behavior is outlined in the preceding section. Here we saw that Young’s modulus relates stress to strain. Young’s modulus can be drastically affected by strain rate, thus resulting in a different value for stress at the same strain. Therefore, the simplest constitutive relation for a polymer should contain time or frequency as a variable in addition to stress and strain [Ward1971]. Also the temperature can have a large influence on the E-modulus. Both effects can be seen in figure 3.7.

Yield Stress

The peak stress in the initial yield stage depends on the strain rate similar to the strain rate effect on the yield stress in metals. However the strain rate dependency follows a different pattern than the Cowper-Symonds model (3.8), which is often used to incorporate strain rate effects in FEA solvers.

\[ \sigma_y = \sigma_0[1 + \left( \frac{\dot{\varepsilon}}{c} \right)^{1/p}] \]  

(3.8)

where \( c \) and \( p \) are constants.

Experimental data [Brow1987] suggest that thermoplastics follow a semi-empirical relation according to:

\[ \sigma_y = \sigma_0 + \beta \log \dot{\varepsilon} \]

(3.9)

where \( \sigma_0 \) and \( \beta \) are constants.

Equation 3.8 describes a reduced strain effect on the yield stress per decade of increasing strain rate whereas equation 3.9 describes a uniform increase in yield stress per decade.
of increasing strain rate. The latter is stated by a former GE study, which showed in the strain range of 0.001/s to 20/s an increase in yield strength of about 7% per decade and an increase in Young’s modulus of about 4% per decade. GE developed the Linear Plastic Elasticity Model, which can be used in LS-Dyna, and this model incorporates these effects.

**Yield Criterion**

Another difference between yielding in thermoplastics and metals is the state of stress upon yield. Unless subject to high pressure, the yield stress of metals depends only on the deviatory stress tensor and therefore follows the Von Mises criterion.

\[
\sigma_0 = \frac{1}{\sqrt{2}} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{1/2}
\] (3.10)

The yield stress of thermoplastics depends also on the hydrostatic components of the stress tensor. A modified criterion has been recommended for plastic materials [1,3,4].

\[
\sigma_0 = \frac{1}{\sqrt{2}} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{1/2} = \sigma_c - \sqrt{3} \mu \sigma_m
\] (3.11)

\[
\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}
\] (3.12)

\(\sigma_c\) represents the cohesion of the material and \(\mu\) is the coefficient of friction. The difference between these criteria can be observed by two cases: uniaxial tension and uniaxial loading. Under uniaxial tensile loading \(\sigma_1=\sigma, \ \sigma_2=\sigma_3=0\). Equation 3.11 gives:

\[
\sigma_y = \sigma_c - \frac{\sqrt{3}}{3} \mu \sigma_1
\] (3.13)

Under uniaxial compression loading \(\sigma_1=-\sigma, \ \sigma_2=\sigma_3=0\), equation 3.11 gives:

\[
\sigma_y = \sigma_c + \frac{\sqrt{3}}{3} \mu \sigma_1
\] (3.14)

The value of \(\mu\) is in the range of 0.1 to 0.2 for plastic materials [1,4]. This translates into 11.5% to 23% difference in yield strength between uniaxial tensile and compression loading conditions.

### 3.2.2 Post yield behavior

**Hardening and Softening**

Plastics experience strain hardening as well as strain softening in the post yield stage, as is the case for metals. There are, however, more softening mechanisms in plastics. Very common mechanisms are crazing in amorphous structure, restructuring of crystalline structure, necking and adiabatic heating. Depending on the stress rate one of the mechanisms may become dominant. As said, plastics experience significant adiabatic heating at lower strain rates due to their low thermal conductivity. Transition between isothermal and adiabatic conditions can be the case for strain rates as low as 0.1/s [1,4].
Poisson’s ratio

Thermoplastics, unlike metals, usually dilate during inelastic deformation and hence \( \nu < 0.5 \). Poisson’s ratio of ABS for instance, reduces from 0.35 to 0.25 during deformation as shown in figure 3.8(a). The effect of Poisson’s ratio variation on true stress calculation will be examined.

\[
\sigma_{\text{true}} = \frac{P}{A} = \frac{P}{A_0} \frac{A_0}{A} = \frac{\sigma_{\text{eng}} A_0}{A} \quad (3.15)
\]

\[
\varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{eng}}) \quad (3.16)
\]

\[
\varepsilon_{\text{true}}^t = \ln \frac{d}{d_0} = -\nu \varepsilon_{\text{true}}^l \quad (3.17)
\]

\[
\frac{A_0}{A} = \left( \frac{d_0}{d} \right)^2 = (1 + \varepsilon_{\text{eng}}^l)^{2\nu} \quad (3.18)
\]

where \( \varepsilon_{\text{true}}^t \) and \( \varepsilon_{\text{true}}^l \) are the strains along the loading axis and transverse to the loading axis; \( d_0 \) and \( d \) are the initial and instantaneous diameter of the cross section.

Combining equation 3.15 and 3.18 gives:

\[
\sigma_{\text{true}} = \sigma_{\text{eng}} (1 + \varepsilon_{\text{eng}}^l)^{2\nu} \quad (3.19)
\]

Equation 3.19 easily reveals the influence of Poisson’s ratio on the true stress. This influence can be significant as can be seen from figure 3.8(b), especially for large strain. However, Keuerleber [Kene2000] showed that the overall significance of a changing Poisson ratio in an FEA of airbag covers is very low. Low temperature effects and reduced failure strain at high strain rates are far more significant.
3.2.3 Fracture

The mechanisms for failure of thermoplastics have been discussed in the preceding section; it depends on the strain rate and the state of stress, as in metals. Unlike the case of Young’s modulus and yield stress, there is no general rule for the variation of failure strain with strain rate.

The glass transition temperature marks the transition from entropy-elastic to energy elastic (going to lower temperatures) and therefore a change in material behavior from ductile to brittle. At low temperatures like the requirement for airbag testing at $-30^\circ C$, most thermoplastics approach their glass transition temperature; a high strain rate situation enhances this effect, thus causing most thermoplastics to behave extremely brittle at low temperatures. As will be learned in the next section, it is very difficult to determine the fracture strain under high strain rates, this causes that the application of high strain rate data sometimes becomes very cumbersome. The test method and conditions should therefore always be investigated to be able to determine the usefulness of the data. In the next chapter currently common ways of high strain rate data generation will be evaluated and the problems will be discussed.

As known, the area under the stress strain curve defines the amount of energy absorbed by the material. So the fracture strain has a direct influence on this. The inability to determine fracture strain, thus the ability to predict energy absorbing capabilities of a material, can make a FEA of an impact sometimes complete useless.

3.3 High Strain Rate Testing

As mentioned in the previous section, in order to be able to perform a realistic FEA it is necessary to obtain realistic material data at high strain rates. This data is required as input for the computational model. If accurate numerical results can be obtained from the computational models and high strain rate data, realistic predictions of the behavior of the system can be done which reduces development time and cost.

Material properties of interest for high strain rates testing include yield and failure stress, yield and failure strain and moduli.

Unfortunately, generating high strain rate test data is much more complicated then generating quasi-static data. The assumptions valid in static tests do not always apply during high strain rate testing. Because only a homogeneous stress state is achieved, high strain rate testing may not provide "true" material properties. Additionally a great deal of engineering judgement and manipulation is required when reducing high strain rate data. Because of this, the tensile data obtained from tests should only be compared with tests having similar experimental setups and data reduction schemes. The fact that it is hard to compare data, puts immediate question marks at the usability for FEA, surely, data that reflect reality should be comparable. However, with the right engineering judgement, results can be obtained, but always pay caution in evaluating the outcome of a FEA with high strain material data.

Because of the problems in measurement of material data at high strain rates, an ISO project has tried to develop a model to predict the data with the aid of extrapolation of quasi-static data. This study however, proved useless for applications where the energy absorbing behavior of the materials is one of the main reasons for FEA, such as energy absorbing capabilities for knee bolsters and airbag covers, because no prediction for the failure strain can be done.

Therefore SAE, the University of Dayton and a hand full of companies, including GE Plastics, are working on a recommended practice according to which tests should be performed in order to be able to compare results and to obtain most realistic data.
3.3.1 Testing Procedures

Many different methods for high strain rate testing are available. Distinction can be made between high strain rate tensile testing, high frequency compressive testing and high speed impact testing.

In general one can say that neither of the methods provides material properties as accurately as quasi-static test methods. Main purpose is to determine the relative effects of increasing strain rate. Results are highly dependent on the test method, strain rate, specimen geometry and test temperature and should always be analyzed intensely.

Main factors that influence the outcome of the measurements are the load application, the strain measuring devices and the equipment response. Of high importance is the conditioning of the material after molding.

To obtain usable results the following goal can be formulated: introduce enough stress waves in the gage area to produce an approximate equilibrium relatively quickly after the load is introduced into the specimen in order to obtain a "quasi-homogeneous" stress and strain field so one can define nominal stress and strain states. Therefore small specimens are dictated in order to maximize the number of stress waves reflected along the gage length. Three areas of concern will be discussed below: specimen size, resonant frequency of the test system and the frequency response of the measurement system.

3.3.2 Test Device Requirements

Ideally the test machine will have a constant displacement rate until the point of necking. In the region of onset of loading variability occurs, generally one can say that the rate should be constant once the load on the specimen is 25% of its yield load. The effect of a changing crosshead rate dependent on the material. If the material appears to be strain rate sensitive a smaller tolerance in crosshead rate should be achieved.

Damping must be used for high strain rate testing and should be optimized to minimize the initial material response to load application. Any damping related effects should be gone when the applied load is 25% of yield.

The grips should be lightweight to minimize inertial effects and to increase the natural frequency.

The displacement signal of the clamps should be used with caution to determine strain. These data reflect the global behavior of the load train and do not have the resolution to record the transition from elastic to plastic deformation or to determine the E modulus. Besides that, the measurement does not reflect the post yield strain accurately, especially if a localized reduction in cross-section occurs, i.e. necking.

Strain along the gage length can be measured with strain gages, low inertia extensometers (LVDT's) and non-contact extensometers (optic extensometers). The measurement technique is not allowed to affect the test results. At strain rates higher then 1/s, the inertia effects of attached extensometers become too significant.

High frequency responses of the measurement equipment are required. It is necessary to determine whether the equipment is capable of accurately recording the test. The maximum test rate of the system depends on the frequency response of the transducers, signal conditioners, signal amplifiers and recorders.

Besides that, each component has a characteristic resonant frequency; it is necessary to determine the combined effect of all system components.
3.3.3 Specimen Configuration

The best specimen configuration depends on the maximum desired strain rate, material stiffness, material density, yield strain, stroke displacement rate and equipment resonant frequency. For all tested strain rates the same specimen geometry has to be used, so geometry cannot be a source of variability.

To obtain an initial test geometry, guidelines are developed by the University of Dayton as shown in appendix A and B. Analysis of some predetermined initial geometries should be the guide as to whether what specimen geometry is optimal.

The goal is to have at least 10, preferably 15 stress waves propagating through the material before yield to ensure an approximate equilibrium in the gage section. If this is not the case, the accuracy in determining elastic properties and yield point becomes difficult.

The load introduction into the specimen will result in stress waves propagating through the specimen and the load train. Reflected waves will occur at each change in specimen profile, interfaces in gripping mechanism and interfaces between the components of the load train.

The time for a wave to travel through the gage is twice the length of the gage divided by the wave propagation speed, which is dependent on the E modulus and the density of the material. Appendix A will provide a method to calculate the number of waves through the material.

3.3.4 System Resonance

Stress waves are also generated if the rate of loading excites the loading systems natural frequency, as can be seen in figure 3.9(a). It is desired to keep the amplitude of the test systems resonant frequency as low as possible, the strain rate can then be relatively constant, which results in minimal ripples in the curve.

![Figure 3.9: Influence of system ringing on stress measurement](Hill2003)

(a) Influence of system ringing on measured stress. (b) Stress measured at two systems with different natural frequencies. (curve is shifted for comparison).

The accuracy of yield point determination is reduced if the resonant frequency of the test system decreases. The resonant frequency can be checked with inducing ringing by tapping the load measurement end. Modifications in test setup, i.e. other clamps, can cause large variations in systems natural frequency.
3.3.5 Frequency of the measurement system

To ensure the accuracy of the data, the system should be able to accurately record the fastest signal change during the test. This can be expressed as a minimum slew rate, measured in Volts/second. However, it is more common to use the frequency response of the measurement system.

A measurement system’s response is normally measured in decibels (dB). The frequency response of sound amplifiers is normally given as the -3 dB point. This corresponds to a reduction of approximately 30% in the signal. However, the -3 dB point is not sufficient in a load measuring system. It is more common to use the -0.5 dB point (or -5%). If the frequency response of the system is low, then the high rate response will be underestimated.

For example, consider a test where the time to yield is 1 millisecond. If the signal up to yield is approximated as the first quarter of the sine wave, the frequency of the signal is:

\[ F \approx \frac{0.25}{t_{\text{yield}}} \approx \frac{0.25}{0.001} \approx 250 \text{ Hz} \]  

(3.20)

The rise time of the measurement system should be much less than the rise time of the load signal, preferably by at least an order of magnitude. A slow response of the measurement system may not define the material response with respect to yield, ultimate stress, or fracture.

Figure 3.10 shows the frequency response of a measurement system with a low pass filter. The system has a drop-off of -0.5 db at 100 Hz, and a -3 db drop-off by 200 Hz. This system would be inadequate to measure the 250 Hz load signal.

The effects of an inadequate response in the measurement system are illustrated in figures 3.11. The system with the low pass filter shows a gradual decrease in stress after failure instead of a clear fracture point (figure 3.11(a)). In addition, the elastic response, shown in figure 3.11(b), is underestimated.

3.3.6 Data Analysis

Caution should be taken for analyzing the following test data.

*Strain rate.* The strain rate varies greatly during a test. Large amplitude stress waves may occur and the instantaneous strain rate may vary from large positive to large negative values. It is important to report the method of rate calculation. Nominal strain rate is given by:

\[ \dot{\epsilon}_{\text{nom}} = \frac{\dot{\delta}}{t_s} \]  

(3.21)
(a) Undefined fracture point due to inadequate measurement response.

(b) Underestimated elastic response due to inadequate measurement response.

Figure 3.11: Influence of measurement response on recorded data [Hill2003].

where $\dot{\delta}$ is the clamp displacement rate and $l_s$ is the initial gage length.

This is a rough estimate and as said the nominal strain rate is not a good indicator of the actual strain rate, especially not in brittle materials or at very low temperatures. The strain rate in brittle materials generally increases up to failure because plastic deformation may not occur. As stated the elastic strain rate may vary, but the plastic strain rate can be indicated by a constant in the region just past yield to the point of instability. The rate for a dynamic test will be described by the plastic strain rate.

$E$ modulus. It might become difficult to define an elastic range for modulus measurement as the test rate increases. Bending often occurs during the onset of load. Compensation for bending is necessary. An often described effect is the occurrence of a toe region in the stress/strain curve. This is the initial part of the curve where initial effects cannot be neglected. The clamp has to be brought onto the desired speed and this may take a while. The data collected before the clamp reached this speed have to be adjusted.

A solution often used in high strain rate tests with thermoplastics, is the use of clamps with a build-in accelerator distance as can be seen in Figure 3.12. Hereby, the piston is brought up to the desired speed, then grasps the clamp and brings it immediately onto the required speed. A disadvantage is that this system can induce a large resonances.

High amplitude stress waves. The potential for system resonance; i.e. ringing, increases with the test rate. Discrete waves can occur in the elastic or plastic portion of the response. The relative wave amplitude may be significant, especially in the pre-yield response.

Time shift. Data streams need to be reconciled as a measurable time lag may be noted between various recorded data channels, such as load and strain, as the test rate increases.

3.3.7 Obtaining more accurate fracture strain data

A technique to determine the fracture strain in impact situations more accurately is the Finite Element Method itself. A specimen is subjected to a dynamic impact test, a dynatub test for ductile materials or an Izod-Notch impact test for brittle materials. The load and displacement of the impactor are recorded. A finite element model of this system is created to simulate the impact event. Material properties are modified by trial and error to obtain a response, which correlates
with the load displacement curve obtained in physical tests. This method provides uniaxial data based on biaxial stress data, but can be difficult to complete if the finite element method uses the same stress-strain curve for tension and compression. Droptower tests are being developed with the purpose of more accurate failure strain data and lower cost than the highly complicated high-speed tensile tests. Problems arise when recording data in a way they are easy applicable in FEA. For companies like GE, this kind of test might be a more cost effective approach for tackling the problem of obtaining high strain rate data.

Summarizing one can say that it is very difficult to generate high strain rate material properties usable for FEA. Depending on material and test method, sometimes data can be generated that are realistic and usable. Very high strain rate data for impact events should always be treated with caution. The influence of strain rate on $E$-modulus and yield stress can often be distinguished. Most difficult is to determine an accurate fracture strain. When using high strain rate data one should always be aware how data are generated and if the test set-up is accurate. Data that might appear realistic might become unrealistic after investigation.
Chapter 4

Soft Seamless Airbag Correlation Study

In order to shorten the design cycle of airbag systems, GE has two tools available. One is the Finite Element Method, used to simulate an airbag to evaluate the deployment behavior. The other is a deployment lab where deployments can be performed with live canisters and with the use of compressed gas.

The cold compressed gas setup is used to be able to do large amounts of deployments in a short period of time at minimal cost. A general live airbag deployment costs, beside the instrument panel, about 1200 US dollar. A compressed gas deployment is much cheaper, about 50 US dollar. In the case large amounts of testing have to be performed, for instance in the case of a New Product Introduction, or NPI, the overall savings with compressed gas can be significant.

However, there is one major drawback. The response of the compressed air set up is slower than a live canister, resulting in a lower peak pressure. In most cases however, to study material behavior such as rupture and scattering, cold gas deployments give a good indication of the material behavior in reality. This can be verified with a low amount of live deployments.

To study the correlation of the available tools with reality, a program with Lear corp. has been defined to study the correlation between an FEA of an airbag deployment in a Volvo XC90 IP with live deployments and with cold gas deployments. For this purpose Lear provided 18 instrument panels with nine loaded canisters for live deployments and the other nine panels are tested with compressed gas. Besides that they have build a steel fixture to hold the IP’s during testing. The airbag testing will be performed at the PPDC and the predictive engineering group at the John F. Welsh Technology Center, or JFWTC, in Bangalore India, will do a FEA of these deployments.

Main interest of the study is the correlation between the different analysis tools, especially at very low temperature. As discussed before, plastics become more brittle at low temperatures and in impact situations like airbag deployments, scattering is a highly prohibited phenomenon. To investigate simultaneously the low temperature behavior, the tests are performed at $-30^\circ C$. Goal of the study is defined as: "A research to the behavior and influence of skin and foam on deployments at very low temperature and the correlation between the available tools for finite element analysis, cold gas and live deployment testing."

In this chapter, first the basics of airbags and the cold gas deployment setup will be discussed. Then determination of material properties and choosing a suitable material model for FEA will get attention and finally the tests and results will be discussed.
4.1 Airbag Basics

Official function description of a passenger side airbag is to protect the front passenger against head and chest injuries in a vehicle impact with a solid obstacle at speeds up to 60km/hr.

The passenger airbag actually consists of a large bag, connected to a high-speed gas generator and its surrounding structure. Depending on vehicle type and structure-deformation response, airbags have different filling capacities and pressure build up. Two types of gas generators are distinguished; the solid conventional generator and the hybrid generator. Both are equipped with a solid pyrotechnic material, capable of very quick combustion to generate enough gas to fill the bag in the desired time. The Hybrid generator has an extra chamber next to the combustion chamber, filled with cold non-flammable gas. The combustion gasses are forced to flow through the cold gas chamber. The stored gas works as a cooling system, thus preventing the occupant from burning (figure 4.2(a)).

Sometimes two stage inflators are used. The second stage is added to extend the time the bag is deployed. Gasses start flowing out of the bag directly after deployment; a second stage refills the bag one time.

An adaptation of the pressure peak to the severity of the accident is possible by multi-stage ignition. Hereby several pyrotechnic storage chambers are incorporated which can be fired one after another, several at the same time or only just a few, depending on the severity of the impact.

(a) Main components of the Airbag system.

(b) Layout of a dual stage inflator unit.

Figure 4.1: Main Airbag components.
As the gases flow out of the inflator unit, they flow through the diffusor, which guides and diffuses the gases into the bag. The bag is folded between the diffusor and the airbag door in such a way that a fast and stable deployment is guaranteed. Different folding patterns cause different inflating patterns and different loading conditions on the instrument panel. The airbag can be rolled-up or be zigzag folded in different ways. In general a rolled-up pattern gives a longer time to fill the airbag completely, but a zigzag pattern results in higher pressure peaks, increased loading on the IP structure, which can result in what is called the Bell Mouth problem.

The Bell Mouth problem is the occurrence of large deformations of the IP structure, caused by the inflating airbag. It is highly undesirable that the whole IP structure must be replaced after a deployment.

Main point of interest is that the airbag is fully deployed before the occupant comes in contact with it. The airbag then responds to upper body contact with partial deflation in a response pattern calculated to combine gentle impact energy absorption with non-critical surface pressures and decelerations of the passenger. The maximum forward displacement of the occupant upon contact is 12.5 cm, corresponding to 40 ms at 50 km/hr after initial impact. It needs 10 ms for electronic firing to take place, thus leaving 30 ms for the airbag to fully deploy. It then takes 80 to 100 ms to deflate through the deflation holes.

The shape of the inflated airbag is determined by two factors, one is the shape and volume of the bag; the other is the length and number of tethers. Tethers are ropes mounted inside the bag; they give the inflated bag a more flat surface and are used to optimize the time of contact between bag and face of the passenger and to prevent the occupant from sliding of the bag.

Most ideal shape of a Passenger Airbag, or PAB deployment can be defined as that the PAB should not produce deformations of its surrounding structure and should fully deploy in planned time to protect occupant from injuries.
4.2 Cold Gas Deployment Facility

At the earlier mentioned Polymer Processing and Development Center in Pittsfield, PPDC, many different tools for research are available. Processing tools like injection molding, blow molding, extrusion and thermoforming are available. Besides that there is the availability for materials characterization and part performance.

One of the part performance tools is the cold gas airbag deployment set up. It consists basically of two large vessels, one with compressed air and one with compressed nitrogen gas. These vessels are connected through high-speed valves to a duct that leads into the environmental chamber, where it is connected to a modified airbag canister (figure 4.3).

The environmental chamber is capable of adjusting the environment for temperature (between $-50^\circ C$ and $200^\circ C$) and humidity (25%RH to 95%RH). That is well within the range for automotive parts such as instrument panels and airbag covers.

Coupled to the system is a high-speed data acquisition system that is capable of recording pressure in the canister, recording time and temperature changes. Monitoring temperature of the environment as well as the temperature of the part is important since changes can occur because of the high intensity of the lamps that have to be used, to support the high-speed video cameras that are used for recording the deployment behavior.

![Figure 4.3: Cold Gas Deployment Setup](image-url)
4.3 Finite Element Analysis capabilities

The Automotive Application Development center in Southfield is closely related to the predictive engineering group at the John F. Welsh Technology Center, or JFWTC, in Bangalore India. Here we have access to process simulation tools to simulate mold filling, packing, fiber orientation, cooling behavior, shrink and warpage of the final parts, gas assist and co-injection molding. Structural simulation tools are for noise vibration harshness (NVH), FMVSS tests simulation, thermal stress analysis, gravity loads (SAG) behavior and airbag cover deployments. Here the actual FEA of the IP with the skin and foam will be performed.

4.3.1 Boundary Conditions

Since GE is only interested in the material behavior of the door and IP, the model can be simplified, i.e. some things that are necessary in a full vehicle deployment can be left out.

In other airbag simulations the windscreen is an important part of the modelling, since it is necessary to determine the load on the windscreen to see if it cracks, or worse, to see if it is blown out of the structure. However, in this study no attention is given to this subject and no windscreen will be modelled.

Another simplification in the boundary conditions seems very strange on first sight; the actual airbag is not modelled but approximated by a pressure load against the door. Studies by Hyun-Tack Cha [Hyun2001] have shown that the pressure distribution of a deploying airbag against the door is uniform and that this simplification is justified.

The pressure load in this study is taken from the actual deployments, both live and cold gas, but is modified for the part after material rupture. To prevent inconsistencies in the model, the pressure load has to drop to zero once the material ruptures, see figure 4.4.

Since the goal of this study is to correlate the material behavior under loading by the given airbag and not the deployment behavior of the bag itself, it is allowed to do this. There is no interest in simulation of the actual airbag. Simulation of the actual airbag is a project on its own and requires a lot of calculation capacity, this method is very quick and efficient.

Further boundaries are the mounting points on the fixture; these are the same as in the vehicle.

![Pressure vs. Time Curve](image)

Figure 4.4: Original and adjusted pressure vs. time curve.

4.3.2 Material Data

As outlined in the first part of this report, in order to perform an FEA it is necessary to obtain the correct material data. These are properties for density, E-modulus, Poisson's...
ratio, yield stress, yield strain, fracture strain and fracture stress. Because an airbag deployment is an impact event it is necessary to obtain the material properties at high strain rates. The high strain rate data for the retainer material, Cycoloy® C1100HF, have already been determined in the past and can be found in PC-EDD. A summary of the data is given in figure 3.7.

More complex is the data for the foam and skin. For these materials high strain rate tests have to be performed. Another complication is that material data that normally can be found in data sheets, such as density, are not available for the foam, because they are dependent on the processing conditions like temperature and pressure.

Decided is to perform tensile high strain rate tests with the skin material at quasi-static speed, 1.000%/s and 10.000%/s. This will provide adequate data for the intended FEA. Foam material is tested at the same strain rates in tensile tests, but besides that, also quasi static and high strain rate compression tests at 1.000%/s have to be performed to be able to calculate the Poisson ratio with the measured E-modulus and Bulk modulus.

All tests will be performed at $-30^\circ C$, the compression tests will also be performed at room temperature so data can also be used in HIC prediction.

**Sample preparation**

In order to obtain the material data, samples have been cut from the TPO skin for high strain rate testing. Lear provided sheets of this material and specimen could be knife cut according to the desired shape, ISO 8256 Type 3. These tensile bars have an initial length of 80 mm.

Specimen preparation for the foam material is much more complicated. In order to be able to cut specimens, plaques of 10, 20 and 40 mm thickness have been molded under the exact same conditions as during production. Blocks of 80x80x40 mm are cut for compression testing. Problem with preparation of the tensile bars is the layer of skin that exists after molding on the surface of the foam plaques. This skin has significant different material properties from the actual foam, and needs to be removed. Therefore the plaques are planed down with a high-speed milling machine. After that the specimens are cut out in a water-jet cutting process, according to DIN 53571 A and B, and DIN 53430. Three different specimens are made, to be able to evaluate which geometry gives the best result in high strain rate testing.

![Figure 4.5: Foam specimens for high strain rate testing.](image-url)
High strain rate test event

The high strain rate tests are performed at the Institute for Kunststoffprüfung in Stuttgart, Germany. This institute has much experience with high strain rate testing of foam and skin materials, especially for FEA simulation of airbag deployments. Tests are performed on a Zwick REL 1856 (figure 3.12), with clamp speeds of 1 and 10 m/s. This universal tensile machine, or UTM, is equipped with the earlier mentioned clamping device with integrated acceleration distance.

Test Data interpretation

As can be seen from Appendix C, the curves for the skin material are very consistent for the quasi-static tests. The E-modulus can be well determined from the 0.025-0.5 strain region. For the different specimen, the recorded fracture strain lies between 300% and 400%, what makes this a very ductile material. The lower fracture strains are due to inconsistencies in the thin material. The influence of these kinds of inconsistencies would be less if thicker samples would be chosen.

The high strain rate curves for both rates show relatively good reproducible curves. The softening effect decreases and the fracture strain decreases drastically. The curve for a rate of 1.000%/s shows an increase in yield stress as expected and a reliable fracture strain. The failure mechanism is crazing, which explains the appearance of the load drop, which is not a straight drop down, but a more gradual decline in stress. That is explained by the occurrence of tearing of material instead of instantaneous break.

The response in the 10.000%/s curve cannot be explained that easily. The gradual decline after the peak force, which can be seen as the fracture point, is due to an inaccurate measurement response. Also the lower peak force then measured at lower strain rates cannot be explained according the theory and is blamed on an inaccurate measurement response.

The recorded curves for the foam material are very reliable. Both the quasi static as well as the high-speed compression curves at both temperatures show good results, fully explainable by the theory. The curves are very reproducible, an effect that is often seen in compression tests because the influence of inconsistencies is less. The quasi-static curves at $-30^\circ C$ can be used to determine the bulk modulus, together with the E-modulus from the tensile tests, it is possible to calculate the Poisson’s ratio, see equation 3.7. A familiar effect is the increased stiffness as can be seen from the high-speed curve at $-30^\circ C$ by the steep initial response and the increased stress levels.

The tensile curves for the foam need more caution when interpret. Foam is a material that is very hard to characterize in tensile tests. Larger specimen are required to reduce the influence of the voids. Still large variability may occur as can be seen from these results.

The quasi static curves are consistent in the elastic region, the E-modulus can be well determined. A very distinct yield point however is absent and the fracture strain differs, just as the fracture stress. However, the results can be modified to use them in FEA. The influence of the inconsistencies in the material becomes more significant in the high strain rate test data. The E-modulus is still determinable but a reliable yield and fracture stress/strain are absent for both the data at 1.000%/s and 10.000%/s. The data at 10.000%/s are very unreliable because of an inadequate measurement response for both the force transducer as well as the LVDT’s to measure strain.
4.3.3 Material Model determination

In order to determine a material model for each layer that best describes the behavior of this material, different material models have to be investigated for their applicability. Based on their mathematical representation four different material models are identified knowing:

- Material Type 19, \textit{Strain Rate Dependent Plasticity}
- Material Type 24, \textit{Piecewise Linear Plasticity}
- Material Type 57, \textit{Low Density Foam}
- Material Type 83, \textit{Fu Chang Foam}

A summary of the description of these material models based on their description in the LS-Dyna manual [LS-D1999], can be found in Appendix D to G. Earlier studies showed that Cycoloy\textregistered{} C1100HF can be best modelled in LS-Dyna with Material Type 24. This material model is based on the Cowper-Symonds model as described in equation 3.8 in section 3.2. This section also states that this model is not accurate in modelling thermoplastics, however, with the viscoplastic option active, the model does describe thermoplastics and their strain rate dependency well. A more detailed description of the visoplastic option can be found in Appendix E. Shell elements are used for this material.

More complicated is a material model that reflects the behavior of this particular foam and also reflects the interaction with the Cycoloy\textregistered{} layer and the TPO skin. Initial trials are performed with material type 57 and 83. Both material models incorporate strain rate dependency. To connect the foam with the surrounding materials one can choose to use common nodes or rigid connections. Both material models prove to be inaccurate and failure only occurs between elements, no element failure could be achieved. Trials are continued with material type 19. This material shows hopeful results when modelled with solid elements and common nodes are used. The foam layer is four elements thick, this way elements can be made to fail faithfully. Because of the good results with the Cycoloy\textregistered{} retainer, initial trials with the TPO skin are also performed with material type 24. The results are good when shell elements are used.
4.3.4 First FEA Results

As we speak, only initial results are available. Material models have been determined, but some things have to be changed in the model. As can be seen from figure 4.6, the complete model does not reflect the behavior between different layers accurately. The layers detach when common nodes are used and rigid connections give unrealistic results. Therefore effort has to be put in modelling an adhesive between the layers. This can be done with the aid of foam adhesion data as they exist for this type of foam to Cycoloy® and for the TPO skin. As can be seen, the pressure curve taken from a cold gas deployment is able to open the Airbag system.

In this phase of the study, correlation between the different analysis tools is far from existent. Results however are hopeful and after optimizing the boundary conditions and the material data, correlation might be expected and FEA can be an helpful tool in developing Seamless Airbag systems.

Figure 4.6: Initial result of FEA of the Volvo XC-90 airbag canister. Only retainer and foam are modelled. Foam is modelled with material type 57 and shows an unrealistic failure between the elements of both layers.
Chapter 5

Hard Seamless correlation study

The tremendous growth of soft seamless airbag systems raised the question if there is a market for hard seamless systems. Soft instrument panels are traditionally applied in the high-end segments, where more care is taken concerning design and aesthetics. A benchmark study described below, shows that there is a large market for these systems and GE responded with the development of a low temperature ductility material, introduced in January 2004.

For a new product introduction, or NPI, a large amount of test procedures have to be followed, in order to obtain approval from the OEM’s for application of this new material. A set of tests has to be identified to cover the majority of the requirements of the major OEM’s. To facilitate the design process of a hard seamless door, a plaque study will be performed.

A tearseam will be laser scored in the plaques. The plaques will then be subjected to different tests, like heat ageing before deployment of airbags with the cold compress gas setup.

The geometry and parameters of the tearseam are determining the opening behavior of the door and it is an extensive process of laser scoring, deployments, modifying design and parameters and repeat of this process. Therefore, the demand arose for an FEA of the tearseam design, in order to vary the parameters, until an optimum design is obtained.

A correlation study between FEA plaque deployments and compressed gas deployments has been kicked off to determine the best way to model a tearseam.

First a seamless airbag assessment study will be discussed, then the manufacturing of the plaques and simulation of plaque deployments will be explained and finally the process of an NPI will be discussed.

5.1 Airbag Assessment Study

First it is necessary to assess the market for hard instrument panels and for current developments in existing seamless airbag systems. Main questions to be answered are:

- How big is the total market?
- What is the market share for soft seamless airbag systems and for hard seamless systems at this moment?
• Is the total market for seamless airbag systems growing?
• Is there still a market for hard instrument panels and is there a demand for hard seamless instrument panels?
• Do car manufacturers apply seamless technologies in all new vehicles, or only in certain segments?

To answer these questions an assessment study has been performed by assessing all vehicles at the Detroit Auto Show 2004 for the type of applied instrument panel, hard or soft and for the type of airbag system. Also the year of design was recorded to be able to do any predictions about trends. At the Auto Show, about 90\% of the vehicles on the market in the US could be assessed, the rest was done by visiting dealerships. The sales figures for 2003 and the production figures for 2004 for the North Americas can be found on the GE intranet as they are weekly updated. Figure 5.1 and 5.2 show the outcome of the study. As can be seen the North American market counts about 17 million vehicles of which 7.5 million vehicles is equipped with a hard instrument panel. The trend in the soft seamless airbag applications shows an increase in application of these systems. These systems are applied in the high-end segments but a significant trend can be seen in application of these systems in the lower segments. To a certain extend some traditionally hard instrument panels are replaced by soft seamless systems, because a good solution in hard seamless systems is unavailable. This is reflected by the small amount of hard seamless systems currently on the market.

Figure 5.1: Total vehicle production figures for 2004.

Figure 5.2: Vehicle production figures per OEM for 2004 in NA.
Only one vehicle, the Nissan Titan is equipped with a real hard seamless system. However, the demand for hard seamless systems appears to be large, especially the truck market is large in North America. Traditionally a hard IP is required in this market because it is more durable, but trucks are also used as luxury vehicles where a seamless system is preferred. Large players in this market are General Motors, Daimler Chrysler and Ford. Focus for application of the GE hingeless design should be with one of these OEM’s. To learn more about the seamless system of Nissan, a benchmark study to the Nissan Titan will be described below. It can be concluded that a significant market for hard seamless airbag systems exists and that there is no good solution yet.

5.1.1 Nissan Titan Benchmark Study

A thorough benchmark study is possible with the aid of the Ford Benchmark center in Dearborn, Michigan. This facility houses about 300 vehicles not older then four years of many different OEM’s. Because GE is a supplier for Ford, access is given to the complete facility and all vehicles can be researched. Most vehicles are already prepared in such a way that all interesting features of the car can be seen without tearing the car apart. The Nissan Titan however, is such an interesting car that a normal version and a complete torn down version are available. Here the complete IP could be researched and design solutions are revealed as can be seen from figure 5.3.

![Figure 5.3: Nissan Titan Hard Seamless Airbag Door.](image)

(a) Airbag mounting structure.  
(b) Tearseam and rupture pattern.

The Retainer is made from a 4mm thick thermoplastic material. The airbag door is defined in the retainer by a laser scored tearseam. As can be seen in the first picture, a complete structure is created to make the airbag door function in the proper way and to prevent it from scattering. An extra structure is added to stiffen the material around the door and to create a basis for the steel hinges. Also a piece of cloth can be distinguished that, together with the steel lath, prevents the material from scattering. The IP is made from a modified TPO material to enhance the low temperature ductility, but the material still behaves brittle at -30°C.

The airbag is deployed at room temperature, as can be seen from the second picture, delaminating of the material already takes place, a phenomenon that is highly undesirable because the chance that small pieces break off is enhanced. After the assessment and the benchmark study it can be concluded that there is a large market for hard seamless airbag systems and that a system like applied by Nissan can
be improved. This is the basis to kick off the development of the GE Hingeless design. As will be seen from the next section, the design is more simple, has less parts and a better low temperature behavior is expected.

5.2 The GE Hingeless Design Solution

The key to the design solution as proposed by GE is actually in the material. Besides the excellent material properties as mentioned in chapter two, this material has a very low temperature ductility. This material is specially developed for hard seamless airbag systems and was available by January 2004. Because of this very low temperature ductility the design can drastically change. Where as in the design for the Nissan Titan hinges and reinforcements were necessary, in the GE design these are all left out. The material is so strong, though ductile, that with a good design, rupture in the hinges and scattering of the material can be omitted. The result is a very simple design, with less parts, a shorter cycle time and lower cost. The IP will have an executive look, though will be suitable in applications where a durable solution is demanded.

Figure 5.4: The GE Hingeless Design Solution for hard seamless airbag systems.

To be able to determine the optimal design of the door and the best geometry of the tearseam, a plaque study will be performed. In this study different tearseam designs will be tested and observed.

5.3 Plaque Study

5.3.1 Different Designs

The opening behavior of the door highly depends on the design of the tearseam geometry. Therefore different designs will be researched to obtain the best geometry. Not only the geometry influences the opening behavior, also the way the tearseam is scored matters. This will be researched in a later stadium. First the geometry will be chosen. Three different geometries have been tested. Main goal is that the door opens uniform from the center of the door and that no rupture or fracture occurs. Plaques have been molded and the different designs have been laser scored in the plaques. Details of the laser scoring process will be discussed more in the next section. After that, the plaques were tested in the cold compressed gas deployment set-up at the Polymer Processing Development Center in Pittsfield, MA. Figure 1.1 shows different stages of deployment. The second design (figure 5.5(b)) appeared to have the most stable opening behavior and will be used for further optimization. The corners
of the hinges appeared to be weak in the first design and the opening behavior of the third design was not uniform, i.e. opening not always occurred from the center of the centerline.

![Figure 5.5: Different tearseam geometry designs.](image)

(a) Design one  
(b) Design two  
(c) Design three

5.3.2 Plaque Manufacturing

Now the optimal geometry has been chosen, it has to be optimized. As stated, not only the geometry of the tearseam matters, but also the way the seam is scored is of influence.

Laser scoring is a complicated process. It is not possible to just define a certain amount of holes with depths, but the result depends on many things, like material, material opacity, distance of the material to the laser, frequency and intensity of the laser and the shut-off energy. This is the energy, calculated with the the amount of light that is measured behind the plaque. During laser scoring, light passes through the material, the laser is shut down if the intensity of the light exceeds a certain threshold to be defined buy the user. The user defines actually a maximum hole dept. But it is not so that this dept is always reached. By defining the emitted energy the maximum hole dept is often not reached and if the plaque is not perfectly flat, the distance to the laser differs, resulting in a different hole dept.

Because of all these problems it is necessary to perfectly record the way the tearseam is scored and what the machine parameters were at that moment. Then the pattern can be reproduced at a later time.

The geometry is divided in different sections. Each section has its own parameters to enhance the opening behavior of the door. The middle of the centerline is weakened to assure opening in this particular position and the hinges are weakened to make sure all hinges actually open. The base of the hinges are stronger to stop the rupturing movement.

5.4 FEA of the Tearseam design

Because the process of trial and error is extensive, expensive and time consuming, the demand for an FEA of a laser scored airbag door arose. First al properties of the
tearseam had to be determined, then a model of the seam with these data has to be defined. Then the model can be compared with the deployments done with the cold compressed air set-up.

5.4.1 laser score data

After laser scoring the parameters of the different sections have been obtained under the microscope, as can be seen in figure H.1. Goal is to approach the real seam as close as possible in the model. Therefor four parameters were measured:

- The hole diameter
- The hole depth
- The distance between the holes
- Sometimes the laser is not shut down completely when moving from one hole to the next. The depth of the gutter is measured. This is called scoring in between.

5.4.2 Boundary Conditions and Material Model

Just as in the soft seamless airbag study, is the airbag deployment simulated by applying a pressure load which is taken from the pressure curve of an original plaque deployment. This curve again is modified for the period after rupture. In the original setup the plaque is clamped between bars and secured by 10 bolts. These are boundary conditions in the model as well. The tearseam is in the initial trials is simplified by weakening the material by modelling a gutter with the width of a hole, that is 0.4mm. For the different sections the residual wall thickness is different, as can be seen from figure 5.6. Finally it is meant to model the seam with a random hole generator tool in UniGraphix with the data obtained with the microscope(figure H.1) for each ID section. Solid brick elements are used, four to form the thickness of 3.5mm. The material model chosen is the linear plasticity model, MAT24 in LS-Dyna. This model uses quasi static and low strain rate material data and extrapolates these to high strain rate material properties. This is done because no high strain rate material properties are yet available. High strain rate tests for the modified Lexan® EXL are being set up.

5.4.3 Initial Results

The initial results (figure J.1) show a pattern that is not so much different from the real deployments. The different weaknesses of the different ID sections is reflected by the breakout in the center of the centerline. But the hinges do not come loose completely and in real deployments the material ruptured in the corners of the hinges, which is also not reflected. However, these results are hopeful and with the more accurately modelled tearseam with the microscopic data, a more realistic result should be possible. As we speak these results are not available. Also the use of high strain rate material properties for Lexan® EXL should enhance the results. Whenever the design is fully optimized and the structural analyses can be used to optimize other laser scored tearseam designs, the new material and the Hingeless hard seamless airbag technology can be brought on the market. The Process to do this will be described in the next section.
The NPI Process

Not only the introduction of a new technology, but also the introduction of a new material requires a lot of testing. OEM’s have each their own requirements and demand their own distinctive tests to be done. For the introduction of a material it is impossible to perform all these tests for all OEM’s. Therefore a set of tests has to be determined according to heat aging, humidity aging, scratch resistance and chemical resistance that cover a wide range of the requirements for all major OEM’s. It is not possible to define a set of most severe tests, so that if you perform these tests, all OEM’s are covered. For example, one OEM requires a 1000 hour heat aging at $85^\circ C$, the other requires 500 hours at $110^\circ C$. It is impossible to say which one is more severe on forehand, if one takes into account that the first one requires a maximum color change of 4 on the AATCC scale and the other a maximum of 3, it is even harder to compare different tests.

However, in order to make choices, tests that seemed to be most extreme on basis of experience and of the OEM’s that will most likely be the first customers, have been identified. A list of initial tests can be seen in appendix L.

The molded and laser scored plaques are subjected to these tests so they can be deployed afterwards and the influence of heat ageing, humidity aging or chemical attack on the material can be evaluated.

If the material performs well in deployment testing and alterations of the material is within limits, the material can be presented. Each OEM will approve the material grade, independent of the application, for the use in their vehicles. Then the material must be approved for the use in instrument panels. Last step is approval of the hingeless design in a prototype IP from the OEM.

A program with Ford has been kicked off. In this program a prototype tool is manufactured to be able to produce hard seamless IP’s. A hingeless design will be laser scored in this IP and if the material behaves as stated by GE, the OEM might decide to use the material and the technology in a real application.
Chapter 6

Conclusion

During my internship with General Electric I learned much about the Automotive industry and the process of developing new products for that market. A lot of knowledge about instrument panels and their design was gained.

Value of the internship for General Electric is the database with test and design requirements for instrument panels for nine different OEM’s that I managed to setup. Besides that, the initiative for investigating the possibilities and the importance of high strain rate testing was taken and good results are booked in this research. Driving the soft seamless airbag program and participation in the hard seamless airbag program provided much insight in existing Airbag technologies and is a basis for improvement of existing computer simulation procedures.

Tools used for development of existing products or the introduction of new ones have been investigated intensely. In order to be useful in the design process, the cold gas deployment facility and computer simulation tools should correlate with reality. Although the two assignments given to obtain this proof have not been finished until this day, some things can be stated.

A realistic FEA of an impact event such as an Airbag deployment requires high strain rate material data. Material properties measured during high strain rate tests are significantly different from data found in quasi static tests. Problems arise in generation and interpretation of this data. Basic properties such as E-Modulus and yield stress can be measured well, but a reproducible fracture strain is hard to obtain. Also, the implementation of data in a suitable material model can cause substantial problems. However, if material models are chosen carefully and material data have been generated with caution, realistic results might be possible.

The OEM’s however, never accept the results of a FEA as a proof for a suitable design. Real live tests always have to be performed to state the results of FEA. Besides that, for a New Product Introduction, extensive testing has to be done, in order to convince the OEM of the quality of the design and material. These tests might be different among OEM’s and therefore cause an extensive trajectory of testing and approval.

Main accomplishment for me however, might not be in the engineering field. During the five months I spent with General Electric, a lot of attention was paid to personal development.

Communication skills by email, telephone and directly interacting with people, have been improved tremendously. Besides that, the opportunity to give presentations to people within and without the team by conference call, net meeting and for a live
audience, have been practiced. Practicing these presentations with a GE employee provided ways for improvement of presentation skills. Learning how an international large company really works is an eye-opening experience and is something that will be of value for a lifetime. Working on projects directly with people in India, Sweden, the Netherlands, Canada and the US is challenging and requires good planning and communication. The chance offered to a co-op to own a project and define the way it is handled results in responsibility and shows direct results of decisions made. If the project develops well and people acknowledge results booked, appreciation is granted. For me this resulted in being able to join the discussion about high strain rate testing with people in- and outside the company, finally resulting in being able to discuss the status of high strain rate testing with the materials characterization team of the Ford Motor Company.
Bibliography


[Hyun2001] Hyun-Tack Cha, Sung-Su Han, "Head Impact and PAB Deployment Simulation of Vehicle Instrumental Panel System- Predicting Failure of Laser Scoring Line on PAB Region", HANPAM 2001


[Suff2001] B. Suffis, "FEA Simulation as a tool to optimize a laminated expanded polypropylene foam instrument panel", SAE Paper 01-0318, 2001


Appendix A

Calculation of the number of reflected waves in the gage section

The time of travel for a reflected elastic stress wave is dependent on the wave propagation speed in the polymer (A.1) and can be estimated by A.2:

$$\nu_m = \frac{E}{\rho}. \quad \text{(A.1)}$$

$$t_{\text{wave}} \approx \frac{2x}{\nu_m}. \quad \text{(A.2)}$$

The time-to-yield is dependent on the yield strain and the strain rate:

$$t_{\text{yield}} \approx \frac{\varepsilon_y}{\dot{\varepsilon}_{\text{elas}}}. \quad \text{(A.3)}$$

Experience has shown that the elastic strain rate from 50% to 90% of yield is slower than the nominal plastic strain rate by a factor of 2 to 3. The elastic strain rate in equation A.3 can be modified to reflect this relationship to:

$$\dot{\varepsilon}_{\text{elas}} \approx 0.5 \dot{\varepsilon}_{\text{plas}}. \quad \text{(A.4)}$$

where the nominal plastic strain rate is defined as:

$$\dot{\varepsilon}_{\text{plas}} \approx \frac{\delta}{x}. \quad \text{(A.5)}$$

Equation A.3 can be rewritten as

$$t_{\text{yield}} \approx \left( \frac{\varepsilon_y}{\dot{\varepsilon}_{\text{elas}}} \right) \approx \left( \frac{2 \varepsilon_y x}{\delta} \right). \quad \text{(A.6)}$$

As mentioned, numerous stress waves are needed in the gage section in order to have an approximate equilibrium. Therefore, one could estimate the number of reflected waves as a function of the test rate by combining equations A.2 and A.6, as

$$N \approx \frac{t_{\text{yield}}}{t_{\text{wave}}} \approx \frac{\left( \frac{2 \varepsilon_y x}{\delta} \right)}{\left( \frac{2x}{\nu_m} \right)} \approx \frac{\varepsilon_y \nu_m}{\delta}. \quad \text{(A.7)}$$

The effect of changes in material and test rate can be quickly determined by using equation A.7.
Appendix B

Calculation of the number of reflected waves in the load train

The guidelines described in Appendix A can be used when considering the reflected waves through the entire load train. As mentioned in section 3.3.3, a minimum of 10 reflected waves in the gage section of the specimen are desired for an approximate equilibrium.

The time of travel for the reflected stress wave is dependent on the wave propagation speed in the specimen and the fixturing. One can consider the primary stress wave generated at the lower grip point and reflected back at the load-measuring device. This distance consists of the distance between the grips, $x$, plus the distance from the load measuring device to load transfer region on the grip closest to the load measuring device.

The travel time for one reflected stress wave can be estimated by:

$$t_{\text{wave}} \approx \left[ \frac{x_f}{\nu_f} + \frac{x}{\nu_m} \right]. \quad (B.1)$$

Typical fixturing will be made of metal and the wave propagation speed through the fixturing will be faster than through the specimen. We get:

$$N \approx \frac{\frac{2 \varepsilon_y x}{\delta}}{2 \left( \frac{x_f}{\nu_f} + \frac{x}{\nu_m} \right)} \approx \left( \frac{\varepsilon_y x \nu_f \nu_m}{\delta (x_f \nu_m + x \nu_f)} \right). \quad (B.2)$$

The estimated number of waves given by B.2 is one more point to consider. Shortening the load train would increase the number of reflected waves.

Example?
Appendix C

High strain rate test results

Figure C.1: Quasi static tensile test results of TPO skin at -30°C
Figure C.2: High strain rate (1000%/s) tensile test results of TPO skin at -30°C

Figure C.3: High strain rate (10000%/s) tensile test results of TPO skin at -30°C
Figure C.4: Quasi static compression test results of Foam at Room Temperature

Figure C.5: High strain rate (2000%/s) compression test results of Foam at Room Temperature
Figure C.6: Quasi static compression test results of Foam at -30°C

Figure C.7: High strain rate (2000%/s) compression test results of Foam at -30°C
APPENDIX C. HIGH STRAIN RATE TEST RESULTS

Figure C.8: Quasi static tensile test results of Foam at -30°C

Figure C.9: High strain rate (1000%/s) tensile test results of Foam at -30°C
Figure C.10: High strain rate (10000%/s) tensile test results of Foam at -30°C
Appendix D

Material Type 19

\textbf{Mat\_Strain\_Rate\_Dependent\_Plasticity}

A strain rate dependent material can be defined. Required is a curve for the yield stress versus the effective strain rate. Optionally, Young’s modulus and the tangent modulus can also be defined versus the effective strain rate. Also, optional failure of the material can be defined either by defining a von Mises stress at failure as a function of the effective strain rate (valid for solids/shells/thick shells) or by defining a minimum time step size (only for shells).

\textbf{Input variables}

- **MID**: Material identification. A unique number has to be chosen.
- **RO**: Mass density.
- **E**: Young’s modulus.
- **PR**: Poisson’s ratio.
- **VP**: Formulation for rate effects.
- **LC1**: Load curve ID defining the yield stress $\sigma_0$ as a function of the effective strain rate.
- **ETAN**: Plastic hardening modulus $E_t$.
- **LC2**: Load curve ID defining Young’s modulus as a function of the effective strain rate (optional).
- **LC3**: Load curve ID defining tangent modulus as a function of the effective strain rate (optional).
- **LC4**: Load curve defining von Mises stress at failure as a function of the effective strain rate (optional).
- **TDEL**: Minimum step size for automatic element deletion. Use for shells only.
- **RDEF**: Redefinition of failure curve.

\textbf{Remarks}

In this model, a load curve is used to describe the yield strength $\sigma_0$ as a function of the effective strain rate

$$\dot{\varepsilon} = \left(\frac{2}{3} \dot{\varepsilon}_{ij} \dot{\varepsilon}_{ij}\right)^{1/2} \quad (D.1)$$

and the prime denotes the deviatoric component. The yield stress is defined as

$$\sigma_y = \sigma_0(\dot{\varepsilon}) + E_p \dot{\varepsilon}^p \quad (D.2)$$
where $\bar{\varepsilon}$ is the effective strain and $E_h$ is given in terms of Young’s modulus and the tangent modulus by

$$E_p = \frac{E E_t}{E - E_t}.$$  \hspace{1cm} (D.3)

Both Young’s modulus and the tangent modulus may optionally be made functions of strain rate by specifying a load curve ID giving their values as a function of strain rate. If these load curve ID’s are input as 0, then the constant values specified in the input are used.

This model also contains a simple mechanism for modelling material failure. This option is activated by specifying a load curve ID defining the effective stress at failure as a function of strain rate. For solid elements, once the effective stress exceeds the failure stress the element is deemed to have failed and is removed from the solution. For shell elements the entire shell element is deemed to have failed if all integration points through the thickness have an effective stress that exceeds the failure stress. After failure the shell element is removed from the solution.

In addition to the above failure criterion, this material model also supports a shell element deletion criterion based on the maximum stable time step size for the element, $\Delta t_{\text{max}}$. Generally, $\Delta t_{\text{max}}$ goes down as the element becomes more distorted. To assure stability of time integration, the global LS-Dyna time step is the minimum of the $\Delta t_{\text{max}}$ values calculated for all elements in the model. Using this option allows the selective deletion of elements whose time step $\Delta t_{\text{max}}$ has fallen below the specified minimum time step, $\Delta t_{\text{crit}}$.

A fully viscoplastic formulation is optional which incorporates the rate formulation within the yield surface. An additional cost is incurred but the improvement in results can be dramatic.
Appendix E

Material Type 24

Piecewise Linear Plasticity
An elasto-plastic material with an arbitrary stress versus strain curve and arbitrary strain rate dependency can be defined. Also, failure based on a plastic strain or a minimum step size can be defined.
Input variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MID</td>
<td>Material identification. A unique number has to be chosen.</td>
</tr>
<tr>
<td>RO</td>
<td>Mass density.</td>
</tr>
<tr>
<td>E</td>
<td>Young’s modulus.</td>
</tr>
<tr>
<td>PR</td>
<td>Poisson’s ratio.</td>
</tr>
<tr>
<td>SIGY</td>
<td>Yield stress.</td>
</tr>
<tr>
<td>ETAN</td>
<td>Tangent modulus, ignored if (LCSS.GT.0) is defined.</td>
</tr>
<tr>
<td>FAIL</td>
<td>Failure flag. LT.0.0: User defined subroutine is called to define failure. EQ.0.0: Failure is not considered. This option is recommended if failure is not of interest since many calculations will be saved. GT.0.0: Plastic strain to failure. When the plastic strain reaches this value, the element is deleted from the calculation.</td>
</tr>
<tr>
<td>TDEL</td>
<td>Minimum step size for automatic element deletion.</td>
</tr>
<tr>
<td>C</td>
<td>Strain rate parameter, C, see formula below.</td>
</tr>
<tr>
<td>P</td>
<td>Strain rate parameter, P, see formula below.</td>
</tr>
<tr>
<td>LCSS</td>
<td>Load curve ID or Table ID. Load curve ID defining effective stress versus effective plastic strain. If defined EPS1-EPS8 and ES1-ES8 are ignored. The Table ID defines for each strain rate value a load curve ID giving the stress versus effective plastic strain for that rate, see figure [XXX]. The stress versus effective plastic strain curve for the lowest value of strain rate is used if the strain rate falls below the minimum value. Likewise, the stress versus effective plastic strain curve for the highest value of strain rate is used if the strain rate exceeds the maximum value. The strain rate parameters: C and P; the curve ID, LCSR; EPS1-EPS8 and ES1-ES8 are ignored if a Table ID is defined.</td>
</tr>
<tr>
<td>LCSR</td>
<td>Load curve ID defining strain rate scaling effect on yield stress.</td>
</tr>
<tr>
<td>VP</td>
<td>Formulation for rate effects. EQ.0.0: Scale yield stress (default). EQ.1.0: Viscoplastic formulation.</td>
</tr>
<tr>
<td>EPS1-EPS8</td>
<td>Effective plastic strain values (optional if SIGY is defined). At least two points should be defined. The first point must be zero corresponding to the initial yield stress.</td>
</tr>
<tr>
<td>ES1-ES8</td>
<td>Corresponding yield stress values to EPS1-EPS8.</td>
</tr>
</tbody>
</table>

Remarks

The stress strain behavior may be treated by a bilinear stress strain curve by defining the tangent modulus, ETAN. Alternately, a curve similar to that shown in figure E.1 is expected to be defined by (EPS1,ES1)-(EPS8,ES8); however, an effective stress versus effective plastic strain curve (LCSS) may be input instead if eight points are insufficient. The cost is roughly the same for either approach. The most general approach is to use the table definition (LCSS) discussed below.

Three options to account for strain rate effects are possible.

I. Strain rate may be accounted for using the Cowper and Symonds model which scales the yield stress with the factor

\[ 1 + \left( \frac{\dot{\varepsilon}}{C} \right)^{1/p} \]  

(E.1)

where \( \dot{\varepsilon} \) is the strain rate. \( \dot{\varepsilon} = \sqrt{\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \) If the viscoplastic option is active, VP=1.0, and if SIGY<0 then the dynamic yield stress is computed from the sum of the static
stress, $\sigma^*_y(\varepsilon^p_{\text{eff}})$, which is typically given by a load curve ID, and the initial yield stress, SIGY, multiplied by the Cowper-Symonds rate term as follows:

$$
\sigma_y(\varepsilon^p_{\text{eff}}, \dot{\varepsilon}^p_{\text{eff}}) = \sigma^*_y(\varepsilon^p_{\text{eff}}) + \text{SIGY} \left( \frac{\varepsilon^p_{\text{eff}}}{C} \right)^{1/p}
$$

(E.2)

where the plastic strain rate is used.

If SIGY = 0, the following equation is used instead where the static stress, $\sigma^*_y(\varepsilon^p_{\text{eff}})$, must be defined by a load curve:

$$
\sigma_y(\varepsilon^p_{\text{eff}}, \dot{\varepsilon}^p_{\text{eff}}) = \sigma^*_y(\varepsilon^p_{\text{eff}}) \left[ 1 + \left( \frac{\varepsilon^p_{\text{eff}}}{C} \right)^{1/p} \right]
$$

(E.3)

This latter equation is always used if the viscoplastic option is off.

II. For complete generality a load curve(LCSR) to scale the yield stress may be input instead. In this curve the scale factor versus strain rate is defined.

III. If different stress versus strain curves can be provided for various strain strain rates, the option using the reference to a table(LCSS) can be used. Then the table input in *DEFINE_TABLE has to be used, see figure[XXX20.7].

A fully viscoplastic formulation is optional (variable VP) which incorporates the different options above within the yield surface. An additional cost is incurred over the simple scaling but the improvement in results can be dramatic.

Figure E.1: Rate effects may be accounted for by defining a table of curves. If a table ID is specified a curve ID is given for each strain rate. Intermediate values are found by interpolating between curves. Effective plastic strain versus yield stress is expected.
Appendix F

Material Type 57

Low_Density_Foam

This model is mainly for modeling highly compresible low density foams. Its main applications are for seat cushions and padding on the Side Impact Dummies. Optionally a tension cut-off failure can be defined.

Input variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MID</td>
<td>Material identification. A unique number has to be chosen.</td>
</tr>
<tr>
<td>RO</td>
<td>Mass density.</td>
</tr>
<tr>
<td>E</td>
<td>Young’s modulus.</td>
</tr>
<tr>
<td>LCID</td>
<td>Load curve ID for nominal stress versus strain.</td>
</tr>
<tr>
<td>TC</td>
<td>Tension cut-off stress.</td>
</tr>
<tr>
<td>HU</td>
<td>Hysteretic unloading factor between 0 and 1 (default=1, i.e., no energy dissipation), see figure F.1.</td>
</tr>
<tr>
<td>BETA</td>
<td>$\beta$, decay constant to model creep in unloading.</td>
</tr>
<tr>
<td>DAMP</td>
<td>Viscous coefficient to model damping effects.</td>
</tr>
<tr>
<td>SHAPE</td>
<td>Shape factor for unloading. Active for nonzero values of the hysteretic unloading factor. Values less than one reduces the energy dissipation and greater than one increases dissipation, see figure F.1.</td>
</tr>
<tr>
<td>FAIL</td>
<td>Failure option after cut-off stress is reached: EQ.0.0: tensile stress remains at cut-off value, EQ.1.0: tensile stress is reset to zero.</td>
</tr>
<tr>
<td>BVFLAG</td>
<td>Bulk viscosity activation flag: EQ.0.0: no bulk viscosity (recommended), EQ.1.0: bulk viscosity active.</td>
</tr>
<tr>
<td>ED</td>
<td>Optional Young’s relaxation modulus, $E_d$, for rate effects.</td>
</tr>
<tr>
<td>BETA1</td>
<td>Optional decay constant, $\beta_1$.</td>
</tr>
<tr>
<td>KCON</td>
<td>Stiffness coefficient for contact interface stiffness. Maximum slope in stress vs. strain curve is used. When the maximum slope is taken for the contact, the time step size for this material is reduced for stability. In some cases $\Delta t$ may be significantly smaller, and defining a reasonable stiffness is recommended.</td>
</tr>
<tr>
<td>REF</td>
<td>Use reference geometry to initialize the stress tensor.</td>
</tr>
</tbody>
</table>

Remarks

The model uses tabulated input data for the loading curve where the nominal stresses are defined as a function of the elongations, $\varepsilon_i$, which are defined in terms of the
principal stretches, $\lambda_i$, as:

$$\varepsilon_i = \lambda_i - 1$$  \hfill (F.1)

The stretch ratios are found by solving for the eigenvalues of the left stretch tensor, $V_{ij}$, which is obtained via a polar decomposition of the deformation gradient matrix, $F_{ij}$. Recall that,

$$F_{ij} = R_{ik} U_{kj} = V_{ik} R_{kj}$$  \hfill (F.2)

The update of $V_{ij}$ follows the numerically stable approach of Taylor and Flanagan. After solving for the principal stretches, elongations are computed and, if the elongations are compressive, the corresponding values of the nominal stresses, $\tau_i$, are interpolated. If the elongations are tensile, the nominal stresses are given by:

$$\tau_i = E \varepsilon_i$$  \hfill (F.3)

and the Cauchy stresses in the principal system become:

$$\sigma_i = \frac{\tau_{ij}}{\lambda_j \lambda_k}.$$  \hfill (F.4)

The stresses can now be transformed back into the global system for the nodal force calculations.

![Figure F.1: Behavior of the low density foam model.](image)

**Additional Remarks**

I When hysteretic unloading is used the reloading will follow the unloading curve if the decay constant, $\beta$, is set to zero. If $\beta$ is nonzero the decay to the original loading curve is governed by the expression:

$$1 - e^{-\beta t}$$  \hfill (F.5)

II The bulk viscosity, which generates a rate dependent pressure, may cause an unexpected volumetric response and, consequently, it is optional in this model.

III The hysteretic unloading factor results in the unloading curve to lie beneath the unloading curve as shown in figure F.1. This unloading provides energy dissipation which is reasonable in certain kinds of foam. Rate effects are accounted for through linear viscoelasticity by a convolution integral of the form:

$$\sigma_{ij}(t) = \int_0^t g_{ijkl}(t - \tau) \frac{\partial \varepsilon_{kl}}{\partial \tau} d\tau$$  \hfill (F.6)

where $g_{ijkl}(t - \tau)$ is the relaxation function. The stress tensor, $\sigma_{ij}$, augments the stresses determined from the foam, $\sigma_{ij}^f$; consequently, the final stress, $\sigma_{ij}$ is taken as the summation of the two contributions:

$$\sigma_{ij} = \sigma_{ij}^f + \sigma_{ij}^r.$$  \hfill (F.7)
Since only simple rate effects are desired, the relaxation function is represented by one term from the Prony series:

\[ g(t) = \alpha_0 + \sum_{m=1}^{N} \alpha_m e^{-\beta t} \]  

(F.8)

given by,

\[ g(t) = E_d e^{-\beta_1 t}. \]  

(F.9)

This model is effectively a Maxwell fluid which consists of a damper and a spring in series. This is characterized in the input by a Young’s modulus, \( E_d \) and decay constant, \( \beta_1 \). The formulation is performed in the local system of principal stretches where only the principal values of stress are computed and triaxial coupling is avoided. Consequently, the one-dimensional nature of this foam material is unaffected by this addition of rate effects. The addition of rate effects necessitates twelve additional history variables per integration point. The cost and memory overhead of this model comes primarily from the need to "remember" the local system of principal stretches.
Appendix G

Material Type 83

Fu_Chang_Foam

Rate effects can be modelled in low and medium density foams as can be seen in figure G.1. Hysteretic unloading behavior in this model is a function of the rate sensitivity with the most rate sensitive foams providing the largest hysteresis and visa versa. The unified constitutive equations for foam materials by Fu Chang provides the basis for this model.

This model also supports load curves generated by drop tower tests.

Input variables

- **MID**: Material identification. A unique number has to be chosen.
- **RO**: Mass density.
- **E**: Young’s modulus.
- **ED**: Optional Young’s relaxation modulus, \(E_d\), for rate effects.
- **TC**: Tension cut-off stress.
- **FAIL**: Failure option after cut-off stress is reached.
- **DAMP**: Viscous coefficient to model damping effects.
- **TBID**: Table ID for nominal stress strain data as a function of strain rate.
- **BVFLAG**: Bulk viscosity activation flag.
- **MINR**: Ratemin, minimum strain rate of interest.
- **MAXR**: Ratemax, maximum strain rate of interest.
- **SFLAG**: Strain rate flag (true or engineering strain rate).
- **RFLAG**: Strain rate evaluation flag. First principal direction, principal strain rates for each principal direction or a volumetric strain rate.
- **TFLAG**: Tensile stress evaluation.
- **PVIND**: Optional load curve ID defining pressure versus volumetric strain.

Remarks

The strain is divided in two parts: a linear part and a non-linear part of the strain:

\[ E(t) = E^L(t) + E^N(t) \]  \hspace{1cm} \text{(G.1)}

and the strain rate becomes

\[ \dot{E}(t) = \dot{E}^L(t) + \dot{E}^N(t). \]  \hspace{1cm} \text{(G.2)}

\(\dot{E}^N\) is an expression for the past history of \(E^N\). A postulated constitutive equation may be written as:
\[\sigma(t) = \int_{\tau=0}^{\infty} \left[ E_t^N(\tau), S(t) \right] d\tau \quad (G.3)\]

where \(S(t)\) is the state variable and \(\int_{\tau=0}^{\infty}\) is a function of all values of \(\tau\) in \(T_\tau: 0 \leq \tau \leq \infty\) and

\[E_t^N(\tau) = E^N(t - \tau) \quad (G.4)\]

where \(\tau\) is the history parameter:

\[E_t^N(\tau = \infty) \leftrightarrow \text{the virgin material.} \quad (G.5)\]

It is assumed that the material remembers only its immediate past, i.e., a neighborhood about \(\tau = 0\). Therefore, an expansion of \(E_t^N(\tau)\) in a Taylor series about \(\tau = 0\) yields:

\[E_t^N(\tau) = E^N(0) + \frac{\partial E_t^N}{\partial t}(0) d\tau \quad (G.6)\]

Hence, the postulated constitutive equation becomes:

\[\sigma(t) = \sigma^*(E^N(t), \dot{E}^N(t), S(t)) \quad (G.7)\]

where \(\frac{\partial E_t^N}{\partial t}\) is replaced by \(\dot{E}^N\) and \(\sigma^*\) is a function of its arguments.

For a special case,

\[\sigma(t) = \sigma^*(\dot{E}^N(t), S(t)) \quad (G.8)\]

one may write

\[\dot{E}^N = f(S(t), s(t)) \quad (G.9)\]

which states that the nonlinear strain rate is the function of stress and a state variable which represents the history of loading. Therefore, the proposed kinetic equation for foam materials is:

\[\dot{E}^N = \frac{\sigma}{\|\sigma\|}D_0c_0\exp\left[-c_0\left(\frac{\text{tr}(\sigma S)}{{\|\sigma\|}^2}\right)^{2n_0}\right] \quad (G.10)\]

where \(D_0, c_0,\) and \(n_0\) are material constants and \(S\) is the overall state variable. If either \(D_0 = 0\) or \(c_0 \to \infty\) then the nonlinear strain rate vanishes.

\[\dot{S}_{ij} = \left[c_1(a_{ij}R - c_2S_{ij})P + c_3W^{n_1}\left(\|\dot{E}^N\|\right)^{n_2}I_{ij}\right] R \quad (G.11)\]

\[R = 1 + c_4\left(\frac{\|\dot{E}^N\|}{c_5} - 1\right)^{n_3} \quad (G.12)\]

\[P = \text{tr}(\sigma \dot{E}^N) \quad (G.13)\]
APPENDIX G. MATERIAL TYPE 83

\[ W = \int tr(\sigma dE) \]  
\[ (G.14) \]

where \( c_1, c_2, c_3, c_4, c_5, n_1, n_2, n_3 \) and \( a_{ij} \) are material constants and:

\[ \|\sigma\| = (\sigma_{ij}\sigma_{ij})^{1/2} \]  
\[ (G.15) \]

\[ \|\dot{E}\| = (\dot{E}_{ij}\dot{E}_{ij})^{1/2} \]  
\[ (G.16) \]

\[ \|\dot{E}^N\| = (\dot{E}^N_{ij}\dot{E}^N_{ij})^{1/2} \]  
\[ (G.17) \]

In the implementation by Fu Change, the model was simplified such that the input constants \( a_{ij} \) and the state variables \( S_{ij} \) are scalars.

![Figure G.1: Rate effects in Fu Chang’s foam](image)

**Additional Remarks**

I The bulk viscosity, which generates a rate dependent pressure, may cause an unexpected volumetric response and, consequently, is optional in this model.

II Dynamic compression tests at the strain rates of interest in vehicle crashes are usually performed with a drop tower. in this test the loading velocity is nearly constant but the true strain rate, which depends on the instantaneous specimen thickness, is not. Therefore the engineering strain rate input is optional so that the stress strain curves obtained at constant velocity loading can be used directly.

III To further improve the response under multi-axial loading, the strain rate parameter can either be based on the principal strain rates or the volumetric strain rate.

IV Correlation under triaxial loading is achieved by directly inputting the results of hydrostatic testing in addition to uniaxial data. Without this additional information which is fully optional, triaxial response tends to be underestimated. Rate effects in Fu Chang’s foam
Appendix H

Tearseam Data

Figure H.1: Example of data obtained with the microscope, necessary to model the tearseam
Appendix I

Cold Gas Plaque Deployment

Figure I.1: EXL deployment with cold compressed gas
Appendix J

Plaque Deployment Simulation

Figure J.1: FEA of an ELX plaque deployment with a pressure curve from a cold compressed gas deployment
Appendix K

NPI tests per OEM

Chart used to define initial tests to be done to start the NPI process for different OEM’s at the same time. OEM’s are Ford, General Motors and Daimler Chrysler.
Appendix L

Initial Tests

- Infrared spectrophotometry and/or thermal analysis
- Density
- Shore A Hardness ISO 868
- Tensile strength, ISO 37
- Tensile stress at yield
- Tensile stress at 100% elongation, ISO 37
- Elongation at break, ISO 37
- Flexural modulus
- Tear strength, ISO 34
- Deflection temperature under load
- Heat aging performance (ISO 188, 1000 hr @ 110°C)
  - Tensile strength
  - Elongation at break
- Properties after heat aging, SAE J2236, 1000 hr @ 135°C, air circulating oven
- Weathering resistance
  - Xenon Arc, SAE J1885, 1240 kj/m²
  - 12 months Florida exposure
  - 12 months Arizona exposure
- Cycle heat/humidity
  - 16 hr humidity soak, 35°C, 95%RH
  - 2 hr ambient soak, 23°C, 50%RH
  - 16 hr hot soak, 85°C, 60%RH
  - 4 hr cold soak, 40°C, 0-3%RH
  - 2 hr ambient soak, 23°C, 50%RH
- Flammability
APPENDIX L. INITIAL TESTS

- Resistance to scratching (7N and 2 N)
- Dime scrap, brittleness GMP9506P
- Thumbnail hardness, GM9507P
- Coefficient of linear thermal expansion (ISO 11359-2(tma), parallel and across flow)
- Mold shrinkage
  - After 24 hr @ 23°C
  - After 48 hr @ 80°C
  - After 60 min @ 120°C
- Multi axial impact at max load (ASTM D 3763), 6.7m/s @ 23°C and -40°C
- Determine recycling code
- Color fastness evaluation procedure, SAE J1545
- Determine melt flow rate
- Low temp brittleness, ISO 812
- Fogging number
- Tape adhesion, Humidity & tape adhesion, 24 hr
- Compatibility, GM9141P
## Appendix M

### Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>CAFE</td>
<td>Federal Cumulative Average Fuel Efficiency</td>
</tr>
<tr>
<td>CTQ</td>
<td>Critical to Quality</td>
</tr>
<tr>
<td>DCX</td>
<td>Daimler Chrysler</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FMVSS</td>
<td>Federal Motor Vehicle Safety Standards</td>
</tr>
<tr>
<td>GE</td>
<td>General Electric Company</td>
</tr>
<tr>
<td>GM</td>
<td>General Motors</td>
</tr>
<tr>
<td>HIC</td>
<td>Head Impact Criterion</td>
</tr>
<tr>
<td>IIHS</td>
<td>Insurance Institute for Highway Safety</td>
</tr>
<tr>
<td>IP</td>
<td>Instrument Panel</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>JFWTC</td>
<td>John F. Welch Technology Center (R&amp;D Research center in Bangalore, India)</td>
</tr>
<tr>
<td>LINCAP</td>
<td>New Car Assessment Program for Lateral Impact</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Variable Differential Transformer</td>
</tr>
<tr>
<td>NA</td>
<td>North Americas (Mexico, USA, Canada)</td>
</tr>
<tr>
<td>NCAP</td>
<td>New Car Assessment Program</td>
</tr>
<tr>
<td>NPI</td>
<td>New Product Introduction</td>
</tr>
<tr>
<td>NVH</td>
<td>Noise Vibration Harshness</td>
</tr>
<tr>
<td>OEM</td>
<td>Original Equipment Manufacturer</td>
</tr>
<tr>
<td>PAB</td>
<td>Passenger AirBag</td>
</tr>
<tr>
<td>PC-EDD</td>
<td>Personal Computer- Engineering Design Data</td>
</tr>
<tr>
<td>PPDC</td>
<td>Polymer Processing and Development Center</td>
</tr>
<tr>
<td>PSIR</td>
<td>Passenger Site Inflatable Restraint</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SAG</td>
<td>Simulation of Applied Gravity</td>
</tr>
<tr>
<td>TPO</td>
<td>Thermoplastic Olefin Elastomer</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Tensile Machine</td>
</tr>
</tbody>
</table>
Appendix N

Symbols

\( a \)  
acceleration

\( A \)  
area

\( \delta \)  
clamp displacement

\( \varepsilon \)  
strain

\( \dot{\varepsilon} \)  
strain rate

\( \dot{\varepsilon}_{\text{nom}} \)  
nominal strain rate

\( \varepsilon_{\text{eng}} \)  
engineering strain

\( \varepsilon_{\text{true}} \)  
true strain

\( \varepsilon_{l} \)  
strain along the loading axis

\( \varepsilon_{t} \)  
strain transverse the loading axis

\( \varepsilon_y \)  
yield strain

\( E \)  
E-modulus

\( l_s \)  
initial gage length

\( \mu \)  
coefficient of friction

\( \nu \)  
Poisson’s Ratio

\( \nu_m \)  
wave propagation speed in the specimen

\( \nu_f \)  
wave propagation speed in the fixturing

\( N \)  
number of reflected waves

\( P \)  
force

\( \sigma \)  
stress

\( \sigma_{\text{eng}} \)  
engineering stress

\( \sigma_{\text{true}} \)  
true stress

\( \sigma_y \)  
yield stress

\( \sigma_0 \)  
initial stress

\( \sigma_{11}, \sigma_{22}, \sigma_{33} \)  
stresses in the principal directions

\( t \)  
time

\( t_{\text{yield}} \)  
time to yield

\( T_g \)  
glass transition temperature

\( T_m \)  
melt temperature

\( V \)  
volume