Material Characterisation and Numerical Modelling of the Interior Trim of B-Pillar during Airbag Deployment

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Abstract

With the widespread use of thermoplastic materials in the vehicle interior trim, such as PP and PP-ABS, the vehicle design to maintain plastic trim integrity during dynamic impact like airbag deployment and head impact requires increased reliability and accuracy. The main focus of this project is on the interior trim of the B-pillar. When an automobile suffers from a side impact, the process of airbag deployment occurs creating an explosive force, which loads the interior of the B-Pillar.

Due to the side airbag deployment, two common failure modes could appear during the first iteration of the design, i.e.

1. Local trim break.
2. B-Pillar Hang-up.

This dissertation is focused on the first failure mode. In order to predict the B-pillar behaviour under airbag deployment, LS-Dyna 3D as a solver and elastic-plastic material constitutive model (MAT24) has been chosen. A range of material tests were performed to obtain stress-strain curves under uniaxial tensile and pure shear stress states, based on which the data sheet for MAT24 was created. Several cases have been simulated to understand the possible failure situations of the interior trim of the B-Pillar. It is also realised that more advanced SAMP-1 material constitutive model should be considered in the future study, which, however, requires more extensive material testing programme, than that required by MAT24.
Declaration

No portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
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1. Introduction

Talc-Filled Polypropylene is a common material widely used in the automotive industry, the main use of Talc-filled PP in the automotive industry is inside automobiles as the B-Pillar interior trim as it is required to withstand harsh and tough conditions due to the crashworthiness. During the impact of crashworthiness, the B-pillar interior trim have to absorb the force applied during airbag deployment and avoid to hang-up it. Therefore, it is essential to design the B-pillar interior trim with the most appropriate material and to obtain the accurate data required.

Finite Element Analysis method is used to predict the B-pillar mechanical behaviour. The chosen software to apply this method is LS-Dyna 3D. LS-Dyna 3D is a general-purpose finite element software. It is widely used in the aerospace, automobile, construction and other industrial sectors. The code is used to simulate highly nonlinear, transient dynamic finite element analysis using explicit time integration.

The objective of this project is to predict the mechanical behaviour of B-Pillar interior trim during airbag deployment using FE model. LS-Dyna has several material constitutive models to predict different material behaviour. More advanced models, such as SAMP-1, need many mechanical parameters, which are not available or associated with large uncertainties. The mechanical testing (e.g. tensile test) of the B-Pillar liner material can be reasonably described by elastic-plastic model developed for metals (Mat_024 model), which has been used by automotive industries for many years,(Bois, P.A, et al, 2015) and therefore, it will be used for the material constitutive model to predict the Talc-Filled Polypropylene behaviour.

In order to predict a failure mode is necessary to identify which is the mechanical variable that is going to drive the failure. MAT_024 depends on two variables stress...
and strain, due to the intensive research that is being done on the variable that is driven the local B-Pillar trim break is strain. It has been defined and correlates with LS-Dyna a test program in order to obtain the piecewise stress/strain curve and the magnitude of the material strain failure, which is going to use in B-Pillar mechanical prediction.
2. Literature Review

Background

As the importance of simulating compound increase, due to the increase in usage, it has become more and more important to identify the characteristics of these compounds. The requirements for the accuracy of these characteristics are also becoming more essential. (Georg, et al, 2011)

In order to find out these characteristics, a method of using SAMP-1 (Semi-Analytical Model for Polymers with $C^1$-differentiable yield surface) is used. SAMP-1 is a very popular model technique used to gain useful data, one of the most popular applications of using SAMP-1 is in the crash simulation especially in modelling thermoplastics.

Other methods have also been used to model the crashworthiness of polymers such as Mat Piecewise Linear Plasticity which is a classical elastic-plastic model based on the vonMises Criteria. However, due to the fact that thermoplastics are not incompressible during plastic flow, this leads to the material laws based on the vonMises plasticity are not suitable and only a simple behaviour of materials was described which in this case, is too simple. Furthermore, a need to develop a new material model was required.

By looking at various experimental works, important factors such as strain rate dependency and tension and strain rate dependent failure are required in the experimental findings of the new constitutive model. By combining these various factors and the models on how to test for these factors - necking by an elastic-plastic law, unloading behaviour by a damage model and pressure dependent behaviour by the standard Drucker-Prager model, a new model is formed, named SAMP-1.
SAMP-1 combines a range of models into one model to provide the most accurate results in crash simulation. SAMP-1 is also more capable with handling complex materials such as the material used in B-Pillar liner (talc-filled polypropylene) as it can also take into account varying compression and tension behaviours which is required to model the crashworthiness. (Kolling, S et al, 2006)

There are many advantages of using SAMP-1. As this method combines a number of material laws, it is a rather trustworthy and accurate method to obtain a numerically robust response. Kolling, S, 2005, concluded that they were able to obtain a reasonable fit of the experimental data that they used, even with plastics with a high rate dependency. This method has shown promising results from previous standard verification test indicating its high validity. However, further work will be required of more advanced methods which can be used for a wider range of plastics.

**Methods**

The most commonly used and popular model of SAMP-1 were derived using a series of formulas using the Material Law as followed;

**Material Law formulation**

Yield surface formulation for plastics

As all plastics are some degree anisotropic, the reason for this could be due to the fibre reinforcement or load induced in which the material is initially isotropic. By using this assumption, the most general quadratic yield surface equation is formed. This can then be reformulated in terms of the first two stress invariants; pressure and von-Mises stress. However, there are some conditions for the convexity of the yield surface - the yield surface is required to be convex and the first Eigen values need to be positive in the full 3D case. Alternatively a linear equation for the yield surface may be used in SAMP-1 rather than the quadratic version, providing an
alternative formulation.

Flow Rule
This indicates the plausible plastic flow which acts as an upper limit to the tensile and compressive yield values. As it is difficult to guarantee the correct flow behaviour from the three independent measures - shear, tension and compression, a simplified flow rule is to be used initially in SAMP-1. In terms of SAMP-1, this value is provided by the user.

Hardening formulation
For this section, the user can simply input the exact measurement results from the three subsequent tests into the software. The test results will then be used by SAMP-1 providing the result of the hardening. This can also be calculated using a series of equations as shown later on the report.

Rate Effects
To prove that plastics are normally highly rate dependent, uniaxial dynamic testing is used. It is also predicted that the rate effects in both compression and shear tests are similar to the rate effects of tensile loading making them interrelated.

Damage and Failure
There are a number of damage models that can be found from numerous literatures. In simple terms, the first type of damage is elastic damage. This is where the damage effectively reduces the elastic moduli of the material. Ductile damage on the other hand, represents the damage that affects the yield stress. This damage parameter is taken into consideration in the model of SAMP-1 material law.
Crazing

This is a localized deformation process which is proven by the change in colour to white of the material. A reason could be due to an increase of volumetric plastic straining with a low biaxial strength.

Numerical Implementation

To solve the various equations in the previous parts of the material law formation, numerical implementation is utilised. Material law, hardening rule, flow rule and the yield surface are combined together to further specify the flow rule. The damage model and rate effect are also added further on to the constitutive equation which is then to be solved.

**Identify the Failure Locus**

Tests such as tension, compression and shear have to be carried out to determine the material parameters to be input into the software, these represent the thermoplastic characteristics in crashworthiness simulations.

For example, when there is a large volume of stress on the talc filled Polypropylene material, using static loading and dynamic loading, a failure locus is identified. Further tests such as tension, simple shear and compression tests are essential to identify parameters for the material in calculating the strain based fracture locus. Through the different tests, there are a number of fracture prediction techniques applied.

In order to identify the failure locus under static loading and dynamic loading, a number of steps had to be made. Firstly after conducting the range of tests to the material, it had to be simulated and compared with the force-displacement curve. The failure moment and fracture element are then required to be identified and the stress triaxiality needs to be calculated. If the stress triaxiality remains stable, then
it is required to calculate the average stress triaxiality and to apply the fitting method to obtain the failure locus. On the other hand, if the stress triaxiality varies greatly, then the damage evolution rule is applied and optimized to identify the failure locus.

Lin, S et al, has identified there are significant differences between the failure locus from static loading and the failure locus from dynamic loading. Therefore, this suggests that the strain rate of the material, largely impacts on the failure locus of the material used. Furthermore, it is concluded that under dynamic loading, the average stress triaxiality method as mentioned previously, is sufficient enough to indicate the failure locus, whereas under static loading, the damage evolution rule is to be applied to optimise the fracture locus as the average stress triaxiality method will vary greatly during the loading process and also for the shear test. (Lin, S et al, 2013)

Hayashi, S, 2012, mentioned automobile polymers have good characteristics in order to help them function. Under impact, they are able to absorb energy through large deformation and failure. Therefore under this statement, it is essential to predict the failure impact, as the structural strength of the polymer decreases substantially after failure occurs.

Through the studies for failure behaviour of the polymers, using material tests and puncture tests and simulating models for the different friction levels, Hayashi came to the conclusion that the deformations and failures for polypropylene can be successfully predicted by using MAT SAMP-1 and MAT ADD EROSION. This supports our study of using SAMP-1 to predict the failure behaviour of polymers.

There are numerous tests to verify and validate the results from the previous tests. This includes; dynamic tensile tests, quasi-static tensile tests, compression tests,
shear tests and bending tests. In terms of this dissertation, the tests used were
dynamic tensile, quasi-static and shear.

Dynamic tensile testing is for investigating the strain rate dependency of SAMP-1
by the simulation produced. On the other hand, quasi-static tensile test focuses on
identifying the parameters in the prediction of elastic rebound structures. Shear
tests are simulated to provide a yield of the stress in an acceptable way. This
comparisons the force and displacement values on a graph. (Kolling, S et al, 2006)

Another way of validating the data is by using MAT Piecewise Linear Plasticity other
than SAMP-1. One of the advantages of using MAT Piecewise Linear Plasticity in
LS-DYNA is that it has high numerical stability and less machine time compared
with MAT-SAMP-1 which is much more complex. However, MAT-SAMP-1 is able to
handle more complex data providing a result which is more accurate, it also takes
into account varying compression and tension behaviours of the materials. (Haufe,
2011)

**Alternative Methods**
The main use of SAMP-1 is to capture von-Mises yield and localisation behaviour in
plastics. The accuracy of the results of this method is highly dependent on the
accuracy and validity of the material data provided beforehand. (Lobo, 2013) There
are also a large number of assumptions used to convert the test data into the
parameters used in the software. Another suggested way of extracting required
data for generating the material parameters required for SAMP-1 is the use of
Digital Image Correlation Methods. The main difference in using this method is
after constructing the experimental tests required such as tensile, biaxial, shear
and compressive tests, the yield locus is to be determined using digital imaging.
This is done by combining the yield stresses and tensile yield stresses into one
graph which then allows us to plot the yield locus of the material, which can then be
used as a material parameter in SAMP-1. (Lobo, 2013)

Disadvantages/Limits

Although there are many advantages of using SAMP-1, and it is currently widely used due to its advantages, there still remain a few limitations and disadvantages when using this method. As mentioned by Kolling, S, one of the limits of doing the experiment of comparing the results from SAMP-1 to von-Mises yield criterion is that the experimental result for certain materials under biaxial tension is not exactly fitted with the von-Mises yield criterion leading to slight differences in values. (Kolling, S et al, 2006)

Another limitation could be identified due to SAMP-1 uses a number of formulas that are simplified to make it a more user friendly system, however this could be questioned on the accuracy of the result and also needs to be taken into account failed models. Bois, 2015 presented a damage and failure procedure in SAMP-1 as one of the disadvantages of using it, using formulations by Johnson-Cook, Chaboche, Lemaitre and Gurson. (Bois, P et al, 2015) The failure criteria in LS-DYNA was analysed, one of the main points was that SAMP-1 does not take into account the non-proportional loading and triaxiality or the strain rate dependency. Therefore it seems unsuitable for failure prediction in real structures with a complex state of stress.

Furthermore, a lot of data is required to be inputted into the software in order to gain a result; this data however is extremely difficult to obtain through a series of test results, especially for shear and biaxial loading tests. This also indicates this is a very time consuming and complicated method to use. There is also a limit on the type of material that could be used for these tests as it is only suitable for ductile plastics that are and remain isotropic throughout the process. This limits most polymeric materials as they do not comply with the requirements. (Kolling, 2005)
Future Improvements

Due to the number of limitations, there are a few improvements that are suggested for future publications and tests by various publishers, which can be taken into consideration. Hayashi, S 2012 suggested using a wider range of materials and polymers to identify whether failure models will work for them also, if not, this could be an area for future research.

In addition, with the increase in complexity of compounds in materials and the higher standards that are required to be achieved, a more complex approach to structure these compounds are required. Georg, G, 2011, suggested a modified approach for simulating compounds with complex structures, providing benefits such as a more accurate simulation with reduced modelling efforts for complicated compounds. His idea is to present a method of overlapping and adapting a few basic material models with one shell formulation. This will allow MAT_24 and MAT_54 to describe all relevant characteristics of materials such as short fibre and reinforced polymers.

In more specific terms, Kim, D et al, 2013, suggested a way of modelling materials for vehicle use in the automotive industry. By comparing the results from material models that could be applied using SAMP-1 and implemented material modelling for plastic models, Kim concluded that there were large differences in the results resulting from whether the strain rates for pillar inner trim of vehicles were considered. Therefore there is a need for a more advanced method which takes into account further characteristics such as the deformation of behaviour of seat foam that is implemented into crash codes for vehicles. (Kim, D et al, 2013)

In terms of the software used, Haufe, 2011, presents an enhanced method of MAT_24. Haufe, compared different ways to validate the different models in LS-DYNA. In terms of this report, the main focus will be on using Mat_24
(MAT PIECEWISE_LINEAR_PLASTICITY) and MAT_187 (MAT_SAMP-1) which are the more classical approach for the elastic-plastic model. Other material cards in LS-DYNA include MAT_81 (MAT_PLASTICITY_WITH_DAMAGE) and MAT_124 (MAT_PLASTICITY_COMPRESSION_TENSION) which will be ignored for simplicity purposes. (Haufe, 2011)

For MAT_24, this more classical approach is to base the generations on measured stress strain curves which correlates with the material laws previously mentioned. However, this does not consider the polymer behaviour of volume increase during loading, therefore a more iterative procedure is presented (Haufe, 2011). This is used by using engineering judgments to find a best indication of the tensile tests which is based on real measurements. Advantages of this method is that it offers the needs of more complex material models with extensive test opportunities, it is also able to link all the tests together to provide a final evaluated outcome. (4a Impetus)

**Talc-filled Polypropylene**

In terms of this report, the material talc-filled polypropylene is used as a sample. Talc-filled polypropylene is a common material widely used in the automotive industry; this is mainly due to the properties it holds. Talc is a hydrated magnesium sheet. On the other hand, PP is a high-volume plastic with many advantageous properties such as it offers good fatigue resistance and chemical resistance. When these two materials are combined together forming Talc-Filled PP, their mechanical properties are enhanced. Due to the additional talc material in PP, the enhanced material offers properties such as higher stiffness, lower coefficient of thermal expansion and heat deflection (Kant, 2013). These are the reasons why Talc-filled PP is so popular especially in the automotive industry.
The main use of Talc-filled PP in the automotive industry is in the vehicle interior B-Pillar interior trim as it is required to withstand harsh and tough conditions due to the vibrations. It also offers an opportunity for significant weight reduction and it is very easy to meet the physical requirements from the car maker. (Maier, 1988)
3. Material test and results

3.1 Test report

3.1.1 Objectives
Polypropylene is a widely used thermoplastic polymer used in a variety of applications, by adding talc. This provides a significant increase in the stiffness and temperature performance of the polymer. Therefore there is a popular demand for talc-filled polypropylene for numerous reasons, many of which derives from the strong characteristics it holds. There is also a need to obtain the mechanical properties for a specific type of talc-filled polypropylene - 18% talc-filled polypropylene, due to the various ways it could be used, for example in the automotive sector for exterior applications. This study was initiated to obtain these mechanical properties using various tests by constructing the test data for the load curve, which is obtained by quasi-static uniaxial tensile test, dynamic uniaxial tensile test and quasi-static shear test. Furthermore, after the 18% talc-filled polypropylene mechanical properties are obtained, it could be applied to simulate the loading of airbag impact for B-pillar interior trim model by using MAT_024 material constitutive model in LS-DYNA.

3.1.2 Material and standard
3.1.2.1 The preparation of the test specimens
Three different inject flow orientation of polypropylene (PP) were tested: 0° orientation of 18% talc-filled polypropylene, 45° orientation of 18% talc-filled polypropylene and 90° orientation of 18% talc-filled polypropylene. These materials are TKC451N which is a very high scratch resistant and high stiffness grade with good impact for interior automotive applications (TKC451N product from Lyondell Basell). The processing method of these materials is injection moulding. Its density is 1.0 g/cm³ and Flexural Modulus is 2000MPa.
3.1.2.2 Material standard
The test specimens have to be prepared and dimensions are required to be calculated of these specimens, in order to have a better understanding and analysis of them.

The quasi-static uniaxial tensile test and dynamic uniaxial tensile test used in this paper are based on the “Plastics – Determination of tensile properties (Part 1 & Part 2)” standard (BS EN ISO 527-1:2012 and BS EN ISO 527-2:2012). The journal “An experimental and numerical investigation of different shear test configurations for sheet metal characterization” (modified simple shear test specimen based on ASTM B831-05) was used as the standard in the quasi-static shear test.

3.1.2.3 Geometry
Each orientation has three specimens to be tested - thickness, width and length. The geometric dimensions of the specimens were measured and recorded by using a Vernier calliper to calculate the cross-section of the test specimen. For injection-moulded test specimens, as the dimensions are very similar, it is not necessary to measure each specimen’s geometric dimensions. Therefore, the average size of these specimens were tested with an extensometer and without an extensometer are shown in Table 1 & 2, the data was measured by the machine and was shown in the test result paper (see Appendix.1 – 18).

Table 1. The geometric dimensions of the specimens were tested with an extensometer.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Orientation</th>
<th>Thickness mm</th>
<th>Width mm</th>
<th>Length mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-static uniaxial tensile test</td>
<td>0°</td>
<td>3.62</td>
<td>9.90</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>3.70</td>
<td>9.61</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>3.64</td>
<td>9.75</td>
<td>65</td>
</tr>
<tr>
<td>Dynamic uniaxial</td>
<td>0°</td>
<td>3.64</td>
<td>9.33</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2. The geometric dimensions of the specimens were tested without extensometer.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Orientation</th>
<th>Thickness mm</th>
<th>Width mm</th>
<th>Length mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quasi-static uniaxial tensile test</td>
<td>0°</td>
<td>3.69</td>
<td>9.97</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>3.69</td>
<td>9.62</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>3.69</td>
<td>9.26</td>
<td>65</td>
</tr>
<tr>
<td>Dynamic uniaxial tensile test</td>
<td>0°</td>
<td>3.73</td>
<td>9.35</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>3.71</td>
<td>9.13</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>3.75</td>
<td>9.28</td>
<td>60</td>
</tr>
<tr>
<td>Quasi-static shear test</td>
<td>0°</td>
<td>3.70</td>
<td>24.80</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>45°</td>
<td>3.69</td>
<td>24.71</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>3.79</td>
<td>24.72</td>
<td>35</td>
</tr>
</tbody>
</table>

From the above tables, the only difference is the length of dynamic tensile specimens test without an extensometer, is double size as the length with an extensometer. The reason is the test with an extensometer used the small gauge specimens instead of the large gauge specimens which issued in the test without an extensometer.

According to the drawings of "Tensile test specimen 3mm" and "Small gauge tensile test specimen 3mm" (See Appendix. 19 – 20), and the standard geometric dimension of specimens, see Fig.1 and table 3.
Table 3. Dimensions of tension test standard specimen.

<table>
<thead>
<tr>
<th>Specimen type</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_3$ Overall length</td>
<td>$\geq 150$</td>
</tr>
<tr>
<td>$l_1$ Length of narrow parallel-sided portion</td>
<td>$60,0 \pm 0.5$</td>
</tr>
<tr>
<td>$r$ Radius</td>
<td>$60 \pm 0.5$</td>
</tr>
<tr>
<td>$l_2$ Distance between broad parallel-sided portions</td>
<td>$108 \pm 1.6$</td>
</tr>
<tr>
<td>$b_2$ Width at ends</td>
<td>$20,0 \pm 0.2$</td>
</tr>
<tr>
<td>$b_1$ Width at narrow portion</td>
<td>$10,0 \pm 0.2$</td>
</tr>
<tr>
<td>$h$ Preferred thickness</td>
<td>$4,0 \pm 0.2$</td>
</tr>
<tr>
<td>$L_0$ Gauge length (preferred)</td>
<td>$50,0 \pm 0.5$</td>
</tr>
<tr>
<td>$L_0$ Gauge length (acceptable if required for quality control or when specified)</td>
<td></td>
</tr>
<tr>
<td>$L$ Initial distance between grips</td>
<td>$115 \pm 1$</td>
</tr>
</tbody>
</table>

With respect to the quasi-static tension test specimen, compare the dimensions of real specimen component with drawings and test standard, the width at narrow portion of real specimen is narrower than the standard dimension, the length of narrow parallel-sided portion $l_1$ of real specimen is 65mm, longer than the length of drawing. Regard to dynamic specimen, the width of the narrow portion of real specimen is narrower than the standard dimension. All thicknesses of real
specimens are thicker than the thickness of standard dimension and drawings. Accordingly, as the dimensions of real specimens are not within the range of test standard dimensions, the dimensions of specimens are out of tolerance.

Apart from these geometric dimensions, the extensometer gauge length used in the quasi-static uniaxial tension test and dynamic uniaxial tension test is 12.5mm, therefore after tests, the strain data need to be calculated by using 12.5mm as the original length of specimens in test with extensometer.

**3.1.3 Mechanical testing**
After measuring the geometric dimensions of the specimens in the previous section, the next step was to construct the mechanical tests. The first tests have been done were quasi-static tension test without an extensometer, dynamic tension test without an extensometer and quasi-static shear test. The second tests have been conducted were quasi-static tension test with extensometer, dynamic tension test with extensometer. All tests were operated in the same atmosphere of room temperature - 19°C as standard conditions. The device used in these tests was the Instron test machine, see Fig.2.

![Instron test machine and operating system](image-url)

Fig.2. Instron test machine and operating system.
The tensile test fixtures in Fig. 3 was mounted in the Instron test machine, fitted with a 10kN load act on the specimens in the quasi-static uniaxial tensile test and dynamic uniaxial tensile test. And a 100kN load acts on the specimens in the quasi-static shear test. In order to obtain more accurate data, a calibration method to the gauge length of the test specimen is needed. The way is to improve the data accuracy by using an extensometer to measure the deformation length. The extensometer should be set symmetrically on the centre line and the middle of the parallel part of the test specimen, see Fig.3.

Test speed

In order to measure the tensile modulus, the test speed should be selected to provide a strain rate, it is similar as possible to 1% of the gauge length per minute. Therefore, quasi-static strain rate was set to be 0.0016 1/s and the tensile velocities would be 0.1 mm/s (0.0001 m/s, 6 mm/min), the dynamic strain rate was selected to be 0.16 1/s which provided the tensile velocities as 4 mm/s (0.04 m/s, 240 mm/min). The first tests and the second tests are the same as the speed mentioned above.
3.1.3.1 Quasi-static uniaxial tensile test

3.1.3.1.1 0° Orientation Direction Specimen

All drawings of specimens of the quasi-static uniaxial tensile test with extensometer are “Tensile test specimen 3mm” (See Appendix. 19), the same as the test without extensometer.

With extensometer

From Fig. 4, in order to easier identification, labelling specimens numbers before testing.

![Fig.4. Appearance of original specimen surface in the 0° orientation direction in the quasi-static tension test with extensometer.](image)

After fixing the specimens onto the Instron test machine, by using the upper clamp and the lower clamp, the extensometer is fixed on to the middle of the surface of the specimen. By inputting the quasi-static strain rate as 0.0016 1/s and the tensile velocities as 0.1 mm/s in the operating system, the machine then starts to provide a tensile force of 10kN to separate the specimen. After the specimens are broken, take the pieces down and recorded. The broken parts are shown in figure 5. The broken section is uneven and not straight, therefore, the conclusion is the fracture place of 0° orientation specimens is rough and flexural.
Without extensometer

The figure 6 shows the test specimens before the test with an indication of where it will be broken. After the test without extensometer, the specimens will be broken. Record the fracture and shown them in figure 7.

Fig.6. Appearance of original specimen surface in the 0° orientation direction in the quasi-static tension test without extensometer.

Fig.5. Appearance and close-up views of fractured specimen surface in the 0° orientation direction in the quasi-static tension with extensometer.
3.1.3.1.2 45° Orientation Direction Specimen  
With extensometer  
In the 45° and 90° orientation tests, the test procedures are alike to the 0° orientation test. The shape and surface of the following 45° and 90° orientation specimens before the tensile test are comparable with the 0° orientation test, so it is not necessary to say them again. From Fig.8, the broken parts of specimen 8 and 9 are similar to the 0° orientation specimens; however the broken part of specimen 7 is straighter and even than 0° orientation specimens.

Fig.7. Appearance of fractured specimen surface in the 0° orientation direction in the quasi-static tension without extensometer.

Fig.8. Appearance and close-up views of fractured specimen surface in the 45° orientation direction in the quasi-static tension with extensometer.
Without extensometer

From Fig. 9, we could see the appearance of 45° orientation specimens after the tensile test without extensometer.

![Image of fractured specimens](image)

**Fig.9.** Appearance of fractured specimen surface in the 45° orientation direction in the quasi-static tension without extensometer.

3.1.3.1.3 90° Orientation Direction Specimen

From Fig. 10 & 11, we could see the appearance of 90° orientation specimens with and without extensometer after the tensile test.

With extensometer

![Image of fractured specimens](image)

**Fig.10.** Appearance and close-up views of fractured specimen surface in the 90° orientation direction in the quasi-static tension with extensometer.
Without extensometer

Fig. 11. Appearance of original specimen surface in the 90° orientation direction in the quasi-static tension test without extensometer.

The broken parts for 90° orientation specimens is much more straight and even than the broken part of 45° orientation specimens and 90° orientation specimens.

3.1.3.1.4 Conclusion
Through the various tests constructed, it could be concluded that when different orientation specimens are pulled by the same force and in the same condition, the broken parts of different orientation specimens are different in terms of the way it is broken. The broken part of 0° orientation specimens are the most uneven and roughest among the three tests, the rougher and evenness of 90° orientation specimens are the most straightest and even. The specimens of with and without extensometer do not differ that much.

3.1.3.2 Dynamic Uniaxial Tensile Test

As the test with an extensometer used the small gauge specimens instead of the large gauge specimens which issued in the test without an extensometer, the drawings of specimens of dynamic tensile test without extensometer used the “Tensile test specimen 3mm” (See Appendix. 19), different from the specimens of test with extensometer are the “Small gauge tensile test specimen 3mm” (See
Appendix. 20).

3.1.3.2.1 0° Orientation Direction Specimen

Before operating the test, the specimens are labelled as shown in figure 12, for better identification. These dynamic tensile test specimens are then fixed onto the Instron test machine. The extensometer is then fixed onto the middle of the specimen. The figures of 0.16 1/s and 4 mm/s as the dynamic strain rate and the tensile velocities are inputted into the computer, the machine will then begin to give the tensile force of 10kN to pull both sides of the specimen much quickly than the quasi-static tests. After breaking the specimens, take them down and record the broken section, see Fig. 13.

With extensometer

Fig.12. Appearance of original specimen surface in the 0° orientation direction in the dynamic tension test with extensometer.
Fig. 13. Appearance and close-up views of fractured specimen surface in the 0° orientation direction in the dynamic tension with extensometer.

Without extensometer

From Fig. 14 & 15, we could see the appearance of 0° orientation specimens without an extensometer before and after the tensile test.

Fig. 14. Appearance of original specimen surface in the 0° orientation direction in the dynamic tension test without extensometer.

Fig. 15. Appearance of fractured specimen surface in the 0° orientation direction in the dynamic tension without extensometer.
3.1.3.2.2 45° Orientation Direction Specimen

As the dynamic tensile test procedures and the original shapes of the 45° and 90° orientation directions are the same as the 0° orientation direction, the tests will not be repeated. Therefore, there are images showing the appearance of the fractured dynamic tension specimen surface in the 45° and 90° orientation directions in dynamic tension test with and without an extensometer, see Fig. 16, 17, 18 and 19.

With extensometer

![Image 1](image1)

**Fig. 16.** Appearance and close-up views of fractured specimen surface in the 45° orientation direction in the dynamic tension with extensometer.

Without extensometer

![Image 2](image2)

**Fig. 17.** Appearance of fractured specimen surface in the 45° orientation direction in the dynamic tension without extensometer.
1.3.2.3 90° Orientation Direction Specimen

3.1.3.2.3 90° Orientation Direction Specimen

With extensometer

![Image of specimen with extensometer]

Fig. 18. Appearance and close-up views of fractured specimen surface in the 90° orientation direction in the dynamic tension with extensometer.

Without extensometer

![Image of specimen without extensometer]

Fig. 19. Appearance of fractured specimen surface in the 90° orientation direction in the dynamic tension without extensometer.
3.1.3.2.4 Conclusion
Comparing these figures, under the same loading and the same condition, the broken sections of 0° orientation specimens are much more uneven and rougher than other tests specimens, the straightest and even broken sections are from 90° orientation specimens.

3.1.3.3 Quasi-static shear test
3.1.3.3.1 Introduction
The shear test used to investigate the behaviour of materials, in this instance is based on the American Society for Testing and Materials Standard ASTM B831 (ASTM, 2005). By using shear loading and a single shear zone, a simple geometry is able to be obtained, therefore an evaluation of the shear stresses and strains can be found out. The sample used in ASTM is used in a tension testing machine where the shear stress could then be calculated from the uniaxial tensile force. However, a disadvantage of this method is that the specimens could possibly rotate whiles the machine enforces a parallel movement of the two lateral groups. The rotation of the specimens could be reduced if the clamp were clamped tighter onto the specimen; however this could easily damage the specimen and change the shape if it is clamped too tight. In 2011, Merklein and Biasutti came up with a modified idea of the simple shear specimen which overcomes the disadvantages. This changes the load direction and brings a way to evaluate the material behaviour under cyclic shear loading which can then be used to describe the kinematic hardening behaviour. This method is described below.

The fixture of quasi-static shear test is shown in figure 20. Firstly, the shear rig head is connected onto the spindle of the machine and the shear rig base plate is fixed onto the machine. The base head is then fixed onto the shear rig base plate. Before starting the test, the specimens needs to be fixed onto the apparatus with the fixed shear clamp and loose shear clamp, and fixed one head of them to the shear rig head and the other head connected with the base head. By using this
method, it is expected that the specimens will be broken at the joint point which we could call a success of the result.

All drawings of specimens of the quasi-static shear test are the “Tensile shear specimen 3mm” (See Appendix. 21).

3.1.3.3.2 0° Orientation Direction Specimen

The figure 21 shows an indication of where the test specimens will be broken. After tests, take broken specimens down and record. The broken at the joint place of the specimens as shown in figure 22.
3.1.3.3.3 45° Orientation Direction Specimen

The shear test methods and the original shapes in the 45° and 90° orientation directions are similar as these in the 0° orientation direction, thus will not repeat them. However, after the specimens are broken, the broken points are different from these of 0° orientation direction. Therefore, in order to increase the accuracy of the results, more extra specimen samples of 45° orientation direction were tested, see Fig.23.
Fig. 23. Appearance and close-up views of fractured specimen surface in the 45° orientation direction in the quasi-static shear test.

After completing the first two specimens, the phenomenon happened differently from 0° orientation direction, because the first two specimens were broken at different places - breaking at the neck instead of breaking at the joint point. The last three specimens’ test results are the same as the 0° orientation direction specimens.

3.1.3.3.4 90° Orientation Direction Specimen

The images of the 90° orientation direction specimens after the test are shown in figure 24.
Fig. 24. Appearance and close-up views of fractured specimen surface in the 90° orientation direction in the quasi-static shear test.

From Fig. 24, we could see the 90° orientation direction specimens break at the neck section just like the first two 45° orientation direction specimens.

3.1.3.3.5 Conclusion
Consequently, it can be concluded that the 0° orientation direction specimen break at the right point as the test standard allowed, the data of 0° orientation direction specimen is suitable for use. Around 40% of 45° orientation direction specimens and all 90° orientation direction specimens break at the wrong place; this means that the specimens bear the tension force and bending force instead of the expected shear force. The specimens are weaker for bearing the tension force and bending force than the shear force, therefore the test data of 40% of 45° orientation direction specimens and all 90° orientation direction specimens are not classed as shear test data and the results could not be used in the following simulation.

To solve this problem, a recommendation is to use a V-Notched shear specimen fixture to fix the specimen to measure the shear response of the 18% talc-filled PP material. The specimen notch gives an effect on the shear strain in the loading direction to make the shear distribution more uniform than that without V-notches.

3.1.4 Collect the test data
After finishing the test, we obtained the stress-strain curve of each test specimen, and the next step is to analyse the data.
3.2. Test results

3.2.1 Results calculation
The test data (force, elongation) was recorded by using an automatic recording system of the Instron machine. Therefore, the load-displacement curve could be shown. In order to calculate all stress values and strain values, several equations should be used as followed.

3.2.1.1 Stress calculation
Calculate stress values, using the following equation 1:

\[ \sigma = \frac{F}{A} \]  
(Eq. 1.)

where \( \sigma \) is the stress value to be calculated, expressed in MPa;

\( F \) is the measured load force, expressed in N;

\( A = T \cdot W \) is the initial cross-sectional area of the test specimens, express in \( \text{mm}^2 \); \( T(\text{mm}) \) is the thickness of the test specimen, \( W(\text{mm}) \) is the width of the test specimen.

3.2.1.2 Strain calculation
Calculate strain values, using the following equation 2:

\[ \varepsilon = \frac{\Delta L_0}{L_0} \]  
(Eq. 2.)

where \( \varepsilon \) is the strain value to be calculated, expressed as a percentage;

\( L_0 \) is the initial gauge length of the test specimen, expressed in mm;

\( \Delta L_0 \) is the increment of the specimen length between the initial gauge marks, expressed in mm.

3.2.2 Results expression

3.2.2.1 Quasi-static uniaxial tension test results

3.2.2.1.1 0° Orientation Direction Specimens
After quasi-static uniaxial tension test, the load-displacement curve can be obtained from the machine system, see Appendix 23.

Figure 25 shows the transformation into Stress/Strain, using the above formulas and the Area A and Length L₀ measured on the test specimens.

Appendix 24 and figure 26 show the load-displacement curve and the stress-strain curve of the other test set with extensometer.
The first set of test shows that all the specimens broke at different point, with almost the same maximum force/Stress and the same plastic trend. The second set of test is important to notice that the Specimen 1 and 2 have recuperation before failing. It is due to the position of the extensometer is not bounded the position of the fracture as in the specimen 3.

Therefore the only test valid in order to evaluate the failure point is the specimen 3 which its failing point is close to specimen 1 from the first set. It is possible to conclude taking into account the information available that specimen 1 from set 1 and specimen 3 from set 2 are giving the same failing point with different instrumentation techniques, so we can take that plots as the representative behaviour of 0° degree injection orientation.

3.2.2.1.2 45° Orientation Direction Specimens
The load-displacement curves of 45° orientation direction specimens in quasi-static tension test without extensometer is shown in Appendix 25.
Using Eq.1 and Eq.2 to obtain the stress-strain curve is shown in the following figure 27. Using $A$ and $L_0$ base on measurements on test specimens.

Fig.27. Stress/Strain curve of $45^\circ$ orientation direction specimens in quasi-static tension test without extensometer.

It is interesting to notice the last part of the curves of the specimen 5, specimen 2, and specimen 3 and in less intensity specimen 4. It seems that the necking effect is higher in these cases.

The load-displacement and stress-strain curves of $45^\circ$ orientation direction specimens in quasi-static tension test with extensometer are shown in the following Appendix 26 and Fig.28.

Fig.28. Stress-strain curve of $45^\circ$ orientation direction specimens in quasi-static tension test with extensometer.
The specimen 2 shows the same recuperation than in 0° orientation. The specimen 1 shows an increase before failing which could be due to the same cause of specimen 2, the extensometer is not perfectly bounded the failure section. But the specimen 3 shows that the extensometer is capturing the full failure process.

3.2.2.1.3 90° Orientation Direction Specimens

The load-displacement curves of 90° orientation direction specimens in quasi-static tension test without extensometer is shown in see Appendix 27. The calculated stress and strain curve is shown in the following figure 29.

![Quasi-static tension test (orientation 90°)](image)

Fig.29. Stress/Strain curve of 90° orientation direction specimens in quasi-static tension test without extensometer.

It is important to notice that the difference in the maximum Force/Stress between the specimens is higher than in the other two cases. 90° injection orientation direction is more sensible under tension loading than 0° and 45°.

The second set of test with extensometer is shown in Appendix 28 and figure 30.
Fig. 30. Stress-strain curve of 90° orientation direction specimens in quasi-static tension test with extensometer.

In this case, the specimen 1 and specimen 2 show the increasing in the strain at the last part, but the specimen 3 is behaving as expected.

3.2.2.1.4 Conclusion
In order to get a conclusion of the results above, it is important to identify the parameters that are going to be assessed.

Young Modulus (Elastic Modulus) as BS EN ISO 527-1-2012 Part 10.3.2.

Table 4. The averages of the Young Modulus of two test sets on three orientations.

|          | With Extensometer (MPa) | Without Extensometer (MPa) | |Δ| % |
|----------|------------------------|-----------------------------|-----|-----|
| 0° orientation | 2001                   | 2141                        | 6.55|
| 45° orientation | 1850                   | 1858                        | 0.44|
| 90° orientation | 1806                   | 1688                        | 7.00|
| |Δ| | 9.72 | 21.16 |

The table above shows the averages of the Young Modulus depend on the orientation of the injection and the sets of tests; Set 2 with extensometer and set 1 without extensometer.
The last row shows the difference in per cent between the maximum and the minimum, which less than 10% in set 1 and higher than 10%, taking into account the specimen 1 in figure 29, which is a specimen that is very different to the others. Accordingly, it is possible to conclude for the set 2 that the Young modulus does not depend on the orientation of the injection. In the case of set 1, the number is higher than 10%, but it has been noticed the specimen 1, so we could accept the argument of the set 1.

The last column shows the difference in per cent between the two sets, which are much lower than 10%, so the data of both set is consistent.

Maximum Stress:

Table 5. The averages of the maximum stress of two test sets on three orientations.

| Orientation       | With Extensometer (MPa) | Without Extensometer (MPa) | |Δ| % |
|-------------------|-------------------------|-----------------------------|-----------------|-----|
| 0° orientation    | 16.73                   | 17.29                       | 3.23             |
| 45° orientation   | 15.84                   | 16.08                       | 1.50             |
| 90° orientation   | 15.56                   | 15.49                       | 0.46             |
| |Δ| %     | 6.97                     | 10.38                      |

The table above shows the averages of the maximum stress depend on the orientation of the injection and the set of test; Set 2 with extensometer and set 1 without extensometer.

The last row shows the difference in per cent between the maximum and the minimum, which less than 10% and very close to 10% respectively, taking into account the specimen 1 in figure 29. Therefore it is possible to conclude for the set 2 and for the set 1, the maximum stress does not depend on the orientation of the injection.
The last column shows the difference in per cent between the two sets, which are much lower than 10%, so the data of both set is consistent.

Strain at failure:
Failure at the strain depends clearly on the orientation of the injection, and even in the same set, every specimen is failing in a different way. In order to evaluate which is the relationship between different orientations of injection, we assume the maximum strain failure of every set.

Table.6. The average of the strain at failure of two test sets on three orientations.

| Orientation   | With Extensometer-Strain | Without Extensometer-Strain | |Δ| % |
|---------------|--------------------------|-----------------------------|-----|----|
| 0° orientation | 0.51                     | 0.64                        | 20.41 |
| 45° orientation | 0.34                     | 0.38                        | 12.36 |
| 90° orientation | 0.31                     | 0.36                        | 13.30 |
| |Δ| % | 38.93 | 78.37 |

The last column of the table above shows the difference in per cent between sets, which are quite close to 10% in 45° and 90°; In the case of 0° is quite big. Therefore, in terms of strain at failure the sets are not consistent.

The last row shows the difference between the maximum and minimum strain at failure, it depends on the orientation of the injection. The numbers are clear. The strain at failure depends on the orientation of the injection.

The difference between the strains at failure specimens of the same set is a phenomenon that should be further investigated.

It is possible to assume that the strain failure is the maximum of every set.
3.2.2.2 Dynamic uniaxial tension test results

3.2.2.2.1 0° Orientation Direction Specimens

Appendix 29 shows the force-displacement curve obtained directly from the machine of the first set of test without extensometer.

![Stress-strain curve](image)

**Fig.31. Stress-strain curve of 0° orientation direction specimens in dynamic tension test with extensometer.**

The figure 31 shows the curve obtained during the second set of test with extensometer. It is clear that the curves of the figure 31 and Appendix 29 are completely different.

The first set of test is not given a logical data in terms of stiffness, therefore, the second set of test with extensometer is going to take as valid and count for post-evaluation.

3.2.2.2.2 45° Orientation Direction Specimens

Appendix 30 shows the force-displacement curve of the first set of test without extensometer.
Fig. 32. Stress-strain curve of 45° orientation direction specimens in dynamic tension test with extensometer.

The figure 32 shows the curve obtained during the second set of test with extensometer. It is the same case of 0° Orientation. Therefore, it is assumed that the second set is the right data, which is going to take into account to post-evaluation.

3.2.2.2.3 90° Orientation Direction Specimens

The figure 33 shows the curve obtained during the second set of test with extensometer.

Fig. 33. Stress-strain curve of 90° orientation direction specimens in dynamic tension test with extensometer.
It is the same case of 0° Orientation and 45° Orientation. Therefore, it is assumed that the second set is the right data, which is going to take into account to post-evaluation.

3.2.2.2.4 Conclusion

It has been assumed that the second set of test with extensometers is the right data to evaluate the orientation of the injection dependency. As it has done in the Quasi-static case, it is going to study the influence of orientation of injection in different parameters.

Table.7. The average of the Young Modulus of two test sets on three orientations.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>With Extensometer (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° orientation</td>
<td>2431.67</td>
</tr>
<tr>
<td>45° orientation</td>
<td>1896.54</td>
</tr>
<tr>
<td>90° orientation</td>
<td>2103.72</td>
</tr>
<tr>
<td></td>
<td>Δ</td>
</tr>
</tbody>
</table>

The table above shows that the difference between the maximum and the minimum Young Modulus, it is quite high between 0° and 90°, the modulus are quite similar. However, between 0° or 90° and 45° is quite big.

The young modulus depends on the orientation of the injection.

Table.8. The average of the Maximum Stress of two test sets on three orientations.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>With Extensometer (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° orientation</td>
<td>21.34</td>
</tr>
<tr>
<td>45° orientation</td>
<td>19.48</td>
</tr>
<tr>
<td>90° orientation</td>
<td>22.25</td>
</tr>
<tr>
<td></td>
<td>Δ</td>
</tr>
</tbody>
</table>

The table above shows the Maximum Stress depends on the orientation of the injection.
The last row shows the difference in per cent between the maximum and the minimum stress. The value of this difference is not higher than 10%. Therefore, the Maximum of stress does not depend on the orientation of injection.

Strain at failure
Due to the failure section is not bounded perfectly by the extensometer. It is very difficult to select the strain at failure in every case.

It is going to be assumed that it is the biggest in every case.

Table.9. The average of the strain at failure of two test sets on three orientations.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>With Extensometer-Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° orientation</td>
<td>0.49</td>
</tr>
<tr>
<td>45° orientation</td>
<td>0.44</td>
</tr>
<tr>
<td>90° orientation</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Δ</td>
</tr>
</tbody>
</table>

The table above shows the maximum values of the strain at failure of the different cases.

The last row shows the difference in per cent between the maximum and the minimum. The value is quite close to 10%. Therefore, the strain at failure does not depend on the orientation of the injection.

3.2.2.3 Quasi-static shear test results
3.2.2.3.1 0° Orientation Direction Specimens
After quasi-static shear test, the stress-strain curve of 0° orientation direction specimens in quasi-static shear test could be calculated and drawn in Fig. 34.
As shown in the figure above, it could clearly be seen how the stress has changed for each specimen. As strain increases, load also increases rapidly at first, then decreases at a slower speed which is due to the break of the joint of the specimens.

According to the above figures, various data of max load, stress at offset yield, and stress at max load of 0° orientation direction specimens in quasi-static shear test could be obtained in the table in T1-S0-25062015(Appendix. 8).

3.2.2.3.2 45° Orientation Direction Specimens

In the following figure 35, the stress-strain curve of 45° orientation direction specimens in quasi-static shear test is shown in the following graph.
As shown in figure 35, for specimens 1 and 2, the graph is different to the previous one of 0° orientation, due to the difference in position where the specimen breaks. In this figure, as the first two specimens did not break at the joint point, the graph decreases at a rapid speed to a certain point where it remains constant. On the other hand, for specimens 3, 4 and 5, these were broken at the same point as of 0° orientation, therefore, the downward slope of the graph remains smoother and does not have a point where it stays constant. This is similar to the graph shown in figure 34.

By means of the above figures, the test data of 45° orientation direction specimens in quasi-static shear test is shown in the table in T1-S45(1)-25062015 and T1-S45(2)-25062015(Appendix. 9 & 10).

3.2.2.3.3 90° Orientation Direction Specimens

The stress-strain curve of 90° orientation direction specimens in quasi-static shear test is shown in the following Fig.36.
For specimens 1 and 2 as shown in figure 36, the graphs are similar to that of specimen 1 and 2 in figure 35. This is due to the position of where the specimen was broken. Whereas for specimen 3, the graph seems to be different to all the other previous graphs, this may be due to the difference in breakage point, as for this specimen, it was broken further to the right. This may be due to an error in the result or when completing the test. Further tests may be constructed in order to improve the accuracy of the results.

Furthermore, as the breakage point of the three specimens shown in figure 36, is different to the expected result. It could be concluded that this indicates a failure in the result as it does not follow the expectations stated previously. Similar for specimens 1 and 2 for 45° orientation, they also did not follow the expected trend of breaking at the point of the joint; this further indicates a failure in result for them two specimens also.

The mechanical properties of 0° orientation direction specimens in quasi-static shear test could be obtained from the above figures and are shown in the table in T1-S90-25062015(See Appendix.11)
3.2.2.3.4 Conclusion
Consequently, as we can see from above graphs, all 0° orientation direction specimens could withstand the shear stress among orientation directions. By comparing the tables (See Appendix. 8-11), the max load and stress act on the 0° orientation direction specimen can be identified, which is a little bit higher than 45°, 90° orientation direction specimens. Furthermore, two specimens of 45° orientation direction and all specimens of 90° orientation direction did not follow the expected trend of breaking at the point of the joint, this 45° orientation direction specimens and 90° orientation direction specimens are failed to use in further application. To summarize, the shear strength and resistance to shear stress of 0° orientation direction specimen, is the most appropriate and meets the expected requirement.

3.2.3 Conclusion
The Quasi-static Tensile test indicates that the Young modulus and the maximum stress do not depend on the orientation of the injection. However, the strain at failure is quite random even between specimens of the same orientation, it must not be, and between the set of test.

The strain at failure in quasi-static test depends on the orientation of injection.
On the other hand, the dynamic tensile test indicates that the Young modulus is quite sensible to the orientation of the injection. However, the maximum stress and the strain at failure do not depend on the orientation of the injection.

The 0° orientation has the highest values of Young Modulus, Maximum stress and strain at failure in both tests. However, the 45° orientation has the lowest values of young modulus and maximum stress and the 90° orientation has the lowest values of young modulus, maximum stress and strain at failure in the quasi-static test.

Due to the discrepancy of results, the shear test is not going to take into account.
4. B-pillar model and simulation

4.1 Test correlation

4.1.1 Introduction
In order to correlate a numerical model with the data of the previous section, it is necessary to choose what test are going to be calibrated. It has been decided that 0° orientation of injection is the most consistent in quasi-static and dynamic tests, due to that has the highest values of young modulus, maximum stress and strain at failure in both tests. In terms of quasi-static the test chosen is 0° orientation set 1 (without extensometer) and dynamic the test chose is the 0° orientation set 2 (with extensometer).

4.1.2 Applied Software

4.1.2.1 LSTC LS-PrePost 4.0
LS-PrePost is an advanced and professional interactive program for preparation of input data for LS-DYNA and processing of the results from LS-DYNA analysis. Its pre-processing features are meshing tools and special applications like metal forming and airbag folding, etc. The post-processing features of this efficient and intuitive software are D3PLOT animation and BINOUT processing. LS-PrePost is delivered free with LS-DYNA made by the Livermore Software Technology Corporation, and the LS-DYNA code of LS-PrePost used for test correlation and B-pillar interior trim simulation in this simulation. The University of Manchester LS-DYNA Software Version is ls971s R6.0.0 (See Appendix. 22).

4.1.2.2 Solidworks
Solidworks is one of the most widely used software for constructing 3D model and simulation by engineers and designers, it was made by Dassault Systems S.A. Company. The software’s key capabilities such as CAD animation, part and assembly modelling were used in this research to make the test specimen models and B-pillar interior trim model
4.1.2.3 Notepad++
Notepad++ is a free source code editor and a text editor. Since many input files need to be done manually, this is more suitable as it is unlike the standard notepad – built-in window software is unusable for this feature. Notepad++ is an appropriate replacement to modify the LS-DYNA keywords format from the test file.

4.1.3 Quasi-static tension test correlation

4.1.3.1 Introduction
As for the quasi-static tension test without an extensometer, the displacement L is the distance between the grips of the machine, it measures the global displacement. The calculated strain $\varepsilon$ is the global strain $\varepsilon_{\text{global}}$. There are five specimens that were tested in the quasi-static tension test without extensometer; the first specimen is the most representative test data of all five test specimens, because the strain at yield point and the elongation at break is the closest to the normal test data. From the above data, the force-displacement curve and the stress-strain curve of single specimen 1 of quasi-static tension test without extensometer are shown at figure 37.

Fig.37. Stress-strain curve of $0^\circ$ orientation direction specimen 1 in quasi-static tension test correlation.
4.1.3.2 Geometry
The size of the model geometry is the same as the physical specimen, see Fig. 38.

![Fig. 38. The geometry of 0° orientation direction specimen 1 in quasi-static tension test correlation.](image)

4.1.3.3 Finite Element Analysis – Model
4.1.3.3.1 Elements and boundary conditions
At the beginning of the finite element analysis, the first step is to identify the element number of this specimen, 16,000 solid deformable elements are used for simulation. The element formulation is selected - fully integrated quadratic 8 node element, see Fig. 39.

![Fig. 39. The solid deformable elements of model in the finite element analysis in quasi-static tension test correlation.](image)

Furthermore, the next step is to set the boundary conditions. At first, it is required to find one model side which is closer to the origin of X, Y, Z coordinates, set nodes of this part fixed in X, Y, Z directions. Then set a boundary condition on the other side, set nodes of this part fixed in the directions of Y & Z coordinates and give an
enforced displacement 29.6mm along with X coordinate direction, see Fig.40.

Fig.40. The boundary conditions of model in the finite element analysis in quasi-static tension test correlation.

4.1.3.3.2 Material Model

For elastic-plastic model simulation, the material model will be used as MAT_024 (PIECEWISE_LINEAR_PLASTICITY) which is the most widely used model for crash, drop and other rate-dependent phenomenon modelling. It is also the simplest material model because the only test available is the tension test. Therefore, the following figure 41 shows the instruction of a MAT_024 model.

Fig.41. The instruction of MAT_024 material model in the finite element analysis in quasi-static tension test correlation.

Where $\rho$ is the density of material;

$e$ is the Young’s Modulus;

$\nu$ is the Poisson Ratio;

$L_{css}$ is the Curve Stress/Strain.

4.1.3.3.3 Young’s Modulus

As the chord slope equation is shown in following equation 3,
\[ E_t = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \text{(Eq. 3.)} \]

Where \( E_t \) is the tensile modulus;
\( \sigma_1, \sigma_2 \) are the stresses;
\( \varepsilon_1, \varepsilon_2 \) are the strains.

The Young’s Modulus could be calculated by equation 3, see Table.10.

Table. 10. The Young’s Modulus calculation in quasi-static tension test correlation.

<table>
<thead>
<tr>
<th>Strain</th>
<th>Stress</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00128085</td>
<td>1.535317</td>
<td>2092.83 E(MPa)</td>
</tr>
<tr>
<td>0.00262589</td>
<td>4.350248</td>
<td></td>
</tr>
</tbody>
</table>

4.1.3.3.4 Yield point

There are two methods to determine the yield point from digital data:

The first method is Point-to-point comparison for a maximum value. This method is a simple procedure, but the drawback is this method requires more checks to avoid choosing noise-related maximum values incorrectly.

The second method is the Slope method. As this method has a smoothing effect and could reduce noise influence, so it is fit to derive a polynomial curve. To determine the strain at yield, this is the centre-point of the evaluation interval for which the slope becomes negative for the first time.

From the above test data, the slope change of the stress-strain curve is shown in Fig. 42, thus strain at yield will be obtained.

![Fig. 42. The slope change of stress-strain curve in quasi-static tension test correlation.](image-url)
The first step to calculate the stress, as the Young’s Modulus is calculated in the previous step, the stress calculation is to multiply Young’s Modulus by the strain - \( \sigma = E \varepsilon \). The second step is to compare the stress from the previous calculation and the stress from the curve.

Thirdly, we could find the yield which is the point when the discrepancy between them starts increasing, see figure 43.

Fig.43. The analysis of improved method in quasi-static tension test correlation. By using the Slope method accordingly, the strain at the yield point is 15.88MPa. If the improved method were utilized, the yield is 11.9MPa.

4.1.3.4 Plastic part

The analysis of MAT_024 model consists of two parts: elastic part and plastic part. The elastic part is in relation to the Young’s Modulus, and the plastic part regards the curve which relates True stress–true strain, see figure 44.
4.1.3.4.1 LS-DYNA Model 1 Plastic input

![Stress-strain curve comparison](image1.png)

Fig. 44. The stress-strain curve of comparison plastic-test and true stress-true strain in quasi-static tension test correlation.

After input the model into the LS-DYNA software, the LS-DYNA shows the first model input curve which is very close to the true stress-true strain curve, see figure 45.

![Stress-strain curve comparison](image2.png)

Fig. 45. The stress-strain curve of comparison true stress-true strain and LS-DYNA input model 1 in quasi-static tension test correlation.

force drops when the necking appears at the moment, see Fig. 46 & 47.
It is necessary to modify the input curve in order to correlate the test results.

4.1.3.4.2 LS-DYNA Model 2 Plastic input

After the initial model simulation, the results are not what we expected. Therefore, the material curve is put as metal approach with two slopes, keeping in mind that the failure is under strain see figure 48.
Fig. 48. The stress-strain curve of comparison LS-DYNA input model 2, true stress-true strain and LS-DYNA input model 1 in quasi-static tension test correlation.

Furthermore, the second model explicit-mass scaling result is shown in the following figure 49 and figure 50. The strain failure is 0.8.

Fig. 49. The simulation of LS-DYNA input model 2 in quasi-static tension test correlation.
From the above graphs, we could identify the second model curve is the typical metal curve. The key has been keeping uniformly the strain, during deformation. The advantage of the second model is that it is possible to obtain the correct failure. However, the disadvantage is that the model stores more energy than in reality, but the important thing is to find the strain failure at the tension, in order to implement it into the real model.

It is possible to create a model which storage the same energy and break at the same point by reducing the maximum force. In this case, the maximum force is going to be lower, the energy and strain at failure are going to be the same.

4.1.3.5 Conclusion

According to the above simulation, the objective is to find the plastic curve which could make the specimen response globally like the test specimen. By means of the two models to match the test displacement at failure point with a reasonable maximum local failure strain, it can be found the first model is not able to obtain it, but model 2 is able to obtain the strain failure at the tension.

Fig.50. The force-displacement curve of comparison specimen 1, model 1 and model 2 in quasi-static tension test correlation.
4.1.4 Dynamic tension test correlation

4.1.4.1 Introduction

The test that has been chosen for the dynamic tensile test calibration is the 0° orientation with extensometers.

Fig.51. Force-displacement curve of 0° orientation direction specimen in dynamic tension test correlation.

Fig.52. Stress-strain curve of 0° orientation direction specimen in dynamic tension test correlation.

The problem that we have in the dynamic test with extensometer is that there is not the global displacement; therefore, the global displacement was taken from the first dynamic test. Although which is not fully correct, it is a good approximation and the displacements were measured properly.
There are two tests, one reaches 11.5mm and the other one reaches 14.8mm, therefore, it has been assumed 13.5mm, because that measured is between the two of the first test data and is matching with $l_0/2$.

4.1.4.2 Geometry
The size of model geometry is the same as the physical specimen, see Fig. 53.

![Fig.53. The geometry of 0° orientation direction specimen in dynamic tension test correlation.](image)

4.1.4.3 Finite Element Analysis – Model
4.1.4.3.1 Elements and boundary conditions
In the first step of the finite element analysis, the beginning is to define the element number of this specimen, 6375 solid deformable elements are used for simulation. The element formulation is the same as the quasi-static tension test correlation selected -fully integrated quadratic 8 node element, see Fig. 54.

![Fig.54. The solid deformable elements of model in the finite element analysis in dynamic tension test correlation.](image)
Moreover, the next step is to set boundary conditions. Firstly, find one model side which is closer to the origin of X, Y, Z coordinates, set nodes of this part fixed in X, Y, Z directions. Then set a boundary condition on the other side, set nodes of this part fixed in the directions of Y & Z coordinates and give an enforced displacement 13.5mm along with X coordinate direction, see Fig.55.

![Figure 55](image)

Fig.55. The boundary conditions of model in the finite element analysis in dynamic tension test correlation.

4.1.4.3.2 Material Model
The material model MAT_024 (PIECEWISE_LINEAR_PLASTICITY) was selected to simulate the elastic-plastic model of dynamic tension test. Therefore, we could set a MAT_024 model by using the following instructions, see figure 56.

![Material Model Instruction](image)

Fig.56. The instruction of MAT_024 material model in the finite element analysis in dynamic tension test correlation.

Where $\rho$ is the density of material;

$E$ is the Young’s Modulus;

$\nu$ is the Poisson Ratio;

$L_{css}$ is the Curve Stress/Strain.
4.1.4.3.3 Young’s Modulus

As the chord slope equation is shown in above equation 3,

The Young’s Modulus could be calculated by equation 3, see Table. 11.

Table 11. The Young’s Modulus calculation in dynamic tension test correlation.

<table>
<thead>
<tr>
<th>Elastic Modulus</th>
<th>Strain</th>
<th>Stress (E(MPa))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
<td>0.000363</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.048276</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2297.739</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.002313</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.528498</td>
</tr>
</tbody>
</table>

4.1.4.3.4 Yield point

As the method to determine the yield point was mentioned above, we just need to use the same method as the quasi-static tension test.

From the following figure 57, the strain at the yield point can be obtained, which is 9.977MPa.

Fig. 57. The analysis of improved method in dynamic tension test correlation.

4.1.4.4 Plastic part

There are two parts to analyse the MAT_024 model, elastic part and plastic part. The elastic part is in relation to the Young’s Modulus, and the plastic part is in regards to the curve which relates to the True stress-true strain, see figure 58.
4.1.4.1 LS-DYNA Model 1 Plastic input

After input the model 1 into LS-DYNA software, the LS-DYNA shows the first model input curve is very close to the true stress-true strain curve, see figure 59.

After the force-displacement curve is checked, the response of this curve is identified as unsuitable. The reason is similar as the quasi-static tension test correlation; when the necking appears on the model, the force drops.
4.1.4.2 LS-DYNA Model 2 Plastic input

In other to solve the problem of model 1, it is necessary to do the same that we did in the quasi-static.

Fig. 60. The simulation of LS-DYNA input model 1 in dynamic tension test correlation.

Fig. 61. The force-displacement curve of LS-DYNA input model 1 in dynamic tension test correlation.
The model 2 implicit dynamic results are shown in the following figure 71 and figure 72.

From the above curve, the curve is the typical metal curve. The key has been to keep uniformly the strain during the deformation. The benefit is that it is possible...
to get the right failure. However, the disadvantage is that the model stores more energy than in reality, but the important thing is to find the strain failure at the tension, in order to put into the real model.

The discrepancy in the initial part is due to the local behaviour of the extensometer and the global behaviour of the model. It is impossible to compare with a global behaviour due to the low credibility of the set 1 (without extensometer) data.

4.1.4.3 LS-DYNA Model 3 Plastic input

The objective is to obtain a model that fails under strain conditions, but at the right force. Thereby, the new plastic curve LS-DYNA input is shown in the following graph 65. The modified LS-DYNA input curve has been reduced at the hardening point.

![Stress-Strain Curve](image)

**Fig.65.** The stress-strain curve of LS-DYNA input model 3 in dynamic tension test correlation.

From results of model 3 - implicit in dynamic tension test correlation, the strain at the failure point is 0.55. The damage appearances of the model 3 are shown in the following figure 66 and figure 67.
In the following figures, by means of comparison between the force-displacement curve of test and model 3, the conclusion is the failure points happen at the same force and at the right displacement.

**Fig. 66.** The damage initiation of LS-DYNA input model 3 in dynamic tension test correlation.

**Fig. 67.** The full failure situation of LS-DYNA input model 3 in dynamic tension test correlation.

**Fig. 68.** The force-displacement curve of LS-DYNA input model 3 in dynamic tension test correlation.
4.1.4.4 LS-DYNA Model 4 Plastic input
This model is exactly the same as model 3, but it has been run in explicit, which is the method that is going to be used for B-Pillar interior trim. The only difference is that it has been adjusted - the strain at the failure point is 0.75. In the following figure 69, the force-displacement curves of test, model 3 and model 4 are shown.

![Force/Displacement](image)

Fig.69. The force-displacement curve of LS-DYNA input model 3 & 4 in dynamic tension test correlation.

4.1.4.5 Conclusion
Conclusively, the objective of the dynamic tension test correlation is to find the plastic curve which could be able to make the specimen response globally as the test specimen. By matching the test displacement at failure point with a reasonable maximum local strain failure to the same force. By comparing model 3 with model 4, we could find that model 3 is an implicit dynamic model, with failure at the right displacement and at the right force. However, model 4 is a dynamic explicit model with failure at the right displacement, the force is a bit higher, but it is still acceptable.
4.2 B-pillar Interior Trim Simulation

4.2.1 Introduction

The B-pillar interior trim is one of the most important parts of the automobile structure, which is attached to the B-pillar and roof rail, fixed by a customized fixture, see fig 70.

![B-pillar interior model in an automobile](image1)

In order to predict accurately the mechanical behaviour of B-Pillar interior trim during airbag deployment, the B-pillar material has been tested and the data has been analysed in the previous sections.

The objective of this part is to present a model which can be used to size the thickness of the B-pillar and design the attachment with the frame of the car.

In order to set up the problem, the figure 71 shows the B Pillar trim cover isolated.

![B-pillar interior trim cover isolated](image2)
4.2.2 Applied Software
The range of software used in the simulation of B-pillar interior trim is the same as the above test correlation.

4.2.3 Geometry
It is important to notice that the geometry in this research is based on measurements, it were taking on a real B-pillar cover component. The principal objective is to describe a procedure to design one. It is not necessary to have the real dimensions.

![B-pillar trim geometry](image)

Fig. 72. The B-pillar trim geometry.

The initial thickness as an assumption is the 3mm.

4.2.4 Procedure
The objective of this part is to describe the procedure that is going to be followed to get the objective.

First of all, it is important to clarify the objective. The idea is to create a method, in order to optimize the thickness of B-Pillar trim against the load created by an airbag deployment and help to obtain the attachment against the frame of the car.
Figure 73 shows the sequence of actions that are needed to follow, in order to optimize the thickness and get the force that the attachments to the car frame have to support.

The material card is coming from the previous dynamic tensile test correlation; the load is defined by JLR as a Pressure/time. The boundary conditions are defined based on the attachments to the car frame which are assumption in this study. Therefore, the parameters that could be modified are the kind and number of the finite element model.

Due to the type of the structure, we are using Shell elements formulation; the thickness is much smaller than the other dimensions that define the structure. The selection of Solid elements is a big mistake, due to the minimum number of elements that is necessary to put through the thickness in order to capture a proper bending behaviour; it is going to lead to a big number of element with a really small edge which for an explicit simulation is a really bad combination, leading to a very...
small time step, so very long computation time.

Regarding the number of elements, it is something that is necessary to take into consideration. It leads to an iterative process which has the objective to increase the number of element that defines the numerical model of the structure until we get the same results.

The last part is to modify the thickness of the structure until we get failure, so the solution is the thickness a little bit higher than that is producing the failure of the structure.

The force on the top of the attachment is the force that has to support the attachment to the frame. This force is an input for the attachment design of an optimize B-pillar trim cover against an airbag deployment.

### 4.2.5 Material card, Load and Boundary conditions

#### 4.2.5.1 Material card

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$#  mid  re  e  pr  sigy  etan  fail  tdel
  1  1.250E-6  2297.739  0.000  0.000000  0.000  0.50  0.000
$#  c  p  lcse  lcsr  vp
  0.000  0.000  2  0  0.000
$#  eps1  eps2  eps3  eps4  eps5  eps6  eps7  eps8
$#  es1  es2  es3  es4  es5  es6  es7  es8

*DEFINE_CURVE
$#  lcid  sidr  sfa  sfo  offa  offo  dattyp
  2  0  1.000000  1.000000  0.000  0.000  0
$#  0  1  0.0000000  6.97796143
  0.00148106  12.26809376
  0.00299259  14.14353425
  0.00432406  15.44150273
  0.00564325  16.38820159
  0.0067007  17.20519885
  1.0000000  27.80000000

Fig.74. Material Card for MAT_024 LS-Dyna
```

This card is coming from the dynamic test correlation.
4.2.5.2 Load
The load is a pressure triangle shape pulse (0N at 0ms, to 15000N at 10ms then to 0N at 20ms) over an area of 10cm (length) by the width of the B-pillar at the top end.

4.2.5.3 Boundary conditions
We are going to assume that the cover is attached to the frame at the top edge of the cover and the bottom part of the cover cannot move longitudinally.

![Fig.75. Area of Pressure application](image)

![Fig.76. Boundary conditions](image)
4.2.6 Elements and number iteration

4.2.6.1 Model 1

Model 1 has 3mm thickness and is formed by 1712 Shell elements.

4.2.6.1.1 Results

Von Mises Stress.

Fig.77. Model 1

Fig.78. Von Mises Stress
4.2.6.2 Model 2

Model 2 has 3mm thickness and is formed by 9440 Shell elements.
4.2.6.2.1 Results

Von Mises Stress.

The figure 81 shows that the maximum strains are quite the similar of the figure 78.

The figure 82 shows plastic strain different to figure 80 that it is quite close to the failure 0.5.
4.2.6.3 Model 3
Model 3 has 3mm thickness and is formed by 21288 Shell elements.

4.2.6.3.1 Results
Plastic Strain

In the figure 84 shows that if the number of elements is increased, the elements are failing, so in the next model the mesh is kept and the thickness is increased.

4.2.6.4 Model 4
Model 4 has 3.5mm thickness and is formed by 21288 Shell elements.
4.2.6.4.1 Results
Plastic Strain

If the thickness is increased to 3.5mm, the model is not failing. In the model 5 we are going to increase the number of elements.

4.2.6.5 Model 5
Model 5 has 3.5mm thickness and is formed by 84980 Shell elements.
4.2.6.5.1 Results

Plastic Strain

The figure 88 shows that the model is not failing. It is very close to fail. It could be possible to increase the mesh a see if the model is failing.

4.2.6.6 Model 6

Model 6 has 3.5mm thickness and is formed by 236627 Shell elements.
The model is failing but it is at the limit. The model 7 we increase the thickness to 3.7mm and keep the mesh.

It could be possible to keep the model 6 due to the model is failing at the corner which is the local stress concentration. The real component is going to be round instead of sharp as the geometry that we are using, so the level of the stress is going to decrease.
4.2.6.7 Model 7
As we saw in the model 6 the failure is happening at the edge that in the real component should be round which is going to decrease the stress level. The model 5 should be the model which can be the optimize structure. However if we follow the procedure, taking into account the numerical result of the geometry without fillet on the edge, we need to increase the thickness to 3.7mm in order to optimize structure.

Plastic Strain

The figure 91 shows that the model 7 does not fail. It is at limit. If we take into account the geometry without potential modifications, the optimize model is 3.7mm thickness.

The next step of the procedure is to get the force that the attachment has to support.
Fx=0N
Fy=-2700N
Fz=7480N

The attachment has to support these forces.

4.2.7 Conclusion

From the above research, we could draw some conclusion. As a classical elastic-plastic model based on the vonMises criteria, Elastic-plastic material with an arbitrary stress vs. strain curve and arbitrary strain rate dependency can be defined. It has many advantages. Firstly, Mat_024 model can work with shells and solids with LS-DYNA Implicit and Explicit. Furthermore, the test requirements of Mat_024 model are very moderate, like this simulation only requires the tensile test data with quasi-static speed and high speed. Additionally, the Mat_024 model is much cheaper and requires less capability and experience.

However, the disadvantages and limitations of Mat_024 should also be considered. Firstly, not like the SAMP-1 model combines a range of models into one to provide
the most accurate results in crash simulation; the Mat_024 model is too simple and
does not support complex failure modes such as necking and cold drawing. Beside
them, thermoplastics are not incompressible during plastic flow, this leads to the
assumption of plastic flow at constant volume and the material laws based on the
vonMises plasticity are not suitable. Finally, the input curves of Mat_024 model
must be monotonically increasing.

The objective of this simulation is to define a numerical failure model of a B-pillar
interior trim which under the load engendered by an airbag deployment. The
procedure is to get the same results by increasing the thickness and decreasing the
element size of the structure. The final outcome of the thickness is 3.7mm while
the model with 236627 Shell elements. Therefore, by means of optimize the
thickness with different shell elements of the Mat_024 model, the Talc-Filled
Polypropylene behaviour has been predicted accurately, it is essential to design the
B-pillar interior trim with the most appropriate material and to obtain the accurate
data required to protect the safety of passengers.
5. Conclusion

The aim of this research is to predict the plastic failure of the interior trim of the B-Pillar during airbag deployment in order to avoid a local trim break mode and obtain the force to determine the dimension of the attachment to the frame of the car using MAT_024 model. The first part of this research is to select the constitutive model (Mat_024) that can predict the material behaviour, define the test that is needed to feed the data of this constitutive model and correlate the test more representative, which is going to give the material card that is going to be used into the structure model. Accordingly, the quasi-static tension test, dynamic tension test and quasi-static shear test were conducted in order to define the elastic-plastic material model (MAT_024).

It was found that the current shear test does not provide proper results. It is recommended that the V-Notched Rail Shear method should be used in future test. Regarding the quasi-static and dynamic tensile tests, it was found that the failure strains of the same specimen type vary in a large range. However, other mechanical parameters, e.g. Young’s modulus and maximum strength are consistent for the same type of specimens. This behaviour should be further studied. In this feasibility study, the $0^\circ$ orientation quasi-static and dynamic tensile testing data were the strongest material properties used to correlate and get the material card used for the B-Pillar interior trim model because of the consistence of the data for $0^\circ$ orientation specimens. Therefore, this research is limited by the selection of other weaker material properties data in the material model to simulate more results to compare, such as using the weakest material properties and find out the differences with the strongest material properties.

The final objective of this dissertation is to define a numerical failure model of a B-pillar interior trim which permits to optimize the B-pillar trim under the load generates by the airbag deployment. An iterative procedure is developed to
optimize the structure and the force in order to define the attachment to the car frame. The procedure involves the decreasing of the element size and the increasing of the thickness of the structure of the model with different element sizes to reach the same results. The optimization procedure and problems were discussed, and it was found that the sharp edge of the trim should be avoided to reduce the iteration numbers.

The second part of the procedure is to obtain the force that could be used for sizing the attachment to the car frame. It is concluded that, in order to optimize a structure, it is necessary to define a numerical model which can predict the behaviour of the structure so that the parameters can be varied for optimization purpose. This part is to define the iterative process to optimize the parameters in which we are interested as the thickness in the case of this dissertation. The final outcome of the thickness is 3.7mm while the model with 236627 Shell elements. Therefore, Talc-Filled Polypropylene behaviour has been predicted accurately, it is significant to design the B-pillar interior trim with the most appropriate material and to obtain the accurate data required to protect the safety of passengers.


References


Appendix

Appendix 1. T1-Q0-25062015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: Tensile test

Croshead Speed: 6.00 mm/min  Test Date: 25 June 2015
Sample Rate (pts/sec): 2.00  Operator name: D. Mortimer
Full Scale Load Range: 100.00 kN  Sample Identification: Qstatic tension 0
Test Mode:  Custom Test Label:
Test Method Number: 1  Test type: Tensile
Specimen Geometry: Rectangular  Width: 9.970 mm
Thickness: 3.69 mm  Specimen G. L.: 65,000 mm

<table>
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<tr>
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<th>Stress at Max. Load (MPa)</th>
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<td>11.690</td>
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<tr>
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</tr>
<tr>
<td>5</td>
<td>0.620</td>
<td>16.492</td>
</tr>
</tbody>
</table>

Sample ID: Qstatic tension 0
Appendix 2. T1-Q45-25062015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: Tensile test
Description 2:

Crosshead Speed: 6.00 mm/min
Sample Rate (pts/sec): 2.00
Full Scale Load Range: 100.00 kN
Test Mode:
Test Method Number: 1
Specimen Geometry: Rectangular
Thicknss: 3.69 mm
Width: 9.620 mm
Specimen G. L.: 65.000mm

<table>
<thead>
<tr>
<th>Load at Max.Load (KN)</th>
<th>Stress at offset Yield 1 (MPa)</th>
<th>Stress at Max.Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.574</td>
<td>10.122</td>
</tr>
<tr>
<td>2</td>
<td>0.576</td>
<td>10.395</td>
</tr>
<tr>
<td>3</td>
<td>0.586</td>
<td>10.268</td>
</tr>
<tr>
<td>4</td>
<td>0.591</td>
<td>10.447</td>
</tr>
<tr>
<td>5</td>
<td>0.583</td>
<td>10.148</td>
</tr>
</tbody>
</table>

Sample ID: Static tension 45
Appendix 3. T1-Q90(1)-25062015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: Tensile test
Description 2:

Crosshead Speed: 6.00 mm/min Test Date: 25 June 2015
Sample Rate (pts/sec): 2.00 Operator name: D. Mortimer
Full Scale Load Range: 100.00 kN Sample Identification: Qstatic tension 90
Test Mode: Custom Test Label:
Test Method Number: 1 Test type: Tensile
Specimen Geometry: Rectangular Width: 9.260 mm
Thickness: 3.69 mm Specimen G. L.: 65.000mm

<table>
<thead>
<tr>
<th>Load at Max.Load (KN)</th>
<th>Stress at offset: Yield 1 (MPa)</th>
<th>Stress at Max.Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.514</td>
<td>9.522</td>
</tr>
<tr>
<td>2</td>
<td>0.514</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0.514</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>0.578</td>
<td>10.014</td>
</tr>
<tr>
<td>5</td>
<td>0.582</td>
<td>10.163</td>
</tr>
<tr>
<td>6</td>
<td>0.569</td>
<td>9.926</td>
</tr>
<tr>
<td>7</td>
<td>0.555</td>
<td>11.123</td>
</tr>
</tbody>
</table>
University of Manchester
M.A.C.E.
Materials Testing

Sample ID: Qstatic tension 90

[Graph showing load vs. displacement]
Appendix 5. T1-D0-29062015

University of Manchester  
M.A.C.E.  
Materials Testing

- Description 1:  
  Tensile test
- Description 2:  

Crosshead Speed: 240.00 mm/min  
Test Date: 29 June 2015

Sample Rate (pts/sec): 50.00  
Operator name: D. Mortimer

Full Scale Load Range: 10.00 kN  
Sample Identification: Dynamic Tension 0

Test Mode:  
Custom Test Label:  

Test Method Number: 1  
Test type: Tensile

Specimen Geometry: Rectangular  
Width: 9.350 mm

Thickness: 3.73 mm  
Specimen G. L.: 35.000 mm

<table>
<thead>
<tr>
<th>Load at Max Load (kN)</th>
<th>Stress at Yield 1 (MPa)</th>
<th>Stress at Max Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.712</td>
<td>18.816</td>
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<tr>
<td>2</td>
<td>0.706</td>
<td>18.666</td>
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<tr>
<td>3</td>
<td>0.698</td>
<td>18.522</td>
</tr>
</tbody>
</table>

Sample ID: Dynamic Tension 0
Appendix 6. T1-D45-29062015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: Tensile test

Croshead Speed: 240.00 mm/min
Sample Rate (pts/sec): 50.00
Full Scale Load Range: 10.00 kN
Test Mode:
Test Method Number: 1
Specimen Geometry: Rectangular
Thickness: 3.71 mm

Width: 9.130 mm
Specimen G. L.: 35.000 mm

<table>
<thead>
<tr>
<th>Load at Max.Load (kN)</th>
<th>Stress at offset (MPa)</th>
<th>Yield 1 (MPa)</th>
<th>Stress at Max.Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.630</td>
<td>17.170</td>
<td>18.786</td>
</tr>
<tr>
<td>2</td>
<td>0.630</td>
<td>16.506</td>
<td>18.447</td>
</tr>
<tr>
<td>3</td>
<td>0.630</td>
<td>17.118</td>
<td>18.697</td>
</tr>
</tbody>
</table>

Sample ID: dynamic tension 45

Sample ID: dynamic tension 45

Displacement mm

Load (kN)
Appendix 7.  T1-D90-29062015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: Tensile test
Description 2:

Crosshead Speed: 240.00 mm/min  Test Date: 29 June 2015
Sample Rate (pts/sec): 50.00  Operator name: D. Mortimer
Full Scale Load Range: 10.00 kN  Sample Identification: dynamic tension 90
Test Mode: Custom Test Label:

Test Method Number: 1  Test type: Tensile
Specimen Geometry: Rectangular  Width: 9.280 mm
Thickness: 3.75 mm  Specimen G. L.: 35,000m

<table>
<thead>
<tr>
<th>Load at Min. Load (KN)</th>
<th>Stress at offset (MPa)</th>
<th>Yield 1 (MPa)</th>
<th>Stress at Min. Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.606</td>
<td>16.203</td>
<td>17.389</td>
</tr>
<tr>
<td>2</td>
<td>0.600</td>
<td>15.153</td>
<td>17.373</td>
</tr>
<tr>
<td>3</td>
<td>0.618</td>
<td>16.143</td>
<td>17.747</td>
</tr>
</tbody>
</table>

Sample ID: dynamic tension 90
Appendix 8.  T1-S0-25062015

University of Manchester  
M.A.C.E.  
Materials Testing

<table>
<thead>
<tr>
<th>Description 1:</th>
<th>Tensile test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crosshead Speed:</td>
<td>6.00 mm/min</td>
</tr>
<tr>
<td>Sample Rate (pts/sec):</td>
<td>2.00</td>
</tr>
<tr>
<td>Full Scale Load Range:</td>
<td>100.00 kN</td>
</tr>
<tr>
<td>Test Mode:</td>
<td></td>
</tr>
<tr>
<td>Test Method Number:</td>
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<tr>
<td>Specimen Geometry:</td>
<td>Rectangular</td>
</tr>
<tr>
<td>Thickness:</td>
<td>3.70 mm</td>
</tr>
<tr>
<td>Test Date:</td>
<td>25 June 2015</td>
</tr>
<tr>
<td>Operator Name:</td>
<td>D. Mortimer</td>
</tr>
<tr>
<td>Sample Identification:</td>
<td>Quasi shear 0</td>
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<tr>
<td>Custom Test Label:</td>
<td></td>
</tr>
<tr>
<td>Test Type:</td>
<td>Tensile</td>
</tr>
<tr>
<td>Width:</td>
<td>24.800 mm</td>
</tr>
<tr>
<td>Specimen G.L.:</td>
<td>35.000 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Load at Max. Load (kN)</th>
<th>Stress at offset Yield (MPa)</th>
<th>Stress at Max. Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.222</td>
<td>1.811</td>
<td>2.43d</td>
</tr>
<tr>
<td>2</td>
<td>0.208</td>
<td>1.770</td>
<td>2.30g</td>
</tr>
<tr>
<td>3</td>
<td>0.213</td>
<td>1.801</td>
<td>2.29g</td>
</tr>
</tbody>
</table>

Sample ID: Quasi shear 0

![Graph of Load vs Displacement]
Appendix 9. T1-S45(1)-25062015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: Tensile test
Description 2:

Crosshead Speed: 6.00 mm/min  Test Date: 25 June 2015
Sample Rate (pts/sec): 2.00  Operator name: D. Mortimer
Full Scale Load Range: 100.00 kN  Sample Identification: Quasi shear 45
Test Mode:  Custom Test Label:
Test Method Number: 1  Test type: Tensile
Specimen Geometry: Rectangular  Width: 24.680 mm
Thickness: 3.67 mm  Specimen G.L.: 35.0000 mm

<table>
<thead>
<tr>
<th></th>
<th>Load at Max.Load (kN)</th>
<th>Stress at offset Yield (MPa)</th>
<th>Stress at Max.Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.215</td>
<td>1.804</td>
<td>2.345</td>
</tr>
<tr>
<td>2</td>
<td>0.200</td>
<td>1.551</td>
<td>2.254</td>
</tr>
<tr>
<td>3</td>
<td>0.220</td>
<td>1.761</td>
<td>2.429</td>
</tr>
</tbody>
</table>

Sample ID: Quasi shear 45

Displacement mm

Load (kN)
Appendix 10. T1-S45(2)-25062015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: Tensile test
Description 2:

Crosshead Speed: 6.00 mm/min  Test Date: 25 June 2015
Sample Rate (pts/sec): 2.00  Operator name: D. Mortimer
Full Scale Load Range: 100.00 kN  Sample Identification: Quasi shear 45
Test Mode: Custom Test Label:
Test Method Number: 1  Test type: Tensile
Specimen Geometry: Rectangular  Width: 24.730mm
Thickness: 3.70 mm  Specimen G. L.: 35.000mm

<table>
<thead>
<tr>
<th>Load at Max. Load (kN)</th>
<th>Stress at offset (Yield 1) (MPa)</th>
<th>Stress at Max. Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.213</td>
<td>1.804</td>
</tr>
<tr>
<td>2</td>
<td>0.206</td>
<td>1.638</td>
</tr>
<tr>
<td>3</td>
<td>0.220</td>
<td>1.761</td>
</tr>
<tr>
<td>4</td>
<td>0.213</td>
<td>1.503</td>
</tr>
<tr>
<td>5</td>
<td>0.216</td>
<td>1.629</td>
</tr>
</tbody>
</table>

Sample ID: Quasi shear 45

Displacement mm
### Appendix 11. T1-S90-25062015

**University of Manchester**  
**M.A.C.E.**  
**Materials Testing**

<table>
<thead>
<tr>
<th>Description 1:</th>
<th>Tensile test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description 2:</td>
<td></td>
</tr>
<tr>
<td>Crosshead Speed:</td>
<td>6.00 mm/min</td>
</tr>
<tr>
<td>Sample Rate (pts/sec):</td>
<td>2.00</td>
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<tr>
<td>Full Scale Load Range:</td>
<td>100.00 kN</td>
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<tr>
<td>Test Mode:</td>
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<tr>
<td>Test Method Number:</td>
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<td>Specimen Geometry:</td>
<td>Rectangular</td>
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<tr>
<td>Thickness:</td>
<td>3.79 mm</td>
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<tr>
<td>Width:</td>
<td>24.800 mm</td>
</tr>
<tr>
<td>Specimen G. L.:</td>
<td>35,000 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load at Max Load (kN)</th>
<th>Stress at Yield (MPa)</th>
<th>Stress at Max Load (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.200</td>
<td>1.992</td>
</tr>
<tr>
<td>2</td>
<td>0.211</td>
<td>1.619</td>
</tr>
<tr>
<td>3</td>
<td>0.206</td>
<td>1.560</td>
</tr>
</tbody>
</table>

![Graph: Load vs. Displacement](image-url)
Appendix 12. T2-Q0-20072015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: General Tensile Test With Extensometer
Description 2:

| Crosshead Speed: | 6.00 mm/min | Test Date: | 20 July 2015 |
| Sample Rate (mm/sec): | 5.00 | Operator name: | D. Mortimer |
| Full Scale Load Range: | 10.00 kN | Sample Identification: | Tensile tension 0 ext |
| Test Mode: | | Custom Test Label: | |
| Test Method Number: | 3 | Test type: | Tensile |
| Specimen Geometry: | Rectangular | Width: | 9.900 mm |
| Thickness: | 3.62 mm | Extensometer G.L. | 12.500 mm |

<table>
<thead>
<tr>
<th></th>
<th>Load at Max Load (kN)</th>
<th>Modulus (E/A) (Mpa)</th>
<th>Stress at Max Load (Mpa)</th>
<th>% Strain at Max Load (%)</th>
<th>% Strain at ASTM Break (%)</th>
<th>Stress at Yield (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.609</td>
<td>2296.683</td>
<td>16.809</td>
<td>3.642</td>
<td>11.640</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.611</td>
<td>2333.527</td>
<td>17.051</td>
<td>3.430</td>
<td>23.000</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.591</td>
<td>2092.319</td>
<td>16.650</td>
<td>3.764</td>
<td>20.528</td>
<td></td>
</tr>
</tbody>
</table>

Sample ID: Tensile tension 0 ext

![Graph showing load vs. displacement](image-url)
Appendix 13. T2-Q45(1)-20072015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: General Tensile Test With Extensometer

Crosshead Speed: 6.00 mm/min  Test Date: 20 July 2015
Sample Rate (pts/sec): 5.00  Operator name: D. Mortimer
Full Scale Load Range: 10.00 kN  Sample Identification: Qstatic tension 45 ext
Test Mode:  
Test Method Number: 3  Test type: Tensile
Specimen Geometry: Rectangular  Width: 9.600 mm
Thickness: 3.70 mm  Extensometer G.L.: 12.500mm

<table>
<thead>
<tr>
<th>Load at Max.Load (kN)</th>
<th>Modulus (GPa)</th>
<th>Stress at Max.Load (MPa)</th>
<th>% Strain at Max.Load (%)</th>
<th>% Strain at Break (%)</th>
<th>Stress at Yls (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.572</td>
<td>2250.367</td>
<td>16.123</td>
<td>3.594</td>
<td>25.594</td>
</tr>
<tr>
<td>2</td>
<td>0.561</td>
<td>2110.149</td>
<td>15.857</td>
<td>3.794</td>
<td>24.688</td>
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<tr>
<td>3</td>
<td>0.561</td>
<td>2034.728</td>
<td>15.805</td>
<td>3.794</td>
<td>24.677</td>
</tr>
<tr>
<td>4</td>
<td>0.581</td>
<td>2137.472</td>
<td>16.351</td>
<td>3.999</td>
<td>38.203</td>
</tr>
</tbody>
</table>

Sample ID: Qstatic tension 45 ext
Appendix 14.T2-Q45(2)-20072015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: General Tensile Test With Extensometer
Description 2:

| Crosshead Speed: | 6.00 mm/min | Test Date: | 20 July 2015 |
| Sample Rate (pts/sec): | 5.00 | Operator name: | D. Mortimer |
| Full Scale Load Range: | 10.00 kN | Sample Identification: | Quatric tension 45 ex |
| Test Mode: | | Custom Test Label: | |
| Test Method Number: | 3 | Test type: | Tensile |
| Specimen Geometry: | Rectangular | Width: | 9.620 mm |
| Thickness: | 3.70 mm | Extensometer G.L.: | 12.500 mm |

<table>
<thead>
<tr>
<th>Load at Max Load (kN)</th>
<th>Modulus (E/Young) (MPa)</th>
<th>Stress at Max Load (MPa)</th>
<th>% Strain at Max Load (%)</th>
<th>% Strain at Break (%)</th>
<th>Str at Break (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.427</td>
<td>2290.267</td>
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<td>23.504</td>
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<tr>
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<td>0.561</td>
<td>2140.140</td>
<td>15.852</td>
<td>3.794</td>
<td>34.680</td>
</tr>
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<td>3</td>
<td>0.561</td>
<td>2347.726</td>
<td>15.905</td>
<td>3.794</td>
<td>34.007</td>
</tr>
<tr>
<td>4</td>
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<td>2377.472</td>
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<td>5</td>
<td>0.568</td>
<td>2055.177</td>
<td>15.961</td>
<td>4.018</td>
<td>35.444</td>
</tr>
</tbody>
</table>

![Sample ID: Quatric tension 45 ex](image)
# Appendix 15. T2-Q90-20072015

**University of Manchester**  
**M.A.C.E.**  
**Materials Testing**

<table>
<thead>
<tr>
<th>Description 1:</th>
<th>General Tensile Test With Extensometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description 2:</td>
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</tr>
<tr>
<td>Crosshead Speed:</td>
<td>6.00 mm/min</td>
</tr>
<tr>
<td>Sample Rate (pts/sec):</td>
<td>5.00</td>
</tr>
<tr>
<td>Full Scale Load Range:</td>
<td>10.00 kN</td>
</tr>
<tr>
<td>Test Mode:</td>
<td></td>
</tr>
<tr>
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<tr>
<td>Specimen Geometry:</td>
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<td>Width:</td>
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<tr>
<td>Thickness:</td>
<td>3.64 mm</td>
</tr>
<tr>
<td>Extensometer G.L.:</td>
<td>12.500mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Load at Max Load (kN)</th>
<th>Modulus (Euler-Young) (MPa)</th>
<th>Stress at Max Load (MPa)</th>
<th>% Strain at Max Load (%)</th>
<th>% Strain at Break (%)</th>
<th>Stress at Mid. (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
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<td>1962.860</td>
<td>16.005</td>
<td>3.047</td>
<td>24.576</td>
</tr>
</tbody>
</table>

![Sample ID: Quarto tension 90 ext](image)
Appendix 16.  T2-D0-20072015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: General Tensile Test With Extensometer
Description 2:

Crosshead Speed: 240.00 mm/min
Sample Rate (pts/sec): 50.00
Full Scale Load Range: 10.00 kN
Test Mode: Rectangular
Specimen Geometry: Width: 9.330 mm
Thickness: 3.64 mm

<table>
<thead>
<tr>
<th>Load at Max. Load (kN)</th>
<th>Modulus (An/Young's) (MPa)</th>
<th>Stress at Max. Load (MPa)</th>
<th>% Strain at Max. Load (%)</th>
<th>% Strain at Auto. Break (%)</th>
<th>Str at 0.2% Yld (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>2471.138</td>
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<td>3.174</td>
<td>48.691</td>
</tr>
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<td>2</td>
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<td>2581.329</td>
<td>21.511</td>
<td>3.372</td>
<td>48.170</td>
</tr>
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<td>21.722</td>
<td>3.298</td>
<td>35.542</td>
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</table>

Test Date: 20 July 2015
Operator name: D. Mortimer
Sample Identification: dynamic tension 0 ext
Custom Test Label:
Appendix 17. T2-D45-20072015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: General Tensile Test With Extensometer
Description 2:

Crosshead Speed: 240.00 mm/min
Sample Rate (pts/sec): 50.00
Full Scale Load Range: 10.00 kN
Test Mode:
Test Method Number: 3
Specimen Geometry: Rectangular
Thickness: 3.68 mm

<table>
<thead>
<tr>
<th>Load at Max Load (KN)</th>
<th>Modulus (E/Young) (MPa)</th>
<th>Stress at Max Load (MPa)</th>
<th>% Strain at Max Load (%)</th>
<th>% Strain at破 (%)</th>
<th>Str at % Yt (M)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2484.238</td>
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<td>3.054</td>
<td>31.213</td>
</tr>
<tr>
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<td>2203.045</td>
<td>19.685</td>
<td>3.320</td>
<td>38.304</td>
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<tr>
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<td>0.663</td>
<td>2101.689</td>
<td>19.735</td>
<td>3.454</td>
<td>28.760</td>
</tr>
</tbody>
</table>

Sample ID: dynamic tension 45 ext
Appendix 18. T2-D90-20072015

University of Manchester
M.A.C.E.
Materials Testing

Description 1: General Tensile Test With Extensometer
Description 2:

Crosshead Speed: 240.00 mm/min  Test Date: 20 July 2015
Sample Rate (pts/sec): 50.00  Operator name: D. Mortimer
Full Scale Load Range: 10.00 kN  Sample Identification: dynamic tension 90 ext
Test Mode:
Test Method Number: 3  Test type: Tensile
Specimen Geometry: Rectangular  Width: 9.250 mm
Thickness: 3.70 mm  Extensometer O.L.: 12.500 m

<table>
<thead>
<tr>
<th>Load at Max Load (kN)</th>
<th>Modulus (E/Young) (MPa)</th>
<th>Stress at Max Load (MPa)</th>
<th>% Strain at Max Load (%)</th>
<th>% Strain at Auto Break (%)</th>
<th>Stress at % Strain (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.681</td>
<td>2565.316</td>
<td>19.215</td>
<td>2.866</td>
<td>36.326</td>
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<td>2</td>
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<td>1917.596</td>
<td>12.247</td>
<td>2.708</td>
<td>36.687</td>
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<tr>
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<td>2173.131</td>
<td>19.866</td>
<td>2.938</td>
<td>43.851</td>
</tr>
</tbody>
</table>

Sample ID: dynamic tension 90 ext

![Graph showing load vs. displacement](image-url)
Appendix 19. Tensile test specimen 3MM

Appendix 20. Small gauge tensile test specimen 3MM
Appendix 21. Tensile shear specimen 3MM

Appendix 22. University LS-DYNA Software Version

Livermore Software Technology Corporation
7374 Las Positas Road
Livermore, CA 94551
Tel: (925) 449-2500  Fax: (925) 449-2507
www.lstc.com

LS-DYNA, A Program for Nonlinear Dynamic Analysis of Structures in Three Dimensions
Version: ls971s R6.0.0  Date: 01/24/2012
Revision: 71482  Time: 10:59:53

Features enabled in this version:
- Shared Memory Parallel
- Interactive Graphics
- ANSYS Database Format
- ANSYS License (ANSYS145)

Licensed to:
- Platform : WINDOWS X64
- OS Level : Windows XP/Vista/7 SRV 2003/2008
- Compiler : Intel Fortran 10.1 & MSVC++ 2008
- Hostname : E-DC7MEDIQ16S
- Precision : Single precision (I64)
- SVN Version: 71482

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Appendix 23. Load-displacement-T2-Q0

Load-displacement curve of 0° orientation direction specimens in quasi-static tension test without extensometer.

Appendix 24. Load-displacement-T1-Q0

Load-displacement curve of 0° orientation direction specimens in quasi-static tension test with extensometer
Appendix 25. Load-displacement-T2-Q45

Load-displacement curve of 45° orientation direction specimens in quasi-static tension test without extensometer.

Appendix 26. Load-displacement-T1-Q45

Load-displacement curve of 45° orientation direction specimens in quasi-static tension test with extensometer.
Appendix 27. Load-displacement-T2-Q90

Load-Displacement curve of 90° orientation direction specimens in quasi-static tension test without extensometer.

Appendix 28. Load-displacement-T1-Q90

Load-Displacement curve of 90° orientation direction specimens in quasi-static tension test with extensometer.
Appendix 29. Load-displacement-T2-D0

Load-displacement curve of 0° orientation direction specimens in dynamic tension test without extensometer.

Appendix 30. Load-displacement-T2-D45

Load-displacement curve of 45° orientation direction specimens in dynamic tension test without extensometer.
Appendix 31. Load-displacement-T2-D90

Load-displacement curve of 90° orientation direction specimens in dynamic tension test without extensometer.