Statistics of Fracture in 3-Point Bending

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Abstract. CrachFEM have a built-in failure probability model. The failure probability can be derived from the scatter of one material batch, next to the deterministic prediction of the CrachFEM failure risk. In this paper a 3-point bending experiment is used to mimic the in-house forming operation of Faurecia and to derive the failure probability. The failure probability of three materials have been determined with a 3-point bending experiment in combination with an optical strain measurement system. A post-processing procedure has been setup for this purpose. Although the three materials are somewhat comparable, the failure probability is different and will reveal whether a material is critical or suitable for the production process.

1. Introduction
Next to the other three core businesses, Faurecia is the world’s number three seat supplier. The seat is what connects the occupant to the vehicle. In case of a crash it plays a key role in driver and passenger safety by being firmly anchored to the floor and holding the human body in place. Over 90% of the seats that Faurecia has produced are fitted in vehicles that have obtained a five-star rating in the Euro NCAP crash tests.

Seats account for 6% to 10% of the vehicle’s weight. As part of the ”Light Attitude” weight reduction program Faurecia uses advanced high strength steels (AHSS), offering superior performance while reducing volume and weight. One of the common ways to make seat parts from AHSS is by bending; therefore it is important to Faurecia to predict failure in crash situations after bending or even during forming. Most of the fracture prediction is currently done with CrachFEM in LS-Dyna. CrachFEM has a built-in failure probability model. The implementation of the CrachFEM failure probability is discussed in detail in [1].

Tata Steel Europe has a lot of knowledge and expertise in fracture testing [2, 3] and optical strain measurements [4]. The end goal of this research collaboration between Tata Steel Europe and Faurecia is to give more meaning to the fracture risk value for the Ductile Normal Fracture (DNF) and Ductile Shear Fracture (DSF), to include the 3-point bending fracture data into the CrachFEM fit and to create statistical data for fracture. Faurecia thought to improve predictive capability for certain forming operations, like bending, and including the statistics could enable the prediction of scrap rate, where deterministic fracture modelling [5, 6] only enables a pass or fail binary prediction. Tata Steel Europe views this approach as a first step to enable quantitative failure prediction of for example a crash box simulations, where nowadays only a qualitative failure prediction is possible according to [7].
The scope of this paper is to present a procedure to measure the statistics of fracture in a 3-point bending experiment and functionally convert the mean and standard deviation into a probability of fracture risk.

The 3-point bending experiment will be treated in the next section. The test setup will be discussed and how the data acquisition has been optimized. The measured force-displacement curves, springback angle and equivalent strain versus crack length will be presented next. Then the CrachFEM probability of fracture parameter identification will be discussed. Understanding, the stochastic scatter of fracture reveals the process robustness of a certain material.

2. 3-Point Bending Experiment
As already mentioned in the Introduction, bending as a very important cold forming operation for AHSS. Therefore a 3-point bending experiment is chosen to assess performance in forming operations. In this section the material properties will be presented for the three investigated materials. Then the 3-point bending test setup will be explained and discussed. The discussion will be more on which experimental parameters have been optimized to get the best results. The post-processing procedure to obtain statistical data for the CrachFEM failure probability model from the experimental data will be explained.

2.1. Material Properties
For this research three materials are investigated to determine the CrachFEM failure probability parameters. The material characteristics are presented in Table 1. The $R_p$ of the DP1000a exceeds the VDA 239-100 standard.

| Material | Thickness [mm] | $R_p$ [MPa] | $R_m$ [MPa] | $A_g$ [%] | $A_{80}$ [%] |
|----------|----------------|-------------|-------------|-----------|-------------|
| DP1000a  | 1.60           | 886         | 1058        | 5.4       | 8.4         |
| DP1000b  | 1.60           | 840         | 1049        | 4.4       | 9           |
| CP1000   | 1.52           | 863         | 991         | 4         | 8.4         |

Table 2 shows the key alloying elements. The CP1000 was not a commercial grade yet but rather a development version. The difference between the two DP1000 is the balance between Mn and C.

| Material | C [Max%] | Mn [Max%] | Si [Max%] |
|----------|----------|-----------|-----------|
| DP1000a  | 0.15     | 2.0       | 0.2       |
| DP1000b  | 0.16     | 1.5       | 0.5       |
| CP1000   | 0.15     | 2.2       | 0.5       |

2.2. Test Setup
The 3-point bending experiments have been done on a Dartec tensile machine with a 50 kN load cell. Faurecia has developed a special die table that accommodates space for placement of the
Aramis camera system. The Aramis Camera system is mounted on a support with five Degrees of Freedom. The advantage of this stand alone configuration is that machine vibrations are not influencing the optical strain measurements. The distance between the camera sensor and the sample is 275 mm. The slider distance for the camera setup is 84 mm. The shutter timer is set to the lowest setting of 0.1 ms. The aperture of both sensors is fully open to 16. A 35 mm lense was used with a 5M camera system. The 5M camera resolution is 2448x2050 pixels. A polarizing lens is used additionally to the camera lenses. The 3D measuring box is 50x42x25 mm. The 3D measuring box starts 3 mm above the jig. The maximum punch displacement is preprogrammed based on several preliminary 3-point bending experiments on the same material batch aiming at just producing fractures. The bending sample is still intact. A CQ/CP20 50x44 calibration tool is used. A maximum calibration deviation of 0.042 is needed to ensure reliable results. Higher calibration deviation values result in early facet loss and non valid strain data. A facet of 19x19 pixels and a step size of 9x9 in combination with a spline strain interpolation have been used to obtain the surface strains.

The punch and jigs are aligned with fixture of 2.7 mm. The punch radius is 0.6 mm. The specimen dimensions are 65x57x1.5 mm. The specimen width is 15 mm wider than the measurement box. There haven been chosen to exclude the 7.5 mm of anti-elastic bending effects at the edges from the measurements. This would interfere with the optical strain measurements. The two rolls are fastened with two bolts each and a torque of 100 Nm per bolt. The radii of the rolls are 15 mm. A fixture frame was used to position the samples. The samples were de-burred. A trigger list is used to capture the images. The first 125 seconds only 1 image is stored and for the last 30 seconds 15 images per second were stored.

Different lighting positions have been tried to find the optimal lighting to prevent less light in the corners. The minimum and maximum shutter time has been determined experimentally for the speckle pattern. The speckle pattern is consistent due to the skilled and experienced technician.

An airbrush is used with a 0.2 mm nozzle and 2 bar of working pressure. The standard GOM paint system was used in combination with an airbrush. The white lacquer was used as a base coat and the black lacquer was used to produce a speckle pattern. The paint was left to dry for 15 minutes. A longer drying time results in bad strain measurements. The question arises if the cracks in the material where covered by the elastic white base coat. A test specimen was sprayed half with a speckle pattern and the other half was just the plain base material. The test showed that fracture initiation occurred 20% earlier in the plain base material than in the painted area. In a 3-point bending experiment the fracture initiation occurs gradually and the crack growth rate is not as fast as in a tensile test for instance. The white base coat was therefore too elastic and was covering up small cracks. A white brittle water based paint was tested and used to make speckles onto the plain base material. With this method the fracture initiation could be captured with Aramis. However, the adhesion of the water based white paint on the base material was not sufficient and the paint started to delaminate before fracture initiation results into facet loss. Therefore no strain measurements could be obtained at fracture initiation. To overcome the adhesion problem the plain base material was etched and then sprayed with white speckles. The strain measurements were successful, although crack initiation was very hard to see on the camera images due to the black background by the etching process. Finally, a very thin base coat of transparent lacquer, Plastik70, is sprayed on the specimen. Faskolor white paint is used to spray white speckles, where the paint has been left to dry for 15 minutes. A spray template have been used to airbrush the samples with a transparent lacquer and white speckles. Different speckle densities and density distributions has been tried. A high shutter time is needed for a higher speckle density. In this way suitable solution was found, where a transparent lacquer was used to increase the adhesion of the brittle white paint on the plain base material. With this method the moment of crack initiation as well as the strains can be captured by the Aramis.
camera system. The magnification has been calibrated to enable posteriori corrections on the measured crack length, which is needed to determine the failure probability risk.

2.3. Post-Processing Procedure for 3-Point Bending Optical Measurement Data

The post-processing procedure is employed to determine the largest initial crack. For this, stage 350, the final crack is followed back in time. When the initial crack is found on the Aramis camera images, stage 220, the crack length and strains are measured on a fixed number of stages throughout the 3-point bending experiments starting from stage 239 instead of stage 220. The crack length is determined by measuring the number of pixels. The major and minor strain are determined by taking the average major and minor strain over the complete width of the bending radii of the specimen. For every 3-point bending experiment eight crack lengths and strains are determined.

A linear regression analysis is used to determine the initial fracture strain for the three different materials. The assumption is that each material has one single or common initial major fracture strain in a 3-point bending experiments. The slope of the linear regression implies a certain crack growth rate. The blue inner lines represent the 95% confidence interval of the mean predicted value, see Figure 2 on the right at the bottom. The outer black lines are the confidence interval of the individual measurements. The linear regression analysis for the individual 3-point bending experiments per material is as follows

\[ y_{ij} = a_i + b_i x_{ij} + \varepsilon_{ij} \]  

where \( a_i \) is the individual intercept, i.e. the major strain at initial fracture, and \( b_i \) is the individual slope or crack growth rate per 3-point bending experiment. \( y_{ij} \) is the major strain and \( x_{ij} \) is the crack length in pixels. Subscript \( i \) indicating the experiment and subscript \( j \) the individual measurement point. The error of the fit can be expressed in \( \varepsilon_{ij} \). The final result is obtained by fitting one common major fracture strain \( a \) with individual slopes \( b_i \) using a linear regression analysis. Equation (1) can be rewritten into

\[ y_{ij} = a + b_i x_{ij} + \varepsilon_{ij} \]  

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Figure 1. 3-Point Bending Test Setup with GOM Aramis system
The theory and the equations to calculate the confidence interval and spread can be found in [8]. A normal distribution is assumed for the major strain and error in the measured major strain. The CrachFEM failure probability model also assumes a normal distribution in the material fracture scatter. The results will be presented in the next section after a short discussion regarding alternative assumptions for the linear regression analysis.

2.4. Discussions
Different assumptions for the linear regression analysis were also investigated, where the 25 to 30 3-point bending samples were fitted, using different initial major fracture strains with different crack growth rates (different slopes) or different initial major fracture strains with the same crack growth rate (same slopes). Eventually, the best fit was obtained for the common major strain at initial fracture with different crack growth rates. These are the only results that will be presented later on in this paper.

The punch displacement versus the major strain was also fitted with one common initial major fracture strain. The punch displacement can be correlated to the Aramis major strain measurements due to the coupling between the Dartec tensile machine and GOM Aramis system. The punch displacement is nicely linear related to the major strain. Unfortunately, this method is not suitable to fit the CrachFEM failure probability model, because this method did not necessarily capture the initial moment of fracture as desired.

3. Results
Three different materials coded DP1000a, DP1000b and CP1000, were tested with the 3-point bending test setup and testing procedure as explained in the previous section. In this section the initial thickness, force-displacements results, bending angles after springback and the statistics of fracture will be shown and discussed.

3.1. Initial Sheet Thickness
This initial thickness measurement for the three materials is presented in Figure 3.
3.2. Force-Displacement
The force displacement curve from the Dartec data acquisition is coupled to the GOM Aramis system. The experiments were done at different total displacements to ensure fracture over the width of the bending radius, but the sample is still intact. For DP1000a the total displacement is 12 mm. For DP1000b the total displacement is 14 mm. For CP1000 the total displacement is 14 mm.

3.3. Bending angle after springback
The bending angles after springback for the for DP1000a, DP1000b and CP1000 are presented in Figure 4. The bending angle after springback is captured by taking a photograph from the sample still in the 3-point bending tool after unloading. The angle between the two red lines were measured with an image manipulation tool, see photograph in Figure 4(a).
3.4. Statistic of Fracture
A single initial major fracture strain with different crack growth rates was fitted with (2) for the three different materials and the results are shown in Figure 6. Each colour is denoting one 3-point bending experiment and processed according to the procedure explained in §2.3 for one single experiment. For the DP1000a 26 samples were tested, for the DP1000b 32 samples were tested and for the CP1000 15 samples were tested.

![Figure 6.](image)

Figure 6. Overview of the equivalent strain versus crack length for the different materials

In table 3 the mean, standard error and root mean square error are shown for all the three different materials. The difference between the measured and predicted major strains are not perfectly normal distributed. However, the overall results look plausible and give a measure for the process robustness of the material performance. If the described procedure was done for the equivalent initial fracture strain instead of the major strain at initial fracture, than this value could be used for the CrachFEM failure model and the Root MSE value can than be used for the CrachFEM failure probability model.

Table 3. Overview initial major fracture strains, standard error and root mean square error

| Material | Mean (a) | Std. (a) | Root MSE |
|----------|----------|----------|----------|
| DP1000a  | 0.56     | 0.0026   | 0.011    |
| DP1000b  | 0.63     | 0.0067   | 0.034    |
| CP1000   | 0.65     | 0.0096   | 0.031    |

3.5. Discussions
In Table 3, the Mean (a) is the common fitted initial major fracture strain. Where the Std. (a) is a measure for how well a (being an average of all experiments) can be determined. The Root MSE is the material spread. With this measure it can be observed that the mean minus 3σ (which would typically be used for robust processes) of DP1000b is comparable to DP1000a. And with this robust measure the CP1000 would be considered the best performing material. The punch with a radius of 0.6 mm was worn out, therefore additional data regarding the CP1000 have been conducted with a punch radius of 0.4 mm due to the smaller sample size. The sample size of this additional data set is consistent with sample size of the DP1000a and DP1000b. Where the Mean (a) is 0.60, Std. (a) is 0.006 and the MSE is 0.031. The Mean (a) is lower due to the smaller punch radius. The Std. (a) of the CP1000 with a punch radius of 0.4 mm is in the same order as the DP1000b. The Std. (a) for the CP1000 with a punch radius
of 0.6 will be smaller and the same order of magnitude as for the CP1000 with a punch radius of 0.4 mm and the DP1000b. The material spread of the CP1000 for both cases is smaller than for the DP1000b.

The chosen approach enforce to fit one common initial major fracture strain, which enables to determine whether a material is critical or suitable for bending operations in the production process. As already mentioned in the Introduction, predicting failure in bending simulations is very difficult due to the nature of the 3-point bending experiment. This method will determine the major strain or equivalent strain at initial fracture. For most plane strain tensile fracture experiments or fracture experiments in general, fracture proceeds after local necking except for pure or simple shear, see [5, 6]. In bending there is no localized neck before fracture. Small cracks initiate at the surface before the bending radius is totally fractured. Meaning that from a design- and production point of view the maximum strain in the part needs to be lower than shown in Table 3. For most AHSS voids are already nucleated in the material when orange skin appears on the bending radius. This is not desirable since seats are also subjected to crash.

4. Conclusion
The described 3-point bending testing- and fitting procedure can be used to fit the CrachFEM probability failure parameters next to the deterministic characterisation of CrachFEM failure parameters, see [1]. The DP1000a has the smallest spread in the force-displacement curves, although it looks like two populations of force-displacement curves, although the samples were from the same batch. It also has the largest spread in bending angle after springback and the smallest spread in initial fracture strain, but it has the lowest initial major fracture strain value. The DP1000b performs in overall averages. The CP1000 has the smallest spread in bending angle after springback, the highest initial fracture strain and a higher standard deviation, see discussions §3.5.

Acknowledgement
We would like to thank Roy Bakker, Frank Schouten, Tushar Khandeparkar and Bart van der Feer for their tremendous effort and great work on the GOM Aramis strain measurements. I would like to thank Carel ten Horn, Matthijs Toose and John Droog from Tata Steel R&D for having their indisputable support on this research project. During this collaboration project Faurecia Automotive Seating provided Tata Steel R&D with their 3-point bending rig. Special thanks to Eisso Atzema for his time & tremendous devotion to carefully-edited our joint paper.

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