Characterizing damage and fracture of sheet metal materials using large scale test specimen

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Abstract. Several approaches to characterizing damage evolution and fracture behaviour of sheet metal materials are currently in existence. These are based on different testing methodologies and test specimen designs, some of which, when combined with higher sheet thicknesses used for aluminium alloys in the automotive field, can reach and exceed geometrical limits required for the plane stress assumption commonly applied to numerical modelling of sheet metal materials. Furthermore, if shell elements are to be used in modelling of such structures, the characteristic length of the element should be larger than the thickness of the modelled sheet material. In order to allow for element sizes accounting for the two considerations outlined above, new test specimen geometries covering a range of stress triaxialities have been developed with a deformation region significantly larger than that of other commonly used test specimen designs. The geometries have been manufactured and tested on an automotive grade AA6xxx series aluminium alloy with DIC strain measurement to determine failure strains. The results were then applied to finite element models using various element sizes and the behaviour of the numerical models compared to the test results.

1. Introduction
In applying phenomenological failure criteria to thin-wall structures, such as sheet metal components on an automotive body in white, using a shell element modelling approach, certain limitations have to be observed in order to ensure that the solution remains physically consistent with the mechanics of the problem. In particular, the characteristic length of the shell element with relation to the thickness of the modelled sheet structure should fulfil certain requirements, otherwise the finite element model may exhibit physically unrepresentative behaviour, as the present work attempts to demonstrate.

If a force-displacement matching approach of determining the input parameters of the damage model [1, 2] is adopted, this becomes of particular significance as the results become highly dependent on the sample discretization and in particular on the size of finite elements used [3]. In this case, care should be taken to ensure that the physical tests on which the input parameter determination is based on, allow for shell elements of sufficient characteristic size to be used for inverse modelling.

A set of large scale mechanical test specimen geometries is proposed and tested in this work, that takes this aspect into consideration. Particular focus is placed on physically derived regularization behaviour and the effects of varying mesh size in fracture prediction modelling.
The experimental work was conducted on a representative AA6xxx series alloy sheet with a nominal thickness of 2.3 mm, heat treated to an in-use like condition emulating a state found on a typical automotive body in white application.

2. Limiting characteristic shell element length

The lower limit on the characteristic length of the shell element is derived from the assumption, that the average stress state in the material volume represented by the shell element should approximately fulfill the plane stress condition. This condition should be met through the entire deformation regime, including the onset and propagation of localized through-thickness deformation, and up to fracture. If this condition is not met, then the shell element cannot accurately represent the deformation state of the material at the length scale under consideration. In practical terms, this translates into the condition, that the region of localized deformation should be of a significantly lower length scale compared to the characteristic shell element size.

Prior to the onset of localized deformation, the stress state is assumed to be homogeneous throughout the considered material volume. Using triaxiality [4, 5] as a description of the stress state and averaging it over different length scales, the change of stress state during localized deformation is demonstrated in figure 1 below [6]. Figure 1 shows a detailed simulation of a plane strain tension test of a sheet material, were the triaxiality has been averaged over reference volumes of varying sizes. The volumes are aligned with the centre of the deformation zone and extend into both directions of the cross-section.

![Figure 1](image)

**Figure 1.** Instantaneous triaxiality over the length of the sample and average triaxiality as a function of averaging length [6] in a plane strain test.

In the case of plane strain deformation of a sheet of 1.4 mm thickness, the average triaxiality remains relatively constant when averaged over a region larger than approximately 2 mm. Below that threshold, the average triaxiality increases significantly, indicating a non-homogeneous state of stress. Based on this, a shell element size constraint is proposed as a guideline, where the minimum characteristic length of a shell element $l_{mn}$ is tied to the sheet thickness $t$ of the component under evaluation using the relation outlined in equation (1):

$$\frac{l_{mn}}{t} \geq 1.5 .$$

(1)
Adhering to this constraint ensures that the behaviour of the shell element in fracture modelling is primarily driven by the phenomenological failure model and not by non-physical deformation modes of the shell element itself.

3. Large scale mechanical tests
The minimum element size constraint outlined above translates into the specimen geometry design by defining the minimum size of an area of approximately homogeneous deformation, prior to the onset of localized deformation, that needs to be present on a given specimen. The size of such an area in turn defines the maximum size of the shell element which can be evaluated for strains at fracture using that particular geometry. Separate tests need to be carried out to cover a meaningful range of stress states and each test needs to fulfill this condition.

Considering these constraints, a set of five tests has been proposed to evaluate fracture strains under the stress states of shear, combined shear and tension, uniaxial tension, plane strain and equal biaxial tension. Equal biaxial tension is evaluated using the standard hydraulic bulge test [7], the remaining four stress states are evaluated using tensile specimen with differently shaped ligaments. The shapes of the proposed tensile specimen geometries are shown on figure 2 below.

![Figure 2. Geometries of the proposed large scale tension specimen: a.) shear, b.) shear-tension, c.) uniaxial tension and d.) plane strain.](image)

The specimen geometries are designed to support testing of materials up to a thickness of 3 mm. The widths of the ligaments perpendicular to the deformation direction on the shear and shear-tension specimen are 10 mm, which represents the upper limit on the size of evaluated shell elements.

3.1. Testing methodology
The tensile testing was conducted using a MTS electromechanical load frame with a 300kN load cell and hydraulically driven wedge action grips with 100 mm wide serrated grip faces. Crosshead speed was chosen to provide an initial quasi-effective static strain rate of 0.001s\(^{-1}\) for all geometries. Stereoscopic images were captured using a pair of 4 megapixel cameras fitted with 50 mm lenses. The images were processed using GOM Correlate Professional digital image correlation (DIC) software. Crosshead displacement and load were recorded in sync with the images. Facet size, facet step, and strain computation size were chosen to be 33, 16, and 1 for the uniaxial specimen geometry and 63, 31, and 1, for the shear, shear-tension, and plane strain geometries leading to consistent virtual strain gauge lengths of approximately 1.55 mm for all tensile geometries. The data and image acquisition rate was 5 Hz.

The hydraulic bulge test was performed using a custom apparatus located at the Novelis Global R&T Center and is based on methods discussed in literature [7, 8]. A die with an internal diameter of
133 mm and a shoulder radius of 10 mm was used. Stereoscopic images were captured using a pair of 4 megapixel cameras fitted with 80 mm lenses. DIC was used to measure specimen deformation and in conjunction with pressure was used to calculate the biaxial flow stress according to the procedures set out in the ISO standard [7]. Facet size, facet step, and strain computation size were chosen to be 37, 18, and 1 to match the virtual strain gauge length from the tensile tests.

4. Physical testing results

The strain fields captured by DIC at the last frame before failure is shown for three of the four sample geometries on figure 3 below. These three specimen geometries, as well as the hydraulic bulge test, behaved in a predictable manner and yielded successful results. The shear specimen geometry exhibited out-of-plane buckling, thus the results could not be used as part of this investigation. Three repeats of each tests were carried out, with consistent results between the repetitions.

![Figure 3. Strain field at last frame before fracture for the a.) shear-tension, b.) uniaxial tension and c.) plane strain specimen geometries.](image)

The shear-tension specimen exhibited a somewhat homogeneous strain distribution over the length of the deformation zone. While no excessive edge effects have been observed, it was also not possible to determine the exact point of initial fracture from the DIC data due to the rate of the crack propagation.

The large tensile specimen exhibited limited diffuse necking, with through-thickness localization bands forming at an inclined angle.

The plane strain specimen showed stress concentrations at the base corners of the ligament, which could not be completely alleviated in the specimen design, and it was found to be sensitive to the alignment of the specimen in the testing frame grips, however, the plane strain zone in the centre of the specimen appears to have fractured independent of the edges.

The hydraulic bulge test specimen fractured at the centre of the dome, perpendicular to the rolling direction of the sheet. No appreciable through-thickness localization has been observed.

4.1. Measured dependence of fracture strains on characteristic measurement length

The strains determined by the DIC system were averaged over areas of increasing size, each corresponding to a specific characteristic length scale. In this way, the effect of the characteristic evaluation length scale on global fracture strains could be determined. This represents a physically based regularization curve for each specimen geometry, which corresponds to a particular state of stress. The implemented averaging areas were square in shape, positioned in the centre of the deformation zone and aligned with the principal straining directions prior to the onset of localization. The resulting regularization curves for the evaluated specimen are shown on figure 4.
Figure 4. Physically derived regularization curves for the four tests.

A clear pattern can be observed, where the apparent strain to failure reduces with the increase of the characteristic evaluation length for the three tensile specimen geometries. The behaviour appears to follow a power law relation with a negative exponent. In the case of the biaxial test, the influence of the characteristic evaluation length appears lower and following a linear decline. A possible reason for this may be the lack of localized through-thickness thinning prior to fracture; if the deformation within the evaluated length scale is homogeneous, there is no reason to expect a large influence of the characteristic evaluation length.

4.2. Failure points in triaxiality space

By plotting each failure point in the regularization curves presented above in the triaxiality – strain to failure space, the dependence of the failure strain at different stress states on the characteristic length scale can be demonstrated. The triaxialities for each failure point were determined using von Mises constitutive relations based on major and minor strains extracted from the above defined averaging areas. The resulting failure points for evaluation lengths of 5, 10, 15 and 20 mm are shown on figure 5.

Figure 5. Failure points in the triaxiality – effective strain to failure space for different characteristic evaluation lengths.

Figure 5 clearly demonstrates that the failure points at different values of triaxiality exhibit varying degrees of dependence on the characteristic evaluation length. For the case of the hydraulic bulge test, where no appreciable through-thickness localization has been observed prior to fracture, the evaluation length dependency is significantly lower.
5. Simulation
To establish the relation between the physical characteristic strain evaluation length and the characteristic shell element length in finite element simulation, a numerical representation of the previously described physical tests has been created. The test geometries were discretized using characteristic shell element sizes of approximately 2, 4, and 8 mm, to evaluate the effect of characteristic shell elements lengths on strains at failure. The uniaxial tension specimen allows for even larger elements to be used, the largest being approximately 14 mm.

The shell elements with a characteristic length of 2 mm were included in the study to examine the effect of elements smaller than the proposed limit of 1.5 times the thickness, which in this case would be approximately 3.5 mm.

Full sample geometries were used for the tension tests, as opposed to a quarter symmetry in the case of the hydraulic bulge test simulation. The constitutive model was a von Mises elastic-plastic model with a tabulated flow curve describing the stress-strain response of the material and no damage model being used. A fully integrated shell element formulation was used in all simulations. The solver was a double precision version of the LS-Dyna R11 commercial finite element code, in MPP architecture.

5.1. Determination of the simulated fracture strains for different element sizes
To determine the equivalent plastic strain at the point of fracture for each specimen and element size combination, the maximum engineering strain achieved in the physical tests, or the maximum dome displacement in the hydraulic bulge test, were taken as the point of failure. Then, the same engineering strain, or total displacement of the centre node in the hydraulic bulge test, were found in each simulated test response, as shown for the case of the plane strain test on figure 6 below. The effective plastic strains of the critical element were then extracted at this point in the simulation and assumed to represent the fracture strain.

![Figure 6](image)

**Figure 6.** Engineering stress – engineering strain comparison between the test and simulation for the plane strain test, for different element sizes.

The behaviour on figure 6 is representative of all the tensile specimen evaluated in this study. It also demonstrates the non-physical mechanical response for element sizes below the established minimum characteristic shell element length of 3.5 mm. While the results are somewhat obscured by the absolute levels of stress being marginally too high, the 2 mm element size case shows significant softening of the mechanical response around the point of localization initiation, which is not congruent
with the physical test. This type of overly soft behaviour could be problematic if a separate phenomenological damage model is to be applied to the simulation for material fracture prediction.

5.2. Simulated dependence of fracture strains on characteristic measurement length

The fracture strains in the critical element for all the tests and considered element sizes were extracted using the method previously described and plotted together with the measured behaviour on figure 7.

![Figure 7](image)

Figure 7. Comparison between measured and simulated failure strains for all the specimen at different characteristic evaluation and shell element lengths.

The simulations show broadly consistent behaviour to the physical tests in terms of the reduction of the failure strains with increasing characteristic shell element lengths. However, for most cases the simulated fracture strains are significantly lower than their measured counterparts. The reasons for this discrepancy are under investigation, primary focus areas being constitutive behaviour and mesh dependency. The difference appears to be largest for the biaxial tension case and smallest for the plane strain case. The state of triaxiality might be relevant for this behaviour and requires further investigation as well.

The results show a high level of mesh dependency, which is expected, but exceeds the scope of the present investigation. This is particularly apparent for the shear-tension case and is a possible explanation for the incongruous behaviour between the simulated fracture strains for 4 mm and 8 mm element sizes. Difficulties were encountered in meshing the shear-tension specimen geometry consistently due to the limited size of the deformation zone.

6. Discussion

A set of mechanical tests has been proposed for determining the stress-state dependant fracture locus for ductile thin sheet materials, with the aim of modelling material failure using shell elements. The tests were designed to address some of the issues concerning shell element sizes, in particular taking into account the behaviour of shell elements after the onset of localized through-thickness necking. In conjunction with this, a soft minimal element size constraint has been proposed based on prior publications [6].

The proposed tests showed good results for the material under investigation, apart for the shear test, which exhibited an out-of-plane buckling mode when deformed. Other approaches of determining the material failure point in shear deformation are under investigation. The shear-tension test specimen
geometry was found to be limiting in terms of size, which caused issues with the discretization of the geometry for the numerical part of the investigation.

Evaluating the strains at failure using different characteristic length scales produced clear physical regularization patterns for all the successful mechanical tests. A power law function appears to provide a good fit for describing the behaviour of the tension specimen, whereas failure under equal biaxial tension, as measured by the hydraulic bulge test, appears to exhibit a linear relation.

All the tension tests showed some degree of through-thickness localization, however, there was no appreciable localization observed prior to fracture on the hydraulic bulge test. Based on this, it is proposed that the degree of influence of the characteristic evaluation length on the apparent failure strain is proportional to the degree of through-thickness localization prior to fracture. Furthermore, if the degree of through-thickness localization under a specific stress state varies between materials, the degree of influence of the characteristic evaluation length will also vary, thus no generalization can be applied.

The experimentally observed behaviour was attempted to be reproduced using finite element simulations of the physical tests. Limited agreement between the tests and simulations was achieved. While similar regularization patterns could be inferred from the data, the absolute values of the fracture strains were significantly different. Aspects of the numerical models, such as constitutive behaviour, element formulation, and discretization need to be considered and investigated further, to determine the sensitivities of the proposed method.

Mesh sensitivity in particular has a large influence on the results of the failure strain evaluation based on global displacements. The optimal meshing of the specimen geometries needs to be carefully considered to ensure the results are physically meaningful, and should be considered in the specimen design. The shear-tension specimen in particular was found to be poorly suited to numerical modelling. In future work, the specimen geometries will be optimized with particular focus on ensuring ease of consistent numerical discretization. Different meshing strategies need to be evaluated as well, to quantify meshing sensitivity and determine an optimal approach.

Experimental and numerical investigation of a strain rate controlled hydraulic bulge test of sheet metal

References

[1] Andrade F X C, Feucht M, Haufe A and Neukamm F 2016 An incremental stress state dependent damage model for ductile failure prediction Int. J. Fracture 200 p 127-150
[2] Effelsberg J, Haufe A, Feucht M, Neukamm F and Du Bios P 2012 On Parameter Identification for the GISSMO Damage Model 12th International LS-DYNA Users Conference (Detroit: LSTC)
[3] Hillerborg A, Modeer M, Peterson P E 1976 Analysis of Crack Formation and Crack Growth in Concrete by Means of Fracture Mechanics and Finite Elements Cement and Concrete Research 6 p 773-782
[4] Mackenzie A C, Hancock J W, Brown D K 1977 On the influence of state of stress on ductile failure initiation in high strength steels Eng. Fracture Mech. 9 p 167-168
[5] Wierzbiicki T, Bao Y, Lee Y W and Bai Y 2005 Calibration and Evaluation of Seven Fracture Models Int. J. Mech. Sci. 47 p 719-743
[6] Woelke P B, Londono J G, Knoerr L O, Dykeman J and Malcolm S 2018 Fundamental Differences between Fracture Behavior of This Sheet under Plane Strain Bending and Tension IOP Conf. Series: Mater. Sci. Eng. 418
[7] International Standard ISO 16808 2014 Metallica Materials – Sheet and Strip – Determination of Biaxial Stress-strain Curve by Means of Bulge Test With Optical Measuring Systems (Switzerland: International Standardization Organization)
[8] Suttner S and Merklein M 2016 Experimental and numerical investigation of a strain rate controlled hydraulic bulge test of sheet metal J. Mat. Proc. Tech. 235 p 121-133