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Ductile Fracture of Aluminium Sheet Under Combined Tension-Compression Loading

Thesis for the Degree of Philosophiae Doctor

Trondheim, August 2026

Norwegian University of Science and Technology
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Preface

This thesis is submitted in partial fulfilment of the requirements for the degree of Philosophiae Doctor at the Norwegian University of Science and Technology (NTNU). The work was carried out at the Department of Structural Engineering between 2022 and 2026, under the supervision of a project studying the low-triaxiality fracture behaviour of aluminium alloys used in automotive crash structures.

The thesis is article-based: the main synopsis chapters summarise the motivation, methodology and conclusions of the work as a whole, and the two papers reproduced in full afterwards carry the detailed derivations, test data and validation results.

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August 27, 2026

Abstract

Automotive crash structures rely on aluminium components that see stress states ranging from uniaxial tension to combined compression-shear during a single impact event, yet most fracture-model calibration campaigns are built almost entirely from tension-dominated specimens. This thesis addresses that gap for cold-rolled AA6082 sheet, combining a rate-dependent necking study with a damage-coupled fracture model calibrated jointly across tension- and compression-dominated stress states.

Paper 1 characterises the rate dependence of diffuse necking onset in AA6082-T6 sheet across four decades of strain rate, and shows that a modified Considère criterion with a single rate-sensitivity parameter predicts the observed onset strains to within 6%. Paper 2 extends a local damage-coupled constitutive model into the low- and negative-triaxiality regime using a purpose-built compression-shear specimen, and shows that models calibrated on tension data alone systematically over-predict ductility in this regime.

Together, the two papers give a calibration and validation route for predicting ductile fracture in aluminium sheet across the full range of stress states relevant to a crash event, rather than the tension-dominated subset typically covered.

Acknowledgements

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Contents

Preface i

Abstract iii

Acknowledgements v

Synopsis 1

1 Introduction 1

2 Objectives and scope 3
2.1 Objectives . . . 3
2.2 Scope . . . 3

3 Research methodology 5

4 Summary 7
4.1 Part 1 . . . 7
4.2 Part 2 . . . 7

5 Concluding remarks and further work 9

References 11

Articles 13

Part 1
Rate-dependent necking onset in cold-rolled AA6082 sheet . . . 13

Part 2

A local damage-coupled model for ductile fracture under combined tension-compression loading 17

Appendices **21**

A Compression-shear specimen drawings **23**

Synopsis

1 Introduction

Ductile fracture of aluminium alloys is a stress-state-dependent phenomenon: the strain to failure of a given alloy varies by more than a factor of two between uniaxial tension and shear-dominated loading (Bao and Wierzbicki, 2004). Automotive crash structures routinely see both regimes within a single impact pulse, so a fracture model calibrated only on tension-dominated specimens can substantially over-predict the ductility available in the compression-shear regions of a deforming component (Bai and Wierzbicki, 2010).

This thesis addresses that gap for cold-rolled AA6082 sheet, an alloy commonly used in extruded and sheet automotive crash components. The work combines a rate-dependent characterisation of necking onset with a damage-coupled fracture model extended into the low- and negative-triaxiality regime, calibrated jointly across a tension- and a compression-dominated specimen set.

2 Objectives and scope

2.1 Objectives

The objectives of this thesis are to:

1. Characterise the rate dependence of diffuse necking onset in cold-rolled AA6082-T6 sheet across a wide range of strain rates.
2. Extend a local damage-coupled fracture model into the low- and negative-triaxiality stress-state regime using a dedicated compression-shear specimen.
3. Evaluate whether a fracture model calibrated jointly across tension- and compression-dominated specimens improves fracture predictions relative to one calibrated on tension data alone.

2.2 Scope

The experimental and modelling work in this thesis is restricted to AA6082-T6 sheet at room temperature and quasi-static to moderate strain rates (10^{-3}–10^{2} s^{-1}). Temperature effects, cyclic loading, and alloys other than AA6082 are outside the scope of this thesis, though the compression-shear specimen design and calibration methodology developed here are not alloy-specific.

3 Research methodology

The work in this thesis follows an experiment-then-model approach common in structural impact research. Paper 1 is purely experimental: uniaxial tensile tests at four strain rates, instrumented with digital image correlation, to characterise necking onset. Paper 2 is a combined experimental-modelling study: a new compression-shear specimen geometry was designed and tested alongside conventional notched-bar tension specimens, and the resulting data were used to calibrate and validate a damage-coupled constitutive model against an independent, fourth geometry not used in calibration.

All mechanical testing was performed on the same servo-hydraulic test rig at the Structural Impact Laboratory, using the same digital image correlation setup for strain-field measurement, so that the necking-onset criterion from Paper 1 and the damage model from Paper 2 are calibrated against consistent strain measurements throughout.

4 Summary

4.1 Part 1

[1] Solheim, A., Vartdal, K., Aune, M. (2025). *Rate-dependent necking onset in cold-rolled AA6082 sheet.* International Journal of Fracture (submitted).

4.2 Part 2

[2] Solheim, A., Vartdal, K. (2026). *A local damage-coupled model for ductile fracture under combined tension-compression loading.* International Journal of Plasticity (submitted).

5 Concluding remarks and further work

The two papers in this thesis together give a calibration and validation route for ductile-fracture prediction in aluminium sheet across the full range of stress states seen in a crash event, rather than the tension-dominated subset typically covered. The rate-dependent necking criterion from Paper 1 and the triaxiality-dependent damage model from Paper 2 share a common experimental basis, which is what allows the two to be combined directly in a crash simulation without a separate re-calibration step.

Further work should extend the compression-shear specimen and calibration methodology to other automotive aluminium alloys, and evaluate whether the rate-sensitivity parameter identified in Paper 1 needs to be re-calibrated at the higher strain rates seen in a real crash pulse, which exceed the 10^2 s^{-1} upper bound tested here.

References

Bai, Y. and Wierzbicki, T. (2010). “Application of extended Mohr-Coulomb criterion to ductile fracture”. *International Journal of Fracture* 161.1, pp. 1–20.

Bao, Y. and Wierzbicki, T. (2004). “On fracture locus in the equivalent strain and stress triaxiality space”. *International Journal of Mechanical Sciences* 46.1, pp. 81–98.

Part 1

A. Solheim, K. Vartdal, M. Aune

Rate-dependent necking onset in cold-rolled AA6082 sheet

International Journal of Fracture (submitted).

Rate-Dependent Necking Onset in Cold-Rolled AA6082 Sheet

A. Solheim, K. Vartdal, M. Aune

Abstract

Uniaxial tensile tests on cold-rolled AA6082 sheet were performed across four strain rates from 10^{-3} to 10^{2} s^{-1} to characterise the onset of diffuse necking. The critical strain at necking onset, identified from digital image correlation strain fields, decreases by approximately 18% between the quasi-static and highest dynamic rate tested. A modified Considère criterion incorporating a rate-sensitivity term is shown to predict the observed onset strains within 6% across the full rate range.

1 Introduction

Diffuse necking marks the practical ductility limit of a sheet metal forming operation, and its rate dependence is of direct relevance to crash and high-speed forming simulations. This short communication reports necking onset strains for AA6082-T6 sheet across four decades of strain rate.

2 Experimental

Dogbone specimens machined from 2 mm cold-rolled AA6082-T6 sheet were tested in uniaxial tension on a servo-hydraulic test rig instrumented with digital image correlation. Necking onset was identified as the strain at which the strain-rate field first develops a localised peak exceeding twice the nominal applied rate.

3 Results

$$\varepsilon_{\mathrm{neck}}(\dot{\varepsilon}) = \varepsilon_0 \left(1 - \beta \log_{10} \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \tag{1}$$

fits the four measured onset strains with $\varepsilon_0 = 0.184$ and $\beta = 0.041$, giving a maximum residual of 6% across the tested range.

4 Conclusion

The modified Considère criterion above captures the observed rate sensitivity of necking onset in cold-rolled AA6082 sheet without requiring a full crystal-plasticity treatment, and is suitable for direct use in sheet-forming process models.

PART 2

A. Solheim, K. Vartdal

A local damage-coupled model for ductile fracture under combined tension-compression loading

International Journal of Plasticity (submitted).

A Local Damage-Coupled Model for Ductile Fracture Under Combined Tension-Compression Loading

A. Solheim, K. Vartdal

Abstract

A local damage-coupled constitutive model is calibrated and validated against notched-bar and butterfly-specimen tests spanning stress states from uniaxial compression to plane-strain tension. The model reproduces the measured fracture strain locus across the full stress-state range tested, including the low-triaxiality compression-shear region where conventional uncoupled damage models are known to over-predict ductility.

1 Introduction

Combined tension-compression loading paths, typical of crash and impact events, subject a material to a stress-state history that most fracture calibration campaigns do not cover, since standard specimen geometries are tension-dominated. This paper extends a local damage-coupled model to the low- and negative-triaxiality regime using a purpose-built compression-shear specimen.

2 Material and Specimens

Three specimen geometries were used: smooth and notched round bars in tension, and a compression-shear butterfly specimen loaded on a modified Arcan fixture, giving stress triaxialities from -0.3 to 0.6.

3 Model and Calibration

The damage-coupled model follows a Lemaitre-type formulation with a stress-state-dependent damage evolution law,

$$\dot{D} = \left(\frac{Y}{S}\right)^{s} \dot{p}\,\eta(T^{*}), \tag{1}$$

where Y is the damage energy release rate, $\dot{p}$ the equivalent plastic strain rate, and $\eta(T^{*})$ a triaxiality-dependent weighting function calibrated against all three specimen geometries simultaneously.

4 Results and Validation

The calibrated model predicts fracture initiation location and applied displacement at fracture within 8% for a fourth, independent validation geometry (a flat-grooved plate) not used in calibration, across the full triaxiality range tested.

5 Conclusion

Coupling damage evolution to a triaxiality-dependent weighting function, calibrated jointly across tension- and compression-dominated specimens, removes the over-prediction of ductility in the low-triaxiality regime seen with uncoupled models calibrated on tension data alone.

Appendices

A Compression-shear specimen drawings

This appendix would normally reproduce the full engineering drawings for the compression-shear butterfly specimen used in Paper 2, including tolerances and the modified Arcan fixture geometry. They are omitted from this starter template; a real thesis appendix would include them as PDF or vector figures alongside a brief note on machining tolerances achieved.