# Numerical Modeling of Aluminum Forgings;

# Issues of Material Failure and Element Formulation

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The increased use of castings, forgings and thick extrusions in vehicle structures has led to the need for modeling certain parts with solid elements in crash simulations. Since the geometries of the considered parts are typically highly complex, using tetrahedral elements seems to be the practical solution. In the LS-DYNA simulation software, a multitude of different tetra element formulations are available however there is some uncertainty whether these elements can be used with confidence in a simulation for accurate fracture prediction based on a stress state dependent failure model. It is well known that linear tetra elements suffer from locking phenomena, though this problem can be partially eliminated through averaging of the hydrostatic pressure term (the so-called element formulation 13). However, recent studies have shown that even in quadratic tetra elements the locking phenomenon is not fully eliminated and numerical results continue to be dependent on the specific element formulation. In addition, the number of integration points used in quadratic tetrahedral elements and their location, which is potentially quite different from those in a regular hexahedral element, contributes to the existing uncertainty.
As a result engineers are justifiably concerned about the accuracy of the predictions made with models based on tetrahedral elements but are left without a practically viable alternative.
In this study we describe the development of a material and failure model for an aluminum forging with very high ductility. Whereas the high ductility of the material already makes this a non-trivial task as we need to consider mesh dependency, regularization and damage coupling, the task is made more challenging by the need of using tetra elements. While isotropic behavior was assumed for the material, specific attention was given to the yield curve in the post-necking region and a full 3D failure model with failure surface and instability surface in function of stress triaxiality and Lode parameter were developed. The instability surface corresponds to incipient diffuse necking (and thus mesh dependency) and is based on a 3D generalization of the Swift criterion. Through numerical solutions for a high number of test specimens a fracture surface has been developed. We selected the quadratic type 16 tetrahedral element with the Cosserat continuum formulation for this project believing this to be easily the most powerful tetra element formulation in the LS-DYNA code. Comparisons were done with the more traditional linear and locking corrected type 13 element as well as with models built from hexahedral elements, the latter serving a baseline comparison. It is found that for most of the specimen tests the response of the selected tetrahedral elements was well behaved, however locking phenomena were still observed in a small number of simulations leading in some cases to overestimated force levels and in some cases invalidating the failure surface. The conclusion of the authors is that numerical results from models based on tetrahedral meshes, although reliable in majority of cases, are not on par with results obtained with hexahedral models.

## 1 Introduction

The increasing demand for mass reduction and optimal component designs in the automotive industry has led to the development of complex shapes and geometries. Casting and forging are the two widely adopted manufacturing processes to produce those parts.
The manufacturing process affects the mechanical property and fracture performance of a material significantly. The effect of manufacturing process upon the microstructure of similar material compositions leads to the requirement of a specific fracture characterization. Furthermore, the auto industry aims to utilize virtual assessments in lieu of physical tests in various stages of vehicle developments. As result, the need for developing accurate and truly predictive numerical fracture models has become a crucial element to assess the crashworthiness and meeting safety requirement in all stages of vehicle development.

To accommodate the iterative assessments for optimizing designs of body structure parts as well as the required accuracy and reliability of numerical simulations, CAE users (or developers) must choose the most efficient fracture model and modelling techniques including element size and formulation. (joints configurations, …)

Through this study it was found that though the adopted modelling and material fracture development practice guidelines are sufficient and accurate for majority of the material models, it may need to be altered for others.

The aim of this project was to develop a material and fracture model for numerical simulation of a forged aluminum component made of Aluminum 6082-T6-310, using (isotropic) Von Mises plasticity coupled with MAT_ADD_EROSION_GISSMO. A Hybrid numerical and experimental methodology was used to quantify the required parameters.
Typically the preferred element of choice to model such complex components are linear Tetrahedral (Formulation 13), However, since the material exhibited high ductility in initial tensile tests, the decision was made to develop and calibrate the fracture model based on type 16 quadratic Tetrahedral elements with the Cosserat formulation.

### 1.1 Material Characterization:

To assess the material homogeneity of the component, a number of uniaxial tensile specimens were extracted from the thin region (web) as well as thicker parts as shown in figure 1.
In addition, to also examine part to part variation, four large uniaxial specimens were extracted from four individual components.

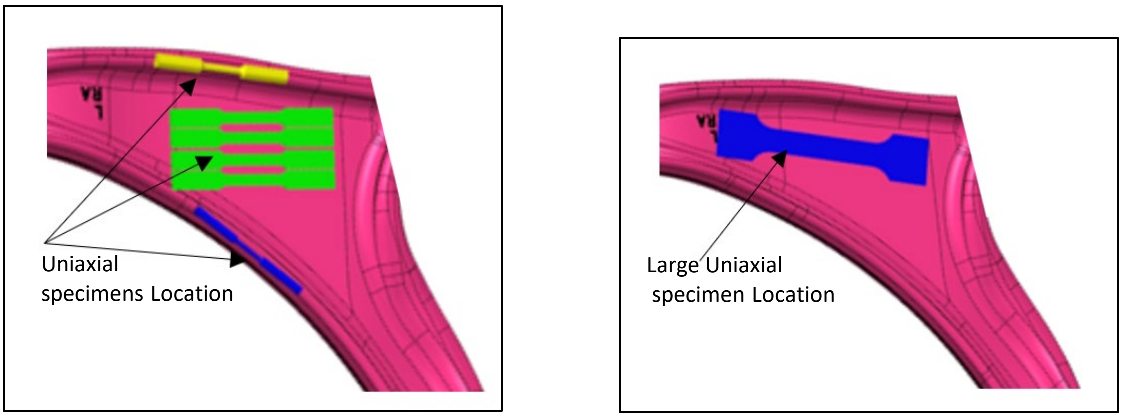



*Figure1: Uniaxial specimens (subsize ASTM, round and large uniaxial)*

Overall, the repeatability of tensile tests was good with consistency in stress responses and local fracture strains measured with DIC.

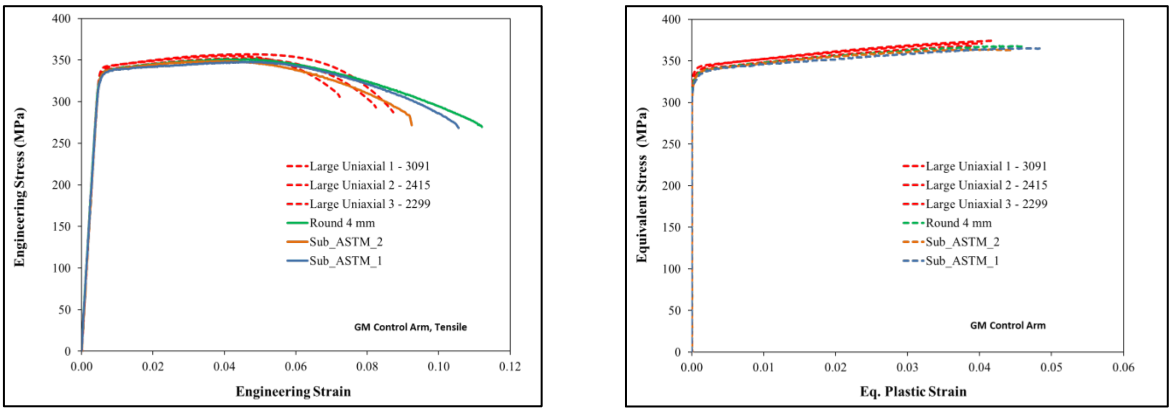



*Figure 2: Engineering and true stress strain from subsize, round & large uniaxial tensile*

| Tensile Property | Tensile Tests | | | |
|---|---|---|---|---|
| | Large Uniaxial | Sub-ASTM E8 | Round – 4 mm | Round – 2.5 mm |
| Yield Stress [MPa] | 340.1 ± 2.1 | 338.3 ± 3.6 | 338.4 | 326.8 |
| UTS [MPa] | 354.5 ± 2.3 | 347.9 ± 2.4 | 349.5 | 343.1 |

*Table1:Material property variation throughout the component and from part to part*

The tensile tests data indicated a considerable ductility and local necking in the forged material Fig 3.

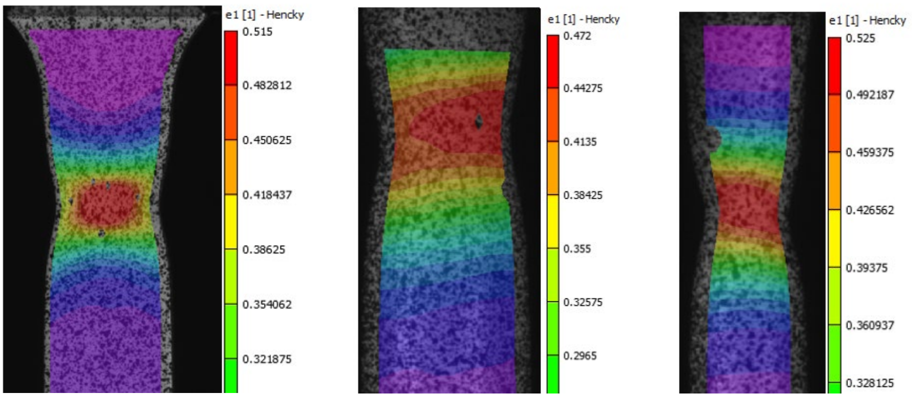



*Figure3: Uniaxial specimens (subsize ASTM, 2.5 & 4mm round bar) major strain DIC contour*

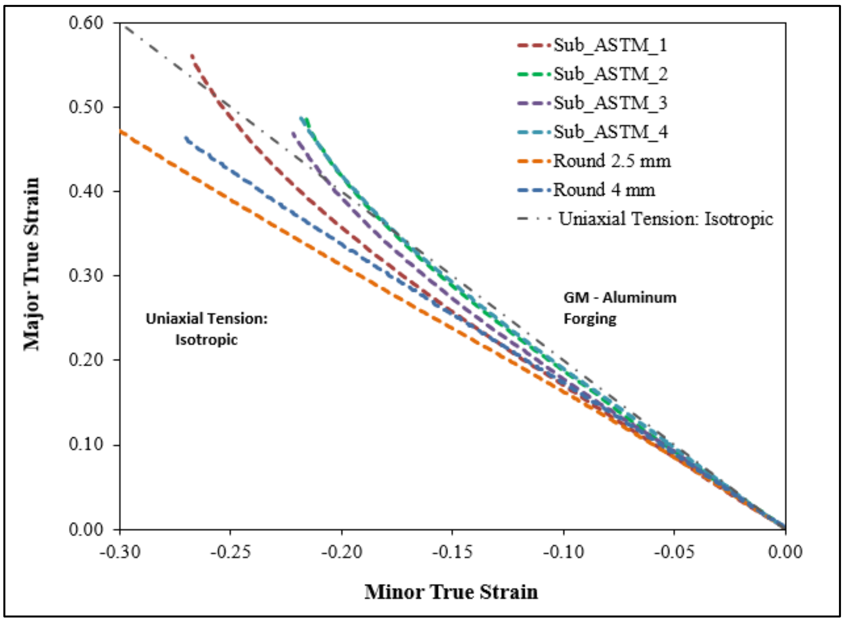
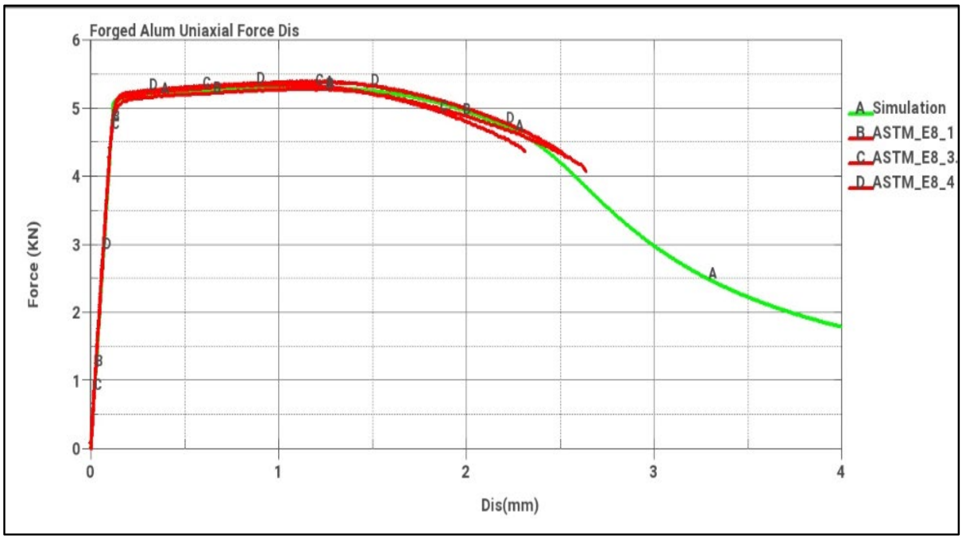



*Figure 4: Measured major and minor strain for all uniaxial specimens*

The measured major and minor strain of the uniaxial tensile tests resemble istropic characteristic. (Fig4)

Using the Swift equation, the material plastic flow and localization of the material was extrapolated beyond the necking point. The predicted major strain from numerical simulation correlated well within the range of the experimental values from DIC prior to fracture. As well, there was a good agreement in force displacement comparison between the experimental data and the simulation.



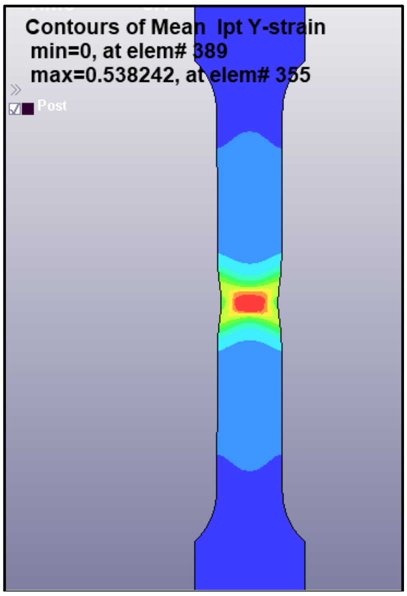




*Figure 6: Contour of major strain*

### 1.2 Experimental Plan:

An extensive set of specimens were designed and simulated using von Mises yield function to study the ductile fracture of the Forged Aluminum 6082 T6 representing the wide range of stress states (Triaxialites of $0.0<\eta<1.0$ Lode angle parameters of $-1.0<\xi<1.0$).
The round notched bars were designed to investigate the fracture strains of triaxialities for Lode angle parameter of 1.0.
The grooved specimens represented the range of triaxialities for Lode Angle parameter of 0.

In addition, while the mini shear specimen was to represent the simple shear stress state, the long shear specimen Butterfly is to simulate the shear tension condition.

*Figure 7: Uniaxial and notched round bar &Grooved specimens*

*Figure 8: Nakazima W5 & Nakazima W10 Specimens*

*Figure 9: Flat specimens*

| | Specimen | η | ξ | Repeats |
|---|---|---|---|---|
| 1 | Axisymmetric#1 | 0.6 | 1 | 3 |
| 2 | Axisymmetric#2 | 1 | 1 | 3 |
| 3 | Axisymmetric #3 | 0.6 | 0.9 | 3 |
| 4 | Nakazima W5 | 0.3 | 0.9 | 3 |
| 5 | Nakazima W10 | 0.4 | 0.8 | 3 |
| 6 | Grooved #1 | 0.9 | 0 | 3 |
| 7 | Grooved #2 | 0.8 | 0 | 3 |
| 8 | Grooved #3 | 0.6 | 0 | 3 |
| 9 | Flat Notched | 0.6 | 0.0 | 3 |
| 10 | Shear Butterfly | 0.1 | 0.1 | 3 |
| 11 | Mini Shear | 0 | 0 | 3 |
| 12 | Large Uniaxial | 0.35 | 1 | 3 |

*Table2: List of experimental specimens and their targeteted Traixiality & Lode Angle Parameter*

All tensile tests were carried out in University of Waterloo Structural Lab with 100 KN AGS-X Shimadzu electromechanical test frame at 0.03mm/sec and the Nakazima tests were conducted using punch test configuration.
DIC camera 12.5 MP Flir with 180mm lens and 0.0197 mm/pixel was used to measure strains.

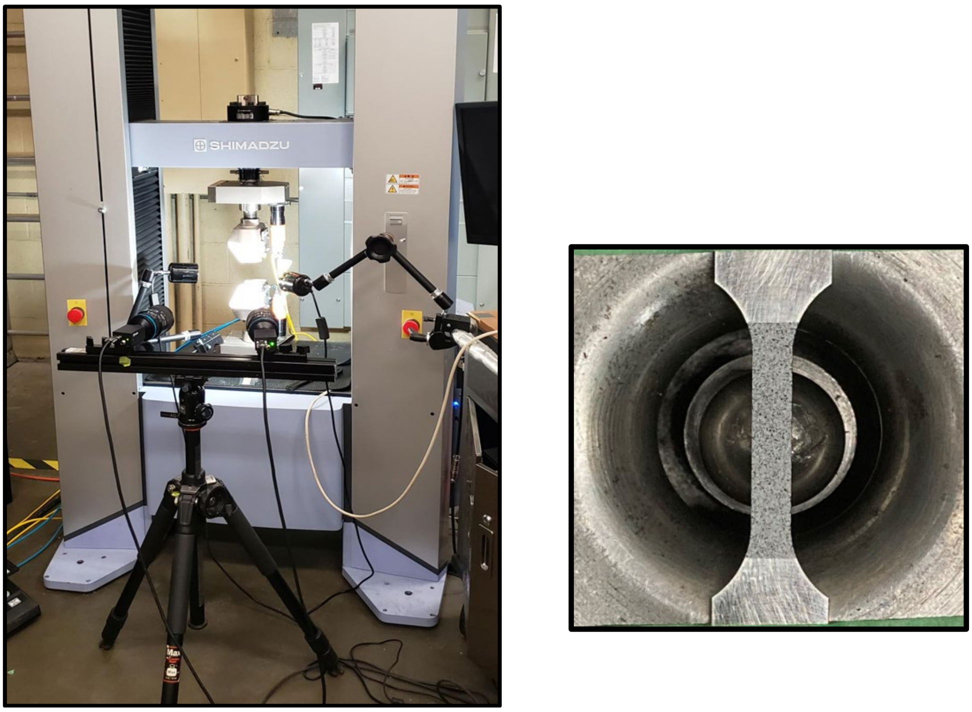



*Figure 10: Tensile Test & Nakazima Test Configuration*

### 1.3 Numerical Simulation:

All specimens were modelled using 0.5mm quadraticTetrahedral elements with Cosserat contnuum element formulation to capture high ductility and damage accumulation of the material properly and simulated using Ls Dyna R10.2.0.
Assuming isotropic characteristic of the material, von Mises yield function (*MAT_PIECEWISE_LINEAR_PLASTICITY) coupled with phenomenological failure criterion (*MAT_ADD_EROSION) was chosen for numerical simulation.
A preliminary fracture locus was adopted and for each specimen the average Triaxiality and Lode angle parameter was recorded.

*Eq 1:* $\eta_{ave} = \frac{1}{e_f}\int_0^{ef} \eta \, d\varepsilon_p$

*Eq2:* $\xi_{ave} = \frac{1}{e_f}\int_0^{ef} \xi \, d\varepsilon_p$

Through an iterative process the fracture locus was calibrated and finalized to match the force displacement from the numerical simulation to the ones from the experiment and the fracture surface (LCSDG) and instability surface (ECRIT) have been finalized.

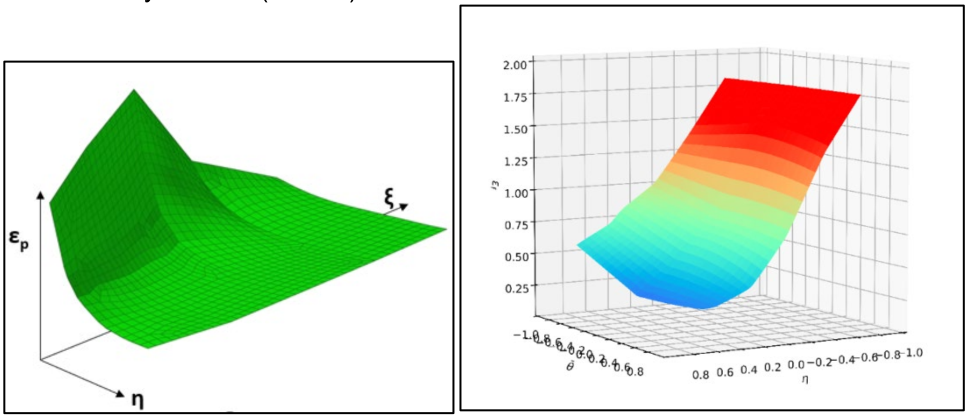



*Figure 11: Fracture & Instability Surface in space of Triaxiality, Lode angle parameter & Fracture strain*

All round axisymmetric notched specimens force displacements were correlated well with their respective experimental values.

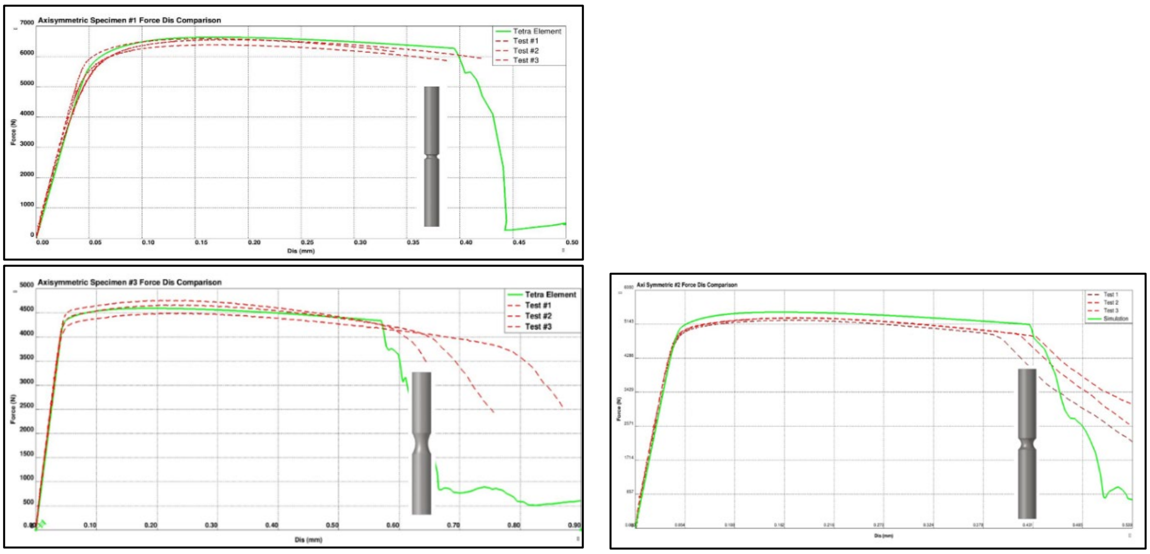



*Figure 12: Round Specimens Force Displacement Comparison*

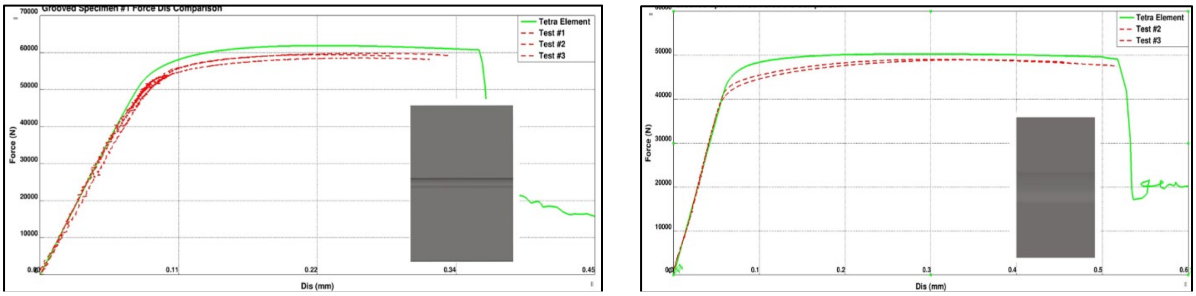



*Figure 13: Grooved Specimens Force Displacement Comparison*

Two of the grooved specimens force displacements had good agreement from the experimental value while the third one had about 10% margin.

The flat notched, uniaxial tension and Nakazima specimens Force displacements were well correlated with the experimental values within the acceptable range.

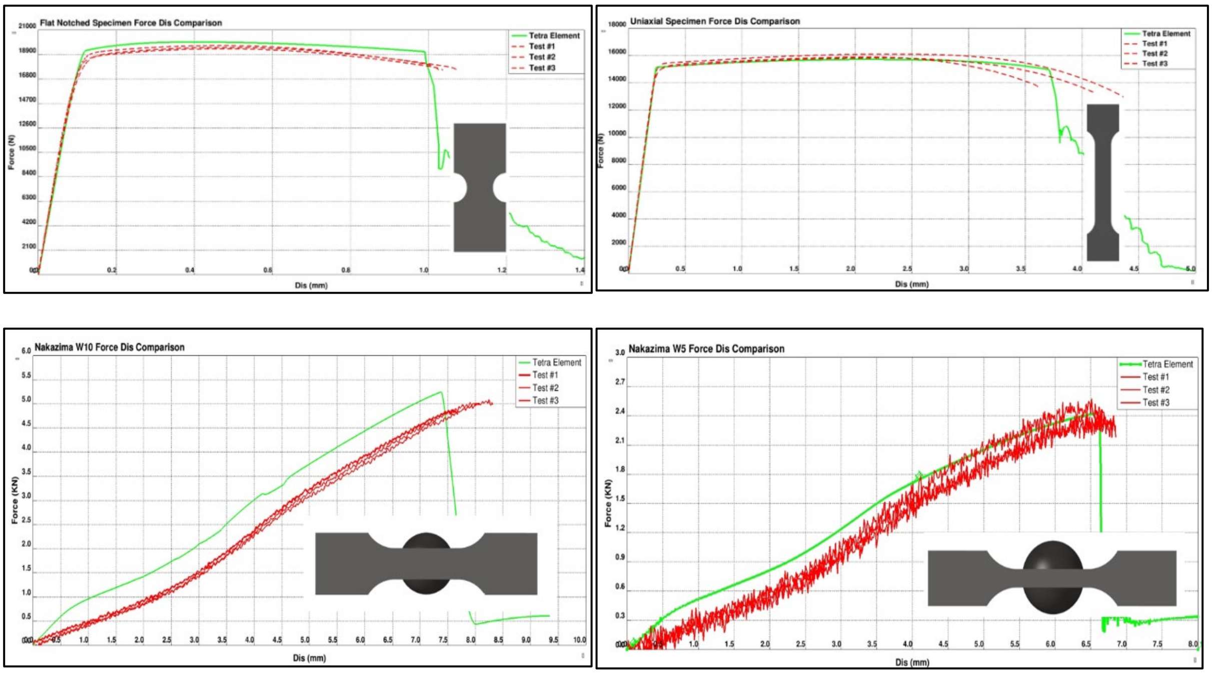



*Figure 14: Flat & Nakazima Specimens Force Displacement Comparison*

Both shear specimens (mini shear and Butterfly) force displacements from simulation exhibited premature fracture.
Additional attempts to adjust the fracture surface at shear region by increasing the fracture strains did not make any significant improvement.
Careful observation of the deformed specimens in simulations prior to fracture occurrence indicated sever distortion of the elements within the region and possibility of the known Tetrahedral elements locking phenomenon.
In addition, the effective plastic strains were significantly lower than the corresponding DIC measured values.

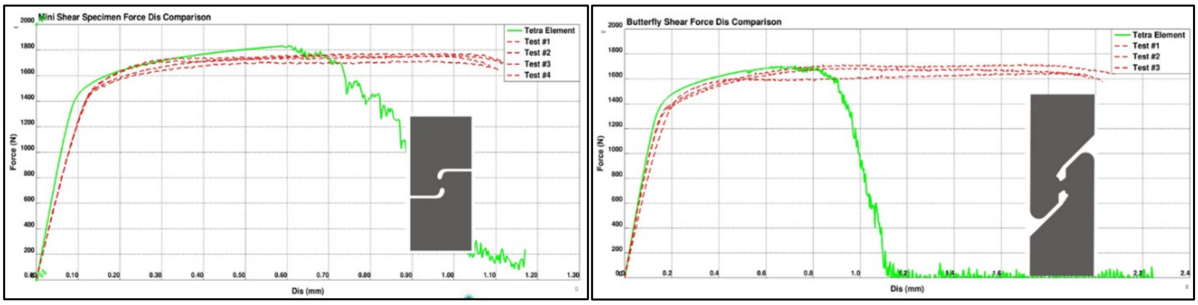



*Figure 15: Mini shear & Butterfly Shear specimens Force Displacement Comparison*

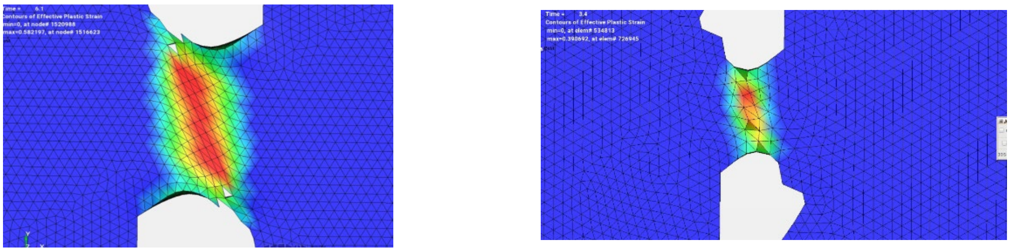


*Figure 16: Shear Specimens Tetra element von Mises Strain contour*

| Specimen | | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Average | Simulation Tetra | Simulation Hex |
|---|---|---|---|---|---|---|---|---|---|
| Butterfly Shear | von Mises Strain | 1.090621 | 1.07305 | 1.06261 | | | 1.07543 | 0.62 | 0.745 |
| Mini Shear | | 0.813422 | 0.81899 | 0.77484 | 0.80669 | 0.77962 | 0.80050 | 0.5 | 0.8 |

*Table3: Shear specimens DIC measurements comparison with simulation with Hex and Tetra element*

### 2.3 Comparison with other numerical approaches

#### 2.3.1 comparison with hexa elements

Remodeling all the samples with hexa elements allowed to develop a failure surface that yielded satisfactory results for all 12 tested samples. This was relatively unproblematic and we show the dramatic difference in numerical results between the quadratic tetra elements and the hexa elements for the 2 samples subjected to loads that are predominantly shear. (Fig17 and Fig18). At this point the potential value of a mesh generation tool able to develop good quality hexa meshes for complex 3D geometries in a user-friendly way becomes overly clear.

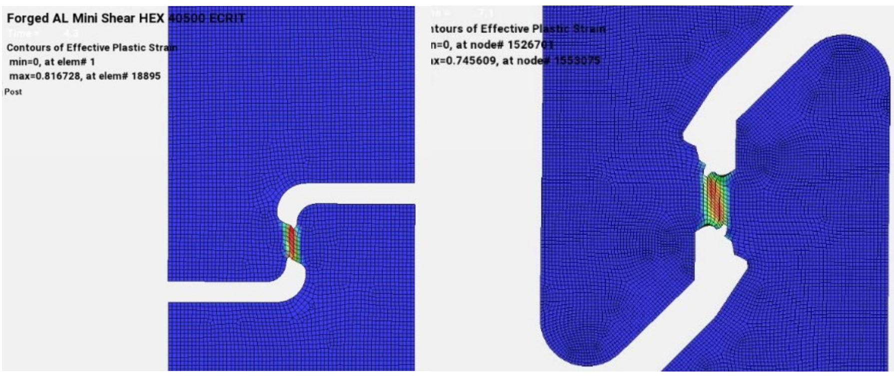



*Figure 17: Shear Specimens Hex element von Mises strain contour*

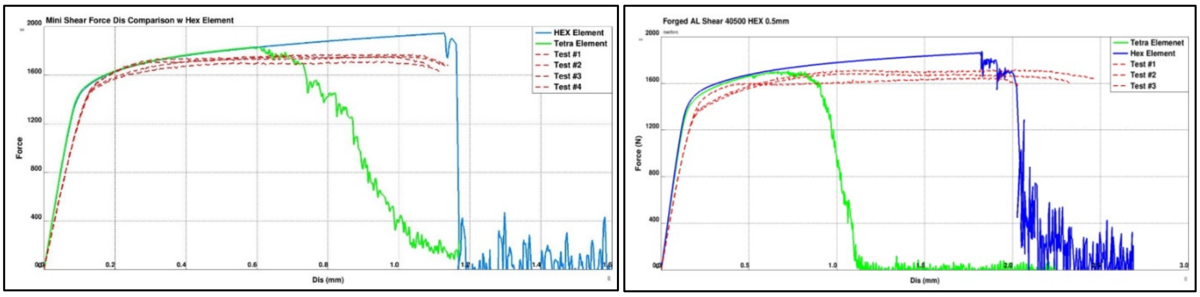



*Figure 18: Shear Specimen Force Displacement Comparison (Hex & Tetra element)*

### 2.3.2 Comparison for different mesh orientations

Through the material model parameters calibration process, it was also noticed that different modelling and mesh generation techniques affect the force displacement (Fig19 and Fig20).
Therefore, extra attention must be made to the mesh generation technique used to model the specimens and maintain the same consistentcy with modelling the components as well.

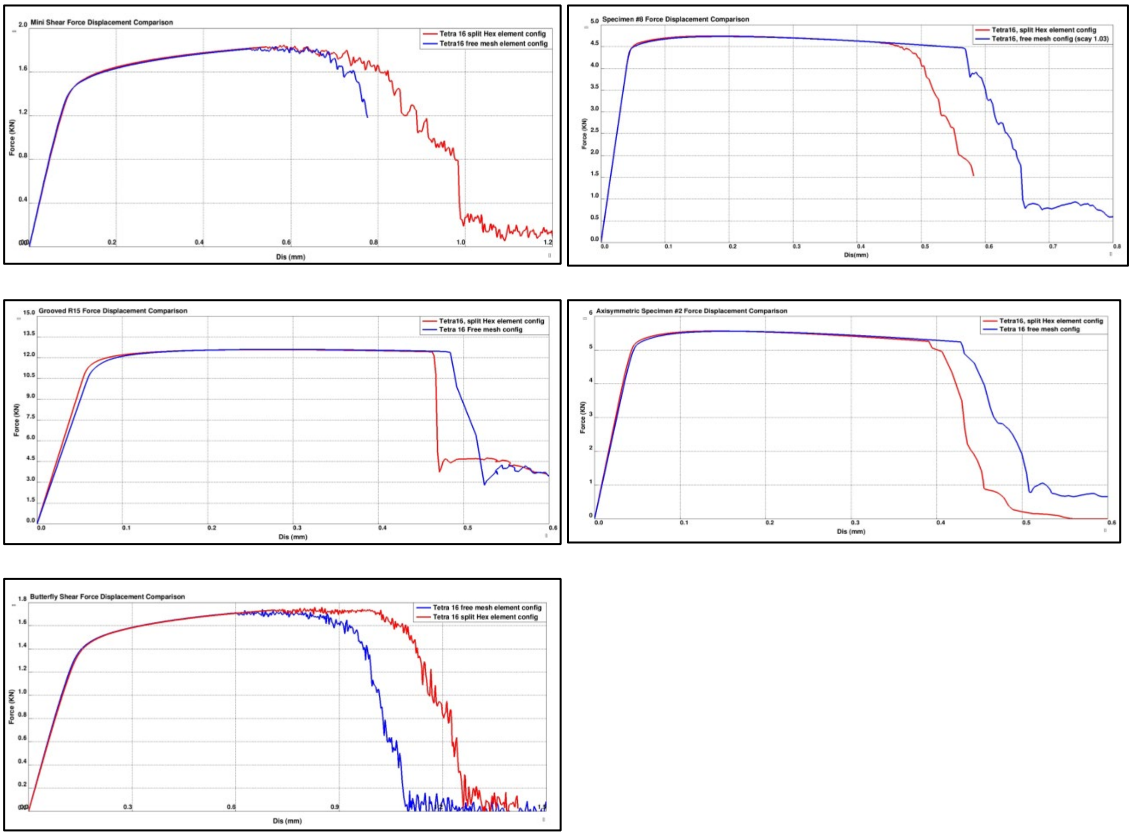



*Figure 19: Force Displacement comparison of different element configurations for mini shear, Butterfly shear, specimen #8, axisymmetric #2 and grooved R15*

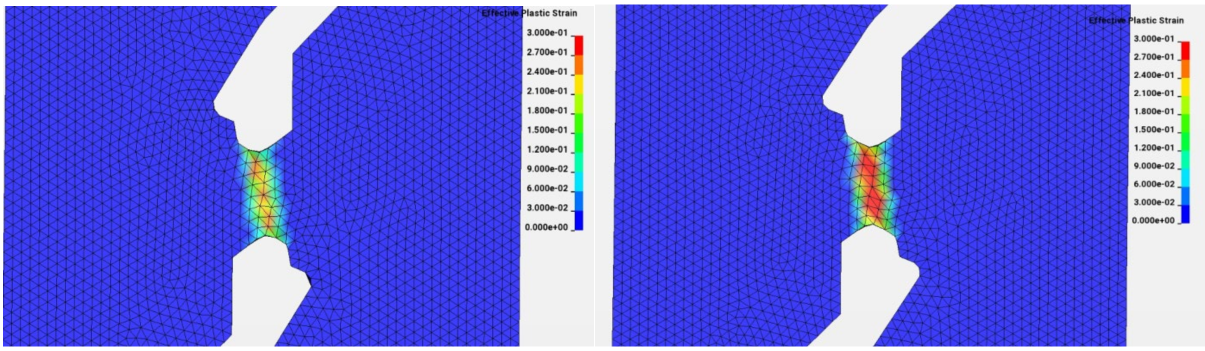


*Figure 20: Comparison of the von Mises strain contour, Butterfly shear specimen, free mesh vs. split Hex element*

### 3. conclusion

Although it is well known that tetra elements suffer from locking phenomena and will likely behave 'overstiff' in many numerical simulations, their accuracy can usually be considered 'good enough' for simulations that need to predict displacements as well as history variables such as equivalent plastic strain in the context of a crashworthiness simulation. The less clear fact is how the use of tetra elements affects the predictive capability of a model with respect to failure, more specifically when the used failure model contains a dependency upon the state of stress and accurate evaluations of stress triaxiality and Lode parameter are of the essence. In this project we have attempted the latter by using the most sophisticated tetra element available in the LS-DYNA code. It was found that a failure surface could be developed that matched 10 out of 12 test cases, however matching the remaining 2 test cases could not be achieved without compromising a number of previously matching results. It was easily shown that the same problem did not exist with hexa elements. Moreover we showed the numerical results to vary with the orientation of the mesh lines in the tetra mesh, something that is hard to control with automatically generated solid models. Consequently the reliability of tetra models cannot be considered comparable to the reliability of hexa models. The evil is rather in the fact that the lack of reliability will not manifest itself by results being generally 10-20% off the physical value. Rather the use of tetra models is expected to yield mostly good results but occasionally giving results that are outside the acceptable range.
It should be pointed out that the material that was investigated in this project was a highly ductile forging leading to large strains and very non-proportional loadpaths prior to failure. The quadratic tetra element with Cosserat formulation has been shwon to perform very well in the realm of small displacements. It would consequently be interesting to investigate if the reliability of the formulation is better when applied to a more brittle material ( such as a casting ) .

### 4. references

[1] LS-DYNA Keyword User’s Manual, Volume II, Version R12, Livermore Software Technology Corporation

[2] LS-DYNA Theory Manual, 2014, Livermore Software Technology Corporation