Comparative Evaluation of Material Models for Crush Simulation of Cast Aluminum Alloy Wheel

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1. Introduction:

Wheels play a critical role in vehicle safety, especially during severe crash scenarios such as small overlap frontal impacts. In these situations, energy typically absorbed by components like bumpers and crash boxes is instead transferred directly to the wheels, which can intrude into the passenger compartment and pose severe risks to occupants. However, most of the current research related to wheels are mainly focusing on the light-weight design, next-generation material selection (HSS, AHSS, DP, etc.), wheel fatigue life improvement, and standards, such as the SAE J175 [1] lateral impact test and the SAE J3203 [2] radial impact test, which may not fully represent the extreme crash scenarios faced in real-world situations.

To address this gap, a quasi-static wheel compression test is conducted for both steel and cast aluminum alloy wheels by major OEMs, especially for the passenger car segment, to understand the wheel's maximum load-carrying capacity under a strain-controlled crush test [3].

The main objectives of this study are to: 1. Evaluate and compare the effectiveness of two material models, MF GenYld+CrachFEM [4] and MAT024 [5]. 2. Identify the correct element formulation and element size by comparing the simulation results with an experimental result of a wheel under quasi-static conditions using LS Dyna. The results will enhance the accuracy of wheel crash simulations and provide valuable insights for improving light weight design and design optimization.

2. Material Modelling:

2.1 MAT_024 Material Card:

The wheel is made up of cast aluminium alloy (LPDC process), and its material model can be represented by the MAT024 material model (refer to Fig. 1: LS Dyna keyword).

- The most common material model for elastic-plastic material with the von Mises yield criterion
- Failure criteria: equivalent plastic strain at failure or minimum time step size through the "FAIL" flag
- No damage evolution (Damage can be coupled with GISSMO and it is not used here)
- Multiple failure criteria can be added with MAT_ADD_EROSION.
- The input parameters are young's modulus, Poisson's ratio, and mass density.
- The hardening curve can be added by LSCC (*DEFINE_CURVE) with no strain rate effect.

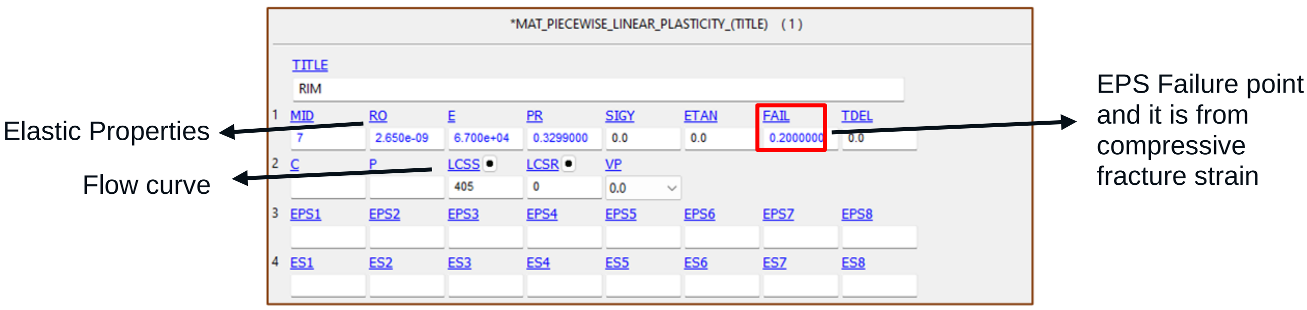


Fig.1: MAT_024 Material card keyword file

2.1.1 *Material characterization experiments for MAT_024:*

A typical MAT_024 material card for metal plasticity can be created from a uniaxial tensile test with different strain rates (0.001 s^{-1}, 1 s^{-1}, 100 s^{-1}). A tensile specimen is made from a Hub, Spoke, and Rim location (refer to Fig. 2 &3) and an experiment tensile test is conducted. A raw engineering stress-strain is converted to true stress-strain without any negative slope and fine-tuning of the curve for better accuracy. The engineering stress-strain curve can be converted into a true stress-strain by using the following formulae, and a flow curve is also created by LCSS ID. The flow curve is a representation of true stress versus plastic strain, and it should be smooth and clean.

$\sigma_{True} = \sigma_{Engg}*(1+\varepsilon_{Engg})$

$\varepsilon_{True} = \ln(1+\varepsilon_{Engg})$ $\varepsilon_{platic} = \varepsilon_{total} - \varepsilon_{elastic}$

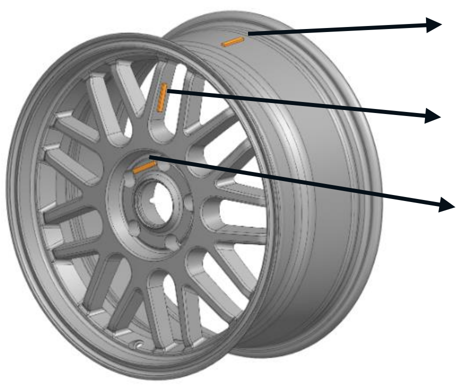


Fig.2: *Tensile specimen preparation location*

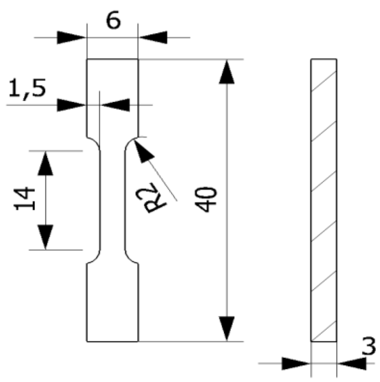


Fig.3: Tensile specimen dimensions

2.2 MF GenYld+CrachFEM Material Card:

The material model MF GenYld describes the elasto-plastic deformation of the material. The elastic behaviour of most materials is isotropic. Strain-rate dependent hardening is a basic requirement for modelling nearly all materials. The hardening can also depend on temperature or other locally distributed values such as hardness or the degree of anisotropy.

A variety of base yield criteria cover a wide range of materials, especially sheet metals. These base yield criteria can be scaled for different stress states and they can be different in tension and compression. Isotropic-kinematic hardening can describe the Bauschinger effect where the yield stress changes after load reversal. The failure model CrachFEM describes the onset of material failure. It includes ductile fracture modes: normal fracture due to micro voids under tensile loads, and shear fracture due to shear band localization. These models are complemented by optional post-critical models. Thin-walled metal parts are subject to tensile instability. The instability itself does not constitute failure. Post-instability models can model the subsequent fracture.

A stress-based fracture criterion can model brittle fracture in metals or polymers. Depending on the material, damage accumulation can be linear or tensorial. Porosity in castings contributes to a higher risk against normal fracture. The porosity can evolve during the simulation starting from an initial porosity.[6]

MF-GenYld+ CrachFEM 4.3.3 for A356-T6 material card characterization and verification are developed and conducted by MATFEM. As a customer, we have sent the samples from different wheel sections like Spoke, Hub, and Rim to evaluate the wheel properties. MATFEM conducted comprehensive material testing, and they prepared a material card with the coupling of commercial explicit software LS Dyna with a license and used the same [7]. The testing details and material card preparation are not discussed here. The overview of the material card is as follows, 2.2.1 **Elasticity**

- Linear elastic properties are taken from literature (E =70GPa & v = 0.3)

2.2.2 **Plasticity**

- Yield Locus- Von mises
- Hardening Law is described by Hocket-Sherby

$$\sigma = a - (a - \sigma_0) \cdot \exp\left(-c \cdot \varepsilon_{eq}^{n}\right)$$

- Isotropic/Kinematic Hardening

2.2.3 **Failure Models**

It has the following failure models namely,

- Ductile Normal Fracture (Refer to Fig 4.)
- Ductile Shear Fracture (Refer to Fig 5.)
- Tensile instability for thin-walled structures (Localized necking)

2.2.3.1 **Ductile Normal Fracture**

- EPS at failure vs Stress state parameter (β)
- (β) depended on 2 stress invariants

$$\varepsilon_{eq}^{**} = d \cdot e^{q \cdot \beta} \qquad \beta = \frac{1 - s_{NF} \cdot \eta}{v} \qquad \eta = \frac{-3 \cdot p}{\sigma_M} \quad v = \frac{\sigma_1}{\sigma_M}$$

2.2.3.2 **Ductile Shear Fracture**

- EPS at failure vs Stress state parameter (θ)
- (θ) depended on 2 stress invariants

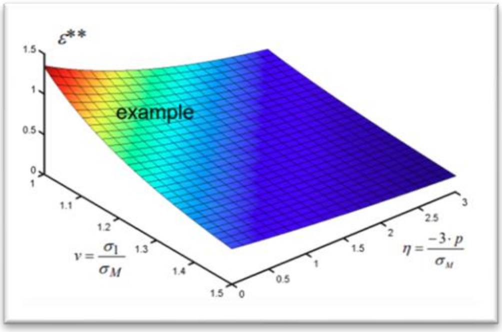
$$\varepsilon_{eq}^{**} = \frac{\varepsilon_{SF}^{+} \cdot \sinh(f \cdot (\theta^{-} - \theta)) + \varepsilon_{SF}^{-} \cdot \sinh(f \cdot (\theta - \theta^{+}))}{\sinh(f \cdot (\theta^{-} - \theta^{+}))}$$

$$\theta = \frac{1 - k_{SF} \cdot \eta}{w}, \qquad w = \tau_{max} / \sigma_M$$

Note: The overall comparison between the MAT_024 & MATFEM CrachFEM material are given in the table 1.

Aspect	MAT024 Material Model	Modular Material Model MF GenYild+ CrachFEM
Software Environment	LS-DYNA	User-Material model for LS-Dyna and other FE explicit software
Element types Supports	All	2D & 3D elements
Material Type	Wide range of metals with isotropic assumptions	Metals(Sheet, extrusion, casting) & Polymers (Non-reinforced, short-fiber-reinforced, UD and fabric glass fiber composites) and glass
Features	Material nonlinearity Strain rate effects Failure criteria	Material nonlinearity Strain rate effects Failure criteria & Damage model
Fracture criteria & Damage Model	EPS & No damage	Ductile fracture& Shear failure with tensile instability
Specialization	General-purpose material model	Specialized for automotive crash Simulations, Aerospace, Steel industry and medical devices

Table 1: Material card comparison



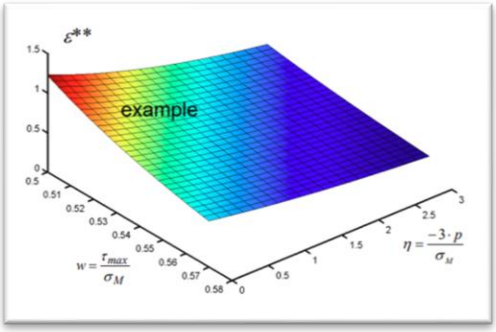


Fig.4: 3D fracture surface for ductile normal fracture *Fig.5: 3D fracture surface for shear fracture*

3 Experimental setup of wheel crush test:

The experimental wheel quasi-static crush test has been conducted at the reputed test center, and Fig. 6 shows the experimental setup for the wheel crush test. The wheel is constrained at all DoF at the fixed top head, and a 30 mm/min loading rate is applied at the moving bottom head. To avoid the wheel slipping and flying away of small parts from the wheel during the loading condition, the wheel is rigidly tied with a fixed top head by means of ropes as shown in figure 6. The test was conducted at room temperature. To position the wheel at the center of the moving head, a light is provided for better fixation and boundary conditions. The load is applied to the wheel until the structural integrity of the wheel is lost.

The displacement is measured by using the actuator/sensors, which are positioned in the moving head, and the load is also measured by using the load cell, which is also placed in the same location. The force vs. displacement curve is plotted, and crack initiation locations are monitored throughout the test.

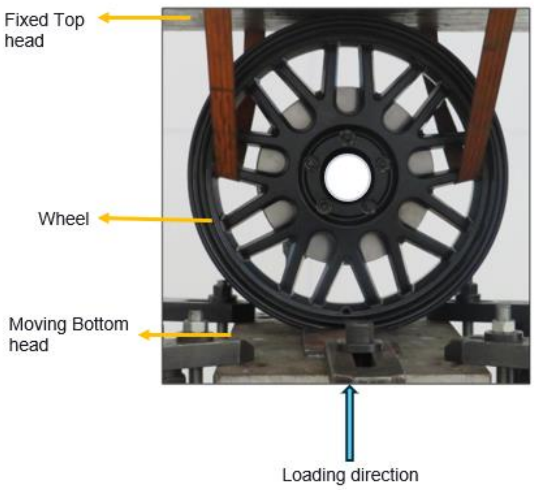


Fig.6: Experimental setup

4 Numerical Modelling of the wheel:

4.1 Model setup:

The pre-processing steps involved in the numerical simulation are as follows: Geometry, Geometry clean-up, Material card preparation, Meshing, contact modelling, Loads & Boundary conditions, and Analysis settings. The wheel geometry was prepared using CAD software, with all the important features modelled accurately to replicate the physical wheel. Material data was assigned to different sections of the wheel, such as the Hub, Spoke, and Rim, for both MAT_024 and MATFEM cards. Both the fixed top head and the moving bottom head were modelled as rigid bodies to reduce computational effort.

Meshing is a crucial stage in numerical simulations, as the accuracy of the simulation results depends entirely on the quality of the mesh. A mesh convergence study is essential to optimize the element type, formulation, and sizing. The wheel is modelled as a 3D solid part, using standard solid elements such as Hexahedrons and Tetrahedrons. Simple, mappable, and sweepable bodies are meshed with hex elements, while complex geometries like wheels are meshed with tetrahedron elements to capture all features accurately. While there are advantages and disadvantages to using these elements, this discussion is beyond the scope of the current text [8].

The wheel has been meshed using tetrahedron elements with various element formulations and sizes. A description of the wheel meshes is shown in Table 2 below. To meet the second objective of this study, the following case studies were conducted. Mass scaling, an explicit simulation technique used to speed up simulations, was not considered in this study.

Aspect	Case 01	Case 02	Case 03	Case 04
Material Model	MAT024	MATFEM GenYld-Crach-FEM	MAT024	MATFEM GenYld-Crach-FEM
Element Formulation	Linear 4 node Tetrahedron LS Dyna El ID:10*	Linear 4 node Tetrahedron LS Dyna El ID:10*	Quadratic 10 node Tetrahedron LS Dyna El ID: 16	Quadratic 10 node Tetrahedron LS Dyna El ID:16
Average Element size	4 mm	4 mm	2 mm	2 mm
Total element count	0.9 M	0.9 M	6.1 M	6.1 M
Mass Scaling	No	No	No	No

Table 2: Element details

*Note: * Default element type in LS Dyna*
EL 10- one-point tetrahedron and EL 16- 4- or 5-point 10 node tetrahedron

A frictional contact is established between the wheel and the fixed top head, as well as between the wheel and the moving bottom head, to accurately represent real contact behavior. The fixed top head is constrained in all degrees of freedom (DOF), while the moving bottom head is also constrained in all DOF except for the direction of movement.

4.2 Model Validation:

After running simulations for all four cases, the Force vs. Displacement plots for Experimental vs. MATFEM and Experimental vs. MAT_024 were compared, as shown in Figures 10 and 11, respectively. Additionally, final failure images for MAT_024 EL16 with 2mm, MATFEM EL16 with 2mm, and the Experimental test are shown in Figures 7, 8, and 9.

The failure initiation points and damage evaluation points are identified as 1, 2, 3, and 4 in Figures 7, 8, and 9. The overall load-carrying capacity path of MAT_024 is very similar to that of the MATFEM material card up to the material's ultimate strength (UTS). However, the damage evaluation beyond UTS is not captured effectively by MAT_024 with EL10 and EL16 element formulations. MAT_024 EL10 (one-point tetrahedron) and MATFEM EL10 (one-point tetra element) are both too stiff, resulting in higher load-carrying capacity for the wheel, as observed in Figures 10 and 11.

The critical points 1, 2, 3, and 4 for crack initiation are the same across all cases, but damage evaluation depends significantly on element size and damage modelling. MATFEM's damage modelling with instability criteria effectively captures damage evaluation, as shown in Figure 8. Analysis of the history variables of the MATFEM material card indicates that under quasi-static loading conditions, DNF is more dominant than DSF in this particular simulation.

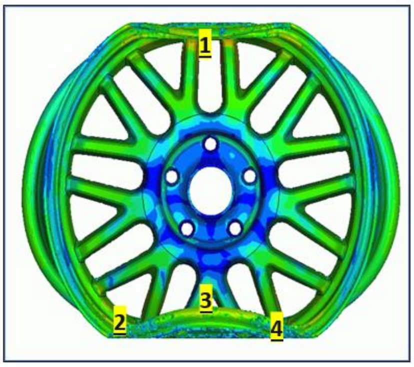


Fig.7: MAT024 Failure image

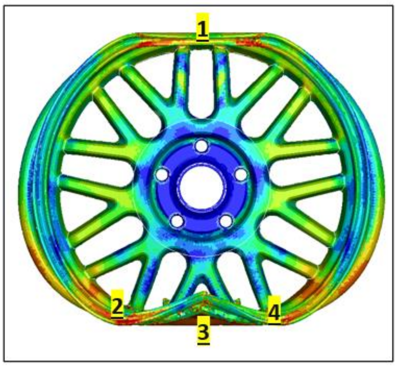


Fig.8: MATFEM Failure image

Fig.9: Actual Failure image

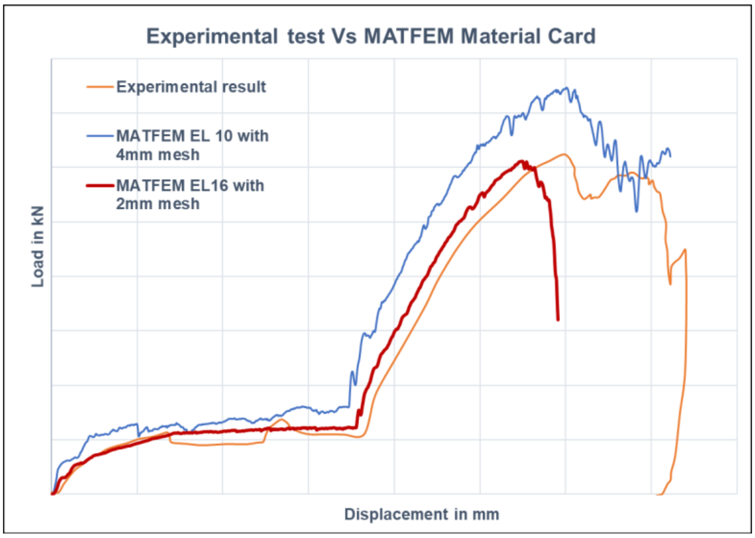


Fig.10: Force Vs Displacement curve of Experimental & MATFEM Card

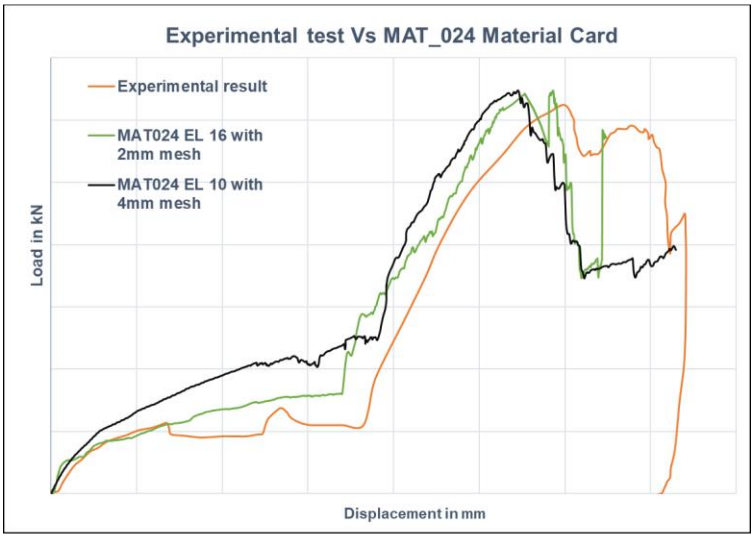


Fig.11: Force Vs Displacement curve of Experimental & MAT_024 Card

From the final failure images in Figures 8 and 9, the critical points of failure patterns 1, 2, 3, and 4 are similar for both the MATFEM material card and the experimental failure image.

This study is a comparative analysis between two material models: MAT_024 and MATFEM CrachFEM. The accuracy of these results depends on several factors, including the calibration of the material models, the type of material testing, the reproducibility and repeatability of the experimental results, and the setup of the numerical simulations. In this study, we assume that material calibration and testing are accurate, and we consider the choice of material card, element type, and size as variables.

5 Summary

From the crush simulations, both MAT024 and MATFEM EL 10 with a 4 mm element size demonstrate excessive stiffness, resulting in a higher load-carrying capacity. However, reducing the element size to 2 mm in EL 16 provides results that more accurately reflect the experimental fracture predictions. Additionally, the crack initiation points in MATFEM CrachFEM align closely with experimental outcomes.

When comparing the two materials, MATFEM CrachFEM offers good result accuracy but demands higher computational efforts and intensive material parameter identification. Conversely, MAT024 provides moderate result accuracy with lower computational requirements and simpler material parameter identification processes.

5.1 Future Plans and Limitations:

A single wheel is taken into this comparative study, which is not sufficient to make a solid conclusion, and the following future work is planned to rectify this limitation,

- Experimental and Simulation Crush Studies: Plan to conduct numerous experimental and simulation crush studies for different categories of wheels (thin/thick spoke, 15” to 20” diameter) for further evaluation.
- Refinement and Standardization: Refine the simulation procedure and establish a standard protocol for FEA (Finite Element Analysis) runs.

6 Acknowledges:

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