A Systematic Approach to Model Metals, Compact Polymers and Structural Foams in Crash Simulations with a Modular User Material

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Abstract:

Today the automotive industry is faced with the demand to build light fuel-efficient vehicles while optimizing its crashworthiness and stiffness. A wide variety of new metallic and polymeric materials have been introduced to account for these increased requirements. Numerical analysis can significantly support this process if the analysis is really predictive. Within the numerical model a correct characterization of the material behaviour – including elasto-viscoplastic behaviour and failure - is substantial. The particular behaviour of each material group must be covered by the material model.

The user material model MF GenYld+CrachFEM allows for a modular combination of phenomenological models (yield locus, strain hardening, damage evolution, criteria for fracture initiation) to give an adequate representation of technical materials. This material model can be linked to LS-DYNA when using the explicit-dynamic time integration scheme.

This paper gives an overview on the material characterization of ultra high strength steels (with focus on failure prediction), non-reinforced polymers (with focus on anisotropic hardening of polymers), and structural foams (with focus on compressibility and stress dependent damage evolution) with respect to crash simulation. It will be shown that a comprehensive material model - including damage and failure behaviour - enables a predictive simulation without iterative calibration of material parameters.

A testing programme has been done for each material group in order to allow a fitting of the parameters of the material model first. In a second step different component tests have been carried out, which were part of a systematic procedure to validate the appropriate predictions of the crash behaviour with LS-Dyna and user material MF_GenYld+CrachFEM for each material group.

Keywords:

FEM, Crash Simulation, Metals, Polymers, Structural Foams, Failure Modeling, Material Models

1 Modular Material Model for Metals, Polymers and Structural Foams

For crash applications - where energy absorption is important - materials are used which are capable to undergo large deformations before failure occurs. In these cases the material behaviour can be described as elasto-viscoplastic. For some materials the elastic behaviour can be non-linear. In case of hyper-elastic material behaviour applied deformations are completely reversible. For metals, polymers and structural foams which are used in crash relevant components the assumption of a linear-elastic material behaviour is a first reasonable approach, but has to be discussed individually in case of material model development. Figure 1 gives an overview on different material classes and their typical behaviour. It has to be mentioned, that only dominating effects are shown. A more detailed view may result in an increasing complexity of the material behaviour. As an example a nonlinear-elastic behaviour might be relevant for polymers but also for groups of metallic materials.

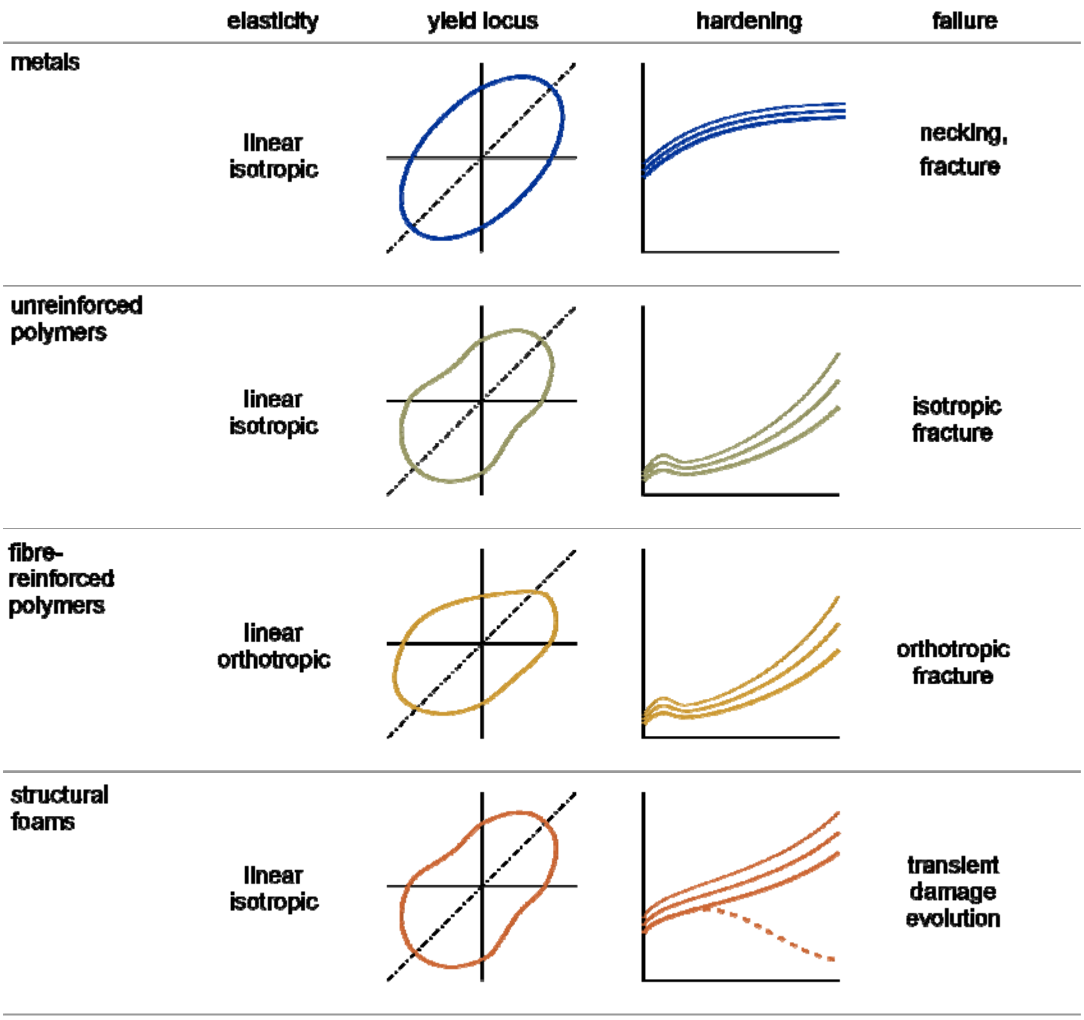


Figure 1: Elasto-viscoplastic material behaviour of different material groups, which are used in crash relevant components

Adjusted to the variety of the different materials used for crash applications MATFEM has developed a material model MF-GenYld+CrachFEM which is able to describe the individual material behaviour. The basic architecture of the material model enables a modular extensibility.

MF-GenYld+CrachFEM is an add-on module for finite element codes with explicit time integration. It can be used as a material model for shell and solid elements. MF-GenYld (Generalized Yield Model) allows for a modular combination of yield loci and strain hardening models to describe the plasticity of metallic materials and polymers. MF-GenYld includes the optional yield loci according to Hill-1948, Hill-1990, Barlat-Lian-1989, Barlat-1996, Barlat-2000 and Dell-2006 for shell elements, as well as orthotropic yield loci according to Hill1948, Barlat-1991 and Dell-2006 for solid elements. Hardening can be described as isotropic (different analytical models or via stress-strain pairs), combined isotropic-kinematic hardening and anisotropic hardening (hardening depends on the state of stress).

The comprehensive material model - including damage and failure behaviour - enables a predictive simulation without iterative calibration, based on a straightforward experimental material testing procedure as shown schematically in Figure 2.

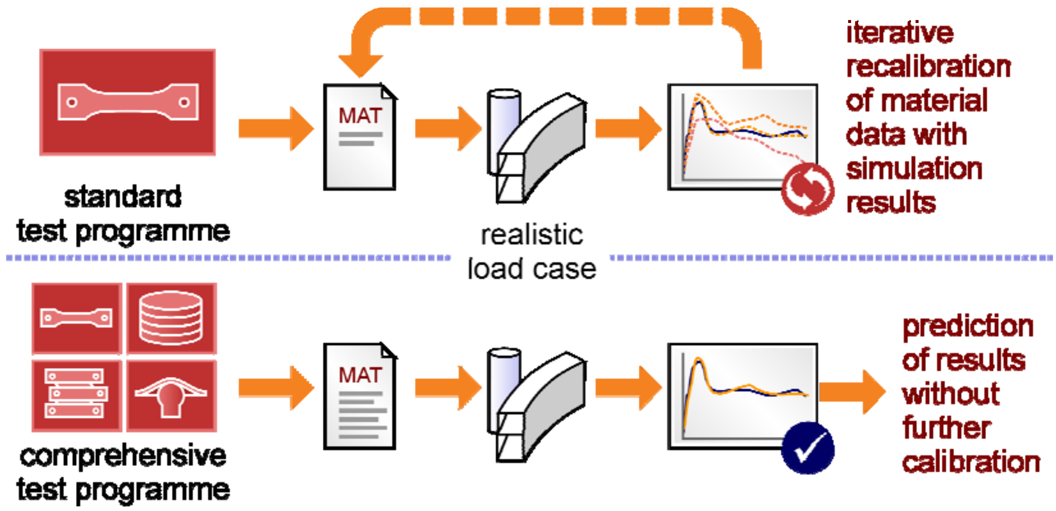


Figure 2: Improved prediction of crash behaviour of components with a material model based on a comprehensive test programme in comparison to standard approach (schematic).

2 Examples

2.1 Ultra high strength steel

2.1.1 Theoretical model for the calculation of tensile instability

A correct prediction of a possible sheet metal failure is an essential part of a sheet metal forming or crash simulation. The use of the conventional forming limit curve (FLC) is the standard approach at an industrial level for this problem. The FLC concept is limited to the case of linear strain paths, however. The initial FLC is no longer valid in the case of nonlinear strain paths as described by Dell et al. [1]. The algorithm Crach (*cf*. Gese and Dell [2]) is included in CrachFEM. It allows for a transient prediction of localized necking in the case of arbitrary strain paths. The standard FLC approach is used for elements with small strains. The Crach algorithm is only introduced for elements with higher strains to avoid a significant increase of CPU time. In some cases also the postcritical strain after onset of necking (elongation of a sheet between initiation of necking an final fracture) can be relevant for a good prediction of a part behaviour in crash. Therefore, the Crach algorithm has been extended by a module for handling the post instability strain. The post instability strain should be nearly independent of the element size of the underlying shell element.

For advanced and ultra high strength steels as well as aluminium sheets, there is a risk of fracture without prior localized necking. A wide range of fracture models is compared and discussed by Wierzbicki [4], showing that the equivalent plastic strain at fracture cannot be described by simple one- or two-parameter models for all possible stress states. CrachFEM includes fracture models that account for ductile fracture (caused by void nucleation, void growth and void coalescence) and for shear fracture (caused by shear band localization). The stress triaxiality η is defined as the ratio σ_m/σ_{eq} of hydrostatic stress and von Mises equivalent stress and is typically used as a stress state parameter for ductile fracture. The parameter has been introduced by Rice and Tracy [3]. It was shown by Wierzbicki, however, that this parameter is only unique for the plane stress condition but not for the general case of a 3D stress state. Therefore a new stress state parameter β has been introduced in CrachFEM [8].

It is a function of stress triaxiality η and ratio of first principal stress and von Mises equivalent stress σ_1/σ_{eq}. The shear fracture model presented uses a stress state parameter θ which is a function of τ_{max}/σ_{eq} and the stress triaxiality η. Like β, this stress state parameter is unique for the general 3D stress state. Fracture limit curves of equivalent plastic strain at fracture $\varepsilon_{pl}^{**}(\beta)$ and $\varepsilon_{pl}^{**}(\theta)$ are determined experimentally and used as a basis for an integral damage accumulation in the sheet metal forming simulation.

A schematic representation of the three different failure mechanism and examples for ductile normal fracture and ductile shear fracture in shown in *Figure 3*.

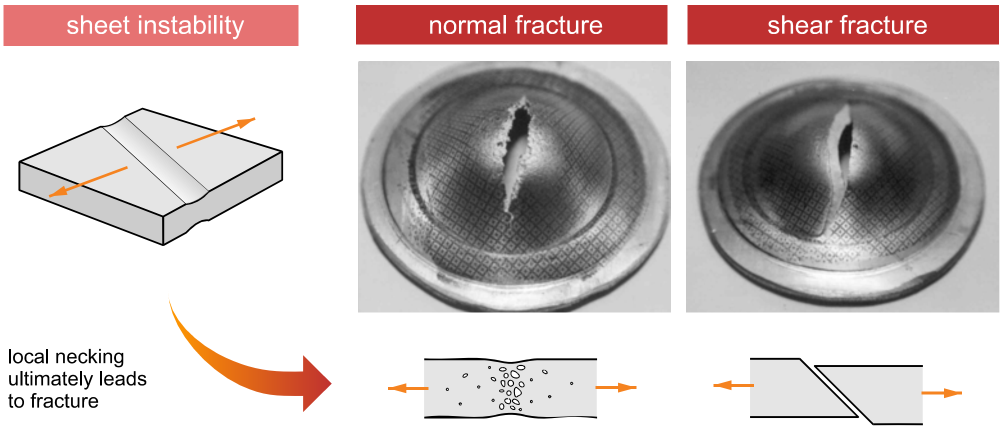


Figure 3: Failure mechanisms in CrachFEM

For mild steel qualities the level of the fracture curves lies above the instability curve as shown in *Figure 4*. In case of ultra high strength steel qualities and aluminium alloys ductile normal fracture and ductile shear fracture can be relevant.

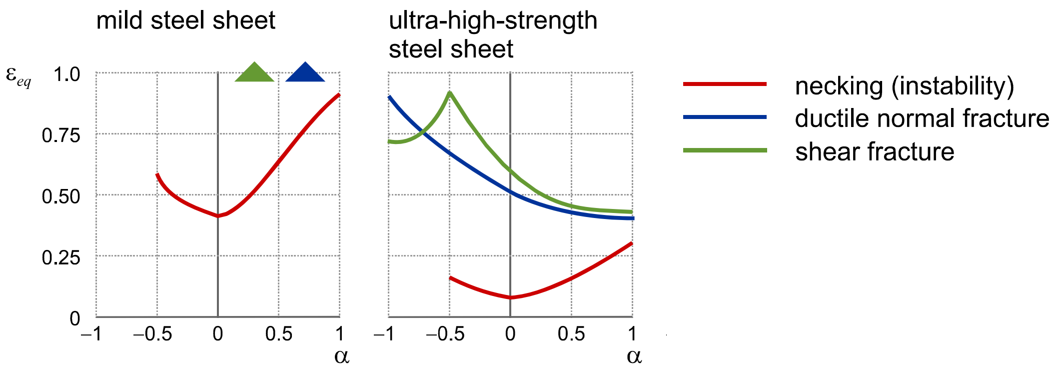


Figure 4: Failure limit curves for different material groups ($\alpha = \varphi_2 / \varphi_1$)

2.1.2 Component simulation

In case of ultra high strength steel (UHSS) qualities ductile normal fracture, ductile shear fracture and instability are the relevant failure mechanism with respect to crash loading. Further on a 3-point bending test of a profile made of UHSS is simulated and the results from simulation are compared to experimental tests. A circular hole has been drilled into the top area of the hat profile. The geometry of the structure is shown in *Figure 5*.

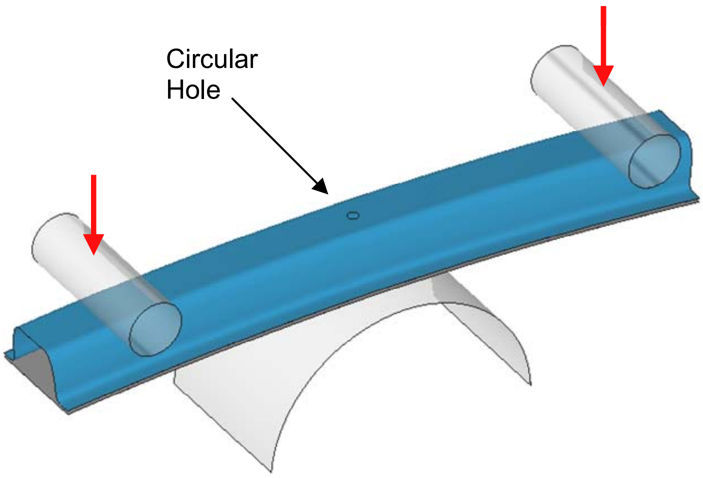


Figure 5: Geometry of a 3-point bending test (closed hat-profile with circular hole)

The simulation has been carried out with material model MF-GenYld+CrachFEM taking into account all relevant failure mechanism. In order to identify the critical failure mechanism 3 additional simulations are performed. In each simulation only one failure mechanism is activated. The resulting force-deflection curves are shown in *Figure 6*.

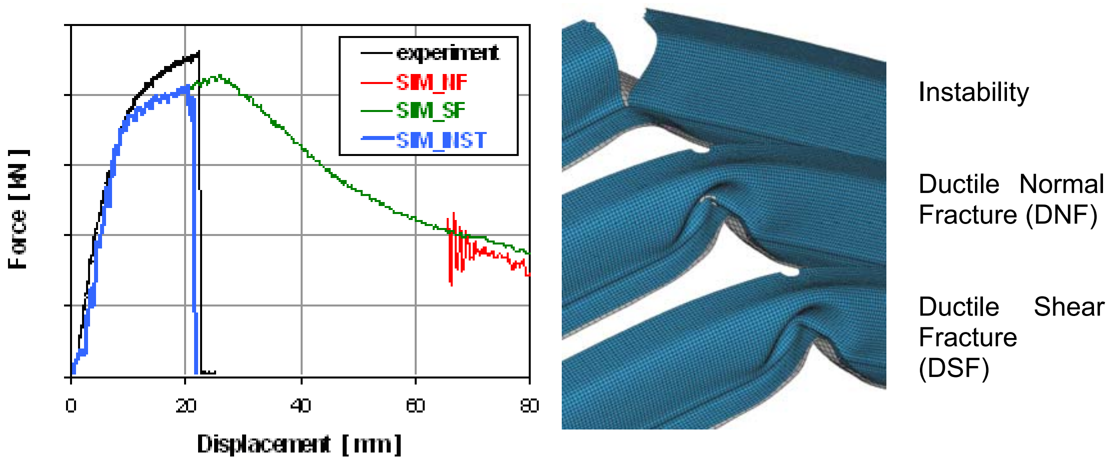


Figure 6: Force-deflection curves and location of failure (SIM_NF = Simulation with DNF calculation; SIM_SF = Simulation with DSF calculation; SIM_INST = Simulation with instability calculation)

For this example instability at the edge of the hole is the relevant failure mechanism. This example shows, that it is inevitable to take into account instability as a separate failure mechanism. The failure of the structure cannot be predicted by the fracture criteria (neither ductile normal fracture nor ductile shear fracture) alone.

2.2 Simulation of polymer components

2.2.1 Theoretical model for the anisotropic hardening

MF GenYld+CrachFEM allows to modify a base yield locus. A symmetric, convex reference yield locus f^* must be chosen. This yield locus should represent the directional anisotropy of r-values and yield strength values well. In case of non-reinforced polymers an isotropic reference yield locus can be reasonable. In the description of the modified yield locus, the stresses σ_{ij} are replaced by modified stresses $k \cdot \sigma_{ij}$:

$$\sigma_{eq} = f^*\left(k \cdot \sigma_{ij}, q_k\right) = k \cdot f^*\left(\sigma_{ij}, q_k\right) \qquad (1)$$

This relation is true because f^* is a homogenous function of stress; the method may be regarded as a projection of the actual yield locus onto the reference yield locus. The projection function *k* depends on:

χ	stress state parameter,
f	tension-compression asymmetry,
a	shear factor,
b_T	biaxial-tension factor,
b_C	biaxial-compression factor.

For shell elements, i.e a plane-stress state, the stress state parameter χ is:

$$\chi = \frac{\sigma_1 + \sigma_2}{\sqrt{\sigma_1^2 - \sigma_1 \cdot \sigma_2 + \sigma_2^2}} \qquad (2)$$

assuming in-plane principal stresses $\sigma_1 \geq \sigma_2$.

According to Figure 2 three different types of yield locus modification are possible by scaling of the reference yield locus in the plane stress condition:

- a scaling of the yield strength in shear (tension-compression regime) by a shear factor *a*,
- a scaling of the compressive yield strength relative to the tensile yield strength by a tension-compression asymmetry factor *f* and
- a scaling of the equibiaxial yield strength in tension-tension regime with a biaxial-tension factor b_T and in the compression-compression regime by a biaxial-compression factor b_C (the amount of scaling in tension-tension and compression-compression may be different).

The scaling function $k(\chi, f, a, b_T, b_C)$ has been chosen in a way that in any condition the yield locus is always monotonous for changing χ in yield stress and plastic strain components (normal on yield locus).

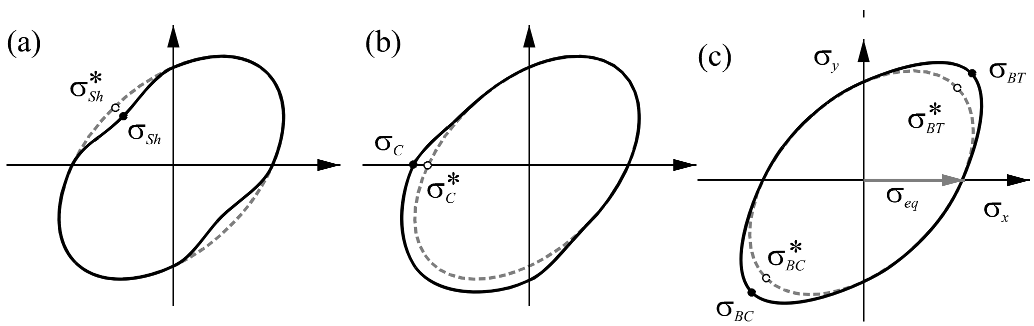


Figure 2: *Scheme for scaling of reference yield locus – a) impact of shear factor, b) impact of compression-tension asymmetry, c) equibiaxial scaling*

Anisotropic hardening is a natural extension of the above projection method for yield locus modification. Here, anisotropic refers to anisotropy of the stress state. The shape of the yield locus changes with anisotropic hardening. Hardening is anisotropic if the correction $k(\chi)$ is a function of equivalent plastic strain ε_{eq} and possibly the equivalent strain rate $\dot{\varepsilon}$. In *MF GenYld*, this can be achieved by making one or several of the factors *f*, *a*, b_T and b_C variable. In order to determine the strain-dependency of these factors, hardening curves for uniaxial compression, for shear and for biaxial tension and compression are required. An equivalent plastic strain based on work hardening is used for the anisotropic hardening model.

Figure 4 shows the flow stress from experiments with different stress states for a non-reinforced thermoplastic polymer. It is obvious that this material exhibits a significant anisotropic hardening. Hardening in shear is lower than in uniaxial compression. This behaviour will result in a waisted yield locus for higher strains.

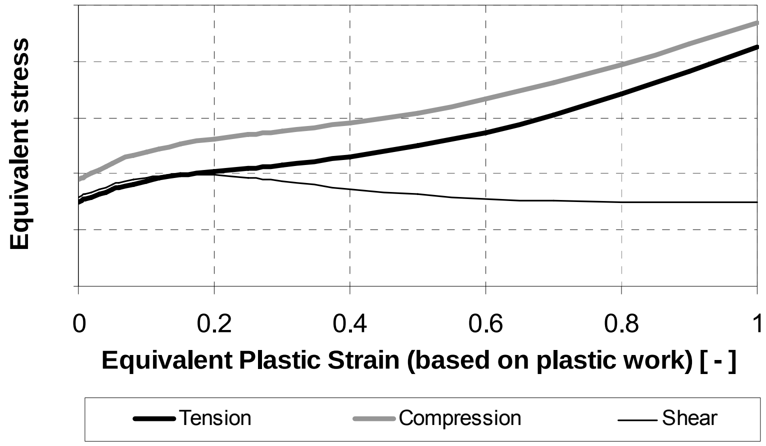


Figure 4: *Hardening behaviour of a non reinforced polymer for different stress states - equivalent plastic strain based on work hardening*

The evolution of the different modification parameters as a function of equivalent plastic strain (based on work hardening) can be expressed with different approximation functions in MF GenYld.

As the anisotropic hardening model in MF GenYld is based on an equivalent plastic strain based on the principle of work hardening, the plastic work will never decrease for deformation paths with changing stress states in the case of a partially concave yield locus.

In MF GenYld the user has the option to use the reference yield locus as a flow potential (non-associative flow rule) or the modified yield locus (associative flow rule). This decision should be taken based on measured material behaviour and numerical stability of the solution.

2.2.2 Simulation of equibiaxial loading - Erichsen Test

In general the hardening behaviour of non-reinforced polymeric materials is significantly anisotropic, which means, that the hardening behaviour depends on the state of stress. As an example the simulation of an Erichsen test with material model MF-GenYld+CrachFEM is compared with a standard isotropic hardening approach and with experimental results.

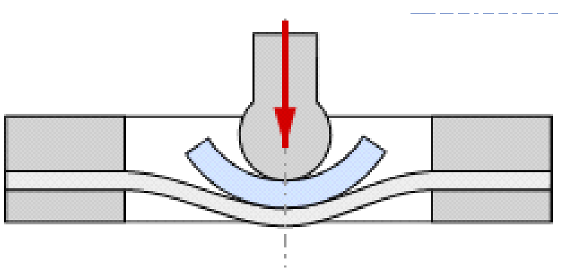


Figure 7: Geometry of the Erichsen test

The resulting force-deflection curves are shown in *Figure 8*.

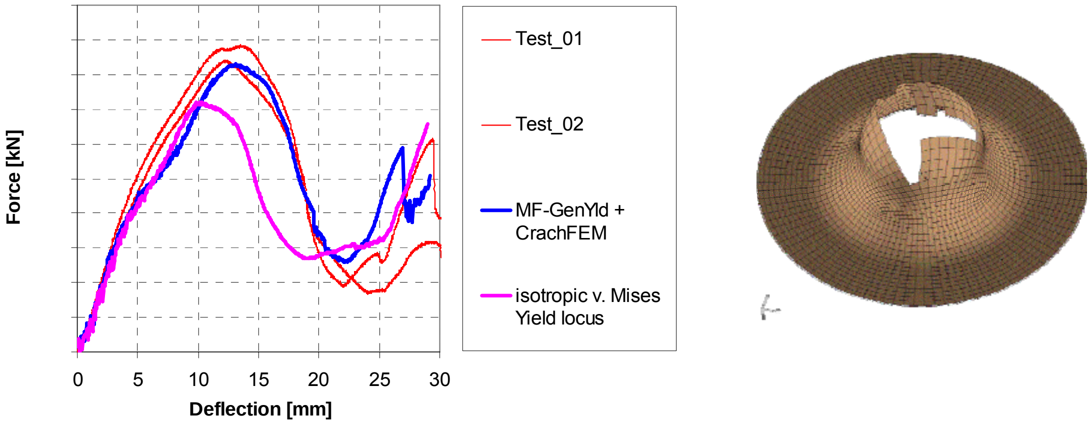


Figure 8: Force-deflection curves and location of failure

For the Erichsen test the dominating load case is equibiaxial tension. The investigated thermoplastic polymer shows a hardening behaviour under biaxial tension which is lower compared to the hardening behaviour in case of uniaxial tension. A possible explanation for this effect is the onset of damage due to crazing. In material model MF-GenYld a different hardening behaviour for equibiaxial tension can be defined. Using an isotropic v. Mises yield locus formulation significantly overestimates the real behaviour.

2.2.3 Simulation of a component test

The geometry of the component test is shown in *Figure 9*. The component is made of a non-reinforced polymer. A compression load is applied onto parts of the structure.

Figure 9: Geometry of the component test

The resulting force-deflection curves are shown in *Figure 10*.

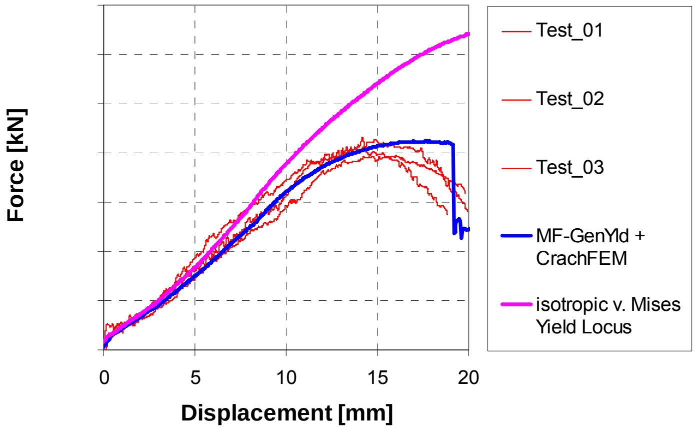


Figure 10: Force-deflection curves for component test

Due to the loading conditions the different hardening behaviour for tension and compression is relevant. The simulation based on an isotropic v. Mises yield locus significantly underestimates the real behaviour.

Both examples show that for polymeric materials it is necessary to take into account the anisotropic hardening behaviour. A good agreement between simulation and experimental test has been obtained for the investigated components.

2.3 Structural Foam

2.3.1 Theoretical model for stress state dependent damage evolution

The basis for the description of structural foams is the approach of modelling strain rate dependent anisotropic hardening behaviour, assuming different hardening behaviour in case of tensile, compressive and shear loading. For structural foams it is necessary to take into account plastic compressible behaviour. Experimental test show that damage and failure behaviour strongly depends on the stress state.

Figure 11 shows experimental results for different load cases.

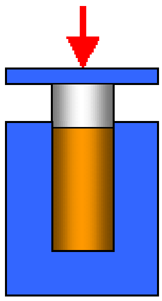
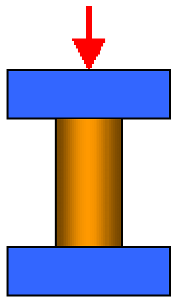
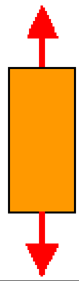
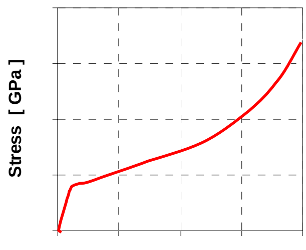
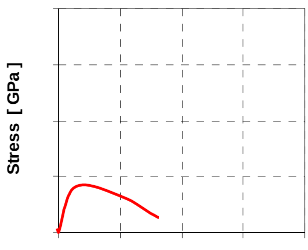
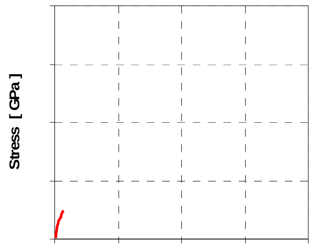
Confined Compression	Uniaxial Compression	Uniaxial Tension
		
		
Typical hardening behaviour of porous material under confined compression	Elasto-plastic behaviour with increasing damage and failure	Small amount of elasto-plastic behaviour followed by sudden failure

Figure 11: Typical Force-deflection curves for a structural foam

In material model MF-GenYld compressibility is described through an equation of state, correlating hydrostatic stress and volumetric straining.

In material model MF-GenYld the damage evolution with ongoing deformation is described through equation

$$d\psi = \frac{d\varepsilon_T + |d\varepsilon_V|/3}{\varepsilon^{**}} \tag{3}$$

The following denotations are used:

ε^{**}	fracture strain which is dependent from stress state,
$d\varepsilon_T$	total strain increment,
$d\varepsilon_V$	volumetric strain increment,
$d\psi$	damage increment.

The stress state is characterized through stress parameter λ.

$$\lambda = \frac{9\sigma_H}{\sqrt{8\sigma_M^2 + 9\sigma_H^2}} \tag{4}$$

In this case σ_M is the equivalent v. Mises stress:

$$\sigma_M = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_y\sigma_z + 3(\sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2)} \tag{5}$$

and σ_H is the hydrostatic stress.

The parameter λ lies in between the boundaries of –3 and +3. It is valid

for hydrostatic tension $\lambda = 3$,
for uniaxial tension $\lambda = 1$,
for shear $\lambda = 0$,
for uniaxial compression $\lambda = -1$,
for hydrostatic compression $\lambda = -3$.

Input parameters for the fracture diagram $\varepsilon^{**}(\lambda)$ are the fracture strain for uniaxial tension ε_t, shear ε_S and uniaxial compression ε_C.

If damage goes beyond the value of 1 the Young's modulus E and the yield resistance curve are multiplied with the correction factor $k_{Kor} < 1$. This factor is calculated through equation 4.

$$k_{Kor} = \exp(-c_S \psi) \tag{6}$$

Here c_S is a damage parameter. In this way the elastic stiffness and yield resistance are reduced towards zero.

2.3.2 Simulation of basic load cases

Basic load cases according to
Figure 12 have been simulated.

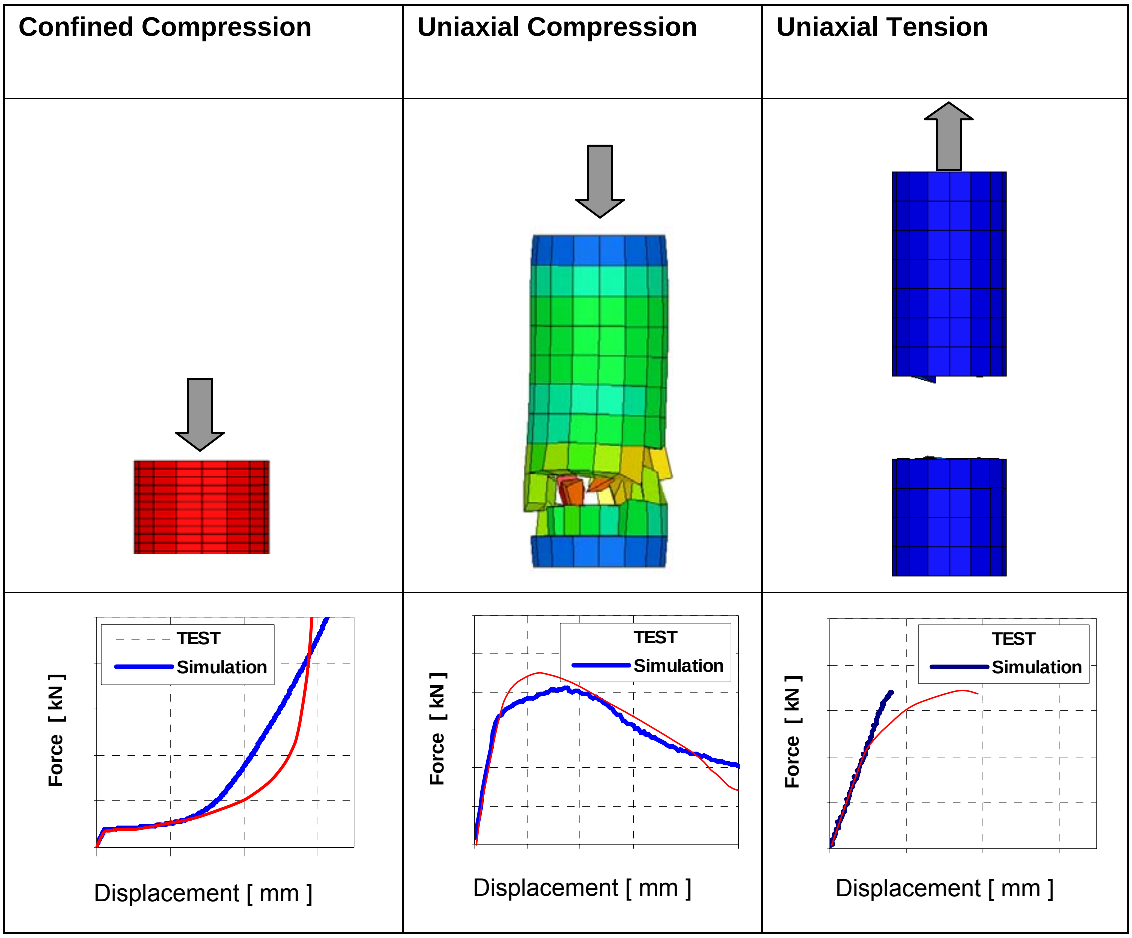


Figure 12: Simulation of confined compression, uniaxial compression and uniaxial tension

The simulation of basic load cases shows, that typical behaviour of structural foams can be described with the chosen approach. Further development steps are focused on the material parameter derivation.

3 Conclusion and Current Developments

It has been shown that the new modular material model approach is able to describe the behaviour of crash relevant components for the different material classes metals, polymers and structural foams. Currently it is possible to take into account parameters from the production process in case of cold-forming simulation. Research work is in progress to take into account the influence from casting, injection moulding and hot-forming simulation. Therefore MATFEM has defined a lock-and-key principle so that the data from the process simulation can be interpreted by the material model correctly. *Figure 13* gives a schematic representation of this method.

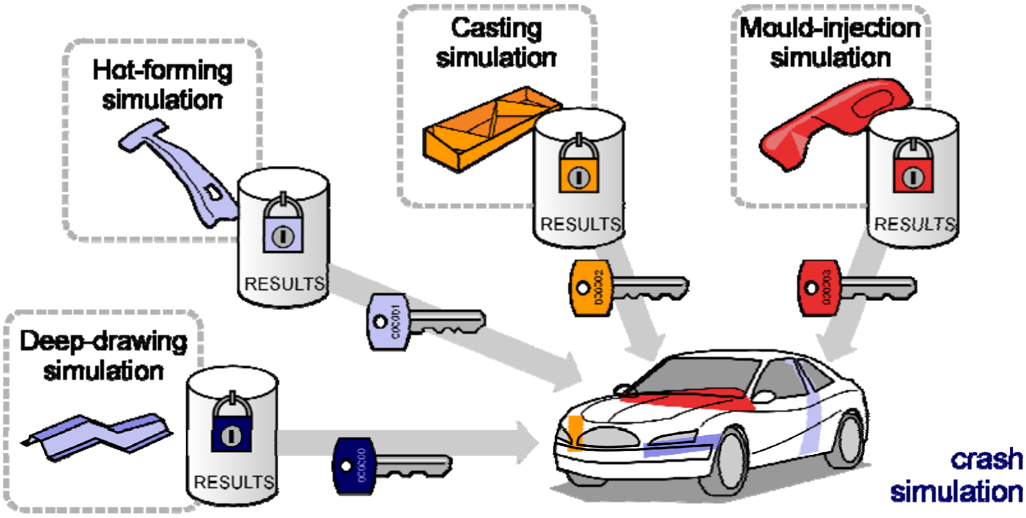


Figure 13: Lock-and-key principle in material model MF-GenYld+CrachFEM

The use of one single material model for different material classes supports the development of a systematic procedure for the derivation of material parameters based on experimental data.

At the Ford Motor Company the global implementation of the failure modelling approach with MF_GenYld+CrachFEM linked to the commercial crash codes in use is ongoing. The link to the commercial crash codes enables a user-friendly application of the new method, long-term maintenance and also allows the efficient involvement of material- ,component- and CAE suppliers into vehicle development projects.

Part of the implementation at the Ford Motor Company, lead by Ford R&A Europe, is a close cooperation with MATFEM to support the development of new capabilities in MF_GenYld+CrachFEM, generate the required material test data and to perform a systematic validation procedure from material tests to full car crash level, done for each material of interest globally.

The new approach improves the crash prediction of parts made of high-, advanced- and ultra high strength steels, plastics, structural foams and light metals in order to reduce the time and cost intensive physical tests late in the program and enable robust lightweight designs. Compared to the standard material models the new approach shows to be significantly advantageous in regards of deformation and failure prediction. Due to its flexibility it is suitable for all kind of materials making it applicable in various areas of the car.

4 Literature

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