Improvements to material 58 (woven composite)
(Addition of strain rate effects)

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Vehicle CAE
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Motivation - Background

- In the global quest to reduce CO\textsubscript{2} emissions, via reduced vehicle mass, there is an increasing use of high strength glass composites in the EU.

- The new generation of new woven fiber composites with thermoplastic matrices (organo-sheet) can be thermoformed and then back over-molded.

- Of these, glass based woven composites have been identified for high strength with low specific weight and cost.
  - Serial Examples:
    - BMW M3 Bumpers
    - Audi A8 Frontend Module
    - Opel Astra OPC Front Seat Pan
    - VW Brake Pedal (SoP 2013)
Motivation - Material Details

- **Organo-sheet is a woven material:**
  - **Fiber:**
    - Glass
    - Carbon fibers
  - **Matrix**
    - Polyamide
    - Polypropylene

- Unlike steel, the material stiffness is anisotropic i.e. the stiffness and strength are unequal in different directions. This makes CAE much more difficult.
Similar to steel, the effect of strain rate on material strength is significant.

Using the 1983 Johnson and Cook expression for strain rate sensitivity the effect of strain rate can be quantified:

\[ \sigma = \sigma_0 \left( 1 + c \ln \frac{\varepsilon'}{\varepsilon_0} \right) \]

Red highlighted strain rate factors (c) for organo-sheet material are greater than those for steel.

Generalized effects of applied strain rate on material properties.
Key to high CAE accuracy is the inclusion of strain rate dependency for strength.

- This is not available for the majority of composite material models and has only recently been included in material 54 in version 971 release R7.

Material model 58 is a good model as it includes non-linearity.

- Material model 158 is limited to 15% strain rate effect. This is not enough.
- No strain-rate effect means the user needs two, or more models for quasi-static and “dynamic” load cases.

Overview of composite material model features
Proposed Changes to Material Model 58

Similar to the changes to mat 54, the following new features were added to the standard mat 58 material model:

1. Out of plane transverse shear damage
2. Generalized strain rate dependency of breaking strength

In addition, the following additional effects were also added:

3. Generalized strain rate dependency of shear hardening stiffness
4. Generalized strain rate dependency of strain to break (damage)
Validation Load Case

- Punch Test
  - DIN EN ISO 6603-2
    ⇒ PA6 GF46 Organo-sheet
  - Loading speeds
    ⇒ Quasi-static (ε'~ 0.001 s⁻¹)
    ⇒ Dynamic (ε'~ 200 s⁻¹)

Simulation Model

Disc Punch Test Configuration
1. Status models
   - Issue: No strain rate effects
     ⇒ 2 separate data sets

2. Beta 1 Review:
   - Issue: Strain rate scaling
     ⇒ Linear resample with 100 points

3. Beta 2 Review:
   - Issue: Strength scaling only
     ⇒ Parameter identification not possible

4. Beta 3 Review: OK
   - Strength & Ductility Scaling
     ⇒ Parameter identification OK
Project Phase 1: Status Model

Status: Fixed Strain rates
- Quasi-static ($\varepsilon' \sim 0.001 \text{ s}^{-1}$)
- Dynamic ($\varepsilon' \sim 200 \text{ s}^{-1}$)

Accuracy

<table>
<thead>
<tr>
<th>WIFac Cross-correlation (%)</th>
<th>Test Static</th>
<th>Test Dynamic</th>
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</thead>
<tbody>
<tr>
<td>CAE (Q-S) standard</td>
<td>85</td>
<td>65</td>
</tr>
<tr>
<td>CAE (Dynamic) standard</td>
<td>60</td>
<td>83</td>
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Disc Punch Test Simulation
Project Phase 2: Beta 1

- **Issue:** Internal curve resampling
  - Only linear rate resampling
  - Underestimates strength

- **Accuracy**
  - WIFac Cross-correlation (%)
    - Test Static
    - Test Dynamic
    - CAE Beta 1: 86

- **Identification of issue:**
  - Resampling of curves

Graphs and charts illustrating the resampling effects and cross-correlation data.
Project Phase 3: Beta 2

- **Issue:** Only Break Stress Scaling
  - Underestimates strength

- **Accuracy**

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![Displacement vs. Force Graph](image1)

- **LSOPT Process – 2 load cases**

- **Identification of issue:**
  - LSOPT parameter identification

![Disc Punch Test Simulation](image2)
Project Phase 3: Beta 2

Identification of Issue:

- LSOPT parameter identification
  - Tensile Strain to break critical
  - Conflicting requirements
    - Quasi-static = low strain
    - Dynamic = high strain

- No solution possible with stress scaling only (e.g. mat 54)

Effect of Breaking Strain Parameter

Quasi-static Meta Surface Response

Dynamic Meta Surface Response
Project Phase 4: Beta 3 - Final

Issue:

- None

Accuracy

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Achievements and Conclusions

- Single model for both static and dynamic CAE
  - Variable strain rate effect

- Flexible implementation of strain rate effects
  - Arbitrary (not limited by Johnson/Cook or Power laws)
  - Independent in 5 directions
    - $0^\circ$ Tension ≠ Compression
    - $45^\circ$ Tension = Compression
    - $90^\circ$ Tension ≠ Compression

- Real Effect Modeling Possible
  - Different strength and damage modes dependent on strain rate

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### Quasi-Static Response

![Graph showing quasi-static response](image1.png)

### Dynamic Response

![Graph showing dynamic response](image2.png)

*HYUNDAI MOTOR GROUP*
Acknowledgements

The work presented is the result of a consortium between:

- Hyundai Motor Europe Technical Center GmbH
  http://www.hmetc.com/

- DYNAmore GmbH
  http://www.dynamore.de/

The author would like to especially express his thanks to:

- Dr. Stefan Hartmann
SpriForm (in-mold forming):
- Woven glass composites with a thermoplastic matrix is generically called “organo-sheet” and consists of:
  - Plain woven (filament glass) fiber mat.
  - Polyamide-6 or Polypropylene matrices.

- A particular advantage of these organo-sheets is that they can be thermoformed and then over-molded in one tool resulting in fast cycle times i.e. low production costs.

- In order to take advantage of the high strength of long fiber thermoplastic material systems and design new products, CAE optimization of proposed designs are necessary.

Integrated forming and injection process

The SpriForm Process (in-mold forming)
## Appendix 2: Material Card

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Appendix 3: Parameter Definitions

- **LCXC**: Load curve ID for $XC$ vs. strain rate ($XC$ is ignored with that option)
- **LCXT**: Load curve ID for $XT$ vs. strain rate ($XT$ is ignored with that option)
- **LCYC**: Load curve ID for $YC$ vs. strain rate ($YC$ is ignored with that option)
- **LCYT**: Load curve ID for $YT$ vs. strain rate ($YT$ is ignored with that option)
- **LCSC**: Load curve ID for $SC$ vs. strain rate ($SC$ is ignored with that option)
- **LCTAU1**: Load curve ID for $TAU1$ vs. strain rate ($TAU1$ is ignored with that option, only active for FS=-1.0)
- **LCGAM1**: Load curve ID for $GAMMA1$ vs. strain rate ($GAMMA1$ is ignored with that option, only active for FS=-1.0)
- **DT**: Strain rate averaging option.
  - EQ.0.0: Strain rate is evaluated using a running average.
  - LT.0.0: Strain rate is evaluated using average of last 11 time steps.
  - GT.0.0: Strain rate is averaged over the last DT time units.
- **LCE11C**: Load curve ID for $E11C$ vs. strain rate ($E11C$ is ignored with that option)
- **LCE11T**: Load curve ID for $E11T$ vs. strain rate ($E11T$ is ignored with that option)
- **LCE22C**: Load curve ID for $E22C$ vs. strain rate ($E22C$ is ignored with that option)
- **LCE22T**: Load curve ID for $E22T$ vs. strain rate ($E22T$ is ignored with that option)
- **LCGAMS**: Load curve ID for $GMS$ vs. strain rate ($GMS$ is ignored with that option)
# Appendix 4: New Output Time Histories

| # 19 | dmg56 | Damage parameter for transverse shear behavior |
| # 20 | e1dot | Strain rate in the longitudinal direction: $\dot{\varepsilon}_{aa}$ |
| # 21 | e2dot | Strain rate in the transverse direction: $\dot{\varepsilon}_{bb}$ |
| # 22 | e3dot | Strain rate in the in-plane direction: $\dot{\varepsilon}_{ab}$ |