# Memo

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Send to TNO Naval and Offshore Structures (NOS)
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## 1. Objective

TNO-NOS is considering a partial transition from LS-DYNA [1] to OpenRadioss [2] in 10 years from now [3]. OpenRadioss is free, open-source available explicit Finite Element Analysis (FEA) software for simulation of impact, shock and highly dynamic events. This memo addresses the required composite material functionality and whether this is available in OpenRadioss. This functionality is based on composite analyses performed in LS-DYNA by NOS. Nice to have features, but not required, are included as well.

It should be noted that the availability of functionality is assessed based on available documentation, i.e. a verification of the feature and/or benchmark with LS-DYNA is not part of this work.

## 2. Composites features

The following overviews are included in this memo:

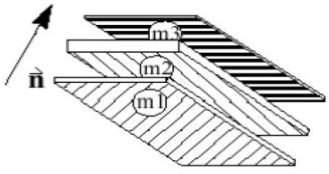
- Table 1.1: an overview of the composite and fabric material models available in OpenRadioss.
- Table 1.2 provides an overview of:
  - the required functionality on composite modelling for NOS based on experience with LS-DYNA. The functionality is organized by topic: analysis, element, material, progressive damage, delamination, both intra- and inter-ply and output;
  - whether the functionality is available in OpenRadioss (√) or not (X);
  - a justification why the functionality is available or not.
- Table 1.3 provides functionality which is nice to have and not required.

**Table 1.1:** Composite and fabric material laws available in OpenRadioss [4]

| Model Description | Law Number in Radioss | Description |
|---|---|---|
| Tsai-Wu formula for solid | 12 | This law describes a solid material using the Tsai-Wu formulation that is usually used to model composites. This material is assumed to be 3D orthotropic-elastic before the Tsai-Wu criterion is reached. |
| Composite Solid | 14 | This law describes an orthotropic solid material using the Tsai-Wu formulation that is mainly designed to model uni-directional composites. This material is assumed to be 3D orthotropic-elastic before the Tsai-Wu criterion is reached. The material becomes nonlinear afterwards. |
| Composite Shell Chang-Chang | 15 | This law is used to model composite shell elements, similar to LAW25. The plastic behaviour is based on the Tsai-Wu criteria) and failure is based on the Chang-Chang failure criterion is used. |

| Model Description | Law Number in Radioss | Description |
|---|---|---|
| Fabric | 19 | This law defines an elastic orthotropic material and is available only for shell elements. It is used to model airbag fabrics. |
| Composite Shell | 25 | Two variations of the same material law type 25 are implemented: Tsai-Wu formulation and CRASURV formulation [4]. The CRASURV formulation is an improved version of Tsai-Wu which is numerically more stable. |
| Fabric | 58 | This law describes a hyper-elastic anisotropic fabric material. It uses an anisotropic coordinate system with an anisotropy angle, following element deformation. |

**Table 1.2:** Overview of required composite functionality based on LS-DYNA and its availability in OpenRadioss

| | Required functionality | Available in OpenRadioss | Justification |
|---|---|---|---|
| analysis | Explicit Analysis for composites | √ | OpenRadioss is an explicit dynamic solver. Composite functionality is included. |
| element | Layered thick shell formulation, i.e. accounting for transverse shear | √ | LS-DYNA uses *ELEMENT_TSHELL_COMPOSITE [5] with an option to define a stack of plies.<br><br>OpenRadioss [6] uses composite shell property /PROP/TYPE22 |
| element | Layered shell element formulation with a stack of plies with individual thickness, orientation and orthotropic material | √ | LS-DYNA [5] uses *ELEMENT_SHELL in combination with *PART_COMPOSITE. Another option in [7].<br><br>OpenRadioss [4] uses /PROP/TYPE11. It defines Composite Shells with Variable Layers.<br>  <br>**Figure 1.1:** Composite shell with variable layers in OpenRadioss [4] |
| element | Layered solid element formulation with a stack of plies with individual thickness, orientation and orthotropic material | X | LS-DYNA uses *ELEMENT_SOLID_ORTHO [5] . An example in [8].<br><br>OpenRadioss [4]-p321 does have a composite solid but is limited to one layer of lamina with orthotropic elasticity. |

| | Required functionality | Available in OpenRadioss | Justification |
|---|---|---|---|
| element | Element deletion is available after exceeding a criterion | √ | In LS-DYNA [9] element deletion is available using e.g. *MAT_ADD_EROSION.<br><br>In OpenRadioss [4] failure models with option for element deletion (brick and shell) are available, e.g. /FAIL/PUCK, /FAIL/CHANG, /FAIL/HASHIN [6]. LAW25 allows for shell element deletion. |
| material | Engineering constants for 3D elasticity with failure | √ | In LS-DYNA [9] *MAT_COMPOSITE_DAMAGE (*MAT_022) can be used.<br><br>In OpenRadioss [6] LAW12 or LAW25 (Tsai-Wu criterion) can be used and becomes nonlinear after the Tsai-Wu criterion. |
| progressive damage | Laws for progressive failure | √ | LS-DYNA [9] has *MAT_COMPOSITE_MSC (*MAT_161-162) to model progressive failure analysis for composite materials of unidirectional and woven fabric layers [10] [11].<br>NOTE: a license for *MAT_161-162 is required.<br><br>In OpenRadioss [6] LAW12 and LAW25 becomes nonlinear after Tsai-Wu criterion. |
| delamination intra ply | Intra-ply delamination | √ | LS-DYNA [9] has *MAT_LAMINATED_FRACTURE_DAIMLER_CAMANHO (*MAT_262) which an orthotropic continuum damage model for laminated fiber-reinforced composites.<br><br>OpenRadioss [6]:<br>LAW25 has out of plane damage (delamination) /FAIL/LAD_DAMA: Ladeveze failure model for interlaminar delamination, available for orthotropic solids and thick shells. |
| delamination intra ply | Inter-ply delamination | √ | LS-DYNA [5] [12] has:<br>A Dycoss Discrete Crack model using *CONTACT. Solid elements only.<br>*MAT_COHESIVE_MIXED_MODE (*MAT_138) includes a bilinear traction-separation law with a quadratic mixed-mode delamination criterion and a damage formulation. Cohesive element formulation. |

| | Required functionality | Available in OpenRadioss | Justification |
|---|---|---|---|
| delamination intra ply | Inter-ply delamination (continuation) | √ | OpenRadioss [6] part of the group “Connection Materials”:<br>p1002 /MAT/LAW117 represents a constitutive relation of ductile adhesive materials.<br>p993 /MAT/LAW116 describes mixed mode, strain rate dependent material model with damage and failure.<br>Solid elements only. All damage and failure defined inside of the material. |
| output | Stress and strain components, failure indicators are available per layer in local fibre orientation | √ | To request output in LS-DYNA in local coordinates set CMPFLG=1 in *DATABASE_EXTENT_BINARY [5].<br><br>In OpenRadioss [6]-p2534,2588 for Brick and Shell local output variables are available. |

**Table 1.3:** Overview on nice-to-have composite functionality based on LS-DYNA and its availability in OpenRadioss

| | Functionality: nice to have | Available in OpenRadioss | Justification |
|---|---|---|---|
| material | Multiscale, micromechanics material model distinguishing between fibre and matrix material. Inelastic behaviour, failure for matrix (ductile) and fibre, available for shell, thick shell and solid element | √ | LS-DYNA has a micromechanical model *MAT_4A_MICROMEC (*MAT_215) using mean field theory [9], [13]. Shell and solid elements.<br><br>OpenRadioss [6] has LAW200 to interface with Multiscale Designer [14] which is a tool for development and simulation of multiscale material models amongst others for continuous, woven and/or chopped fibre composites. Shell and solid elements. A paid license is required.<br><br>Limitations:<br>- Not compatible with failure models, viscous model or thermal options.<br>All damage defined inside material directly. |
| failure | Failure model with direction dependent failure behaviour, i.e. plastic and brittle, specific for ballistic modelling | √ | OpenRadioss [6]-p.8 has LAW12 which behaves 3D orthotropic plastic before Tsai-Wu and nonlinear afterwards. The Tsai-Wu criterion can be set dependent on the plastic work and strain rate in each of the orthotropic directions and in shear to model material hardening. |
| material | Anisotropic elasto-visco-plastic material model | x | LS-DYNA has a micromechanical model *MAT_4A_MICROMEC (*MAT_215) using mean field theory [9], According to [13] it allows for anisotropic elastic visco-plastic material behaviour.<br><br>In OpenRadioss no option is available. |

# 3. Conclusions & recommendations

The availability of composite functionality required in OpenRadioss compared to LS-DYNA is assessed. It is concluded, based on scrutiny of documentation, that OpenRadioss for composite modelling can be used as of today. The only missing required functionality in OpenRadioss is a layered composite solid element (Table 1.2). Finally, it is strongly recommended to run verification and benchmark tests on the required composite functionality.

# 4. References

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# 5. Approval

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