

EFFICIENT SCREENING OF COMPOSITE STRUCTURES USING THE EXTENDED 2D FEM APPROACH IN META TOGETHER WITH A STATE OF THE ART FAILURE INITIATION CRITERION

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ABSTRACT –

In order to assess complex composite structures, the full 3D stress tensor is needed to ensure that all possible failure modes can be captured. Conventional shell elements only give accurate results for the in-plane stress components, while the out-of-plane components are neglected. The implementation of the Extended 2D FEM approach [1] into Metapost [2] makes it possible to get the full 3D stress tensor from second order shell elements. With the full stress tensor, state of the art set of failure initiation criteria can be used to evaluate the component. Two different cases are used to show the applicability of the procedure. The first example is a simply supported plate from the literature [3] is in particular used to demonstrate the visualisation capabilities in Metapost. The second example is a set-up used to measure the out-of-plane strength of composite materials [4], it is here analysed using both the Extended 2D FEM approach and a state of the art set of failure initiation criteria, LaRC05 [5].

TECHNICAL PAPER –

1. INTRODUCTION

When composite structures are analysed, it is of uttermost importance to be able to assess all potential failure modes. High performance fibre reinforced composite materials possesses very high specific properties in the fibre direction, typically in the order of 10^3 MPa in strength. However, in the transverse in-plane direction this is reduced to 10^2 MPa and in the out-of-plane direction it could be as low as 10^1 MPa.

Neglecting out-of-plane stresses, as it is done when using common shell elements, can lead to catastrophic and unpredicted failure during physical verification of components or structures. Shell elements are computationally efficient, but only give the in-plane stress state. To retrieve an accurate description of the full 3D stress state, engineers need to build models with solid 3D elements. Moreover, state of the art failure initiation criteria for fibre reinforced composites, e.g. Puck [6], LaRC05 [5], LaRC05NCF [7] etc., are all based on the full 3D stress state.

This paper describes how the full 3D stress state can be predicted using efficient shell models and presented to the engineer using BETA CAE System post processing software Meta, implemented in version 19.1.0.

2. MODELLING TECHNIQUES TO RETRIEVE THE FULL STRESS STATE

Traditional modelling of thin structures as metal sheets with first order shell elements give accurate and efficient in-plane stress results. However, as they are built on plane stress, the out-of-plane is neglected.

For modelling with composite materials, these elements have been used extensively too. And in many solvers, failure initiation predictions can be made using built in failure criteria, e.g.

max stress, max strain, Tsai-Wu, Hashin etc. However, these only take the in-plane components into account. While this is acceptable for flat structures subjected to in-plane loading, this assumption of plane stress is no longer valid as soon as the geometry becomes curved and complex, or the loading is more complex. For metals or isotropic materials in general, the out-of-plane stress components does not become critical, but for composite materials, since only a few percent in out-of-plane strength compared to the fibre direction is retained, this can quickly become crucial.

For areas that a priori can be identified to show high out-of-plane stress components, solid 3D models can be built and analysed. The drawbacks with this approach are that it 1) is hard to be sure that all such locations are found and 2) these models are not computationally efficient.

In the late 1990 Rolfes and Rohwer with co-authors [1] proposed an approach based on second order elements, called the Extended 2D FEM, to back-calculate the 3D stress state based on the displacement and rotation of the nodes. The approach is based on two assumptions, 1) the influence of the in-plane force derivatives on the transverse stresses is neglected and 2) the actual displacement field is approximated by two cylindrical bending modes. This approach is implemented in Meta version 19.1.0.

3. NEW COMPOSITE FEATURES IN METAPOST

When analysing composite materials it is of uttermost importance to cover all relevant failure modes that can occur under the present loading condition. To assess failure initiation in composite materials, the full 3D stress state is needed. From version 19.1.0, the Extended2D FEM approach is included into Meta to predict the full stress tensor. The application of this method is shown in section 3.1 and then demonstrated on two different structures in section 4 and then also used in section 5 as an intermediate step.

With the full stress tensor available, it is possible to use state of the art failure initiation criteria that take out-of-plane stresses into account. From version 20.0.0(beta) the LaRC05 [5] set of failure initiation criteria has been implemented with addition for orthotropic material behaviour proposed by Molker et al. [7]. This is shown in section 3.2 and demonstrated in section 5.

3.1. FULL STRESS TENSOR PREDICTIONS IN SHELL MODELS WITH EXTENDED2D FEM

With the release of Metapost version 19.1.0, it is now possible to calculate the full stress tensor from Abaqus models built with 2nd order shell elements (S8R-elements). The feature is available under the "Read Results" tool as Scalar results denoted "Stress – Extended 2D (S)", see Figure 1.

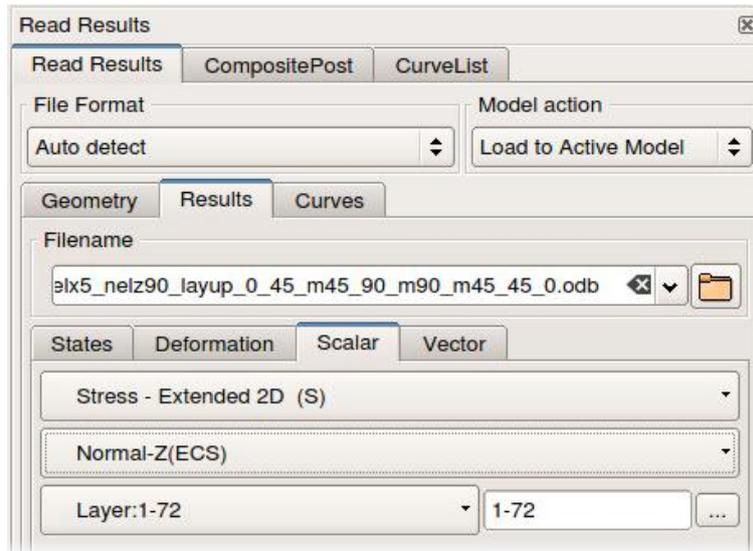


Figure 1 – The Read Results tool in Metapost version 19.1.0 with the possibility to read Extended 2D stresses. In this case the out of plane stress component “Normal-Z(ECS)” for all integration points through the thickness.

The result is shown for an L-shaped out-of-plane tensile test specimen at the most critical ply in Figure 2.

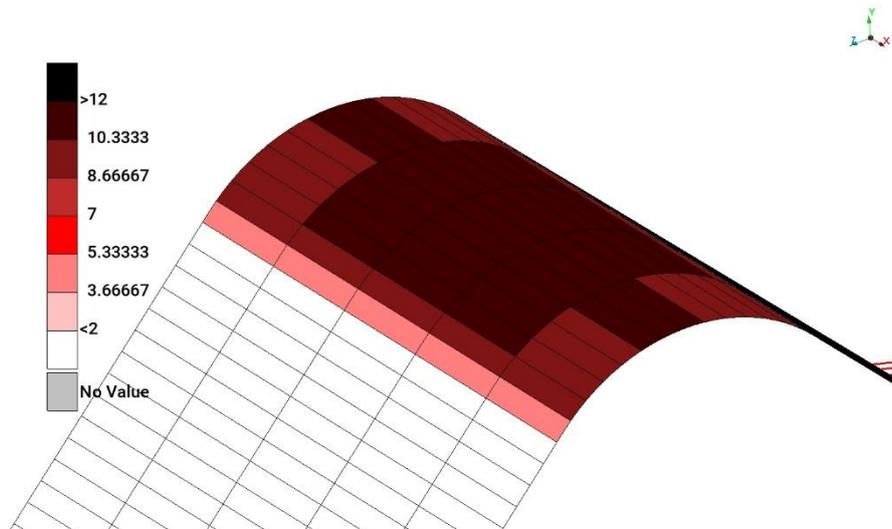


Figure 2 – The out-of-plane stress component, Normal-Z, at the most critical ply for an L-shaped test specimen as a fringe plot. (Stress - Extended2D,Normal-Z(ECS),Max of In Out/All Layers).

These stress results are not only available for fringe plots but also available for post processing in the standard “CompositePost” tool from Metapost version 20.0.0. With this tool, it is possible to see how the stress components varies through the thickness at selected elements as shown in Figure 3.

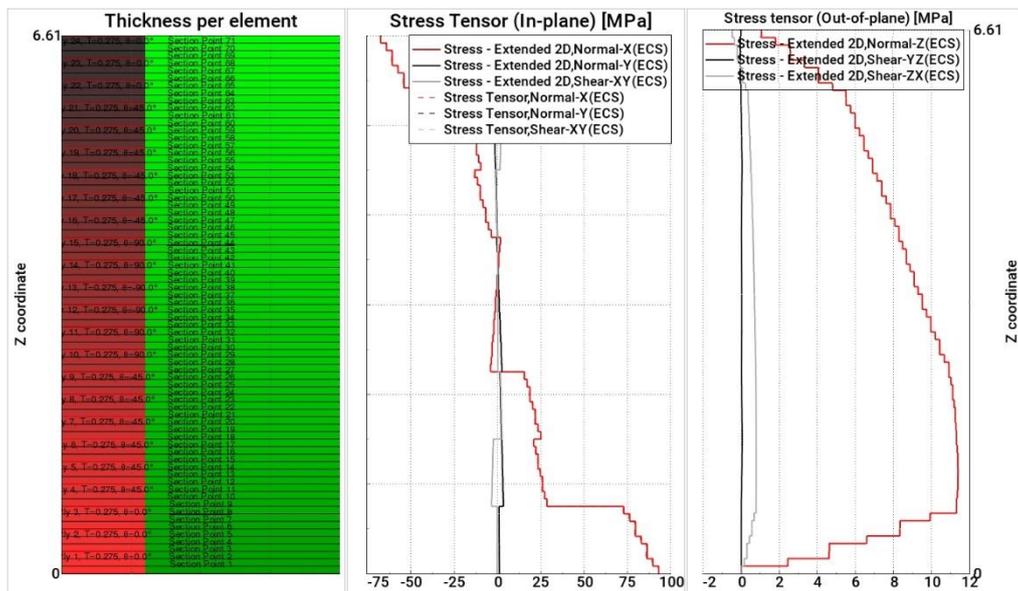


Figure 3 – Through the thickness plot from the Composite Post panel with 2D plots vs thickness. To the left is the layup and section points shown. In the middle are the in-plane stresses from Abaqus are compared to the stresses calculated by the Extended2D routine. To the right is the out-of-plane normal stress component shown calculated with the Extended2D method.

3.2. 3D STRESS BASED SET OF FAILURE INITIATION CRITERIA, LARC05

With the full stress tensor at hand, state of the art set of failure initiation criteria can be used that take the full 3D stress state into account. In Metapost ver 20.0.0(beta), the stress based set of criteria proposed by Pinho et al. [5] named LaRC05 is implemented. The implementation also includes the addition by Molker et al. [8] to address orthotropic Non-Crimp Fabric (NCF) reinforced composite materials with weaker out-of-plane strength.

The calculation of failure initiation according to LaRC05 can be done as a “Scalar” under the “Read Results” tool found under “Stress – Extended 2D (S)” and “FailureIndex: LARC05-” shown in Figure 4.

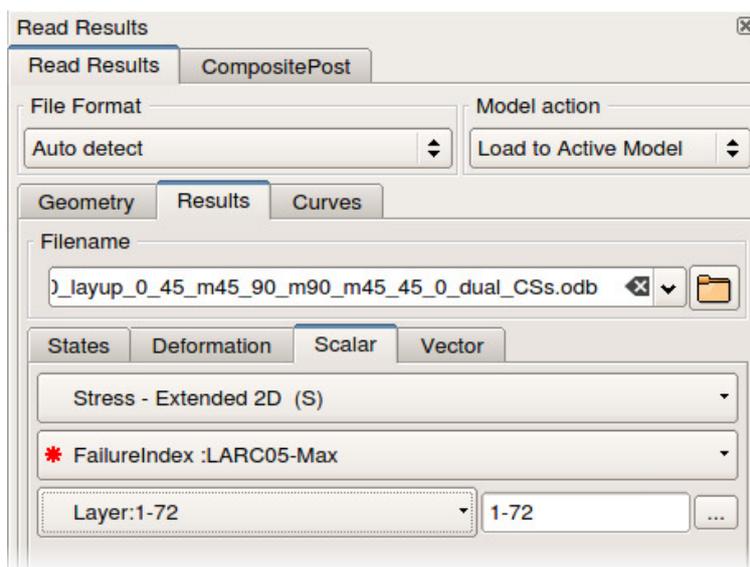


Figure 4 – The Read Results tool in Metapost version 20.0.0(beta) with the possibility to read Extended 2D stresses. In this case the most critical failure mode from LaRC05 “FailureIndex: LARC05-Max” is chosen for all section points.

The implementation distinguishes between 4 different failure modes; *Matrix cracks*, *Matrix split*, *Fibre tensile* failure and *Fibre Kinking* failure, see Figure 5. *Matrix cracks* actually takes orthotropic effects, found in NCF materials, into account and utilize the set of criteria proposed by Molker et al. [7].



Figure 5 – List of the available failure modes from the LaRC05 set of criteria in Metapost version 20.0.0(beta) in The Read Results tool.

The material data needed to be able to use the failure criteria are tensile and compressive strengths in all three material directions (X_T , X_C , Y_T , Y_C , Z_T and Z_C) together with the shear allowable (S_{XY} , S_{XZ} , S_{YZ}) and the fracture plane angle under pure compressive loading (α_0). As the different failure modes will occur on a specific fracture plane, it is needed to find the most critical fracture plane. In the implementation, this is done by calculating the Failure Index on a number of planes by incrementally rotating the plane and then take the plane that causes the maximum value as the most critical plane. In the implementation, the incremental increase in angle can also be specified (α_{inc}).

The material data is added as follows in Meta (text in *italics* should be replaced with appropriate numerical values and Material Id):

```
model models 0 matlimit mids x_tension XT MatNum
model models 0 matlimit mids x_compression XC MatNum
model models 0 matlimit mids y_tension YT MatNum
model models 0 matlimit mids y_compression YC MatNum
model models 0 matlimit mids z_tension ZT MatNum
model models 0 matlimit mids z_compression ZC MatNum
model models 0 matlimit mids s23 SYZ MatNum
model models 0 matlimit mids s13 SXZ MatNum
model models 0 matlimit mids s12 SXY MatNum
model models 0 matlimit mids f23 alfa0 MatNum
model models 0 matlimit mids f13 alfaInc MatNum
```

4. DEMONSTRATION ON A FLAT PLATE SUBJECTED TO PRESSURE

The first example is a flat composite plate with a $[90_2/0_2]_S$ cross ply laminate made of carbon fibre reinforced polymer. The plate is supported along the boundaries and subjected to a double cosine pressure as shown in Figure 6. More information of the plate and set-up can be found in [3, 8]. The plate is made from AS4/3501-6 composite material [9] with elastic data according to Table 1.

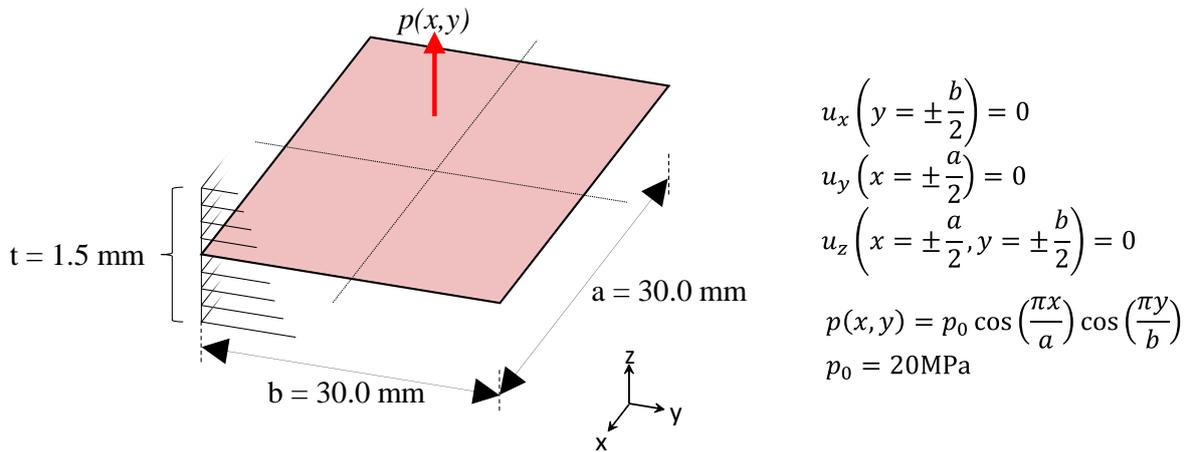


Figure 6 – A Cross ply laminate subjected to a double cosine pressure while supported at the edges.

Table 1 – Elastic properties for AS4/3506-1 at the homogenised ply level [9].

| E_{xx} (GPa) | E_{yy} (GPa) | E_{zz} (GPa) | ν_{xy} | ν_{xz} | ν_{yz} | G_{xy} (GPa) | G_{xz} (GPa) | G_{yz} (GPa) |
|-------------------|-------------------|--------------------|------------|------------|------------|-------------------|-------------------|-------------------|
| 140.0 | 11.0 | 11.0 ^{a)} | 0.3 | 0.3 | 0.4 | 5.8 | 5.8 | 5.8 |

^{a)} Assumed transversely isotropic.

The normal stress through the laminate is studied and compared to a solution from a high fidelity model built with solid elements and 4 elements over the thickness of each ply and shown in Figure 7.

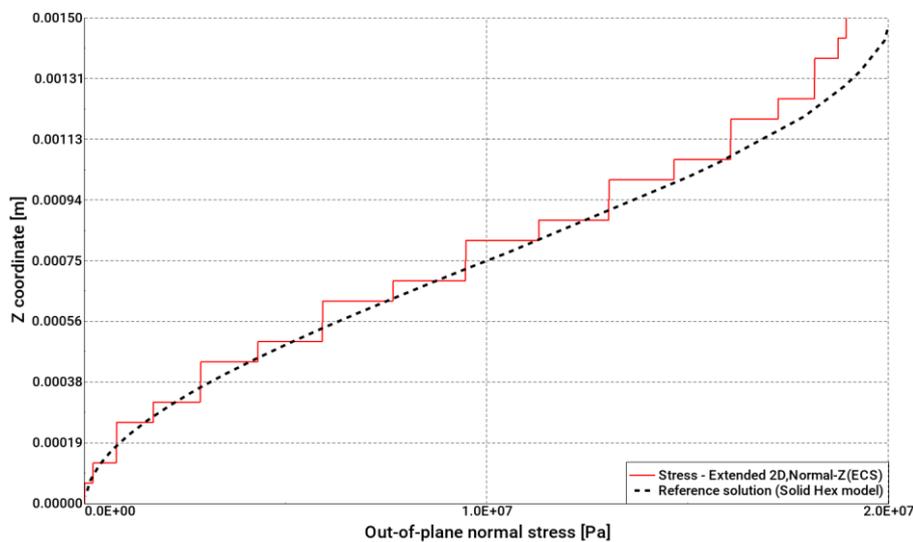


Figure 7 – Stress distribution through the cross ply laminate at the centre of the plate. The out-of-plane normal stress calculated with the Extended2D method through the thickness (solid red line) is compared to the result from a detailed solid model (dashed black line). The dashed horizontal lines represent the interfaces between different plies.

5. DEMONSTRATION ON MATERIAL TESTING RIG

To investigate the applicability of the Extended 2D approach together with a state of the art set of failure initiation criteria, an interlaminar test set-up for testing out of plane strength is modelled. The structure is an L-shaped strip of composite material with a 90 degree curve assembled into a tensile testing machine, as shown in Figure 8. The tested specimen is made

from a uni-directional composite material (AS4/3501-6 [9, 10]). Strength data for the material are listed in Table 2. The load level in the specific set up is chosen to give a failure index = 1 according to LaRC05.

Table 2 – Strength properties for AS4/3506-1 at the homogenised ply level [10].

| X_T (MPa) | X_C (MPa) | Y_T (MPa) | Y_C (MPa) | Z_T (MPa) | Z_C (MPa) | S_L (MPa) | β_0 (deg) | $ILSS$ (MPa) |
|----------------|----------------|----------------|----------------|------------------|-------------------|----------------|--------------------|-----------------|
| 1950 | 1400 | 48 | 200 | 48 ^{b)} | 200 ^{b)} | 78 | 53 | 78 |

^{b)} Assumed transversely isotropic.

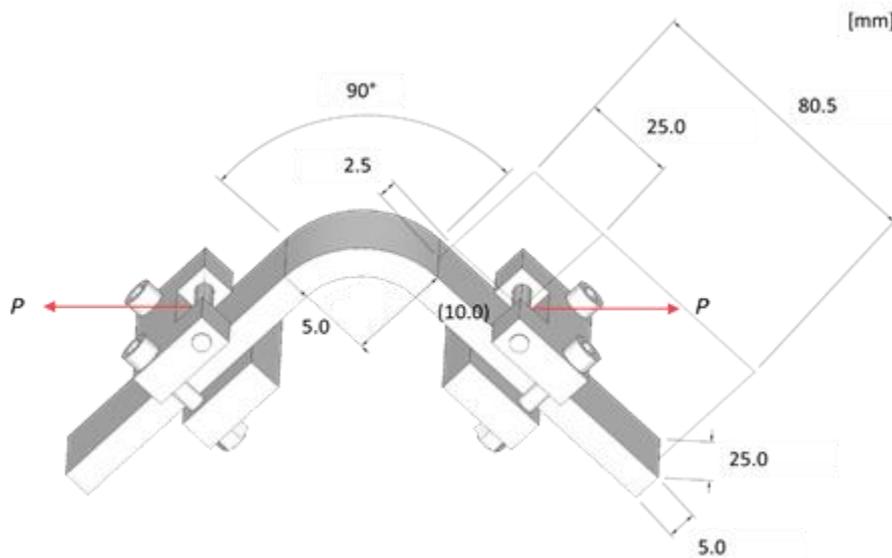


Figure 8 – Interlaminar test specimen for tensile strength subjected to applied load, P .

In the model, the specimen is modelled with 2nd order shell elements to allow for analyses with the Extended 2D FEM approach. These stresses are then used together with the material data in Table 2 to calculate failure according to LaRC05 in Metapost. The result from this is shown in figure 9.

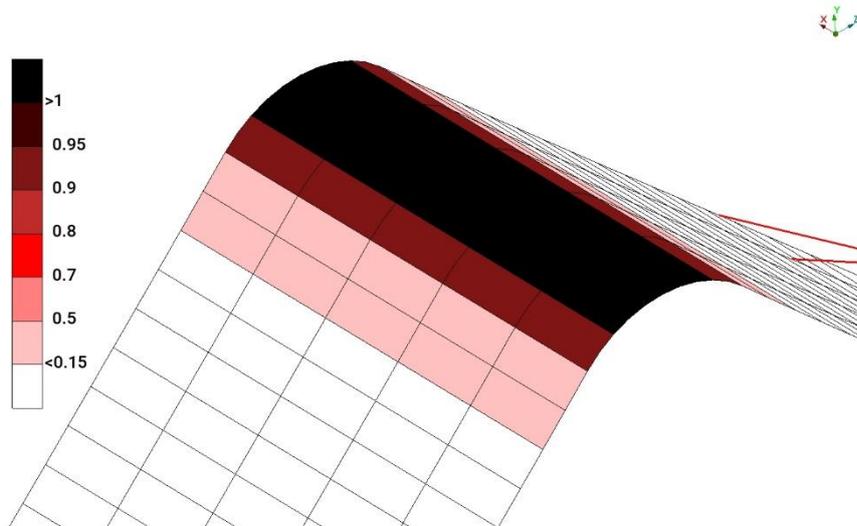


Figure 9 – Predicted failure initiation with LaRC05 in Metapost version 20.0.0. The load level in the model is chosen to give a failure index = 1.

6. CONCLUSION

The incorporation of the Extended2D FE approach and a state of the art 3D stress based set of failure initiation criteria to the set of tools available for post processing composite materials

enhances the capabilities to analyse materials and structures where out-of-plane components are of interest, e.g. fibre reinforced polymers. The Extended2D approach allows for use of shell elements also in areas where out-of-plane stresses can contribute to critical failure modes. Something that makes it possible to screen large assemblies with composite materials and to find areas that potentially could be critical.

Knowledge of critical areas could be used in subsequent analysis to verify only those areas with detailed models as proposed by Molker et al. [10]. An approach where results from a global screening are used in an automated process to verify only critical areas using submodelling to create an efficient analysis procedure.

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