FE analyses of new geometries of cruciform specimens

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OPTIMAT BLADES

TG 2

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### Change record

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<td>MARC Global Elastic Strain tensor replaced by Total Strain in Preferred system. Results and conclusions totally changed (bug in MARC)</td>
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Although for an elastic analysis the total strain in the preferred system ought to be equal to the global Elastic Strain, the results are completely different, due to a bug in MARC. This version replaces the draft version.
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1. Introduction

A number of cruciform test specimen geometries has been investigated, in order to check the influence of variations in shape, thickness and material properties. The aim was to come to a set-up where the highest stresses would occur in the central area, so as to cause failure in that area. Furthermore this area should also have a relatively homogeneous stress distribution, irrespective of material properties and loading.

Additionally, a number of preliminary tests was carried out at VUB [2] and results were reported in [3]. Since those results were not satisfactory, a new series of geometries was proposed in [4]. A number of geometries from that proposal will be analysed by means of an FE model and compared.
2. Modelling used

2.1. Geometry of the models 1, 2 and 3

It turns out that geometries 1, 2a and 2b can be modeled from one basis, shown in Figure 1.

![Figure 1 Basis geometry for FE models of model 1 and 2](image)
For geometry 3 another model is used, shown in Figure 2

2.2. General Material modelling

The material is modelled as the layers involved, for instance the tabbed part of MD material with glass-fibre tabs looks like the 27 layers of Figure 3. Descriptions of the material and tab built-up are taken from [5]. Note that, in contrast to the document with the proposals for new geometries [4], the fibre orientation is in horizontal direction (X-direction). Due to errors in the MARC post processing for non-0° fibres at the outside, the composite materials have been modelled with 0.01 mm of air (E=100 N/mm²).
2.3. Material tapering modelling
In the geometries proposed by VUB [4], there are two thicknesses used in each model, either by adding tabs to the arms of the cruciform (geometries 1 and 2), or by milling away the outer layers of a central round or square area (geometries 3 to 8).

Smooth transitions are proposed between the thicker area and a thinner area. In the FE analysis, this transition is modelled as three rows of elements by decreasing the thickness from the outer to the inner area in three intermediate steps in either the area “outer_tab”, “mid_tab”, inner_tab” (geometries 1 and 2) or the areas “outer_ring”, “mid_ring” and “inner_ring” (geometries 3 to 8).

Note that this stepwise decrease of thickness is a simplified approach of the actual shape, which is a smooth tapering of the tabs. Furthermore, instead of defining three intermediate lay-ups (with the extensive material descriptions of all layers), the transition area is simply modelled with the material of the ubtablled part, which means that not the outer layers are milled away as in reality, but all layers are proportionally reduced in order to reach the desired intermediate thickness. As a result, a small change in the stress patterns is introduced. By choosing the material of the untabbled part, this change is kept away from the area of interest.
Geometry 2b has the central parts made up of 3 layers UD and 4 layers of ±45°, for a total thickness of 5.08 mm. The outer part (called “tab” in Figure 1) includes tabs of a thickness of 2.5 mm at both sides, for a total thickness of 10.08 mm. The thickness of the elements in the “outer_tab” area is 8.83 mm, “mid_tab” 7.58 mm and “inner_tab” 6.33 mm.

Geometry 3 has the outer part made up of 4 layers UD and ±45° for a total thickness of 6.57 mm (standard Optimat MD material). The central part has only 2 layers of UD for a total thickness of 3.59 mm. The smooth transition between the two thicknesses is modelled as three rings with thicknesses of 5.825, 5.080 and 4.335 mm with the same material lay-up as the central part.

2.4. Loads modelling

The loads are applied at the ends of the specimen, 500 N as a distributed load of 20 N/mm² along the 25 mm wide ends of the specimen.

Since the test set-up at the VUB cannot introduce compressive forces, only tensile forces were considered. The two load cases plotted in the next chapters represent uni-axial load in X-direction and equal loads in X- and Y-direction, since these are the extreme cases of the test set-up. The third extreme, a uni-axial load in Y-direction was not considered, since in practice the loads in the 0° fibre direction can be expected to be far larger than the loads in perpendicular direction.
3. Geometry 1

3.1. Geometric model

All elements with a thickness of 10.08 mm have gotten the material properties of MD composite with aluminium tabs, all other elements just have the material properties of MD composite (3 layers 0° and 4 layers ±45°). The layers in the elements in the tapered parts (with a thickness of 6.33, 7.58 or 8.83 mm) are simply scaled up, to arrive at the correct thickness.

Figure 4 Thickness in the test specimen
3.2. Results of the FE analysis

Figure 5  Deformation and strain in X-direction, Fx=500 N, Fy=0 N

Figure 6  Deformation and strain in Y-direction, Fx=500 N, Fy=0 N
Figure 7  Deformation and strain in X-direction, Fx=500 N, Fy=500 N

Figure 8  Deformation and strain in Y-direction, Fx=500 N, Fy=500 N
3.3. Analysis

Three areas of possible strain concentration can be identified, shown in Figure 5:

**Line A:** A strain concentration is found in Figure 5 and Figure 7 in the horizontal arm, as well as in Figure 8 in the vertical arm, due to the abrupt change in material from MD laminate + tab to MD laminate only, with the thickness as given in Figure 4. This strain concentration can be expected to be much smaller in reality, when a gradual transition in tab thickness occurs.

**Area B:** The other strain concentration is due to start of the corner radius. Note that this strain concentration is also partly due to the FE model, which contains some deformed elements in this area, due to the difficulties caused by the ends of the untabbed part, see the boundary between the part with thickness of 5.08 and 10.08 mm in Figure 4. In the FE model, this boundary is already changed from the real geometry to enable an acceptable element shape. But of course, the abrupt boundary between the tabbed and untabbed part in the real test specimen is also a cause for the strain concentration, as is the start of the radius itself.

**Area C:** Notably absent is a strain concentration between the corners of the tabs. It seems the tapering effectively combats this strain concentration.
4. Geometry 2a

4.1. Geometric model

All elements with a thickness of 10.08 mm have gotten the material properties of MD composite with glass fibre tabs, all other elements just have the material properties of MD composite (3 layers 0° and 4 layers ±45°). The layers in the elements in the tapered parts (with a thickness of 6.33, 7.58 or 8.83 mm) are simply scaled up, to arrive at the correct thickness. Compared to model 1, the only change is that the tabs are now made from glass fibre, rather than aluminium and therefore less stiff.

Figure 9  Thickness in the test specimen
4.2. Results of the FE analysis

Figure 10  Deformation and strain in X-direction, Fx=500 N, Fy=0 N

Figure 11  Deformation and strain in Y-direction, Fx=500 N, Fy=0 N
Figure 12  Deformation and strain in X-direction, Fx=500 N, Fy=500 N

Figure 13  Deformation and strain in Y-direction, Fx=500 N, Fy=500 N
4.3. Analysis

The differences between geometry 1 and 2a are very small, so that the actual test results would be expected to be the same. A choice between the two models would depend on other factors, such as the tab behaviour in the clamps. Aluminium tends to give less slippage, provided the glue between the tabs and the test specimen is good enough.

However, the strains near the start of the corner are marginally higher, so model 1 seems to be slightly preferable. Also the strains in the tabbed area are higher, increasing the chance of failure in this area.
5. Geometry 2b

5.1. Geometric model

All elements with a thickness of 10.08 mm have gotten the material properties of MD composite with glass fibre tabs, all other elements just have the material properties of MD composite (3 layers 0° and 4 layers ±45°). The layers in the elements in the tapered parts (with a thickness of 6.33, 7.58 or 8.83 mm) are simply scaled up, to arrive at the correct thickness.

Figure 14 Thickness in the test specimen
5.2. Results of the FE analysis

Figure 15  Deformation and strain in X-direction, Fx=500 N, Fy=0 N

Figure 16  Deformation and strain in Y-direction, Fx=500 N, Fy=0 N
Figure 17  Deformation and strain in X-direction, Fx=500 N, Fy=500 N

Figure 18  Deformation and strain in Y-direction, Fx=500 N, Fy=500 N
5.3. Analysis

The differences between geometry 2b and the previous two geometries is more significant. The good news is that, due to the tabs ending far away from the central area, the strain concentration at lines A is absent and since the corners of adjacent tabs are very far away from each other, there is no point C where possible strain concentrations could occur.

Compared to the previous models, model 2b has higher strain concentrations near the start of the corner radius, which could be a reason for selecting longer tabs.

However, the major difference with model 1 is that model 2a seems to have very high strains in the tabbed parts, which would lead to failure in the tabbed part, rather than in the centre. Therefore, this solution does not seem to be a viable option.
6. Geometry 2c

This model is identical in shape to models 1, 2a and 2b but consists of 2.5 mm Aluminium.

6.1. Results of the FE analysis

Figure 19  Deformation and strain in X-direction, Fx=500 N, Fy=0 N

Figure 20  Deformation and strain in Y-direction, Fx=500 N, Fy=0 N
Figure 21  Deformation and strain in X-direction, Fx=500 N, Fy=500 N

Figure 22  Deformation and strain in Y-direction, Fx=500 N, Fy=500 N
6.2. Analysis
This geometry will not be tested, but serves as a reference for models 1 and 2, to show which strain concentrations are caused by the shape and which concentrations are due to the ends of the tabs, or the orthotropic properties of the laminate material. A slight strain concentration (about 30%) can be observed near the start of the corner radius, near point B.
7. Geometry 3

7.1. Geometric model

All elements with a thickness of 6.57 mm have gotten the material properties of MD composite with 4 layers UD and 5 layers ±45°, all other elements just have the material properties of 2 layers UD and 3 layers ±45°. The elements in the tapered parts (with a thickness of 5.08, 5.83 or 6.57 mm) have 2 layers UD and 3 layers ±45°, which are simply scaled up, to arrive at the correct thickness.

Figure 23 Thickness in the test specimen
7.2. Results of the FE analysis

Figure 24  Deformation and strain in X-direction, Fx=500 N, Fy=0 N

Figure 25  Deformation and strain in Y-direction, Fx=500 N, Fy=0 N
Figure 26  Deformation and strain in X-direction, Fx=500 N, Fy=500 N

Figure 27  Deformation and strain in Y-direction, Fx=500 N, Fy=500 N
7.3. Analysis

The difference between geometry 3 and the previous two geometries is quite significant. Some strain concentrations are apparent near the start of the corners (near B). Furthermore, the stresses in the arms tend to be higher than in the central area, which would cause premature failure. The strains in the central area are reasonably uniform, but no better than models 1 and 2.
8. Conclusions

The differences between models 1, 2a and 2b are rather small. Based on the current study the conclusion can be drawn that model 1 is the most promising of the models studied here.

However, the overall conclusion is also that the corner radius is still a bit small, giving rise to undesired strain concentrations near the start of the corner.

For Model 3, rather than a difficult and error-prone process for removing material without damaging the central layers, the choice can be made for tabs (three specimens glued together, with a hole with a diameter of 25 mm in the outer parts, tapered if desired, as was suggested in the preliminary study [1]. In that case, the thick part would be three times as thick as the centre part, so that the strains in the arms would be sufficiently low so as to avoid premature failure.
9. References

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