A NEW GENERATION OF COMPOSITE LAMINATES

What is the similarity between apple-pie and composites? Perhaps not a lot at first sight, but this article will explain. Composites are very sensitive to damage, so new ways to prevent delaminations are being investigated. At the National Aerospace Laboratory (NLR) a new fibre architecture is developed together with TU Delft which combines the advantages of woven fabrics and unidirectional laminates in an automated production process, making composites more damage tolerant. Inspiration was found in pastry, and the high-tech fibre placement machine at NLR makes the cost-efficient production possible. During recent tests these laminates showed smaller delaminations and higher residual strength after impact.

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PROBLEM
Composite materials are sensitive to damage, which is mainly caused by impact and resulting delaminations. These impacts can be caused by for instance tool drop, bird strike or inattentive baggage lorry drivers. Where aluminium shows a visible dent after impact, composites have a lot of invisible internal damage. In between the layers consisting of fibre and resin, only resin is present to keep the layers together. Obviously this is much weaker, especially out-of-plane, than the fibre/resin layers. Upon impact the layers separate resulting in a weaker structure.

Impact sensitive parts, such as leading edges and tail surfaces, are generally made of woven fabrics. These fabrics provide through-the-thickness strength and multiple load paths, but have to be processed by hand and part size is limited. Other production processes, such as braiding and winding, have similar advantages and disadvantages.

Modern, large composite structural parts, such as Dreamliner fuselages, are made using fibre placement machines placing unidirectional fibres. This makes production much more efficient and in general unidirectional laminates exhibit better in-plane properties. Due to reinforcements needed for impact resistance these parts are however heavier than absolutely necessary. More and more composites are used in commercial airplanes such as Boeing’s 787 Dreamliner and the Airbus A350-XWB, and when these problems are solved it will make future aircraft even lighter.

SOLUTION
The solution is simple; your grandmother already used it when making her favourite apple-pie. When looking at figure 2, one can see that fibre bands are placed parallel to each other, while leaving room in between. A next series of bands is placed at an angle with respect to the first series, with room in between as well. Up till here it’s similar to an apple-pie crust, but now the gaps will be filled up. The previous steps are repeated while shifting the pattern every step, and thus creating a laminate with a uniform thickness.

What you have now is a unidirectional laminate mimicking a woven fabric, with the difference that once a fibre band is placed it will never be able to pass underneath a previously placed fibre band. The weak resin interfaces between the layers are reinforced by fibre bands in the out-of-plane direction, similar to a woven fabric. Instead of the fibre bundles in a woven fabric, which are almost circular in cross-section, this laminate has thin, wide and relatively flat fibre bands. Compared to fabrics the fibres cause only very small local changes in the thickness variation, with better in-plane properties as a consequence. Undulation is present however, slightly decreasing the in-plane properties as compared to completely unidirectional laminates.
As you can imagine angles other than 90° are also possible, as well as skipping more than one band. Several of the possible patterns already produced and tested are displayed in Figure 3. The last one shows a pattern where the angle is changed every other band, instead of placing a parallel series. This will increase production time however and will also increase the heterogeneity of the material.

**TEST RESULTS**

For damage tolerance Compression After Impact (CAI) testing is one of the most important measures used in industry. These tests include an impact with a certain energy level and subsequently a compression test, both performed at NLR’s TestHouse. A commonly used thermoset material, AS4/8552, is used for these tests. Later on the same tests will be performed with a thermoplastic material, AS4/APC-2, having the same fibres but different resin. Pre-impregnated slit tape is placed in 1/8 inch bands on a flat mould to produce a large plate. An autoclave cycle cures the material under elevated temperature and pressure. Specimens are cut from this large plate with a quasi-isotropic lay-up and a thickness of approximately 4mm, meaning 24 layers. Fabrication times of these new laminates are only marginally longer, as the same time is spent on the mould as before. Only more ‘airtime’ is needed, which is a proportionately higher penalty for small parts.

In between impact and compression testing the amount of damage, which is typically delaminations and fibre breakage, is measured by an ultrasonic C-scan. As can be seen in Figure 4 the delaminations in the new architecture are smaller and of different shape. It seems that the delaminations are confined by the pattern! All results presented here are for the 90° skipping 1 pattern. Indentation depth for the new laminate is slightly larger than for the unidirectional laminate, meaning that damage can be detected and repaired earlier.

In addition to smaller delamination damage, compression tests of the impacted specimens show an up to 14% higher residual strength for the new architecture as compared to their unidirectional counterparts. So for the same impact energy level, damage is detected earlier and the residual strength of the structure is higher. As can be seen in Figure 5, still a lot of scatter is present, which is common for this kind of test but is also due to the difference in location of the impact with respect to the pattern. This heterogeneity is one of the issues that need to be addressed in the future.

**FUTURE**

Future research will focus on the optimisation of the pattern. Angle, bands to skip and number of plies that are interwoven can be varied and combined into one superior new laminate configuration. Especially band width is a property that determines the ‘resolution’ and thus the homogeneity of the laminate. Using smaller bands makes the laminate’s performance less dependent on impact location but may increase production cost and time. Only quasi-isotropic lay-ups are tested, whereas a more dispersed stacking sequence could also be beneficial in terms of damage tolerance. Apart from slit tape NLR’s fibre placement machine can also place dry fibres, which are impregnated afterwards in a Resin Transfer Moulding (RTM) process. This pattern could replace the woven fabrics used nowadays in RTM processes, again improving production efficiency.

While writing this article a pattern is developed interweaving four plies, which has less ply interfaces and thus possibly less delaminations. Possibilities are endless and this opens a whole new area of composites research where all help is welcome. When interested in internship or graduation projects, please contact the author and be part of the future of composites!