Use of Finite Element Analysis to Create Robust Composite Designs – Going Beyond First Ply Failure

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ABSTRACT

The history of fibre reinforced composite product development has shown an evolution from the classical laminate analysis approach through to modern techniques. This paper shows how finite elements can be used to create composite structures which perform better and provide enhanced safety in critical applications.

The paper shows how a structure can be made more robust by the analysis of failure through to ultimate load. Understanding how this failure occurs allows us to make a better assessment of the structures performance in extreme load conditions.

Failure prediction methods such as progressive failure analysis (PFA), virtual crack closure (VCCT) and cohesive zone modelling (CZM) have been available for years. This paper looks at the practical use of these methods and how material behaviour influences the results. It also looks at what material testing can be needed to make these new techniques more accurate.

These methods are illustrated with examples such as a plate with a hole. In this example we can change the behaviour of progressive failure by modifying FE solver settings for the way that the material degrades. Understanding this is important to ensure that we get better analysis results.

Practical comparison of analysis with theory and test of some typical L-sections from an aircraft structure is given. Of particular interest is the ability of structures to survive beyond initial failure. This can be due to loads being re-distributed due to the failure and also due to material non-linearity in certain failure modes. Using this practical example we can see how composite failure can involve a combination of different failures including resin cracking, delamination, buckling and fibre failure. A complete finite element solution needs to be capable of including all of these effects.

The conclusion suggests some questions which the analyst can ask of a design to ensure that it is safe, robust and damage tolerant.

All analyses described in this paper use MSC Software solutions.

CLASSICAL ANALYSIS METHODS

Initial composite analysis approaches were based upon classical laminate theory. This is broadly based upon assumptions similar to those for engineers bending theory. It is well documented (ref 1) and is currently accepted practice in most composite applications.

Failure analysis is classically performed using a “first ply failure” criteria. This assumes that as soon as there is some degradation to the composite then it is failed and no longer acceptable. This approach is suitable for normal operating loads but may be too conservative if you are looking at single high load events. In these scenarios it would be good to predict the capability of the structure to go beyond this initial failure.

The failure theories developed for composites are often empirical derivations based upon observed tested behaviour. For example the Tsai-Wu failure theory creates a rotated ellipsoidal failure envelope for the material. This rotation is based upon an interaction term which is nominally derived from test. However most people don’t do this testing and assume a value of

-0.5 which seems to work. These theories are not foolproof and it is possible to create structures which will fail at loads significantly lower than predicted by classical theory. (ref 2) These limitations are most serious when basic design rules such as minimum ply numbers in individual directions or not separating plies in the same direction are ignored.

Another issue with these classical approaches is that we do not consider flaws or variability in the structure.

IMPROVEMENTS IN ANALYSIS METHODS

To overcome some of the issues seen with the classical methods some advanced approaches have been developed.

Stochastic Analysis

Stochastic analysis is not a method that was developed for composites but the large scope for variation in a composite structure makes it very interesting to use this technology. At the most basic level the materials we use have higher variation in stiffness or strength than a metallic material. This can be handled by using a pure statistical approach to calculate expected worst case values. However we can compound this problem by considering variations in resin content and fibre angle. By varying these values as random design changes it is possible to do repeated analyses and get a "cloud" or "anthill" of design responses which can represent the scatter we would expect to see in real life. Figure 1 shows an example output from this type of analysis. We can identify from this analysis areas of a design where there is a high sensitivity to variation which may cause problems.

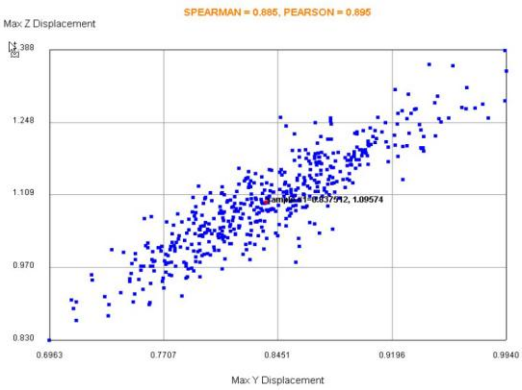

Figure 1 Example Stochastic "Ant hill" plot

Progressive Failure Analysis

This analysis approach allows the structure to degrade after first ply failure, but continue to take load until there is an ultimate failure. The method reduces the local ply stiffness at the failure location by a factor of, for example, 100. This is effectively "switching off" the ply on that element. We can use our standard polynomial failure theories and even augment these with advanced failure modes for micro-mechanical failure such as fibre buckling and relative rotation between plies. There are also controls which govern how the ply stiffness is reduced. We can introduce a failure where the failed ply reduces its modulus in a gradual rather than instant way. This can be used to simulate materials which do not have a brittle failure.

The following figures show the analysis of a tension specimen with a hole. Figure 2 is a plot of element damage at the ultimate failure. Figure 3 is the load-deflection behaviour for the same specimen. This figure has 2 curves, the red one shows the behaviour with immediate "brittle" degradation and the blue one shows gradual degradation. As can be seen there is a big difference here which we need to understand when doing our analysis. In reality the behaviour is due to the nature of the fibre failure. The analyst needs to know this from material testing. Also note in Figure 3 that the first ply failure occurs at around 6000 but the structure still has a very similar stiffness up to 8000. Even after the failure we see a residual load capability of around 25% of the peak. This can be seen in real life testing.

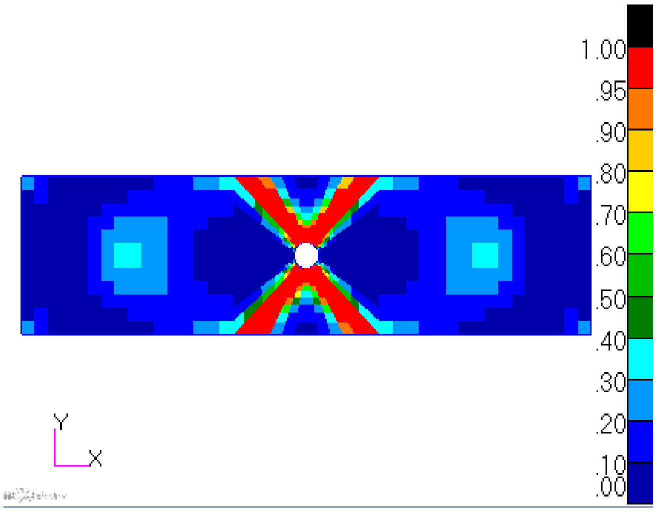

Figure 2. Progressive Failure Damage Plot

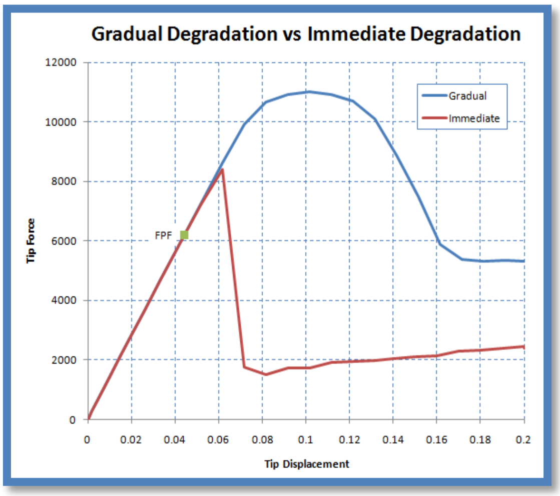

Figure 3 Tension specimen Load-deflection curves

Virtual Crack Closure Technique

Virtual Crack Closure is a method that was originally developed for crack growth analysis in metal structures in 1977 (ref 3). Its use for composites gives us a tool for predicting crack propagation, primarily in adhesives and resins. The use of this technique relies on the user having knowledge of the material fracture toughness. This is not a problem but we then need to factor in the influences on these material properties. For example temperature, humidity, speed of loading and ageing may influence the toughness values. This could be a very expensive test programme!

The following example of the use of VCCT illustrates its ability to show if an existing inter-laminar flaw will grow. (Figure 4) In this particular analysis the delamination grows until the skin can buckle. The analysis also includes contact effects between the plies. Figure 5 shows the final buckled shape and Figures 6 and 7 show the initial and final crack front.

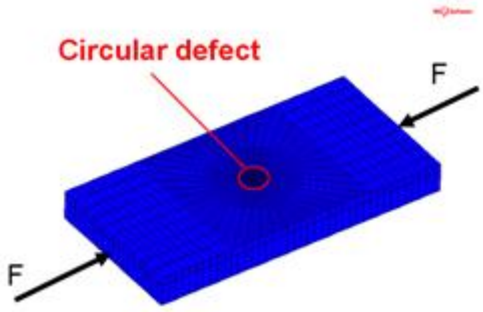

Figure 4. Example model for Virtual Crack Closure

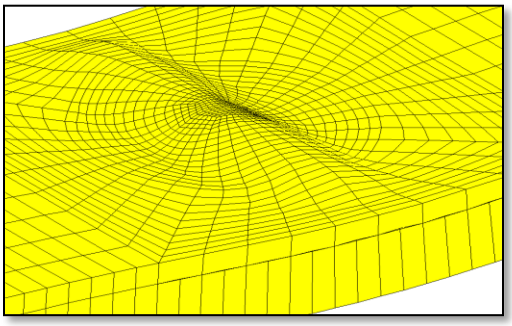

Figure 5. Detail of buckled shape.

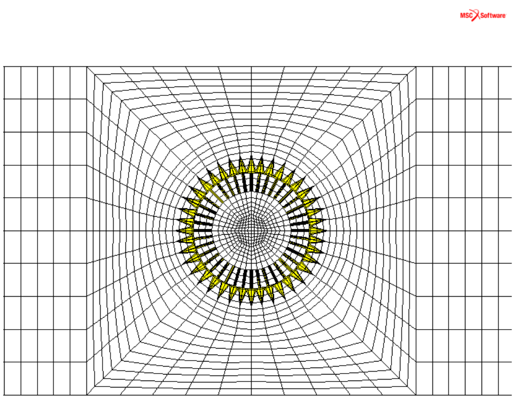

Figure 6. Initial crack front

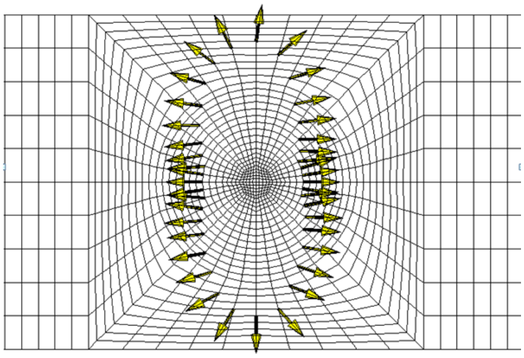

Figure 7. Final crack front

Aside from the obvious issues with getting the correct material data VCCT does have other limitations. In particular the failure progresses as a brittle crack. This may not be correct for more flexible adhesives. In this situation we would switch to using the next method, cohesive zone modelling.

Cohesive Zone Modelling

Unlike virtual crack closure, cohesive zone modelling uses an interface element to model the adhesive joint that is failing. This gives the advantage that we can have a failure model for the adhesive which allows a gradual release. This is suitable for flexible adhesives. Figure 8 shows a typical stress/strain plot for a cohesive material. The area under this represents the "cohesive energy" or critical energy release rate.

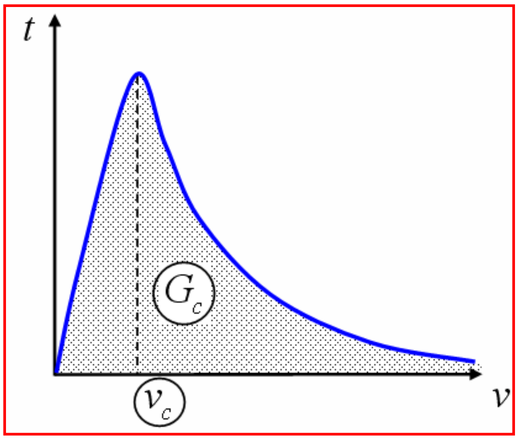

Figure 8. Cohesive Material stress/strain curve

This failure modelling approach is more appropriate for a non-brittle failure mode, which may be more common than we think! Epoxy resins do show a visco-elastic behaviour which is not really brittle.

Breaking Glued Contact

As well as the material based failure analyses with VCCT and CZM it is also possible to use a breaking glued contact approach. In this approach to analysis we use the glued interface shear and tension stress to decide when a delamination occurs using an interaction formula. This approach is the initial method which has been used to assess the strength of laminated angle brackets with a 4 point bending test.

PRACTICAL EXAMPLE OF FAILURE ANALYSIS COMPARED WITH TEST RESULTS

This work is an overview of some collaborative work performed with DLR, Braunschweig. The background to this testing is that corner L-brackets have some specific failure modes related to the "unfolding" of the bracket causing large out-of-plane stresses. The testing investigates different thicknesses and layups. Initially simple 4 point bending tests were performed on samples (Figure 9). These have the advantage that the out-of-plane stresses are not high so can provide a baseline set of test results which don't include the unfolding effect. These tests were followed up by tests on the L sections. (Figure 10)

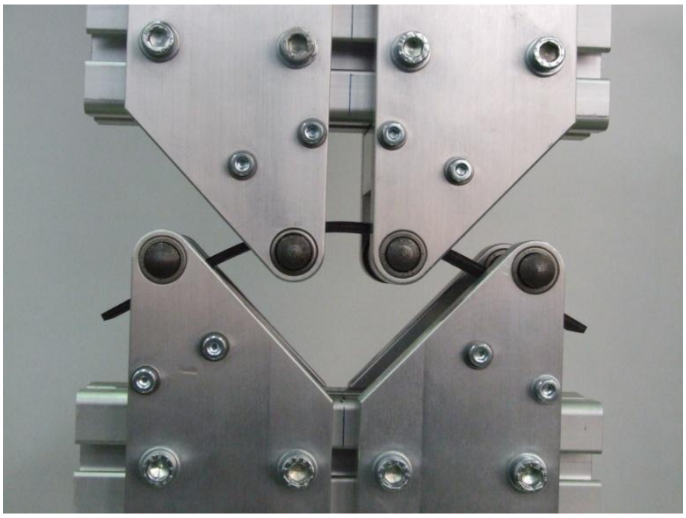

Figure 9. Four-point bending test

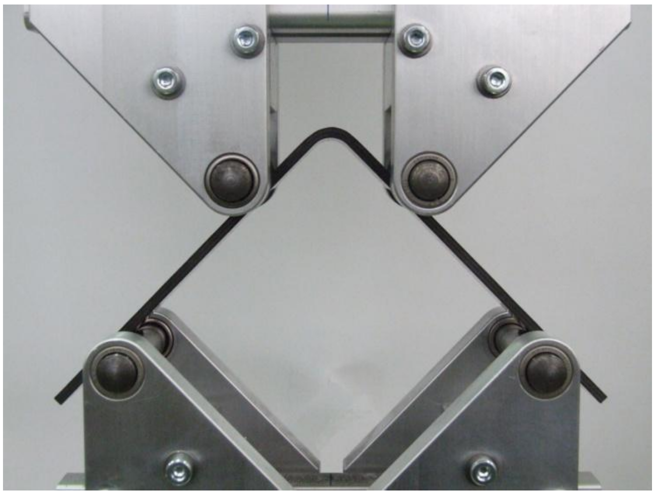

Figure 10 L Bracket test setup

Theoretical basis for stresses in radius

The theoretical solution to this problem is presented by SG Lekhnitskii [4]. From this we can see typical radial stress variations (figure 11) and tangential stress variations (figure 12). We can use this to help interpret some of the test results. As can be seen from the curve on figure 9 the radial stresses are at their maximum typically 1/3 of the thickness from the inner radius. Very approximately we can say cracks in this area are likely to be from unfolding.

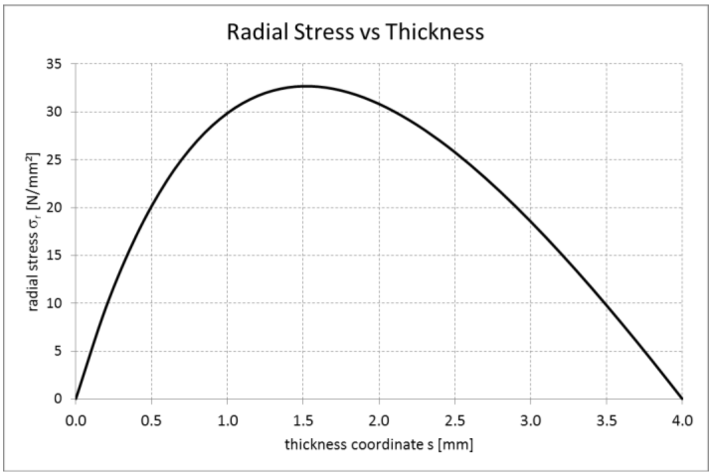

Figure 11 out-of-plane stresses in radius area

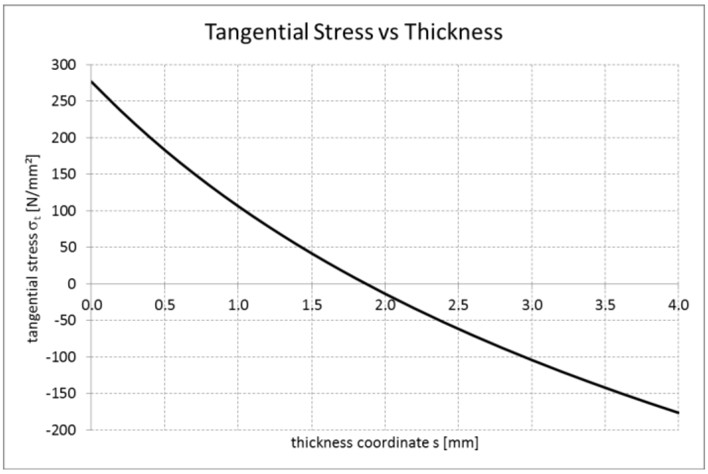

Figure 12 Tangential stresses in radius area

Observations during test

Testing is more than just load-deflection graphs. During the testing observations can be made which can aid interpretation of the results. For example during some of the straight 4 point bend tests cracking noises were heard at load levels which were still within the expected safe loads. The specimens were lightly covered in dust and it was possible to see from the “puffs” of this dust that the cracks were on the tension side of the specimen. With these particular specimens further loading resulted in delamination due to inter-laminar shear. This delamination then allowed a section to buckle which then resulted in fibre rupture to complete the failure. So this specimen showed 4 individual failure mechanisms.

1) Resin cracking
2) Delamination
3) Buckling
4) Compressive fibre failure

Our analysis needs to deal with these situations.

Material Test Results

Initially materials tests were performed according to EN standards including EN6031 for shear. The problem with this test method is that it gives shear strengths but not the stress/strain behaviour for the resin. To overcome this tests were performed using ASTM D5379 (Iosipescu) which gives you the shear stress/strain curve. Figure 13 shows normalised results for unidirectional and fabric tests. The EN standard tests would give the peak values of strength which are significantly beyond the linear limit of the material.. (By a factor of more than 2) This can have a significant effect on the failure analysis and may indicate that you may have resin failure earlier than predicted.

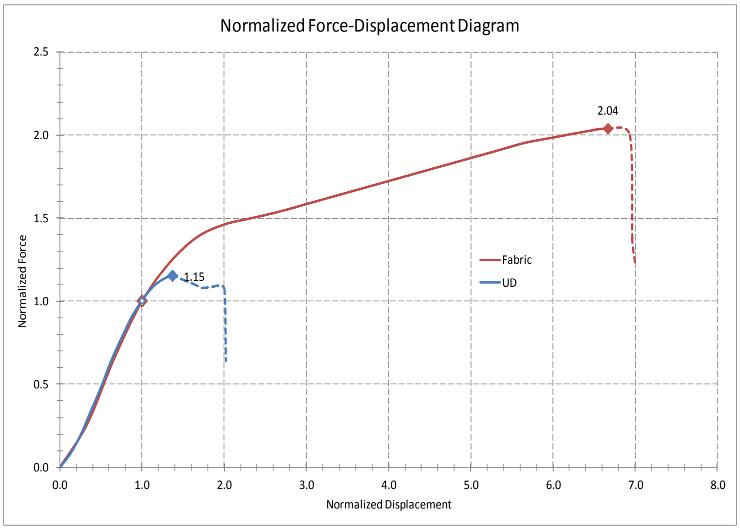

Figure 13 In-plane shear test results

L Section Test results

Figures 14 and 15 show typical failures of the L angles in interlaminar shear and out-of-plane delamination (AKA "unfolding")

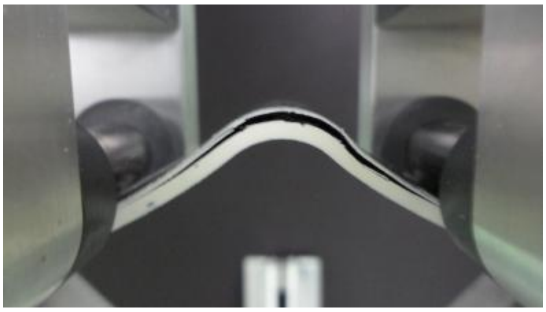

Figure 14. Example of Interlaminar Shear Failure

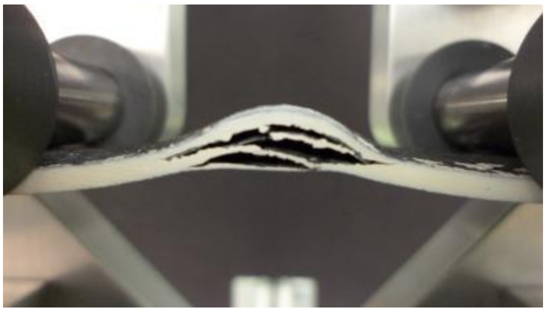

Figure 15. Example of "unfolding" failure

The interesting question here is why do some layups fail as a shear and some as an unfolding? Looking at the results we can see a tendency to fail in shear where we have 0 and 90 plies together as this increases inter-laminar stresses. Almost all specimens with 0/90 together fail due to interlaminar shear. This reinforces the rule that designs should avoid 0/90 together. In this scenario maybe we should use cloth? The weave of the cloth would prevent delaminations in the 0/90 interface.

Figure 16 shows a set of test results combined with an analysis where failure is not included. As you can see the finite element model stiffness is accurate in the initial unfailed part of the curve. What you can also see is the degree of scatter in the test results. Also after the failure the structure will continue to take load. This is how we can almost flatten the specimen in figure 16.

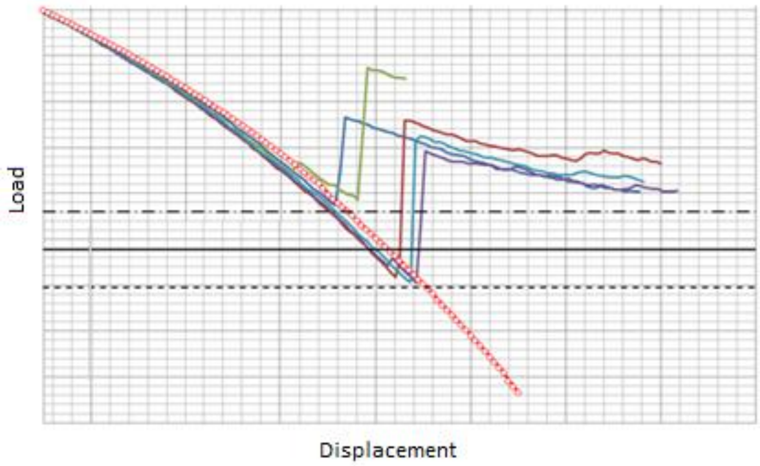

Figure 16. Load deflection curves for test and analysis

If we now add a breaking glued contact model to the analysis we get behaviour as shown in Figure 17. Here you can see the delaminations in the corner.

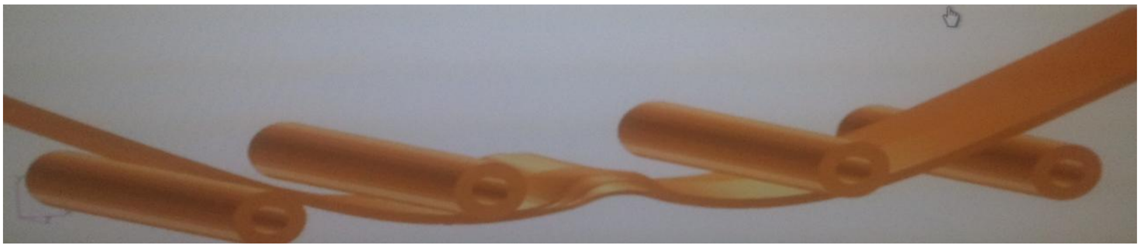

Figure 17. Deformed model showing delaminations

Figure 18 shows an example of this analysis compared with test. The analysis (red curve) is correlating very well with the typical test behaviour. In this case we have an interlaminar shear failure.

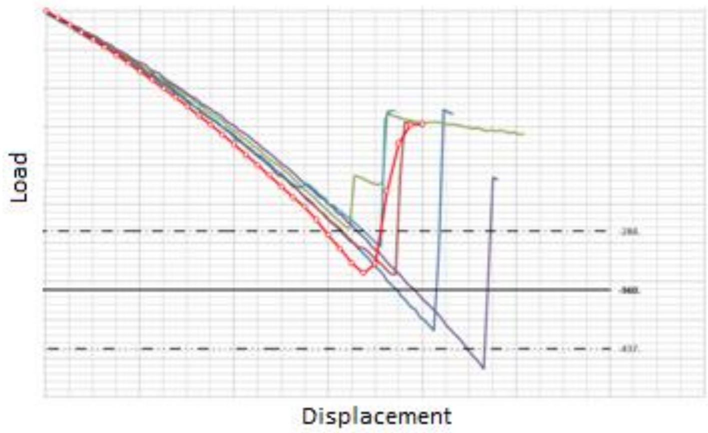

Figure 18. Correlation of results for an interlaminar shear failure

Not all results correlate so closely with this basic approach. Figure 19 shows a correlation plot with unfolding behaviour. In this example the analysis overpredicts the strength. The reason for this is probably due to the non-linear behaviour of the resin.

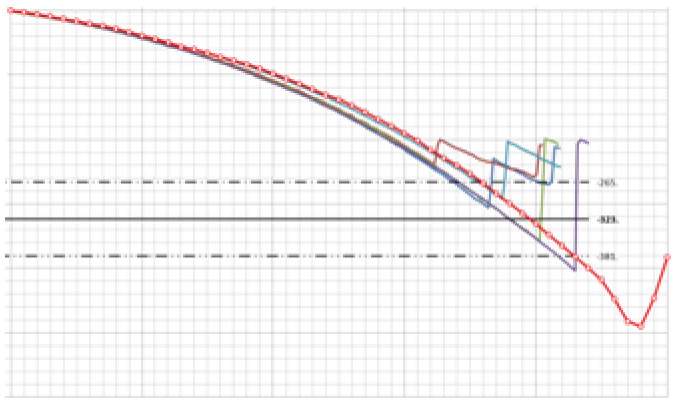

Figure 19. Correlation of results for an unfolding failure.

Next steps

The analysis of these failures is continuing using a combination of non-linear resin properties and VCCT. This may also be combined with progressive failure and cohesive zone modelling. We anticipate that this analysis will improve the correlation and allow us to get a better understanding of what is needed in modelling methods to get closer to reality in the simplest way. Once the L bracket correlation is complete DLR will be looking at a T stiffener to increase the complexity and verify the methodology still gives good results.

SOME QUESTIONS TO ASK ABOUT YOUR DESIGN

The following are some questions that should be asked about a composite part which will help make your design more robust and reduce development costs.

1) Have you obeyed basic design rules? Symmetry? Separation of plies with the same angle? Separation of plies with 90 degree difference? Having a good ply “mix” to avoid unexpected failures?
2) Do you understand your materials? For example carbon fibres are typically brittle in that they will break with minimal non-linear behaviour. Your resin will possibly show more ductile behaviour. New fibres such as hemp or flax based ones may also exhibit significant non-linearity in their failure.
3) Do you understand the environment? Temperature, humidity and aging will cause changes to resin behaviour which will influence strength and life predictions.
4) Is “as-designed” the same as “as-built”? The answer is always “NO” but understanding if variability of ply angles etcetera will degrade the design performance is important. Analytically we can assess this by running random variations of the analysis and seeing if these changes degrade the performance.
5) What happens if there are flaws in the structure? Are you happy these flaws will not propagate? We cannot assume the structure is perfect.
6) What happens in corners? There may be 2 considerations. Bending of a corner can cause delamination. Corners will also be prone to spring-back which may cause assembly issues as well as those nasty little interlaminar pre-stresses which we all forget about.

CONCLUSIONS

In recent years software development has made significant progress in helping the designer to create composite structures which are safer and more robust. As engineers we need to adopt these new techniques and be aware of their limitations and their advantages. Assumptions which we previously used can be avoided. True non-linear failure can be predicted. In the same way that a metallic structure can be designed to yield in overload situations we can design a composite to fail safely.

To borrow the Olympic motto “Faster, Higher, Stronger” there should be a composite motto

“Lighter, Stiffer, Stronger”

The journey is still not complete. We need a fuller understanding of composite fatigue, particularly with high cycle fatigue being an issue. At MSC we are working with organisations such as DLR and the NCC to ensure that we keep our software at the front of the technology.

ACKNOWLEDGEMENTS

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