Composites design in the real world

Designing with composites is a complex process. Christian Laval of MATERIAL SA describes the issues involved and the development of the company's Composite Star design software and materials database.

The design of composite structures is much more complex than for most other materials. Descriptions of different calculation models are scattered throughout the respective literature. Every year researchers come up with new methods of design. This makes it very difficult for the less experienced engineer to familiarize himself with the technology. For the experienced engineer it is time consuming to keep up-to-date with the latest developments.

For efficient research and design work on a daily basis the following tools have been missing: a calculation procedure including all state-of-the-art models and calculation methods; a modern, user-friendly software system which uses this procedure; and a powerful materials database.

Needing these tools in its work, Belgian company MATERIAL decided to develop its own materials database and design software, Composite Star. With the support of composite design specialists from universities and industry, the latest calculation methods were gathered and integrated into a single software system. MATERIAL's engineers will continue to monitor ongoing developments and update the software accordingly.

The development of Composite Star led to a deeper insight into the nature of computerized composite design. The following is a description of the main issues.

CLT

The basis for the calculation of composite laminates and structures is the Classical Laminate Theory (CLT). The CLT first looks at unstructured thin laminate plates composed of two or more unidirectional layers (often called plies). These plate elements have no specified dimensions in length and width. Only the thickness, fibre orientation and stacking sequence of its plies are important. This allows the calculation of the laminate's properties as well as its load response to the imposed forces and moments.

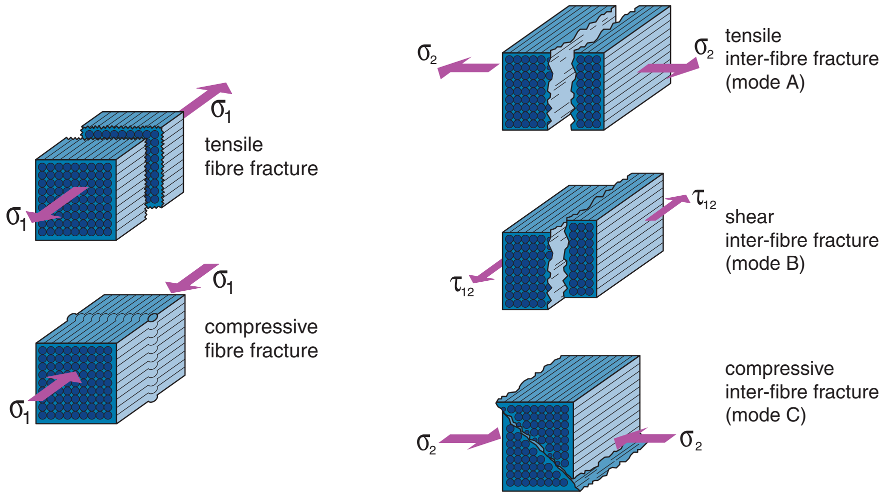

Figure 1: Fibre failure and inter-fibre failure modes.

Structural composite parts can be seen as a composition of these thin laminate plate elements. For simple structural parts (eg. beams, tubes, plates) an exact solution can be found. Their properties and load response (eg. bending, stresses, failure, buckling) can be calculated with analytical formulas. More complex structures need to be calculated by Finite Element Analysis (FEA).

The failure criterion

The most important task of composite design calculation is the strength prediction. The external loads which affect the composite part can be transformed so that the loads for each of its composing laminate elements are known. Then the CLT allows the calculation of the stresses in each ply of the laminate element.

Once the stresses in the plies are known the strength of the laminate can be calculated by applying a failure criterion to each ply. The strength of the weakest ply is the first ply failure strength of the laminate, which is generally not its ultimate strength. The laminate's ultimate strength can be predicted by progressive failure analysis after the first ply failure.

The right choice of the failure criterion is crucial. Many different failure criteria for unidirectional plies have been developed over the years. The first criteria were global failure criteria. Global criteria do not distinguish between failure modes. They were formulated as a single, mathematically simple equation (the calculation power of modern computers was not available yet) which can be easily adapted to the results of the experiments. Examples for such criteria are Hoffmann, Tsai-Hill and Tsai-Wu. Tsai-Wu is the most commonly used.

Physical observations led to the development of differentiating criteria, which distinguish between fibre failure (FF, or fracture of the fibres) and inter-fibre failure (IFF, fracture of the matrix). Different mathematical formulations are used for the physically different phenomena FF and IFF. Because the effects of the two failure modes and the methods to avoid them are completely different, it is vital for the designer to know which failure is occurring. Examples of such criteria are Simple Puck, Modified Puck and Hashin.

Based on physical models Puck developed one of the most modern differentiating criterion in order to integrate the numerous experimental observations into one theory. This Puck Action Plane Criterion does not only distinguish between FF and IFF but also between three different modes of IFF (Figures 1 and 2).

The phenomenon of oblique IFF especially (Figure 1 mode C) motivated Puck to identify the ply plane with the highest effort as the 'action plane' and to transform the fracture calculations for brittle materials into that plane. Whereas the IFF modes A and B are often tolerable, mode C can lead to a catastrophic failure of the complete composite part. If the angle of the fracture plane exceeds ±30° the wedge shape of the crack can damage the neighbouring plies in the laminate and thus result in an explosive failure of the whole laminate.

Another important feature of the Puck Action Plane Criterion is the consideration of the interaction between the stresses in the fibre direction and transverse to the fibre direction. If the stresses in fibre direction come close to the FF limit, the first cracks of single filaments will cause damage in the neighbouring matrix. These matrix microcracks then reduce the plies' IFF limit.

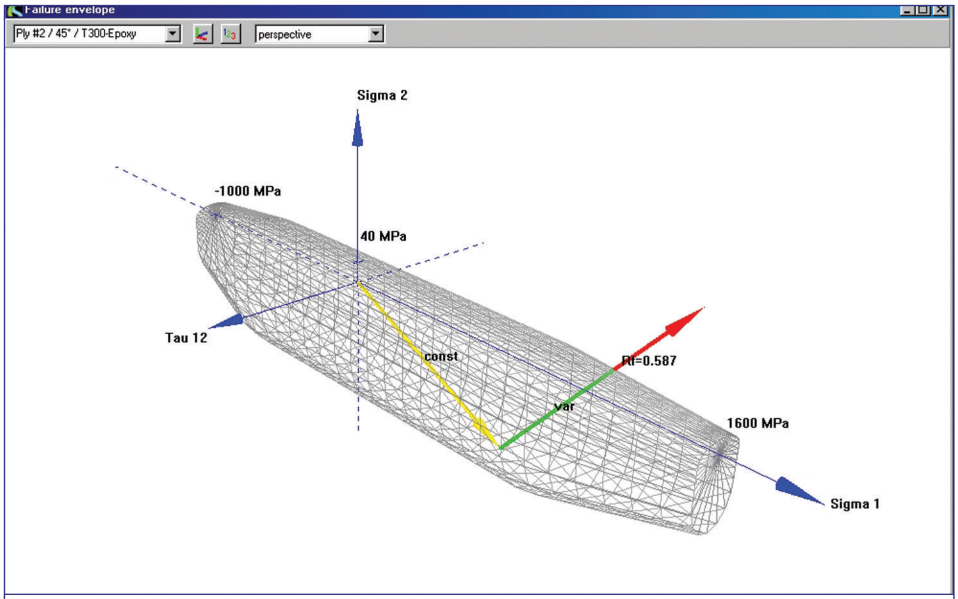

Figure 2: The Puck Action Plane Criterion uses different mathematical equations for the different failure modes. Together these equations define a three-dimensional closed surface, the failure envelope, in the (σ1, σ2, t12) stress space. Composite Star's graph engine can display the failure envelope together with the constant and variable stress vector. This allows immediate recognition of the stress state and the reserve factor in the critical plies.

But which failure criterion should be used? For many applications global criteria are not detailed enough. Their results can differ significantly from reality. Therefore only differentiating criteria should be used. The Puck Action Plane Criterion is one of the most detailed differentiating criteria. It is also one of the criteria which corresponds best with experimental results.

Degradation models

Together with degradation models the progressive failure analysis can simulate the laminate's failure process after the first ply failure.

After a ply in the laminate reaches its IFF limit, local matrix cracks will appear. These cracks do not lead to the total loss of this ply's strength since neighbouring laminate layers bridge them. However there is a reduction in the ply's stiffness. This results in a new distribution of the stresses within the laminate. With increasing load beyond the IFF limit more local matrix cracks will appear until a saturation limit is reached.

In laminate calculation the physical reduction of the stiffness is taken into account by degrading the ply, ie. by mathematically decreasing the ply's stiffness. In the respective literature only a few degradation models can be found. Mostly the plies are degraded by a constant factor directly after the IFF. This does not reflect the crack building process as described above. Consequently Puck introduced a non-linear degradation model in connection with his Action Plane Criterion.

In order to simulate this process on the computer an iterative algorithm is used which increases the load step by step. After each step the complete laminate as well as the stress distribution has to be recalculated and over-stressed plies have to be degraded.

Normally a fibre failure in the laminate is not acceptable and the progressive failure analysis is stopped. However laminates with several fibre orientations can still have load-bearing capacities. Consequently it can be interesting to continue the calculation beyond the first fibre failure. In this case the fibre-failed plies are degraded by setting their stiffness to zero. Only their geometrical dimensions and positions within the

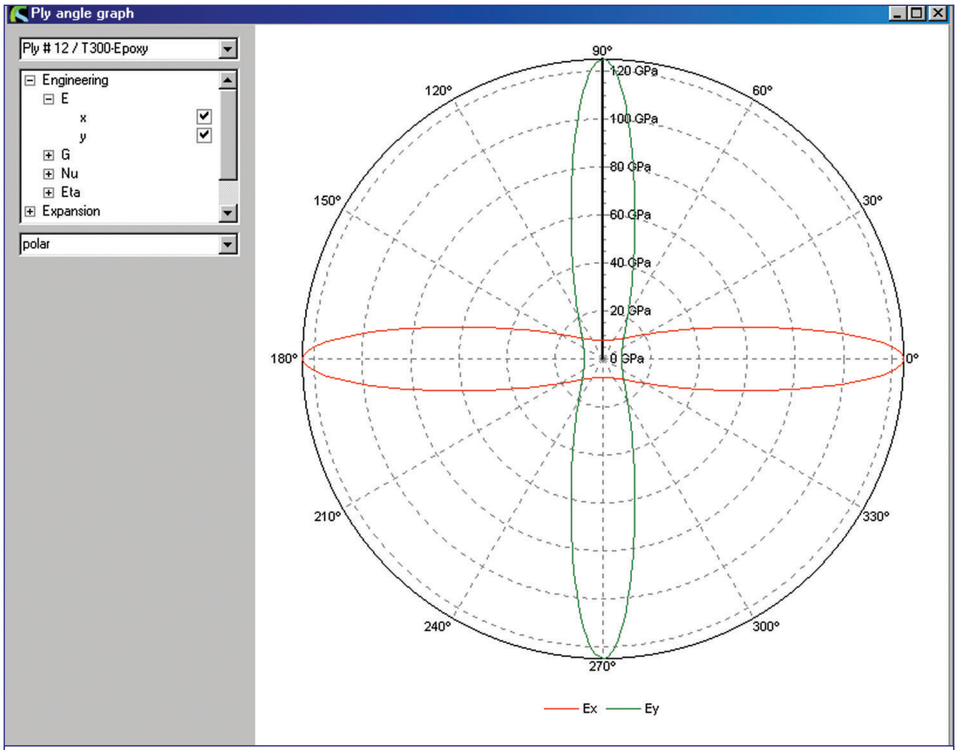

Figure 3: Example of a polar diagram of Young's moduli.

laminate are kept. The calculation process can be continued until the last ply fails in the fibre direction.

Puck's Action Plane Criterion and degradation model has been tested thoroughly by university and industry research laboratories throughout the world. They show high conformity with results of experiments. Tests conducted at the IKV (Institute for Plastics Processing), Technical University Aachen, in Germany, were positive. A detailed evaluation and comparison with other failure criteria has been established in the 'Worldwide Failure Exercise' at the University of Manchester, UK. This exercise compared 12 different failure theories applied to 14 different test cases. An overall assessment concludes that the Puck theory "appears to be one of the best available currently." It should also be mentioned that the criterion and degradation model is the new standard in VDI (Association of German Engineers) guideline 2014.

Even though Puck's Action Plane Criterion and degradation model is one of the most advanced theories and should be used for all applications, all common failure criteria and a simple degradation model are also included in Composite Star. This gives the designer the freedom of choice and allows him to compare the different models.

Hygrothermal stresses

Changes of temperature (operating temperature is different from the curing temperature) and moisture content (the matrix material absorbs moisture after curing) lead to thermal or hygroscopic residual stresses inside the laminate. Together with the external mechanical loads these stresses result in the total load which affects the laminate.

Residual stresses are often ignored. But they must not be. For each ply the combination of the residual and the external stress vector has to be calculated and taken into consideration in the failure criterion. Two questions often asked are: How far can I increase (under a given constant residual stress vector) the external load until failure occurs? and How far can I change (under a given constant external load) the operating temperature until failure occurs? To answer these Composite Star introduces a constant and a variable load (Figure 2). Since the constant as well as the variable load can be either mechanical, hygrothermal or a combination of both, the designer has all calculation possibilities.

Composite structures

As mentioned above, simple structures like beams, tubes or plates can be calculated analytically. More complex structures have to be analyzed by FEA. There is a wide range of FEA software available. Some are more suitable for composite materials than others. With its extended FEA interface Composite Star gives the design engineer state-of-the-art laminate calculation together with existing FEA programs. Any of the fibre, matrix, ply, laminate, stacking sequence, load or structural data can be imported from, or exported to, the FEA program.

Material data

Poor input data make the best calculation theory useless. The material input data needed for the CLT consists of the mechanical and physical properties of the laminate's plies. In general, material suppliers only provide data about their fibres or resins. With these data and the help of micromechanical models it is possible to calculate the ply data required. Composite Star includes this micromechanical calculation with all major models. However these models are only approximate. To get more exact values test plies have to be manufactured and their properties measured. Another source of error arises from the fact that material suppliers do not always present their product data in a standardized way and some data are not specified at all.

Composite Star's database comes with a basic set of common fibre and resin data records provided by materials manufacturers. Typical ply data are also included. This will be sufficient for many applications. However the advanced composite design engineer might prefer to collect or measure his own data and enter it into the database. In the future

MATERIAL will seek the co-operation of materials manufacturers in order to gather a complete, standardized data collection of all raw materials on the market.

Besides data on fibres, resins and plies, the database can store data on laminates, stacking sequences, loads and structures, to enable an efficient and fast use of the software. Features like searching, filtering and sorting allow direct access to the data for immediate calculation. In addition to physical and engineering parameters information like comments and text notes or quality control data can be stored.

Software for the real world

Calculation potential alone is not sufficient for modern design software. A user interface is equally important.

The difficulty with the designing of the user interface has been how to present the large number of input and output data to the user in an efficient way. For example more then 1500 values are calculated per ply in the laminate. For a laminate of 100 plies this results in 150 000 values. Not all these values are equally interesting for the user. A way had to be found to divide this data into groups and to display only the value of current interest. This problem has been solved by using table grids, which can be configured individually by simple mouse click and allow a spreadsheet style use of the software.

One of the best ways to present data is a graph. Composite Star's sophisticated graph engine allows display of any X-Y or polar graph, including any ply's property versus the ply's orientation angle, carpet plots, ply-by-ply stress and strain diagrams and failure process diagrams (Figure 3). An additional important tool for the designer is the three-dimensional model of the failure envelop together with the constant and variable stress vector for each ply (Figure 2). This allows immediate recognition of the stress state and reserve factor in the critical plies.

What's next?

MATERIAL will continue to monitor research in the field of laminate and composite structure design. New developments will be included in the software. Future possibilities include: considerations of non-linearities in the stress-strain-relations; analytical calculation of more complex structures (eg. thick wall parts, pressure vessels); joints; integration of simple FEA capabilities; and consideration of interlaminar stresses. ■

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