FINITE ELEMENT IMPLEMENTATION OF ADVANCED FAILURE CRITERIA FOR COMPOSITES

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1 Summary

The need for high performance-to-weight ratio structures coming from the most advanced engineering fields is the main driver of the increasing usage of composite materials for critical applications. In order to design light and safe systems on time to meet the market requirements, accurate and effective analysis tools are necessary.

NASA has recently developed LaRC02, a set of first-ply-failure criteria for composites which have been shown to be accurate and physically consistent. The LaRC02 formulation seemed to be particularly well suited for design purposes, due to its optimal trade-off between accuracy, material characterization requirements, computational effort and ease of results interpretation.

The present work describes with some insights the LaRC02 criterion features and its implementation into NEiNastran, a commercial finite element software package. The accuracy and usefulness of the method are shown through some application examples, ranging from simple validation cases to a real-world structure.

2 Introduction

The application of composite materials for mission-critical structures is becoming more and more common in advanced aerospace and automotive designs. However, the composites failure criteria currently available within most commercial finite element packages suffer from limitations concerning accuracy, range of application and/or ease of results interpretation.

In recent years, several interesting investigations have been published in regards to a general procedure for stress assessment of structures made up of composite materials under multiaxial stress states. These studies are still an open issue for engineering, since experimental testing of the physical components is typically required for final validation.

By consequence, more room was made for improving the current analysis tools, which is the aim of the work described in this paper.

After a thorough review of various composite failure theories, a set of criteria recently developed by NASA, and called LaRC02, was selected as the best candidate, since it satisfies the requirements which were judged as mandatory for effective use in a typical CAE department for every day work:

(a) have a reasonable accuracy for the broadest possible class of stress field scenarios.

(b) provide decision-making feedback to the engineer, by giving information about why a structure may fail, thus enabling efficiency and awareness in improving modifications.

(c) use material data which is as easy as possible to measure experimentally or find in an existing database, avoiding the need for specific testing / data fitting.

(d) have the highest possible numerical efficiency within an FE code, considering that models with more than 1 million of DOF are now quite common.

A short description of the theoretical background of the LaRC02 criteria, its interesting practical features and field of application is provided in the next section. Then some details of the LaRC02 criteria implementation in the NEiNastran commercial package are given, and a couple of validation cases are shown. Finally, an application of the LaRC02 criteria on an actual mechanical component is discussed.

3 Background

The main difficulties underlying the development of a comprehensive failure theory for composites are their intrinsic anisotropy and the existence of multiple failure modes, i.e. how the material fails at the micromechanical, ply and laminate level.

The classical criteria implemented in most commercial FE codes (maximum stress or strain, Hill, Hoffman, Tsai-Wu) are not able to physically capture the failure mode. Some of them cannot deal with materials having a different strength in tension and compression.

On the other hand, most recent failure theories for composites require peculiar material characterization in order to deduce the material data needed.

In addition, as it was demonstrated during the World Wide Failure Exercise (WWFE) [1], a single criterion capable of predicting the failure accurately, even of a simple laminate under general load combinations and with no use of very specific empirical data, is not available yet.

The LaRC02 approach was thought to overcome, or at least reduce, the limitations mentioned above. Instead of a single failure formulation, a set of failure criteria was proposed, each correlated to a specific load combination. Some of those criteria are already known, while new formulations have been produced for particular stress states.

LaRC02 is a first ply failure (FPF) set of criteria, and can deal with laminates made of unidirectional plies, in a plane stress state.

LaRC02 produces four distinct failure indices, related to different failure modes: matrix cracking under tension (FI-MT) or compression (FI-MC) and fiber failure for tensile (FI-FT) or compressive (FI-FC) loadings. Each failure index is calculated using different theories depending on the stress state.

3.1 Matrix Cracking Failure Index

In the case of tensile loading along the matrix direction, the failure index FI-MT is calculated by using the well known Hashin theory [2], which has been shown to be particularly accurate for this specific loading condition, even when the interaction between matrix tension and in-plane shear makes the stress state biaxial.

In the case of compressive loading along the matrix direction, LaRC02 proposes a new theory for calculating the first-ply-failure, which was derived as an extension of the Hashin criterion mentioned above and the Puck’s action plane [3] concept.

The mathematical details of the LaRC02 procedure can be found in [4]. The main physical assumptions and findings behind it are as follows:

(a) the beneficial influence of transverse compression on matrix shear strength is accounted for by increasing the shear strength by a term proportional to the normal stress σ_n acting at the fracture plane shown in Figure 1 (Puck's action plane concept);

(b) the FI-MC is calculated by: i. first applying the Mohr-Coulomb [5] criterion along each possible fracture plane, in order to compute the shearing stresses acting on it, then ii. calculating the failure index on each plane by assuming a quadratic interaction between τ^L and τ^T (see Figure 1), and finally iii. taking the maximum value of the computed failure index as FI-MC. Therefore, the actual fracture plane is found as the plane which maximizes the failure index versus the fracture plane orientation angle;

(c) the matrix cracking fracture plane under matrix compression alone (pure transverse compression) is supposed to be the plane with $\alpha = \alpha_0 = 53°$, according to experimental results made on several graphite-epoxy composites [3].

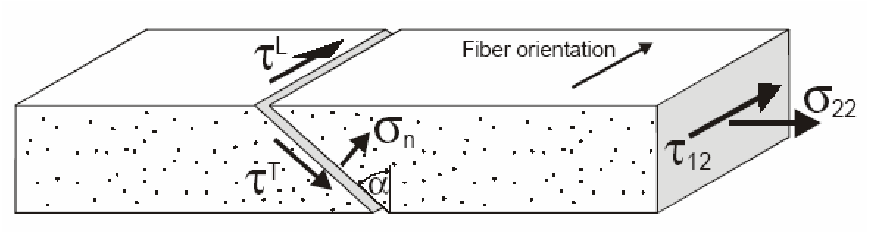

Figure 1: Fracture of a unidirectional lamina subjected to transverse compression and shear.

The assumptions mentioned above made possible to compute the FI-MC without additional empirical parameters with respect to the set of in-plane material strengths.

3.2 Fiber Failure Index

In the case of tensile loading along the fiber direction, the FI-FT is calculated by using the (uniaxial) maximum allowable strain criterion.

Under fiber compression, the LaRC02 assumes that the failure mode is the fiber buckling occurring as shear deformation which leads to the formation of a kink band (see in Figure 2), driven by the damage of the supporting matrix.

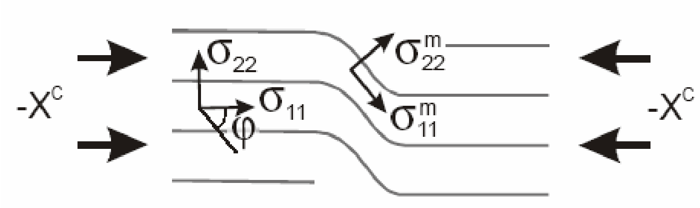

Figure 2: Fiber compression kink band.

The fiber kinking failure mode is based on the assumption of a local initial fiber misalignment φ, which leads to shear stresses between fibers that rotate the fibers themselves, increasing the shearing stress until an instability arises.

Basically, the fiber failure under compression is evaluated as matrix failure in the rotated (kinked) reference system, where the stresses σ^m_{11} and σ^m_{22} act (see Figure 2 again). Therefore, the FI-FC is computed by two different formulations depending on whether the rotated matrix stress σ^m_{22} is tensile or compressive, following the same concept shown above for matrix failure calculation (same as for FI-MC / FI-MT).

4 FE Implementation

The LaRC02 set of criteria was implemented into NEiNastran [5], a commercial FE code developed by Noran Engineering, Inc. (USA).

As already stated, one of the useful features of the LaRC02 criteria is that they don’t require additional material properties compared to classical multiaxial criteria like, for example, Hoffman or Tsai-Wu [7], already covered by NEiNastran. For this reason, from the input user interface point of view, the only change to the code was adding LaRC02 to the available failure criteria selection list.

The calculation phase of the failure indices is somewhat longer with LaRC02 compared to classical closed-form criteria. This is due to two reasons: a) more than one failure index are computed, b) for compressive loadings, the FI-MC and FI-FC have to be calculated as the maximum of a function (failure index versus fracture plane angle) and not as direct results of an expression. When benchmarking the FE implementation, a negligible 5% increase of calculation time for a 120.000 elements / 80 plies FE model has been found, so that the usability of the LaRC02 formulation in real world applications was definitely concluded.

As for the output, since LaRC02 generates multiple failure indices for each finite element (matrix / fiber, tension/ compression), additional vector results need to be defined.

As it will be shown in the next section, getting distinct failure indices for each failure mode is, by the FE analyst standpoint, one of the most valuable aspects of using LaRC02, because it enables a fast and knowledgeable interpretation of the possible reasons why the composite may fail and of the structural improvements needed.

5 Validation

Two test cases were selected for the validation of the FE procedure.

In Figure 3 and Figure 4 the comparison between experimental data, original NASA LaRC02 theory, and the NEiNastran numerical implementation of LaRC02 criteria is shown.

Figure 3 shows results for an unidirectional laminate made of E-glass/epoxy plies loaded biaxially. The failure envelope provided by the LaRC02 criteria is reasonably accurate within the plane [σ_{22}-τ_{12}].

Figure 4 shows results for a series of [±θ] angle-ply laminates made of carbon/epoxy layers loaded in compression. The strength prediction provided by the LaRC02 criteria stays very accurate when varying the lamination angle θ from 0° (load aligned with fiber direction) to 90° (load along the matrix direction).

In both cases, the NEiNastran numerical results are practically coincident with those given by the analytical LaRC02 formulation.

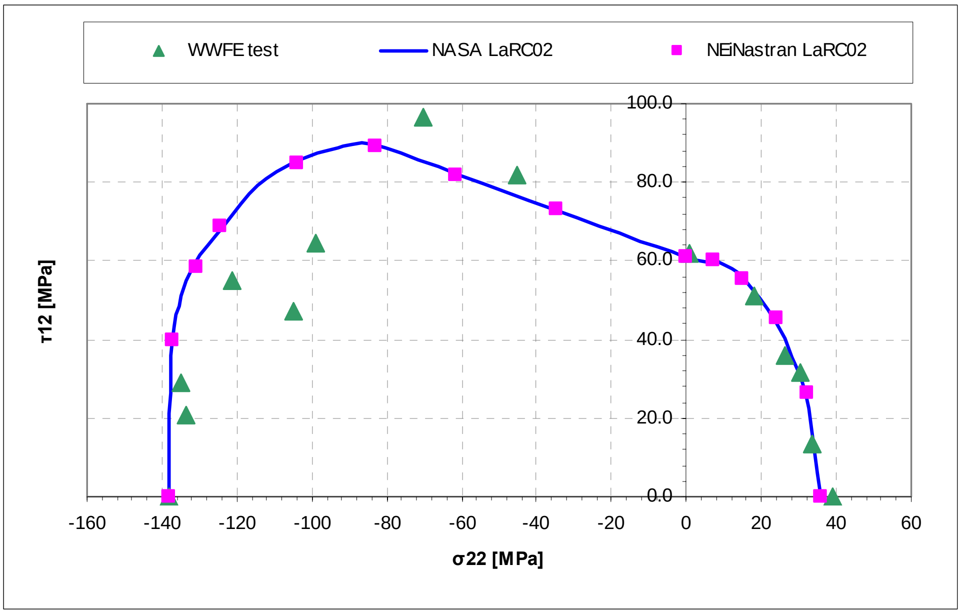

Figure 3: Failure envelopes and WWFE test data [1] for unidirectional composite E-Glass/LY556.

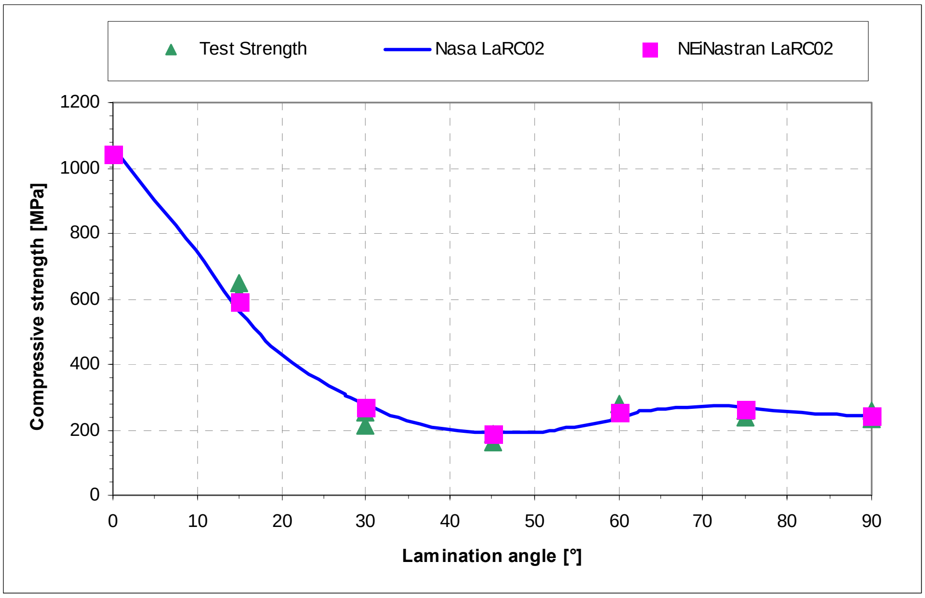

Figure 4: Compressive strength as a function of ply orientation for [±θ]s AS4/3502 laminates [4].

6 Application Example

For illustrative purposes, an application example is described in this section.

The component under analysis is a racing car front wing (courtesy of Minardi F1 Team), under aerodynamic loadings (see Figure 5). Due to the nature of the loads and the cantilever-type constraint set, the structure is mainly solicited by bending and, secondly, by torsion.

The local effects due to notches and stiffness changes (local reinforcements and changes in the lamination / thickness) made the stress field very complex and intrinsically multiaxial.

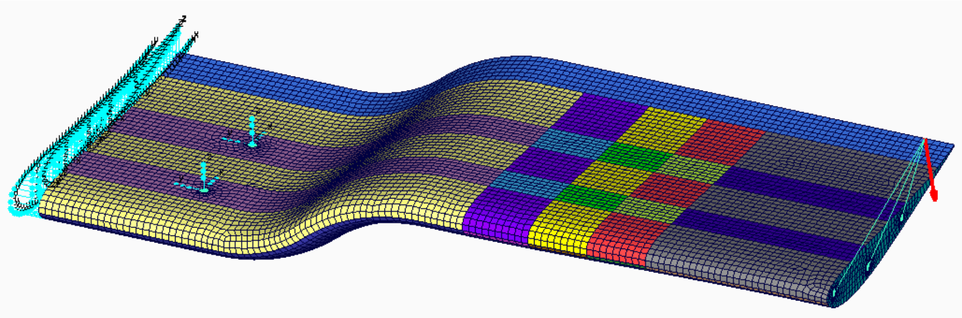

Figure 5: Application case: Racing car front wing (courtesy of Minardi F1 Team). FE model.

In Figure 6 the LaRC02 failure index envelope contour plot is depicted. For each finite element, the maximum between FI-FT, FI-FC, FI-MT and FI-MC through the laminate is plotted. This is the classical way the failure index is post-processed, i.e. assuming that it is a single valued quantity.

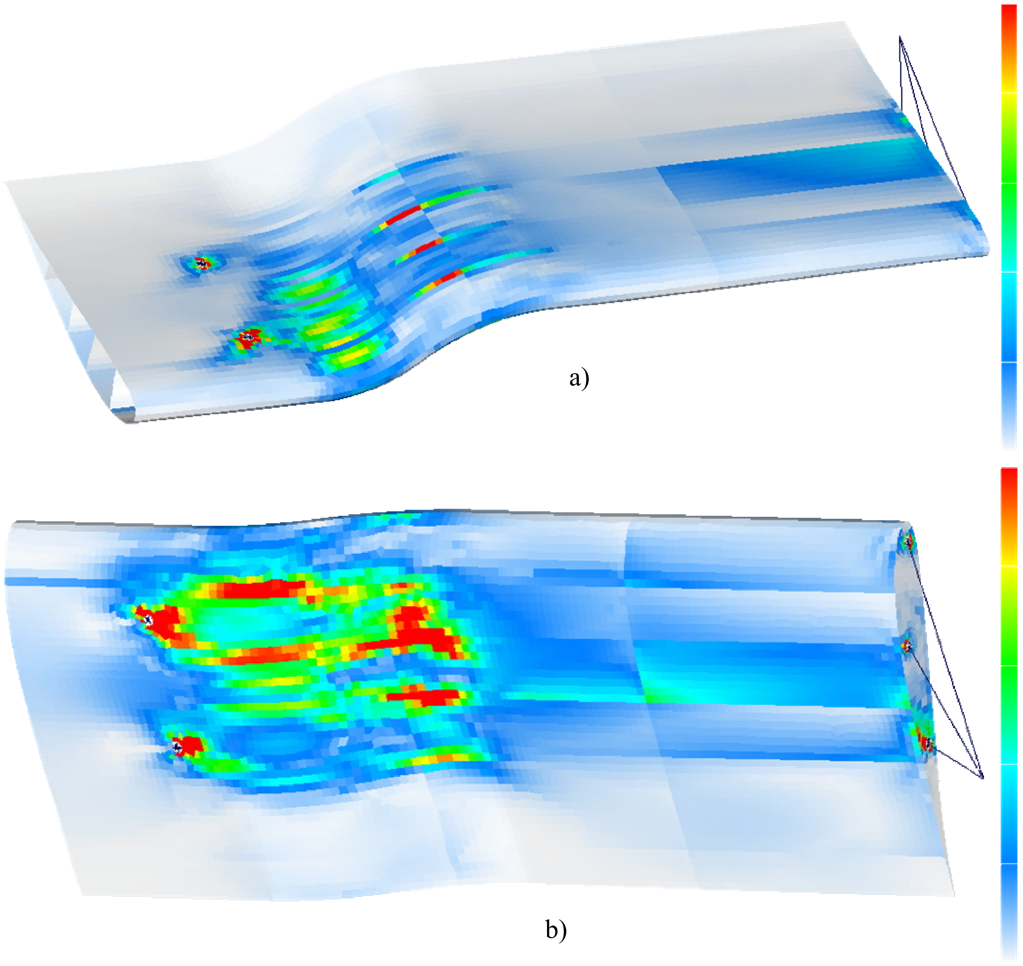

Figure 6: Application case: Racing car front wing (courtesy of Minardi F1 Team). Maximum Failure Index Envelope (a) Top view, (b) Bottom view.

In Figure 7 and Figure 8, the fiber failure indices for compressive and tensile stresses respectively are shown, while Figure 9 and Figure 10 represent the compressive and tensile matrix failure indices.

By comparison with Figure 6 it can be seen that the failure mode varies throughout the structure, but it is generally associated with fiber failure under compression (Figure 7) on the lower surface of the wing, while the upper surface is prone to the matrix tensile cracking failure mode (Figure 10).

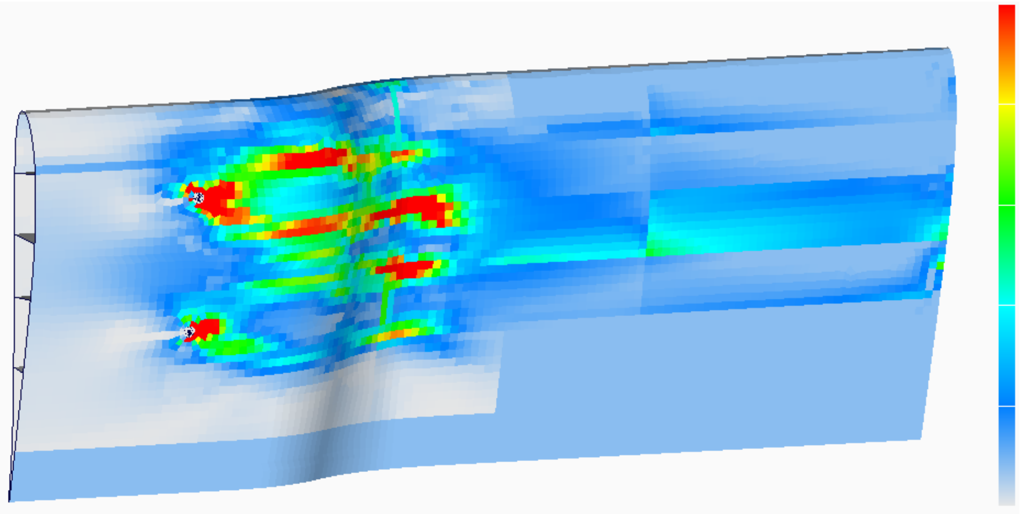

Figure 7: Application case: Racing car front wing (courtesy of Minardi F1 Team). Fiber Failure Index – Compression (FI-FC).

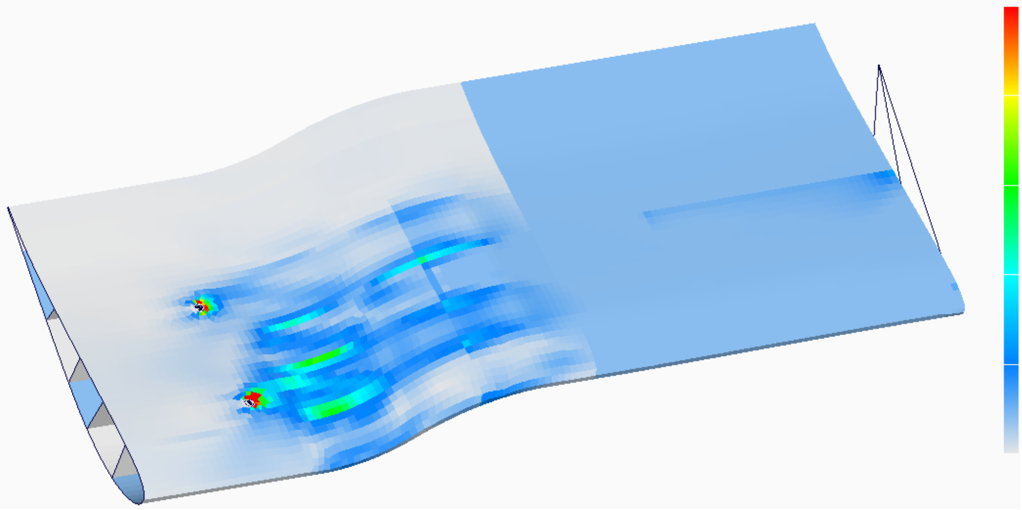

Figure 8: Application case: Racing Car front wing (courtesy of Minardi F1 Team). Fiber Failure Index – Tension (FI-FT).

It can also be seen (Figure 9) that in some particular areas of the structure the matrix compression failure mode is prevailing.

Finally, due to the loading type, and to the difference between tensile and compressive strength of the adopted materials, the fiber tensile failure mode is in general the less probable to occur (Figure 8).

Based on these observations, which are made straightforward by the peculiar LaRC02 approach, a direct and clear input for the engineer about how to improve the strength of the structure may be derived.

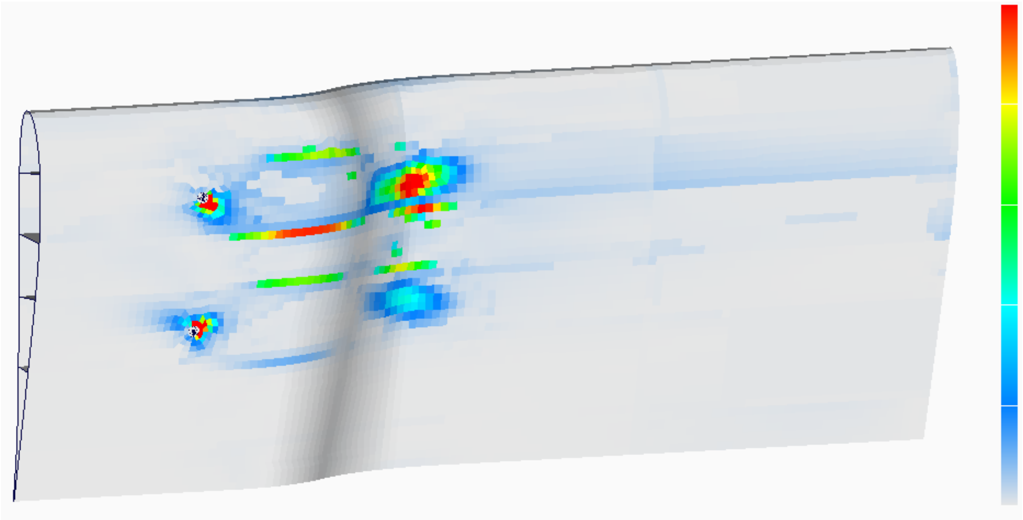

Figure 9: Application case: Racing car front wing (courtesy of Minardi F1 Team). Matrix Failure Index – Compression (FI-MC).

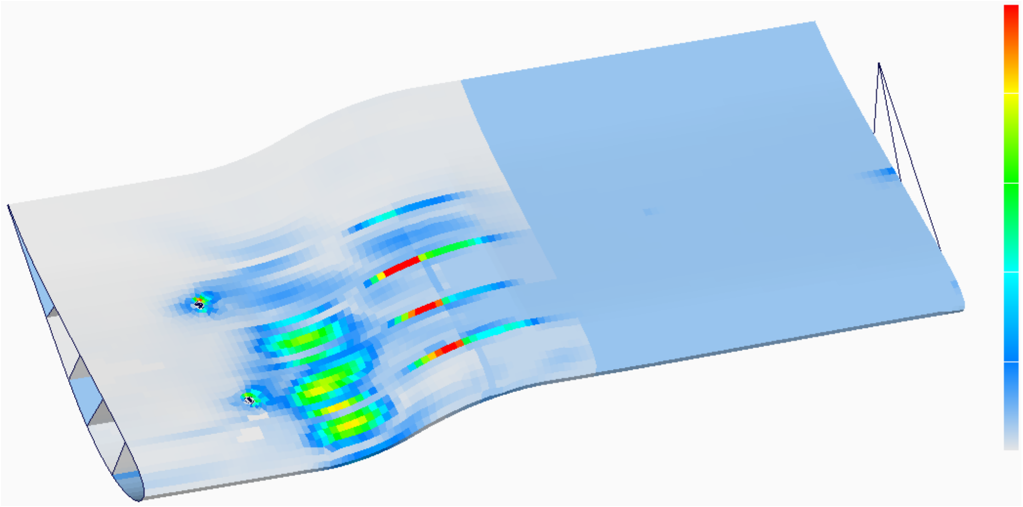

Figure 10: Application case: Racing car front wing (courtesy of Minardi F1 Team). Matrix Failure Index – Tension (FI-MT).

7 Conclusions

LaRC02, a recent set of failure criteria for laminates made of unidirectional plies under plane stress conditions which has demonstrated to be accurate and to give useful design information, has been implemented into NEiNastran, a commercial finite element code.

The numerical implementation of LaRC02 has been validated by using test data and analytical LaRC02 computations.

By applying the LaRC02 criterion to a real-world application, its usefulness has been shown in tracking the failure mode on a structure, thus providing physically based indications to the engineer about how the component is loaded locally. This information turns out to be necessary for the improvement of the strength of the composite part, and it is not based on trial-and-error methods.

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