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A critical review on the rationality of popular failure criteria for composites

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ABSTRACT

Popular failure criteria for fibre reinforced composites are subjected to critical scrutiny on their rationality. The rationality of a theory is about the mathematical and physical logic underlying the theory, rather than the closeness of its results in comparison with experimental data. Seeking for close comparisons with a set of experimental data before obtaining a basic level of rationality is not a scientific attitude, although the practice is becoming the norm in the community of science and engineering. A theory lacking of rationality can never be a sound one no matter how closely it compares with experimental data in one respect or another, since a good comparison in one respect comes at a price of poor agreement in some other respects usually, either unknown for the time being or hidden deliberately. The objective of this paper to raise the awareness of rationality, or the lack of it, in existing theories so that the users will be warned to exercise their judgement on the applicability of these theories before employing them in future. It should also help the researchers avoid incorporating illogical considerations into the formulations of the new theories they are developing.

1. Introduction

How composites fail under loading has been a key question to answer from day one of serious applications of these materials, and the emergence of various failure criteria reflected such needs. Some of the criteria have been routinely publicised, e.g. through textbooks, and widely employed, e.g. in commercial analysis and design codes. However, serious engineering practices seem to present a rather different picture, in particular, in the aerospace industry, where considerations are mainly based on the so-called design allowables [1]. There are two basic categories of such design allowables, one at materials level based on coupon tests and the other on the structural level ranging from typical laminate layups to various degrees of sophistication with features, such as notches, holes, joints, etc. and scales, such as parts, subcomponents, components and complete structures in a so-called ‘building block approach’ [2]. Theoretical failure criteria have largely been by-passed in such an approach, given the efforts made to the development of various failure criteria. The root reason, said or unsaid, has been the simple fact that the theoretical criteria do not seem to offer useful enough guidance to the actual design practices. In response to the complaint of lack of accuracy of existing theories, theoreticians have been showing their determination to resolve the problem by escalating their levels of sophistication, often, coming with more unsupported assumptions or undeterminable (in terms of existing testing standards) material properties. As a result, instead of bringing direct solutions to engineering practitioners, new theories tend to drive them further away, sometimes, to such an extent that they could not be bothered by those theories anymore but plunged back to their exercise of determining the design allowables. The endeavours seem to bifurcate widely and deeply.

It is fair to say that the design allowables, once available, are simple and safe to use. There have been established procedures to follow in engineering [1]. However, the shortcoming of this approach is that the process of obtaining a sufficient set of design allowables for a given material is very demanding, as it is both labour intensive and time-consuming, in addition to high material costs. Practical affordability would restrict the scope to a limited number of materials, layups, geometric dimensions, etc. More critically, it makes the process of adopting any new material a formidable task. It is certainly not a comfortable position a creative designer would like to find him/herself in. However, there does not seem to be any alternatives.

It is worth noting that practical failures of composites often involve delamination due to impact. Delamination mechanisms are usually associated with the structural behaviour, rather than the material failure that conventional failure criteria aim to address. This indicates that there is a significant gap between the existing failure criteria and engineering practices. One might argue that there are a lot of attempts to understand impact and delamination. However, if one is honest and also really knows what he/she is saying, the truth would be that the existing understanding with reasonable reliability on this subject is very limited. Examples have been shown in a recent paper [3] demonstrating that, even for the simplest problem of this kind, lack of understanding

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could be easily identified, let alone for any more sophisticated scenarios.

Without discouraging theoreticians completely, one would probably agree that there is a substantial set of problems where failure is dictated by ideal mechanisms of failure of materials as opposed to structures. For these problems, can the state-of-the-art failure criteria have high enough fidelity in capturing the failure? Surely, one would like to have a categorically positive answer to this question. However, to practitioners' dismay, an honest answer would likely to be 'Not sure'. This will be the focal point of the present paper, before one is in any credible position to address more sophisticated problems, such as impact and delamination.

The series of World Wide Failure Exercises [4–6] have made significant contribution to the clarification of the position, where a wide range of popular theories have been appraised primarily based on comparisons with a large, but still limited, number of experimental data. On the theoretical side, those involved in theoretical developments probably have no shortage of occasions when correct results were accidentally obtained from wrong theories. On the other hand, without undermining the role of experiments, an honest and critical experimentalist probably would agree that there could be just as many chances to obtain wrong results in experiments as in theoretical work. The assessments achieved solely by comparisons with experimental data are bound to be of limited authority on the fidelity of any specific criterion.

There is lack of systematic reviews on the rationality of failure theories. It is the intention of the present paper to make an attempt along this line. By disclosing the irrational aspects embedded in existing popular failure criteria, the aim of this paper is to ring a loud alarm bell for a sober reflection of the state-of-the-art before meaningful efforts can be channelled to the genuine front line to solve engineering problems.

To facilitate the discussion in this paper, attention will be paid only to the class of composites exhibiting transverse isotropy. Practically, the applicability of all existing failure criteria has been limited to this class of materials. Although some criteria presented themselves as if having wider applicability, their meaningful applications always narrow down to transversely isotropic materials. For instance, the Tsai-Wu criterion was initially proposed for orthotropic materials in general as far as its formality is concerned before being specialised to transversely isotropic materials. However, any attempt of applying it to an orthotropic material, e.g. a quasi-isotropic laminate, hardly produces any results bearing relevance to reality. In addition, regarding other considerations, such as thermoset or thermoplastic, with toughened matrix or untoughened, with strong bonding between fibre and matrix or weak bonding, high strength or high modulus fibres, glass or carbon fibres, etc. all theories under review in this paper fall in the category of phenomenological approaches. The spirit of such approaches is that they apply to all systems. Any difference in the composite systems should be duly reflected in the strength properties employed in the criteria. Whilst this reveals the shortcomings of phenomenological approaches in general, it offers attraction to design practitioners.

For the clarity of the present paper, a rational theory is defined as one that is based on well-established physical rules (often, common sense), e.g. the objectivity, and a definitive number of independent assumptions, e.g. the existence of a failure envelope. These assumptions should be sufficient (even better, if also necessary) for the theory. They should not compromise the physical rules and not be self-contradictive, explicitly or implicitly. The theory should be deduced from the physical rules and the assumptions free from any logical fallacy.

It is certain that no one sets off to produce an irrational theory. However, this alone does not prevent irrational theories from being produced. Theoreticians are supposed to bear the rationality requirements as stated above in mind during the development of their theories but the reality is that not all theories available were produced by such theoreticians. Without these requirements tightly fastened in their minds, theory developers are likely to overlook one aspect or another. It is usually far more difficult to iron any irrational elements out than putting them in, as before any of them can be ironed out, their presence has to be appreciated first, which defines the purpose of the present paper for a range of popular failure criteria. It may be true that some of the points made in this paper had been realised by other researchers in the past. As they are not found in the open literature, to the best of the authors' knowledge, they deserve to be made available to a wide community to benefit other researchers and practitioners.

2. The maximum stress criterion

The maximum stress criterion is definitely one of the most popular criteria in use. It can be presented as

$$\frac{\sigma_i}{\sigma_{it}^*} \le 1 \quad \text{if } \sigma_i \ge 0 \text{ or } \frac{|\sigma_i|}{\sigma_{ic}^*} \le 1 \quad \text{if } \sigma_i < 0 \quad (i = 1,\ 2 \text{ and } 3)\frac{|\tau_j|}{\tau_j^*} \le 1 \quad (j = 23,\ 13 \text{ or } 12) \tag{1}$$

where $\{\sigma_1 \ \ \sigma_2 \ \ \sigma_3 \ \ \tau_{23} \ \ \tau_{13} \ \ \tau_{12}\}$ defines the stress state in the material's principal axes, σ_{1t}^* and σ_{1c}^* are the tensile and compressive strengths in the fibre direction, $\sigma_{2t}^* = \sigma_{3t}^*$ and $\sigma_{2c}^* = \sigma_{3c}^*$ the tensile and compressive strengths transverse to the fibres, and τ_{23}^* and $\tau_{13}^* = \tau_{12}^*$ the transverse and longitudinal shear strengths.

Apparently, the title of the criterion is not meant to be understood literally. It is not the maximum stress but the maximum stress ratio that counts. This criterion is so traditional that its origin can hardly be traced. It is perhaps a good thing, as it is the glitch in the criterion that this paper is to reveal, hence it would not be considered as any individual's fault. If anything, it should be the collective failure of the community for having overlooked basics of this criterion.

The weakness of the maximum stress criterion has been commonly pointed out as the lack of interactions between different stress components. Many subsequent developments tended to incorporate interactions as will be reviewed later in this paper. Assuming perfectly measured strength properties employed in constructing the failure envelope, one can place absolute confidence only on the predictions at the intersections between the envelope and the coordinate axes, as these are the test data experimentally measured directly.

There is a more fundamental deficiency which does seem to have been overlooked by large. It is the lack of objectivity. Objectivity is a basic rule of physics and, in fact, science in general, which requires that the consequence of any physical process should not vary with the coordinate system, i.e. the perspective of the observer, employed to describe the physical process. To reveal the aspect lacking objectivity in the maximum stress criterion, consider a 2D equal tensile and compressive biaxial stress state in the plane transverse to the fibres in a UD composite which is usually regarded as a transversely isotropic material. The application of the criterion predicts a tensile failure at the tensile strength, σ_{2t}^*, due to the tensile stress component, as most composites are typically brittle and hence have lower tensile strength than the compressive one. The failure mode would be in the way as depicted in Fig. 1(a). However, if one views the same stress state at 45° off the axis, it is in pure shear as shown in Fig. 1(b) with $\tau = \sigma$. Application of the same criterion would result in prediction of the failure at the transverse shear strength, τ_{23}^*, with a fracture surface likely being on the action plane of the shear stress (marked by the dashed line in Fig. 1(b)). It has been shown now that different results are obtained for the same problem simply due to the fact that the same physical process has been observed from two different perspectives with reference to two coordinate systems between (a) and (b) in Fig. 1. This is an apparent violation of the objectivity rule of physics.

One might argue that failure under pure shear is expected at 45° to the action plane of the shear stress. However, this results from the use of the maximum principal stress criterion [7] for isotropic materials (UD composites are isotropic in their transverse plane to fibres)

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