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Progressive failure analysis of thin-walled Fibre Metal Laminate columns subjected to axial compression

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ABSTRACT

The subject of the paper is the progressive failure analysis (PFA) of thin-walled Z-shape cross section members subjected to axial compression. This study concerns angle-ply multi-layered Fibre Metal Laminates (FMLs) which consist of alternating thin layers of aluminium and glass fibre-reinforced unidirectional prepreg. Laboratory damage tests were performed by the static testing unit that provided displacement control loading. Experimental results were compared with FEA wherein based on the profile's nonlinear stability investigations the failure analysis was performed. Nonlinear FE simulation combined with available progressive failure mechanics allowed to predict the initiation and propagation of the multi-failure modes within composite material. Hashin failure criterion was used to monitor the initiation of damage, whereas material degradation method (MPDG) was applied in FRP layer to define the damage evolution law. Damage variables were specified according to FEM modelling procedures in order to control material stiffness reduction after damage initiation. For aluminium layers the J2 plasticity model was employed. Progressive failure assessment by FEM allowed to estimate the post-buckling equilibrium paths and damage modes with particular regions of laminate's fracture that were found to be in a good agreement with experimental evidences.

1. Introduction

Composite structures have been extensively used in recent years with important developments in the aviation, automotive and wind energy industries. A wide group of composites is represented by Fibre Metal Laminates (FMLs) which are hybrid composites constructed by binding fibre-reinforced laminates with metallic layers [1]. Furthermore, particularly in aviation industry most of the FMLs applications are based on unidirectional glass fibre-reinforced prepregs combined with aluminium alloy sheets (Glare type) [2]. Ply combinations such as this provide high bearing strength, large impact resistance and improved damage tolerance [3]. Fibre-reinforced material guarantees also improved strength and stiffness, particularly when compared to other structural materials on a unit weight basis. What is more important, depending on fibre alignment, FRP can be designed to be stiffer in a specific direction [4]. This makes them the material of choice for multiple applications. Such achievements within the FML concept have inspired the research community over the years to investigate its mechanical behaviour under specific loading conditions [5,6].

Nevertheless, FMLs still need to meet the stringent requirements of the aerospace applications in components such as fuselage sections or cargo interiors [3]. Apart from high damage tolerance and fatigue resistance, lowest possible weight of the structure needs to be maintained. Therefore, one can observe the accelerating adoption of the thin-walled Glare structures within the aviation industry [7]. However, study aiming to reduce the thickness of the specific wall's section gives rise to the stability considerations of the thin-walled structures [8,9]. Particularly for relatively slender and thin-walled components, the stability phenomenon and structural optimisation becomes the interest of today's investigations [10]. For that reason, numerous buckling problems with specific stability constraints were posed in order to determine solutions for critical load and buckling mode shape of the compressed members [11,12].

Another stage of stability considerations includes the post-buckling analysis to observe the structure's behaviour in full load range [13]. It requires the implementation of semi-analytical and numerical methods to verify the analytical solutions [14,15]. Based on the stability solutions, the failure analysis can be applied to investigate the damage initiation in the post-buckling range. In FMLs, aluminium constituent is claimed to dominate the material response and the failure modes vary with ductility [16]. However, due to the presence of FRP, the stacking sequence and particular fibre alignment greatly influence the damage pattern [4,17].

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For failure analysis of angle-ply multi-layered FML columns the experimental tests and numerical simulations need to be performed simultaneously. Particularly for composite laminates, advanced concepts and developments in failure and damage analysis need to be considered [18]. Numerical computation requires FEM implementation wherein the earliest and most simplified modelling technique to address material failure is the First Ply Failure (FPF) analysis. Such preliminary analysis to FML study is given in the paper [19], where different failure criteria are implemented to assess either matrix or fibre failure in the composite material layers. Further study requires material degradation model by means of ply discount method [20] or progressive damage analysis (PDA) [21,22]. The latter includes the failure initiation and material degradation algorithm that are defined in FEM software by specific damage evolution law.

Separate failures modes of the material constituents of FMLs are already identified [23] but their specific interaction has not been proven yet [16]. In the literature one can find various examples of the PFA application to the failure analysis of the composite structures [24,25]. However, according to the World Wide Failure Exercise (WWFE), to date there is no particularly satisfying method in FEM to model the progressive damage analysis in order to assess the propagation of the multi-failure modes in the composite material [26]. There are also relatively few papers devoted to failure analysis of thin-walled laminated profiles in the post-buckling state where local buckling effects are considered [14]. Hence, there is a need for fundamental understanding of the various failure mechanics and its impact on the structure stability. The purpose of this study is to reveal the initial FE results of progressive failure analysis for FML Z-section columns subjected to compression.

2. Progressive failure analysis

A large variety of failure criteria and degradation models have been developed over the years with different applications depending on loading conditions and material properties [23,26]. For ductile, isotropic material the Huber-Mises-Hencky criterion (also referred as J2 plasticity condition) is widely applied, regarded as most reliable when dealing with ductile materials. The issue of failure criteria is more ambiguous for fibre-reinforced layered materials of orthotropic and anisotropic nature. For that reason, Classical Laminate Plate (CLP) theory is generally applied to determine the properties of the entire composite together with its stress and strain distributions when subjected to loading. Further GFRP strength analysis requires failure criteria application, wherein stress and strain components are combined to allow a direct failure assessment. By means of specific failure criteria the strength analysis of the laminate can be carried out at each ply separately. The weakest layer, which fails first according to adopted criterion, determines the First Ply Failure (FPL) strength of the laminate [1]. However, it is claimed that the load corresponding to FPF does not always correspond to the loss of carrying capacity of the entire composite. Most of the advanced structural materials such as GFRP can still carry further loading after the failure initiation and for that reason the progressive failure analysis with material degradation model is required to predict the laminate's ultimate strength [27,28].

2.1. Failure initiation

The strength analysis of the laminate is carried out in order to predict first failure initiation. The methodology includes failure criteria implementation that could assess the strength of each composite ply separately. In case of Fibre Metal Laminate different criteria need to be adopted for aluminium and GFRP layers.

In the aluminium layer, the aforementioned Huber-Mises-Hencky (HMH) criterion is used to determine the equivalent stress σ_{EQV} (Eq. (1)) based on the stress tensor elements in plain stress case. Such assessment allows one to predict the failure initiation within the aluminium layers in the area where equivalent stress reaches the yield limit.

$$\sigma_{EQV} = \sqrt{\sigma_{11}^2 - \sigma_{11}\sigma_{22} + \sigma_{22}^2 + 3\sigma_{12}^2} \tag{1}$$

For fibre-reinforced laminate various failure criteria can be considered to indicate failure initiation. These available in many FEM codes and commonly used in research for orthotropic plies analysis are as follows: Tsai-Wu (1971), Hashin (1980), and Alfred Puck (1996) criteria. Each of them is applied to predict material failure and the relative differences result from the way in which stress and strength components participation is defined in the failure function. In the case of Alfred Puck criterion, additional inclination parameters need to be accepted as constants according to specific guidelines [29]. Note, that Hashin and Puck criteria consider various failure mechanisms by developing four different damage initiation modes: fibre tension (rupture), fibre compression (kinkling), matrix tension (cracking), and matrix compression (crushing). Hence, these criteria allow one to track the matrix and fibre failure that can occur either separately or sequentially. Certainly, several researchers have also proposed modifications to Hashin criterion in order to improve its predictive capabilities [30]. However, some of them can be simple reduced to Hashin criterion providing certain assumptions. There are works in which the shear stress component in the failure function is associated with the additional weight factor that is usually denoted as α. That provides different failure factor by solely increasing or decreasing the shear stress effect onto the fibre failure [31]. Furthermore, according to the World Wide Failure Exercise (WWFE) most criteria were unable to capture some of the trends in the failure envelopes of the experimental results [26]. However, various studies claim that Hashin criterion provides sufficient predictive capabilities and there is an increasing adoption of this criterion especially for the purpose of FRP's failure prediction [17,28]. Therefore, for the purpose of PFA model the authors decided to use Hashin criterion to assess failure initiation in the composite layers.

Different failure modes developed by Hashin criterion can be defined in terms of nominal Cauchy stress components and material strength to recognize different failure modes (Eqs. 2–5)[32]:

- Fibre tension ($\sigma_{11} \geq 0$)

$$f_f^t = \left(\frac{\sigma_{11}}{X_t}\right)^2 + \left(\frac{\sigma_{12}}{S}\right)^2 \tag{2}$$

- Compression ($\sigma_{11} < 0$)

$$f_f^c = -\frac{\sigma_{11}}{X_c} \tag{3}$$

- Matrix tension ($\sigma_{22} \geq 0$)

$$f_m^t = \left(\frac{\sigma_2}{Y_t}\right)^2 + \left(\frac{\sigma_{12}}{S}\right)^2 \tag{4}$$

- Matrix compression ($\sigma_{22} < 0$)

$$f_m^c = \left(\frac{\sigma_{22}}{2S}\right)^2 + \left(\frac{\sigma_{12}}{S}\right)^2 + \left[\left(\frac{Y_c}{2S}\right)^2 - 1\right]\frac{\sigma_{22}}{Y_c} \tag{5}$$

where f_f^t, f_f^t, f_f^t, f_f^t - are the failure factors (FF); σ_{ij} - the nominal stress tensor components; X_t, X_c - the longitudinal tensile and compressive strength limits; Y_t, Y_c - the transverse tensile and compressive strength limits; S - the shear strength limit. Similarly, as for other criteria, failure factor indexes indicate whether a damage initiation criterion is satisfied or not, for value greater or lower than 1 respectively.