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Thickness scaled compression tests in unidirectional glass fibre reinforced composites in static and fatigue loading

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ABSTRACT

Thick laminates can be found in different wind turbine blade sections, such as the root or the spar caps. However, static and fatigue design of thick laminate components is based on thin coupons tests (around 4 mm thick) and safety coefficients determined by the guidelines and standards.

The aim of this work is to study the size effect in compression for unidirectional glass fibre reinforced composites. Scaled static and fatigue compression tests were performed on glass/epoxy laminates of 4 mm, 10 mm and 20 mm thick. A series of scaled coupons were designed taking into account the influence of the manufacturing process and the final testing conditions. While static tests on laminates with different thicknesses showed no significant change in the static ultimate stresses, fatigue tests showed a decrease in the fatigue life for increasing thicknesses as well as wider intervals of confidence. In addition, fatigue data were compared with the reduced fatigue capacity reported by the design guidelines showing reserve factors larger than 2.0.

1. Introduction

Concerns about size effects were already reported in the 15th century, when it was suspected that among cords of equal thickness the longest is the weakest [1]. Since then until our times different size effects in composites and other materials have been studied. In Bažant's [2] review on size effects on structural strength, the size effect in solid mechanics is understood as the change of the nominal strength of the structure when geometrically similar structures are compared.

In review papers by Zweben [3], Sutherlands et al. [4] and Wisnom [5], evidence and suspected causes for the existence of size effects are reported. The causes reported in those references are the influence of test configuration, the manufacturing defects, the difficulty of scaling fibres and the scaling of ply thicknesses.

Moreover, Wilkins [6] reviews the nature of scaling effects with special emphasis on the use of the Weibull theory, which states that the probability of occurrence of defects increases as volume increases. Weibull theory is also used to represent the inherent scaling effect that composites exhibit due to the impossibility of scaling fibre diameters and geometries. Wang [7] defends that there is a dependence of material strength on volume that should be understood as a scaling effect of material properties.

Regarding scaled compression tests, Camponeschi [8] reported the effect of the thickness of carbon reinforced polymer (CFRP) laminates up to 7 mm thick concluding that in most cases there is a drop in the compression strength with thickness increase, which can be related to the material quality or testing side effects. Bing [9] studied the size effect on end loading compression coupons for off-axis tests, observing a decrease of strength with an increase of thickness. This strength decrease was found to be more pronounced when the off-axis angles are close to 0 degrees.

Hsiao [10] performed static tests on unidirectional (UD) CFRP coupons up to 10 mm thickness observing no significant reduction of the ultimate strength for increasing thickness and a reduction of the coefficients of variation. On the contrary, Lee and Soutis [11] performed several series of static thickness scaled open hole compression tests on CFRP laminates with thicknesses up to 8 mm, observing a reduction of the ultimate strength. However, in these tests, instead of scaling the geometry as the thickness increases, the same geometry with different thicknesses was used in all the cases. In a similar manner, un-scaled CFRP coupons were statically tested by Baldini et al. [12] with thicknesses up to 5.5 mm showing a decrease of the ultimate stresses. In addition, Cordes [13]

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performed a series of compression tests on 10 mm thick specimens with different cross-ply lay-ups, where it was concluded that the quasi-static behaviour of the cross ply composites is dominated by the zero degree layers.

Common practice to determine static design limits of composite glass fibre reinforced parts such as wind turbine blades is to reduce the test material characteristic values (stresses and strains) to a probability of failure of the 5% according to a normal distribution. Later such characteristic value is divided by a safety factor in order to obtain the static design limits. Such safety factor can be obtained from previous experimental tests [14] or standards such as Germanischer Lloyd guidelines [15].

A similar approach is used to determine fatigue limits with standards such as Germanischer Lloyd guidelines [15]. To predict durability due to fatigue a Miner's rule or a residual strength model [16] is used, in conjunction with the Goodman diagram [17,18]. It allows to predict the cycles to failure as a function of mean stresses and amplitude stresses. Such models are constructed based on test material characteristics values (stresses and strains), S–N curve slopes and safety factors defined by the standards.

In both static and fatigue design limits, the test material characteristic values are based on specimens which are not thicker than 4 mm. Therefore, scaling effects, manufacturing effects and ageing effects that are present in the final structural behaviour are considered via safety factors.

Taking into account that limited references are available in literature related to static scaled compression tests on composites, and even less in the case of fatigue properties, the aim of this work is to study the size effect in static and fatigue properties with thickness scaled compression tests on unidirectional glass fibre reinforced polymers (GFRP). Measurements are compared with the reduced fatigue capacity given by design guidelines as a reference.

2. Materials and methods

The aim of this study is to investigate the influence of thickness on compressive failure of unidirectional GFRP. To ensure that the desired failure mode occurs in all cases, the experiments are engineered with care. Special attention is paid to the coupon geometry, the manufacturing process and the test setup.

2.1. Coupon geometry

The coupon geometry is described by the parameters shown in Fig. 1. The specimen can be loaded in three different ways: by end loading (ASTM D695, DIN 65375), by shear loading (ASTM D3410) or combined loading compression (CLC) setup which is a combination of the first two (ASTM D6641). In this work, a CLC setup is considered, where the total load exerted by the test frame actuator is divided into a shear load and an end load according to a distribution coefficient that varies with the clamping pressure. In order to pre-dimension the geometry, four different failure modes (see Fig. 2) were considered: compression failure in the gauge section, shear failure in the tab section, crushing at the end section and buckling of the gauge section. Of these, the first is the desired failure mode. Compression failure of the gauge section is the design failure parameter, and for a glass fibre UD composite a maximum stress of 800 MPa was considered. Thus for a certain thickness e and a certain width w the main load F_{load} required can be calculated. The shear failure mode in tab section was designed for a maximum shear τ_{tab} of 10 MPa, thus the tab length (m) can be dimensioned as,

$$m > \frac{F_{load}}{\tau_{tab} \cdot w \cdot 2} \tag{1}$$

The end loading failure mode is driven by the bearing stress $\sigma_{bearing}$, which was considered as 200 MPa for dimensioning purposes. Thus the tab thickness (t) can be sized as,

$$t = \frac{h-e}{2} > \frac{1}{2} \cdot \left(\frac{F_{load}}{\sigma_{bearing} \cdot w} - e \right) \tag{2}$$

The buckling failure mode was considered according to the Euler formula, in such way that the gauge section thickness exceeds the critical thickness by at least 20%. Based on these analytical failure modes, the geometry was pre-dimensioned and refined with a FEM parametric analysis [19].

Such FEM parametric analysis showed that due to the combined loading, a stress gradient occurs through the thickness where the middle layers are on lower stresses levels than the outer layers. Assuming that a maximum stress allowable is equal for each layer, stresses between the outer layers and the middle layers should be as even as possible in order to promote a synchronized failure through the gauge section thickness, leading to higher failure forces.

The increase in the coupon length (parameter l) does not influence the behaviour of the gauge section, but does reduce the mean shear stress between the tab and the UD core.

The increase in the gauge section length (parameter g) reduces the through-thickness stress gradient. In the same way the increase in parameter n related with the tab taper angle or the reduction of the tab modulus, reduces the stresses gradient through the thickness. The increase in the gauge section length and the reduction of the tab taper angle, both increase the possibility of the desired failure due to the cross sectional main stress. However, the freedom to select these parameters is limited by the risk of buckling of the gauge section.

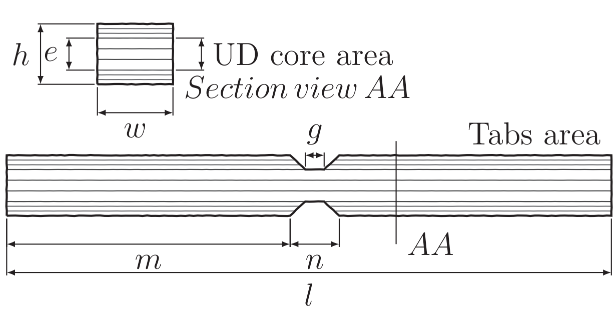

Fig. 1. Parametric coupon geometry.

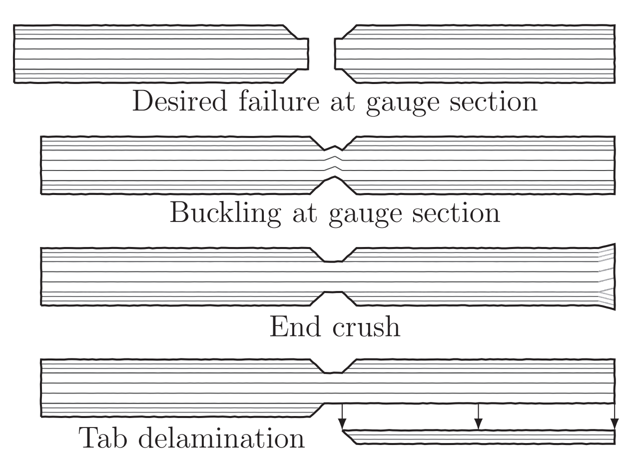

Fig. 2. Failure modes considered in the analytical geometry pre-dimension.