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Experimental identification of static and dynamic strength of epoxy based adhesives in high thickness joints

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ABSTRACT

Epoxy based adhesives already have a long history in structural joining. Commonly with this type of adhesive, the bond layer is thin. However, as the thickness of a joint increases (e.g. over 10 mm), its structural properties may alter very much. In such a case, both the interfacial strength and the intrinsic adhesive strength need to be verified in static and dynamic conditions. This research work identifies joint strength using a mainly experimental procedure. Coupons are subjected both to quasi-static and fatigue loads at different conditions. In order to take into account the variability present in the experimental campaign, a probabilistic approach identifies the most appropriate failure criterion. The strength prediction method considers a statistical size effect in the strength of the material by considering not only the magnitude of the stress distributions, but also the volume over which these act. Both quasi-static and fatigue results are analysed using probabilistic tools, leading to quite fine results.
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1. Introduction

Joint design and structural adhesives technology have been the subject of much research work. Extensive literature is available discussing both numerical and experimental approaches. A balanced selection of this can be found in Adams (2005), Banea and da Silva (2009), da Silva, Öchsner and Adams (2011), He (2011); da Silva and Campilho, 2012. In some sectors of industry however, the procedure for application of the adhesive is less accurate, mainly for economical reasons. A typical example is a wind turbine blade. Due to its large size, it is economically unfeasible to control dimensional tolerance to the order of millimetres. Wind turbine blades are made of three main components: the shear webs and the upper and lower shells with the spar cap (Jensen, 2008). As shown in Fig. 1(a), shear webs are commonly bonded to the spar cap by adhesive, as well as the upper shell to the lower shell. The bonded joint is a fundamental part of the structural integrity of the blade because the joint directly transfers shear loads due to shear force and to torsion from the spar cap to the shear webs. In addition, the joint is further subjected to normal stresses applied by the spanwise and flap-wise bending moments in the wing box.

Typical blade joints use paste adhesives with a thickness of several millimetres and a variable joint cross section geometry. Bonded joints with a thickness in the order of 10 mm are common in wind turbine blades, which induce a higher probability of the presence of voids and cavities (Griffin and Malkin, 2011; Galappaththi et al., 2013; Wetzel, 2009) in the bonding layer (Fig. 1(b)). These cavities in the bonded joint reduce the effective width of the adhesive, and therefore the capacity of transferring structural loads is reduced. Moreover, these voids increase average effective stresses and they also create stress concentrations. The former effect may trigger crack initiation, leading to premature failure in quasi-static conditions, while the latter effect reduces joint resistance in fatigue.

Despite the availability of extensive literature, there is still a considerable lack of knowledge in the understanding of both bulk adhesive and bonded joint behaviour, particularly in the case of large thickness adhesive bonds. The aim of the present work is to study the behaviour of both adhesive and bonded joint both experimentally and numerically for the structural requirements of a wind turbine blade. For that purpose, Section 2 gives an overview of the defined experimental campaign, it describes the manufacturing of the different coupons and the process for the definition of the bonded joint specimen geometry is defined. Then, in Section 3 the experimental campaign procedure and the obtained results are presented. Finally, Sections 4 and 5 analyse numerically

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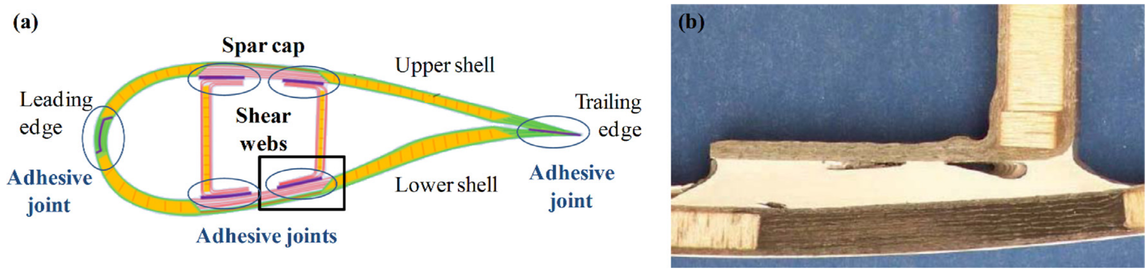

Fig. 1. (a) Typical wind turbine blade cross section and (b) cross section of the adhesive joint from spar cap to shear web in detail (Griffin and Malkin, 2011).

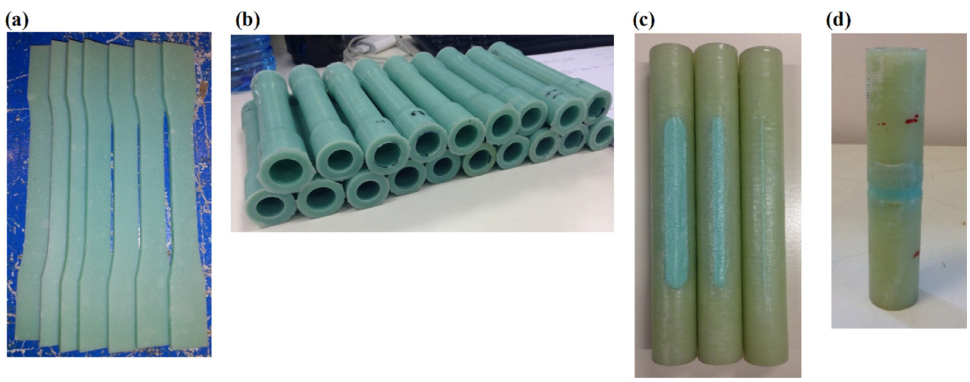

Fig. 2. Specimen geometries: bulk adhesive (a) dog-bone shape, (b) hollow cylindrical and bonded joint (c) specially designed hollow cylindrical, (d) butt joint hollow cylindrical.

Table 1
Summary of the experimental campaign for bulk and bonded joint coupons.

Material	Test type	Coupon geometry
Bulk adhesive	Quasi-static tests in uni-axial tension	Fig. 2(a)
	Quasi-static tests in torsion	Fig. 2(b)
	Quasi-static tests in combined tension and torsion	Fig. 2(b)
	Fatigue tests in tension and in torsion	Fig. 2(a) and (b)
Bonded joint	Quasi-static tests in combined tension and torsion	Fig. 2(c)
	Fatigue tests in torsion	Fig. 2(d)

the generated data. In particular, the need for a probabilistic approach is discussed. Both quasi-static and fatigue results are analysed using probabilistic tools, leading to quite fine results.

2. Experimental campaign definition and coupons manufacturing procedure

2.1. Experimental campaign definition

The definition of the test campaign is inspired by the application on wind turbine blades, but results could be transferred to other applications as well. In wind turbine blades, shear stress is combined with normal stress along the length of the adhesive joint. Thus, different stress state levels are tested with the objective to obtain a full stress state map to be able to compare to the stress state in the blades and the failure criteria described in Section 4.

In order to characterise the adhesive material in both, uni-axial and bi-axial states of stress, together with quasi-static and cyclic loading, two levels of tests are performed. First bulk adhesives were tested, and second the bonded joint. The adherend is a glass-fibre reinforced composite. In the case of bonded joints, a particularly designed specimen shape is used as shown in Fig. 2(c). Section 2.3 explains the background of the development of this specimen. Both the former and the latter levels are again split up in two sublevels, each with its own type of specimen.

Table 1 summarises the experimental campaign while Fig. 2 shows the different coupon geometries.

The dimensions of the specimens are summarised in Table 2.

2.2. Manufacturing process of bulk coupons

The selected bonding paste for all tests is a two-component adhesive from Momentive/Hexion. This is an epoxy based polymer which includes a glass filler that is suitable for application on vertical surfaces. The resin is Epikote BRP 135 G 3 and the hardener is Epikure BPH 137 G. The adhesive is approved by Germanischer Lloyd (GL) standard for use in wind turbine blades. It has a high viscosity, which affects coupon manufacturing as explained below.

The manufactured specimens are cured at different conditions (see Table 3), motivated by the ambition to derive some conclusions on the curing procedure and material quality. Some of them are cured in a climate chamber where fine temperature control is possible, while other coupons are cured in a common kitchen oven which does not allow an accurate temperature control (minimum temperature increments of 5 °C). On the other hand, before the curing process, some coupons are kept in a vacuum system for a limited period of time to try to reduce the porosity. And finally, some coupons are cured at different humidity conditions (30%, 60% and 90%).

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