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Fatigue behaviour of metal pin-reinforced composite single-lap joints in a hygrothermal environment

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ABSTRACT

In this study, the fatigue behaviour of stainless steel pin-reinforced cocured composite single-lap joints in a hygrothermal environment was experimentally investigated. Specimens were exposed to a temperature of 71 °C and a relative humidity of 85% until moisture saturation was achieved. Fatigue tests were conducted on the specimens in three different environmental conditions (RTD, room temperature and dry, ETD, elevated temperature and dry; and ETW, elevated temperature and wet). Tension–tension cyclic loads were applied to the specimens with a stress ratio of 0.5 and the maximum stress levels ranging from 50% to 90% of the static strengths of the joints. The results showed that the fatigue strength of a z-pinned joint at a million cycles of repeated loads was improved up to 48.3% compared to that of a joint without z-pins for the ETW condition.

1. Introduction

Because composite materials have excellent mechanical properties, such as high specific strengths and stiffnesses compared to existing metallic materials, their application range is expanding to various lightweight structures, such as aircrafts, automobiles and vessel structures. Particularly in terms of aircrafts, the application range of composite materials, which has been limited to secondary structures, such as control surfaces and doors in the past, is now expanding to the primary structures, such as bulkheads, spars, ribs and stringers [1–6]. Aircrafts made of composite materials such as the Boeing 787 or A350 that have been recently developed or are currently under development, represent typical examples of the trend because the portion of composite materials is more than 50% [4]. While the application range of composite materials is increasingly expanding, the joining methods of the parts are also changing from the existing mechanical joints to adhesive bonding [5,6]. The adhesive bonded joints do not require the fasteners such as a bolt, pin or rivet, and therefore the weight of the joints can be reduced [7]. In addition, by removing the fasteners, the local damages such as the rupture of fibres and the micro cracks which are generated during the fastener hole fabrication can be prevented.

Adhesive joining methods are generally divided into the cocuring and the secondary bonding. The cocuring does not use additional adhesive; it joins the composite structure through a single curing process by using the resin in the prepreg, which results in a relatively high joining strength, and can reduce the manufacturing cost. However, when the shape of the structure is complicated, it is difficult to produce the structure in one step by using the cocuring method. The secondary bonding can be used instead; in this method, two pre-cured parts are bonded through an additional curing process.

However, if composite laminated parts are assembled only by bonding, they may be vulnerable to through-thickness failures such as the delamination, intra-lamina failure, cohesive failure, debonding. These failures occur most commonly around the interface of the parts to be joined [8,9]. In particular, as the service environment changes to a hot and humid one, the mechanical properties of the matrix and the adhesive are significantly degraded, resulting in a reduced joining strength of the bonded joint [10].

To increase the through-thickness strength of bonded joints, various methods such as stitching, braiding, knitting, weaving or z-pinning have been studied [11–15]. Among these methods, the stitching may easily damage the fibres. The braiding, which tridimensionally weaves fibres, may degrade the strength of a structure due to the winding fibres. The z-pinning method is a typical technology that reduces the strength of structures less than other methods but also minimises the fibre damage and strengthens the through-thickness mechanical properties of the structures [16].

Experimental, analytical and numerical studies on the effects of the z-pinning method are in progress [17–25]. Grassi [17–18] suggested a numerical method that is capable of predicting failures in the z-pinned single-lap joint and predicted the effective stiffness of

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z-pinned laminate. Park et al. [19] experimentally studied the pull-off strength of composite bonded T-joints transversely reinforced by carbon pins. They showed that ultimate strength of the joint with a 4.0% pin density of 0.5 mm diameter pins increased by more than 70% compared with the unpinned joints. Yan et al. [20,21] performed numerical analysis for delamination strength of z-pinned composite plates. Chang et al. [22,23] conducted static and fatigue tests on the z-pinned plates and single-lap bonded joints under both room temperature and high temperature conditions. The work showed that z-pinning technology is effective in improving the strength of the single-lap joints.

When real structures are exposed to various temperatures and moisture environments during the operation, the degradation of the structural performance can become severe. The published studies on z-pinning have been primarily confined to room temperature conditions. In addition, to enhance the reliability of a long-life structure, studies are required not only on static failure but also on fatigue failure to build up the database of fatigue strength of the structures. However, the studies on the fatigue properties of z-pinned joints that consider various temperature–humidity environments are rarely found.

Therefore, in this study, we investigated the fatigue properties of a composite single-lap joint strengthened by stainless steel pins after it was exposed to various temperature–humidity environments. The diameter of a z-pin is 0.5 mm and its areal density is 2.0%. Three environmental conditions considered in the tests were RTD (20 ± 5 °C, 45–55% relative humidity (RH)), ETD(82 ± 3 °C, 45–55% RH) and ETW (82 ± 3 °C, wet). The fatigue tests were performed with a stress ratio of 0.5 and a frequency of 5 Hz. From the test results, we evaluated the fatigue strength at 10^6 cycles and identified changes in the fatigue life by using normalised *S–N* curves.

2. Test

2.1. Specimen preparation

The specimen configuration used in the study is illustrated in Fig. 1. The overall design of the specimen was based on the combination of the ASTM D3165-07 specification [26] with the ASTM D1002-01 specification [27]. The bonding length of the joint was 25.4 mm. The unidirectional prepreg from Toray, T700GC-12K-31E/#2510, was used as the base material to manufacture the specimens. The glass transition temperature of this material is 142 °C in a dry state, and 127 °C in a wet state. The thickness of a ply after curing is 0.152 mm. Not only the specimen but also its tabs were manufactured by applying the cocuring method. The manufactured specimen consists of 24 plies with a stacking sequence of $[45/0/-45/90]_{3S}$.

In this study, the z-pin was made of stainless steel STS304, which has an excellent corrosion resistance and heat resistance as well as excellent low-temperature strength and superior mechanical properties. As shown in Fig. 2, the pin diameter is 0.5 mm and its length is 7.2 mm. The length of the pin is equal to the thickness of the cured laminate. To easily insert the pin, the pin edges were processed in the form of wedges. The strengthening pins had an angle of 22.5° with respect to the fibre direction, as shown in Fig. 1, to avoid the generation of a resin channel that causes the degradation of in-plane properties [19]. The allocated pins occupy 2% of the bonding area.

The different types of tests and the number of the associated specimens are summarised in Table 1. In the case of an unpinned joint, which was not reinforced with pins, the number of specimens for tests in the RTD environmental condition was 11, for the ETD environmental condition was 14 and for the ETW environmental condition was 11. Additionally, we performed static tests on 6 specimens to obtain the strength recovery due to the water evaporation of the ETW specimen. In the case of the z-pinned joint, the number of specimens for tests in the RTD environmental condition was 15, for the ETD environmental condition was 8 and for the ETW environmental condition was 12.

2.2. Z-pinning

Fig. 3 illustrates the entire z-pinning process used to strengthen the joint. First, acrylic moulds were piled to form layers on the uncured laminate. Then, pre-processed pins were inserted into the holes. After inserting the pins into the holes of the acrylic mould, the pins were pushed into the first acrylic layer by using an ultrasonic horn. At this time, high frequency vibrations were produced in the ultrasonic horn, and these vibrations were delivered to the prepreg via the pins, resulting in the generation of heat in the prepreg. Due to the ultrasonic vibrations, epoxy resin turns into liquid locally, and it is available to easily push the pins in the through-thickness direction by manually exerting a force onto them. After completing the insertion of the pins and the removal of the first acrylic layer, the pins were then projected down again with a depth the same as the thickness of the acrylic layer that was previously removed. Then, the pins were inserted repeatedly by using ultrasonic waves until they were inserted and pushed to the end of the prepreg. In the existing UAZ (Ultrasonically Assisted Z-fibre) technology, a foam supports the pins, and when the pins are inserted by using the ultrasonic horn, the foam melts and sticks on the pin, possibly leading to the insertion of foreign substances. In the process of cutting the projecting pins, local damage to the prepreg may occur such that it triggers degradation in the mechanical properties. In this study, by using acrylic layers instead of the foam, it is not likely that foreign substances are inserted in the process of

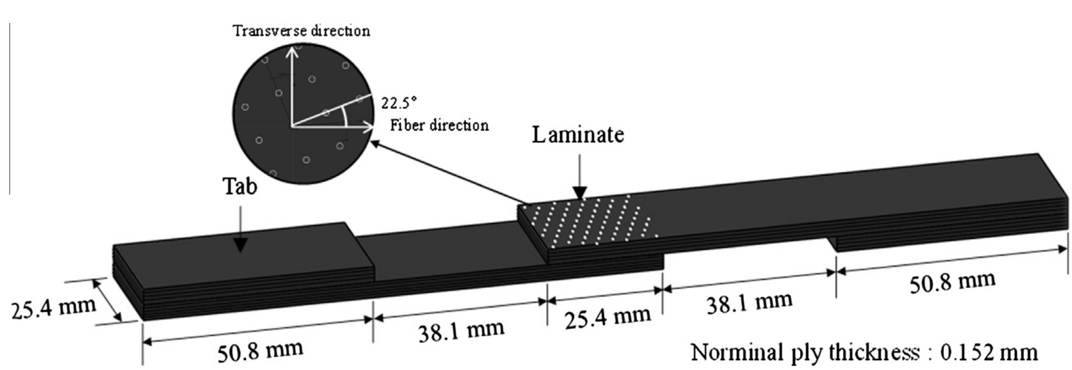

Fig. 1. Specimen configuration.