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Failure of Tapered Composites Under Static and Fatigue Tension Loading

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One glass fiber-epoxy and two carbon fiber-epoxy rapidly tapered sections with dropped 0- and ±45-deg plies have been designed, manufactured, and tested. Under static loading, close to net section tensile strength was achieved. The glass fiber taper also achieved net section strength under tension fatigue loading, but the carbon fiber tapers showed a significant reduction in fatigue strength due to delamination from the ends of the terminating 0-deg plies. The most significant factor controlling strength is the number of plies dropped together. Unidirectional dropped plies are much more susceptible to delamination than ±45-deg plies. Satisfactory strength predictions can be made for both static and fatigue tension loading based on net section stresses and a simple equation for the strain energy release rate. This approach looks promising as the basis for a general method for designing tapered composites.

I. Introduction

TAPERED sections involving the progressive dropping of plies are prone to delamination, especially under fatigue loading. Such tapered sections are very commonly used to achieve changes in thickness. A typical example is a helicopter rotor blade, where increased thickness is necessary near the root. Normally a short tapered transition region is desirable. However, due to the lack of reliable methods for predicting delamination, a very gradual taper is usually used.

A number of authors have investigated static strength of tapered laminates.[1–8] However, there is no consensus on how to predict failure. Various approaches have been proposed based on maximum stresses,[2] stresses averaged over a distance,[6] stresses evaluated at a characteristic distance,[8] and strain energy release rates.[5] Several investigations on tension fatigue of tapered specimens have been published.[9–11] The problem of predicting fatigue strength has not received very much attention, although in the latter study a method was proposed for predicting onset of unstable delamination based on strain energy release rate analysis.[11]

A program of research has been undertaken at Bristol University to investigate failure in tapered composites under static and fatigue loading. A series of tests on very simple symmetric specimens have enabled failure mechanisms to be studied.[12] Much of the work has been on unidirectional material, avoiding some of the potential problems with edge effects. It has been found that the dominant failure mechanism for these specimens is delamination initiating above and below the ends of the terminating plies and propagating into the thick section along the interface between continuous and discontinuous plies. The results have indicated that the most important parameter affecting failure is the strain energy release rate associated with the terminating plies.

Based on this work, a method has been proposed for predicting static strength of tapered specimens. A simple equation is used for calculating the strain energy release rate. This is then compared with a value of fracture energy deduced from a tension test on a constant thickness unidirectional specimen with the central plies cut across the complete width. Satisfactory correlation has been obtained for tapered unidirectional glass fiber-epoxy specimens under static tension and compression loading.[13]

Tension fatigue tests on similar specimens have shown that the failure mechanisms are similar to those under static loading.[14] However, delamination propagates immediately, and so it is necessary to consider delamination rates. This suggests that a similar approach could be used for predicting fatigue strength as for static strength, based on the simple equation for the strain energy release rate and experimental data for delamination rates. Fatigue data could be obtained from tension tests on the same constant thickness unidirectional specimens with cut central plies as used in the static tests to measure fracture energy.

To assess the validity of this approach for more realistic tapered geometries involving ±45-deg as well as 0-deg dropped plies, three types of rapidly tapered specimens have been produced and tested. The tapers have been designed to achieve maximum strength under both static and fatigue tension loading. This paper presents the results of the tests carried out on these specimens to determine strength and investigate failure mechanisms. Comparisons are made between predicted and measured strengths, and it is found that correlation is good for both static and fatigue loading.

II. Design of Tapered Specimens

Three symmetric specimens were designed, each with a thick section at both ends and two tapers down to a central thin section. The sections were designed with thickness ratios typical of those at the root of a helicopter rotor blade. One carbon fiber-epoxy and one glass fiber-epoxy specimen were designed for maximum strength with a rapid taper angle. Calculations indicated that these were both likely to fail as a result of fiber breakage under static loading, and so a second carbon epoxy specimen was designed deliberately to delaminate to validate the delamination predictions. The same number of plies were used but dropped in a different way. The taper angle was also changed to be more shallow. This was done to demonstrate that the angle is not the critical factor determining failure.

Figure 1 shows schematically one end of the tapered glass fiber section. There are eight 0-deg plies in the thin section. The thick section contains eight 0-deg and six pairs of ±45-deg plies. This gives a transition from a nominal thickness of 2.5 mm down to 1 mm. To maximize strength, the ±45-deg plies were dropped in six single pairs, with continuous interleaving 0-deg plies between them. Plies were dropped symmetrically in three steps, with the plies closest to the midplane terminating at the thin end. To investigate the effect of the taper angle, different values of the distance d between dropped plies were used at each end of the specimen. At one end a spacing of 1 mm was used, producing a tapered section only just over 2 mm long, with a theoretical angle between the outside surface and the centerline of about 16 deg. A spacing of 2 mm was used at the other end, producing a tapered section of just over

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