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Failure mode shifts during constant amplitude fatigue loading of GFRP/foam core sandwich beams

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ABSTRACT

This paper presents fatigue results for sandwich beams that exhibit a transition in failure mode, from core shear failure to face laminate tensile failure, as function of load amplitude only. The basis of this are fatigue tests of foam cores in shear and tensile tests on composite laminates. These results show that the slopes of the stress–life (*S*–*N*) relation are different for the core and laminates. By using the obtained stress–life relations, a simple design scheme is given for sandwich beams which are anticipated to have a transition of failure mode for a particular load level. Two designs are manufactured and tested in fatigue under constant amplitude loading. The results clearly show the aim of investigation with transitions in failure modes giving a structural stress–life diagram a bi-linear shape. For high load and small number of cycles to failure, the beams fail by core shear fracture while for lower loads, and large number of cycles to failure the beams fail by face sheet tensile failure.

1. Introduction

Sandwich structures offer many potential advantages such as high relative stiffness and strength to weight ratios which is utilised in many weight critical applications. A challenge in the design of sandwich structures is to accurately predict the many potential modes of failure that may occur. Two of the most obvious competing failure modes in the design of simple sandwich beams and panels are face tension/compression fracture and core shear failure. For static loading conditions, one can actually choose which failure mode should be active by appropriate design of the beam or panel, simply by ensuring that the load required for one failure mode is sufficiently higher than for the other(s). In shipbuilding for example, this is commonly utilised. Underwater hull panels in composite sandwich ships are normally designed so that core shear failure appears before fracture of the laminates. In this way, the panel can fracture, but still be watertight. In fatigue loading, the design towards particular failure modes is slightly more complex, and this is what this paper deals with.

An industrial sector where fatigue of composite laminates is very important is in wind power. Many wind turbine blades are made from glass NCF's and fatigue is one of the main design constraints [1]. There is a very comprehensive investigation of fatigue of laminates for wind turbine applications made by Nijssen [2]. There are some constant amplitude data in there, though most of the work focuses on spectrum fatigue loading.

Some early work on fatigue of foam core sandwich structures were performed by Burman and Zenkert [3,4], Shenoi et al. [5], Kanny et al. [6,7] and Kulkarni et al. [8]. They all used beam bending tests, designed for core shear failure, to find the fatigue response of foam cores subjected to shear loading. The testing resulted in stress–life relations for various polymeric foam cores. In [9] the authors used an initial flaw approach model through which the crack propagation data could be transformed to stress–life curves. The model gave excellent agreement with measured crack propagation data and tension–tension fatigue testing results for two closed cell polymer foams, the same two foams used herein. In a subsequent investigation, the fatigue behaviour of Rohacell WF-foams in tension, compression and shear was investigated [10]. It was found that the slope of the stress–life curve was different for different load cases and relative densities.

Since sandwich structures also can fail by face sheet failure, the fatigue behaviour of the face sheet laminates also needs to be established. There exists quite a lot of information about fatigue of composite laminates in the literature, albeit more limited concerning laminates made from so called non-crimp fabrics (NCF's). Shah Kahn and Mouritz [11] compared stitched and non-stitched composite laminates and concluded that the stitching has a negative influence on the tensile fatigue performance. The same conclusions were drawn from a later investigation [12]. Gagel et al. [13,14] studied the formation of cracks and stiffness degradation of glass–fibre NCF-laminates subjected to tensile fatigue loading concluding that some of the micro-crack formation processes are the same as under quasi-static loading. They also developed a model for the mechanical degradation under fatigue loading.

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Vallons et al. [15,16] studied the formation of micro-cracks in carbon fibre NCF-laminated under fatigue loading. They used Acoustic Emission (AE) techniques and X-ray imaging to study micro-cracks and experimental measured the stiffness degradation. An interesting finding was that for a $[+45/-45]_s$-laminate the fatigue endurance limit (the strain under which there is an apparent infinite fatigue life) can be found from the linear part of the stress–strain relation in a simple tensile test. For $[0/90]_s$ it seems that the fatigue endurance limit is well above the stress level for damage initiation under static loads. Aono et al. [17] performed tension–tension and tension–compression fatigue experiments on $[+45/-45]$ NCF-laminates. There are two interesting observations from this work; testing at $R = -1$ gives higher fatigue life than at $R = 0.1$, and the failure modes are different. In a subsequent paper, Aono et al. [18] also studied glass–fibre NCF-laminates and used replica methods to monitor fatigue damage progression under tensile fatigue loading. They found that damage was first initiated near the stitches, in resin rich regions.

This paper will not deal with a detailed description of the fatigue damage progression but will study fatigue as a design problem. It is rationalised that even if a sandwich structure is designed to fail with a given failure mode (e.g. core shear failure) under quasi-static loads, the failure mode can shift (to e.g. face sheet failure) under fatigue loading. The foundation for this hypothesis is that the slope of the stress–life relations for different failure modes can be different. Thus, the same sandwich structure, with the same material combination, under the same loading condition, but with different loading amplitude, can have different failure modes in fatigue.

2. Materials

Two high performance rigid polymer foams with closed cell structure were used in this study; Divinycell H-grade and Rohacell WF-grade. Divinycell is a cross-linked rigid cellular PVC foam and it is produced in a variety of densities where mechanical properties (higher strength and moduli) increase with density. The quality used here was H100, with a nominal density of 100 kg/m^3. Any details on this material can be found in [19]. The other core material used in this study is Rohacell, a PMI foam with predominantly closed cells but is more brittle than the PVC foam. The quality used herein was WF51, where WF is the particular grade of Rohacell and the number corresponds to the nominal density in kg/m^3. Details on this material can be found in [20]. The reason for choosing these two materials is that one exhibits a fairly brittle behaviour (Rohacell) in the context of foams and the other (Divinycell) has a more ductile behaviour (higher strain to failure, a more pronounced plastic regime). They further exhibit different behaviour in fatigue. Both materials are close to being isotropic, with only small variations in moduli and strengths in the in-plane and out-of-plane directions.

The laminates used herein were made from glass–fibre NCF fabrics of the type DBLT-850-E10 [21]. This is a quadriaxial non-crimp fabric (NCF) with approximately equal amount of fibres,

Table 1
Basic material data for the material used.

	WF51	H100	Laminate
E (MPa)	75	126	15,000
G (MPa)	27	40	-
σ_1 (MPa)	1.6	3.3	310
τ_{yield} (MPa)	0.66	1.13	-
τ_{failure} (MPa)	0.77	1.21	

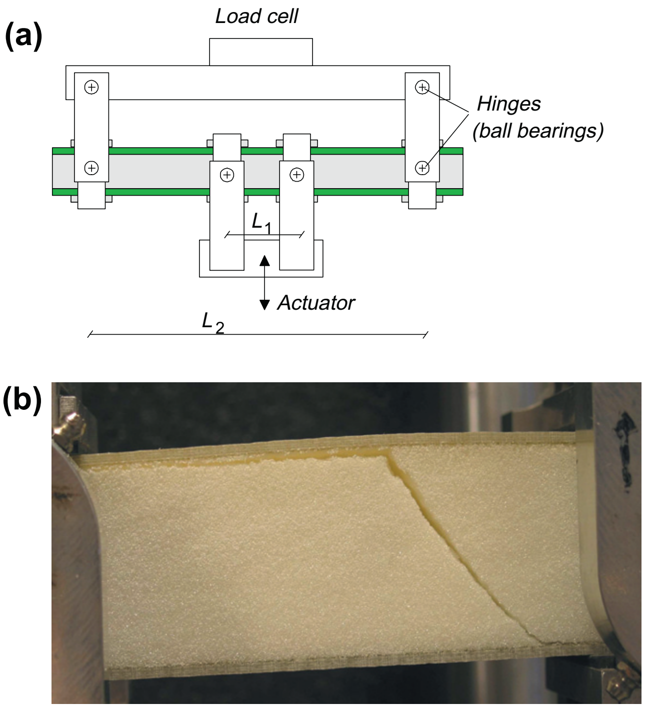

Fig. 1. (a) Schematic set-up for fatigue testing of foams using four-point bending test. (b) Photograph of a fractured WF51 test specimen in the test rig.

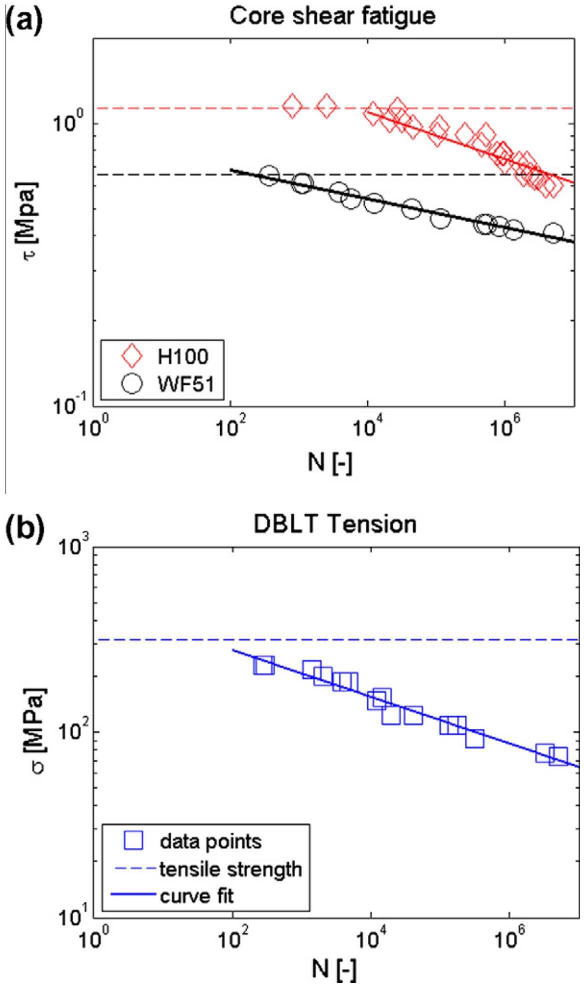

Fig. 2. (a) Shear fatigue data for H100 and WF51 core and (b) tensile fatigue data for the DBLT laminate in tension.