Composite Structures 113 (2014) 31–39

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

High cycle fatigue under reversed bending of sandwich panels with GFRP skins and polyurethane foam core

Hale Mathieson [a], Amir Fam [b,*]

[a] Department of Civil Engineering, Queen's University, Canada
[b] Donald and Sarah Munro Chair Professor in Engineering and Applied Science, Department of Civil Engineering, Queen's University, Canada

ARTICLE INFO

Article history:
Available online 28 February 2014

Keywords:
Fatigue
Sandwich panel
Foam core
FRP skin
Reversed loading

ABSTRACT

The effect of fully reversed loading ($R = -1$) on high cycle fatigue performance of sandwich panels composed of polyurethane foam core and Glass Fiber Reinforced Polymer (GFRP) skins is studied and compared to that of similar panels tested under fully unloaded ($R = 0$) conditions. Fatigue life curves are established and compared based on maximum loads of 30–70% of the ultimate monotonic strength (P_{ult}). It was shown that panels consistently fail in shear of the foam core. The fatigue life reduces significantly at $R = -1$, to about 10% of that at $R = 0$. In order to achieve at least 2 million cycles – the commonly acceptable fatigue life in structural engineering – the maximum service loads should be limited to 30% and 45% of P_{ult}, respectively, for the cases of $R = -1$ and $R = 0$. It is estimated that the threshold loading levels at infinite fatigue life are 23% and 37% of P_{ult}, for the cases of $R = -1$ and $R = 0$, respectively. By the end of fatigue life, up to 25% reduction in stiffness occurs. The transition between high and low cycle fatigue occurs between 200 and 5000 cycles. A 3-D Haigh diagram is also established for design purposes.

1. Introduction

The use of Glass Fiber Reinforced Polymer (GFRP) composites in structural application is increasing due to several advantages, including primarily durability against environmental exposure and high strength-to-weight ratio [1]. Sandwich panels utilize flexural strength of a system composed of outer stiff skins spaced by a softer core of low density [2,3]. Spacing between skins is increased to improve flexural resistance, thermal insulation, and minimize relative slip from shear transfer [4]. Softer foams can be better insulators and will generally result in better continuous strain transfer, minimizing de-bonding failure. However, this will result in serviceability concerns due to high transverse shear strains, unless ribs connecting the skins are used [5].

Fatigue is a critical serviceability design concern in response to repetitive non-critical loads [6]. Previous research on sandwich panels revealed that soft cores, rather than the skins, may govern fatigue life through shear failure [7]. The most common method to represent fatigue response is using a Wöhler curve (also known as *S*–*N* curve) [8]. Developing an *S*–*N* curve requires cycling loading between consistent maximum and minimum stress levels (S_{min} and S_{max}) until failure occurs at a specific number of cycles (N_f). The mean stress (S_{mean}), stress amplitude (S_{amp}) and loading ratio (R) can be calculated by relating S_{min} and S_{max} as shown by Eqs. (1)–(3). For *S*–*N* curve development, all the tests should have a consistent loading ratio (R).

$$S_{mean} = \frac{S_{max} + S_{min}}{2} \tag{1}$$

$$S_{amp} = \frac{S_{max} - S_{min}}{2} \tag{2}$$

$$R = \frac{S_{min}}{S_{max}} \tag{3}$$

Previous work compared variable density cores as well as Carbon-FRP (CFRP) skinned panels to GFRP panels [5]. It was determined that the structural performance of the panels increased with core density, but insulation properties were dramatically reduced. Using lower density and better insulating foam, 9145 × 2440 × 78 mm cladding wall panels for building applications were designed and tested [9]. The ultimate capacity of the panel, at failure, showed a factor of safety of 2.6 for ultimate based on maximum wind gust loading in Canada. The code limit for service load deflection was reached at a load equal to 18% only of the capacity of the section. Further testing of these panels [10] investigated one-directional bending fatigue performance (i.e. under full load–unload fatigue cycles ($R = 0$)), where 15–20%

---

* Corresponding author. Tel.: +1 6135336352.
E-mail address: fam@civil.queensu.ca (A. Fam).

http://dx.doi.org/10.1016/j.compstruct.2014.02.027
0263-8223/

stiffness degradation was observed and a general *S–N* curve was developed. Another study examined fatigue behavior of sandwich panels at various frequencies [11].

This study investigates the fatigue and degradation performance of sandwich panels under fully reversed bending ($R = -1$), to simulate structural applications such as light weight continuous decking or flooring subjected to moving loads or wall panels subjected to wind pressure and suction.

2. Experimental program

This section provides details of test specimens, materials, test setup, procedure and instrumentation.

2.1. Test specimens

As shown in Table 1, a total of 10 specimens, including five 318 mm-wide panels (1220 × 318 × 78 mm), referred to as N1, D1, D5, D7 and D9, and five 635 mm-wide specimens, 1220 × 635 × 78, referred to as D2, D3, D4, D6 and D8, were tested. All specimens were composed of two GFRP skin layers of 1.55 mm thickness each, spaced at 75 mm by a low density polyurethane foam core. Control specimen N1 was loaded monotonically to failure in one direction. As shown in Fig. 1(a), all the remaining specimens were tested under fully reversed cyclic loading ($R = -1$) up to certain maximum loads of various percentages of the ultimate static load of N1, as follows (see Table 1): D1 to 70%, D2–D4 to 60%, D5 to 50%, D6–D7 to 40%, D8 to 35% and D9 to 30%. Specimens D2–D4 were repetitions of the same parameter, same with D6–D7. The results from this study will also be compared with other identical specimens C1–C7 tested by the authors in another study [11] under un-reversed bending fatigue (i.e. $R = 0$) at various maximum load levels of 45–70% [11] (Fig. 1(b)).

Table 1
Summary of test matrix and results.

ID	Maximum load			Cycles to failure (N_f)
	Applied (kN)	Equivalent (kN)	% Age of static	
N1	14.55	7.28	~100	0.5
D1	10.12	5.06	70	5089
D2	4.34	4.34	60	8872
D3				15,893
D4				22,428
D5	7.23	3.61	50	46,208
D6	2.89	2.89	40	297,936
D7	5.78			134,498
D8	2.53	2.53	35	724,090
D9	4.34	2.17	30	2,358,795

2.2. Materials

Prefabricated Corafoam U020 polyurethane foam blocks with a density of 31.6 kg/m^3 [12] were used for the core. Fig. 2(a) shows the normal stress–strain relationship of the core material, while Fig. 2(b) shows the shear stress–strain of the core [12]. Each of the skins consisted of one layer of woven E-glass/epoxy resin. Fig. 2(c) shows the normal longitudinal tensile and compressive stress–strain curves for the GFRP skins [12].

2.3. Test frame

As depicted in Fig. 3, a specialized test frame was designed with the intent of inducing four-point bending fatigue with the ability to

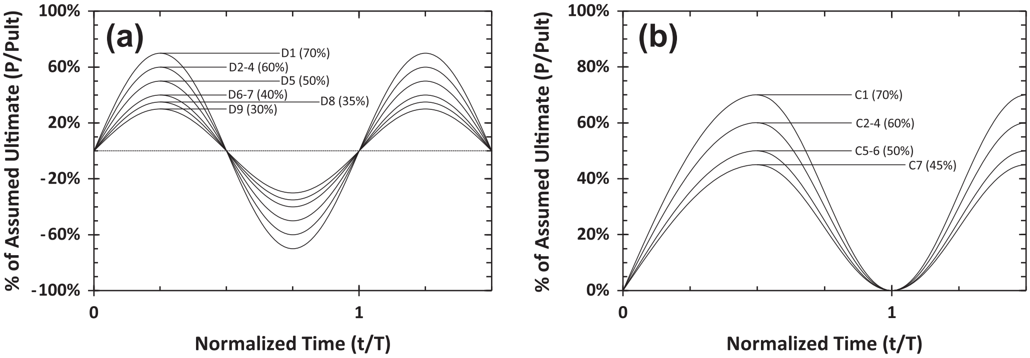

Fig. 1. Normalized applied loading ranges and rate for (a) $R = -1$ and (b) $R = 0$ [11].

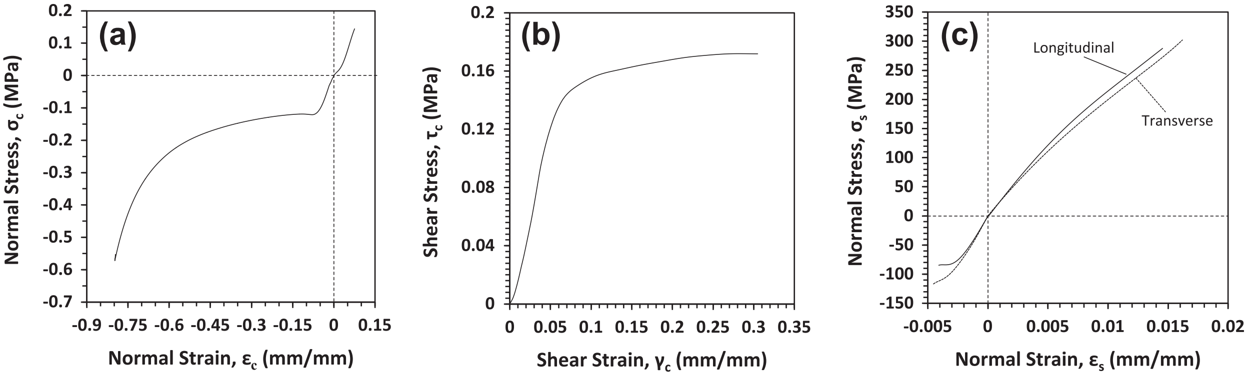

Fig. 2. Stress–strain behavior for polyurethane core under (a) axial tension, (b) in shear and (c) axial stress–strain curves for GFRP skin in tension and compression.