Composite Structures 160 (2017) 560–573

Contents lists available at ScienceDirect

Composite Structures

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

Adhesively-bonded GFRP-glass sandwich components for structurally efficient glazing applications

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ARTICLE INFO

Article history:
Received 5 August 2016
Revised 30 September 2016
Accepted 18 October 2016
Available online 18 October 2016

Keywords:
Adhesively-bonded connection
Analytical models
Glass
Glass fibre-reinforced polymer
Composite sandwich structure

ABSTRACT

Composite sandwich structures made of thick glass face sheets adhesively-bonded to glass fibre-reinforced polymer (GFRP) core profiles have the potential to outperform existing non-composite glazing configurations but their feasibility has yet to be investigated and there are no analytical models that describe their structural response. This paper presents the new analytical models for predicting deflections and strains in adhesively-bonded GFRP-glass sandwich beams. The new analytical models successfully account for: the shear deformations of the core and adhesive layers; the local bending of the constituent parts about their centroidal axes; and the global bending of the sandwich component as a whole. The deflections and strains predicted by analytical models are validated by finite element simulations and compared with the results of destructive tests performed on adhesively-bonded GFRP-glass beams in a four-point bending configuration. The analytical models were also evaluated for alternative GFRP-glass configurations tested by others. The GFRP-glass beams specially assembled in this study confirm the physical feasibility of constructing these proposed components.

1. Introduction

1.1. Motivation

Sandwich structures are layered components generally made of two thin, dense and stiff face sheets (traditionally metal or fibre-reinforced polymer laminates) separated by, and structurally bonded to, a thick, low density and less stiff core layer (traditionally metallic honeycomb, foam or balsa core). This arrangement results in a lightweight structure with much greater flexural rigidity than the sum of the individual constituent layers. Sandwich structures are therefore adapted for resisting bending loads, e.g. wind loads acting on building envelopes. In fact, sandwich components in building envelopes date back to the 1950s, when prefabricated lightweight and opaque sandwich panels, e.g. made of steel or aluminium face sheets adhesively-bonded to resin-reinforced paper honeycomb, were widespread in the American building construction market [1]. Over the last decades, the design intent of maximizing the transparency of building envelopes has increased the interest of architects for polymer-based sandwich components exhibiting different degrees of light transmittance. For short-span building applications, low-cost prefabricated sandwich components can be designed with transparent and high-durable unreinforced polymers, e.g. acrylic honeycomb cores bonded to outer acrylic face sheets [2]. However, the fabrication of large-span translucent sandwich components commonly requires laborious and costly hand lay-up processes, e.g. hand-laminated sandwich components made of an orthogonal grid of glass fibre-reinforced polymer (GFRP) core-webs and outer GFRP face sheets [3] [4]. Furthermore, in such GFRP sandwich components it is often necessary to fill the grid with opaque foam blocks (to prevent buckling of webs and face sheets) and to paint external surfaces (to improve the long-term durability) – thereby reducing or eliminating the light transmittance of the structures [3,4].

It is possible to devise load-bearing sandwich structures for building envelopes which simultaneously provide a high degree of transparency, structural efficiency, durability and thermal performance. In their most basic form these would consist of two monolithic and thick glass face sheets structurally bonded to GFRP pultruded core profiles (Fig. 1). In this configuration, light transmittance is largely unimpeded, the GFRP material is effectively protected from weathering and the air cavity between the two face sheets offers potential for high thermal insulation. This GFRP-glass sandwich concept involves a radical shift from the current use of glass in buildings envelopes – from its traditional use as inefficient infill panel to a robust and structurally efficient load-bearing component.

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http://dx.doi.org/10.1016/j.compstruct.2016.10.059
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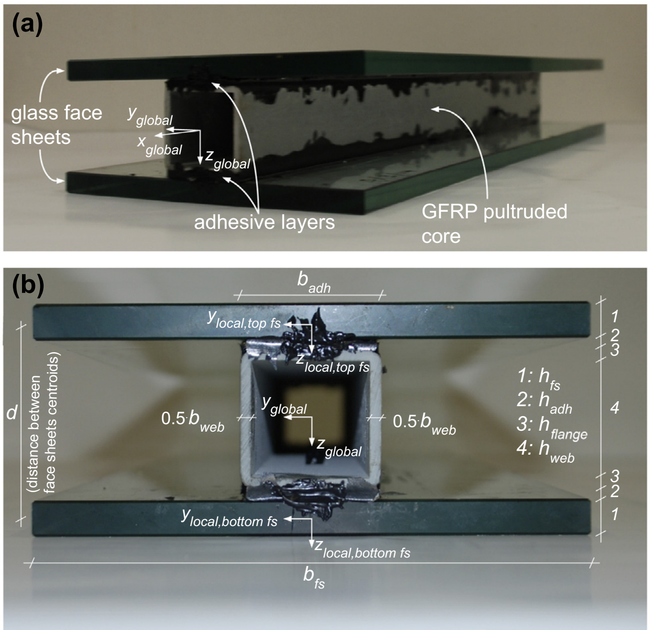

Fig. 1. (a) General view and (b) cross-section of the proposed adhesively-bonded GFRP-glass sandwich beam referred in the following as GFRP-DP490-glass beam.

1.2. Literature review

The idea of bonding fibre-reinforced polymers to glass components is not in itself new. Palumbo et al. [5] and Louter et al. [6,7] performed experimental research on glass beams reinforced in the tensile zone with adhesively-bonded fibre-reinforced polymers. Wurm [8] performed a basic experimental study of sandwich structures for facade applications made of pultruded GFRP core profiles adhesively-bonded to thin glass face sheets. Peters [9] and Knippers [4] investigated experimentally the feasibility of fabricating adhesively-bonded GFRP-glass façade panels and built mock-up specimens using structural adhesives DC993 (silicone) and 3M DP490 (epoxy). Polymeric foils made of TSSA (structural silicone) and SentryGlas® (ionomer) might be also candidate adhesives for bonding GFRP and glass components however autoclave lamination processes are required to produce the connection [10]. Tomasi et al. [11] concluded from the numerical modelling of GFRP-glass facades that adhesives with elastic modulus $E > 0.2$ GPa are required to achieve high degrees of composite action between GFRP and glass constituents. However adhesives that are sufficiently stiff to mobilise significant composite action, yet flexible enough to reduce stress concentrations and therefore minimize the risk of premature glass or adhesive failure, could provide an optimal solution for the design of safe and efficient adhesively-bonded glass-GFRP sandwich structures. Overend et al. [12] showed that the load-bearing capacities of adhesive connections can exceed those of equivalently sized bolted connections. This is largely due to the fact that adhesive connections generate smaller stress concentrations than those in similarly sized bolted connections and in addition adhesive bonding does not involve processes that weaken the glass such as the flaw-inducing process of drilling or the difficulties associated with thermally toughening of glass in the vicinity of a bolt hole [13] [14].

The deflections of adhesively-bonded sandwich components subjected to transverse loads (e.g. wind loads) result from the contribution of two coupled responses described analytically by Allen [15]: a local response in which the cross-sections of core and face sheets bend independently of each other about their own centroidal axes and a global response in which sandwich cross-section bends as a whole about its centroidal axis. The former response produces bending moments and shear forces in the core and face sheets cross-sections, whose sum is termed local bending moment, M_{local}, and local shear force, Q_{local}, respectively; and the latter response produces a bending moment and shear force on the whole sandwich cross-section, referred to as global bending moment, M_{global}, and global shear force, Q_{global}, respectively. However Allen's work considers the adhesive layers to be thin and with a high shear stiffness and therefore assumes these layers to have negligible shear deformations (henceforth referred to as shear-rigid). Another model developed by Natterer and Hoeft [16] captures the deflections of sandwich structures with relevant shear deformations in the adhesive layers (henceforth referred to as shear-flexible) but disregards the shear deformations of the core. Recently Osei-Antwi et al. [17] developed an analytical model for predicting the deflections of sandwich beams with multilayer shear-flexible cores, however the model is based on classical sandwich theory and therefore assumes thin face sheets and disregards local bending moments [18]. Similarly Overend at al. [19] developed an analytical model for predicting deflections of three-glass-ply laminated units with shear flexible adhesive interlayers however external glass laminates were assumed to be thin and local bending moments were disregarded. In recent experimental investigations Correia et al. [20] uses classical Euler-Bernoulli beam theory to investigate the deflections of adhesively-bonded sandwich beams with glass cores and GFRP face sheets – however predictions largely mismatched the experimental results for beams bonded with shear-flexible adhesives. There is currently no analytical means of calculating the load-deflection response of a sandwich component that considers both the shear flexibility of adhesive layers and cores and the local flexural rigidities of cores and face sheets. However such a model would constitute a valuable tool for the preliminary design of adhesively-bonded GFRP-glass sandwich envelopes such as envelopes based on the component proposed in this study – and in combination with other analytical models (e.g. thermal heat transfer), the influence of sandwich materials and geometry on the structural and thermal performance of building envelopes could be easily assessed.

1.3. Objectives

The objectives of this research are to extend Allen's work to adhesively-bonded sandwich structures with shear-flexible adhesive layers and cores and to demonstrate the feasibility and structural efficiency of the proposed sandwich component for building envelopes made of two thick glass face sheets structurally bonded to thin-wall pultruded GFRP core profiles. This paper, firstly, presents the new analytical models of the cross-sectional flexural rigidities and shear stiffness specifically developed for predicting the deflections and strains of sandwich structures subjected to transverse loads. Secondly, the elastic and shear moduli of the polymeric materials required for fabricating the proposed sandwich component are characterized from single-lap shear experiments (for the adhesive) and burn-off experiments (for the pultruded GFRP profiles). Thirdly, the validity of the new analytical models is evaluated by comparison with the results obtained from numerical modelling and from experimental destructive tests of three nominally identical adhesively-bonded GFRP-glass sandwich beams (Fig. 1) subjected to four-point bending. The analytical models developed in this paper are also tested by comparison with the experimental results obtained independently by Correia et al. [20] for an alternative adhesively-bonded GFRP-glass sandwich configuration.