Composite Structures 110 (2014) 163–173

Contents lists available at ScienceDirect

Composite Structures

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

The mechanical performance of laminated hybrid-glass units

M. Overend [a,*], C. Butchart [a], H. Lambert [b], M. Prassas [c]

[a] *Glass & Façade Technology Research Group, Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK*
[b] *Eckersley O'Callaghan Engineers, Kingsgate, 1 Bravingtons Walk, London N1 9AE, UK*
[c] *Corning European Technology Centre, 7bis avenue de Valvins, 77210 Avon, France*

ARTICLE INFO

Article history:
Available online 22 November 2013

Keywords:
Laminated glass
Chemically strengthened glass
Post-fracture
Equivalent stiffness

ABSTRACT

Conventional laminated glass has a relatively low post-fracture strength and stiffness, which imposes several constraints on the structural use of glass in buildings. This paper proposes a new generation of laminated hybrid-glass units, built-up from plies of chemically strengthened glass, conventional polymer interlayers and heat treated/annealed glass, that aim to outperform conventional laminated glass units. The paper describes the experimental investigations on the novel laminated hybrid-glass units subjected to quasi-static out-of-plane loads and presents the corresponding analytical models developed to characterise the load–deflection response of the units, both in the unfractured and post-fractured states. The experimental data shows that laminated hybrid-glass units can achieve significant post-fracture stiffness and their post-fracture strength can equal or exceed the strength at first fracture. The analytical models are successfully validated and the equivalent shear modulus approach developed in this paper facilitates future numerical analysis and optimisation of these units.

1. Introduction

Laminated glass units are used in building, automotive and aerospace applications where the structural integrity of monolithic glass is deemed insufficient. The units consist of plies of monolithic glass, typically annealed or heat treated soda-lime silica glass, bonded together by polymer interlayers, typically Polyvinyl Butyral (PVB), Ethylene Vinyl Acetate (EVA) or SentryGlas Plus ionomer (SGP). The interlayers provide a degree of shear coupling between the glass layers, which governs the mechanical response of the unfractured laminated units. Upon glass fracture, the polymer interlayer adheres to the glass fragments and the composite action between two offers a degree of post-fracture (residual) capacity, which reduces the risk of human injury or loss of property. Typical applications are blast and impact resistant glazing, vehicle windshields, overhead glazing and "structural glass" installations.

Hybird-glass laminated units are known to provide a good balance between strength to first fracture and post-fracture stiffness [1,2], but determining the unfractured, and particularly the post-fracture, response of laminated glass is not a trivial task and draws on research in three areas which are reviewed briefly here.

1.1. Bulk material properties

Soda-lime-silica glass is a linear elastic material ($70 \leqslant E_g \leqslant 74$ GPa; $0.22 \leqslant \nu_g \leqslant 0.23$) that fails without any observable plastic deformation [1]. The tensile strength of glass is governed by the stress-raising surface flaws. Fast fracture occurs when the crack opening stress intensity K_I at the tip of the critical flaw exceeds a critical value K_{IC} (known as the critical stress intensity factor) [3]. However in the presence of humidity and when $0.33 < K_I/K_{IC} < 1$, flaws grow sub-critically until a flaw reaches a critical size that triggers fast fracture. This phenomenon, first characterised by Wiederhorn [4], forms the basis of the lifetime prediction of ceramics and has been researched extensively since the 1960s [5–7]. The tensile strength of glass can be enhanced by introducing residual compressive stresses in the surface regions of the glass which must be overcome by load-induced stresses before any crack growth can occur. The two established techniques for inducing a residual compressive stress in glass are:

1. Thermal treatment, wherein the glass is heated and quenched to produce a parabolic stress distribution through its thickness. The two grades of thermally treated glass are fully toughened (FT) glass with residual surface stresses in the order of 80–170 MPa and heat strengthened (HS) glass with residual surface stresses in the range of 24–52 MPa. The depth of the compressive zone is approximately $0.2h$ from the glass surface [1].
2. Chemical strengthening (CS), wherein the glass is immersed in a bath of potassium salts at approximately 400 °C, which causes the smaller sodium ions in the glass to be replaced by larger potassium ions, thereby creating a thin compressive layer (20–50 μm thick). Residual surface stresses in excess of 250 MPa may be achieved with soda-lime-silica-glass, however the most effective ion exchange occurs in alkali-alumino-silicate glass

---

* Corresponding author. Tel.: +44 (0)1223 332659; fax: +44 (0)1223 332662.
E-mail address: mo318@cam.ac.uk (M. Overend).

0263-8223/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2013.11.009

where residual surface stresses of up to 981 MPa have been obtained [1,8].

Glass edges are generally weaker than the far-field regions due to the presence of larger flaws [9] and reduced levels of residual stresses [10,11]. The edge strength will therefore govern the strength of the glass when the edges are exposed to high tensile stresses (e.g. in the 4-point bending test set-up adopted in this study (Fig. 1). Knowledge of the edge strength is therefore essential for predicting the transitions between the unfractured and the fractured states, but the fracture strength is not the primary focus of this study and will not be discussed further.

Polymer interlayers typically used in laminated glass assemblies (PVB, SGP, EVA) are viscoelastic in nature, i.e. their stiffness is sensitive to both temperature and load duration. However the response of the interlayers can be approximated by an equivalent Young's modulus equal to the secant modulus for the relevant load duration or temperature. The errors from this approximation were shown to be negligible when the interlayer strains are small [12,13]. The secant modulus can be found by interpolation from tables published by interlayer manufacturers. For the load durations adopted in this study the equivalent elastic modulus for PVB is $2.52 \times 10^6 \leqslant E_{\mathrm{PVB}} \leqslant 4.92 \times 10^6$ Pa [14] and $4.26 \times 10^8 \leqslant E_{\mathrm{SGP}} \leqslant 5.85 \times 10^8$ Pa for SGP [15].

1.2. Unfractured response of laminated units

The research on the flexural response of unfractured laminated glass units dates back to the 1970s, and forms part of the wider research efforts on sandwich structures, which have in turn been studied since the mid-20th century [16,17]. A detailed account of these publications is beyond the scope this paper, and may be found elsewhere [18,19]. Only salient developments will be described here.

Newark derived a mathematical model for composite beams with thick and stiff faces connected by an intervening layer of negligible thickness that transfers shear across the interface [20]. A similar approach was taken by Hooper [21] who derived a mathematical model for the bending of 2-ply laminated glass subjected to 4-point bending. He did so by solving the governing differential equation for the interfacial shear force by Laplace transform. He concluded that the shear coupling is very sensitive to the shear stiffness of the interlayer which is in turn a function of load duration and temperature. From this early research it became evident that the mechanical performance of a laminated glass unit is a function of the flexural rigidity and the shear rigidity of the unit. The latter is associated with longitudinal shear deformations in the interlayer, which provides a degree of shear coupling between the glass layers. This gives rise to two limiting responses: (a) unrestrained shear deformation, known as the layered limit, which is equivalent to free sliding glass plies and (b) negligible shear deformation, known as the monolithic limit, where plane sections remain plane across the plies. From experiments on PVB-laminated glass beams Behr et al. [22] concluded that at room temperature and short load durations the response of the laminated beams approached the monolithic limit. Allen [23] did not specifically work on laminated glass, but he decoupled the bending deformations and the shear deformations for sandwich panels with various boundary conditions. This approach is attractive because a direct relationship can be drawn between every term in Allen's equations and the physical response of the sandwich panel, furthermore the formulations are particularly simple for sandwich panels with thin faces. This is fundamentally identical to the approach taken by Norville et al. [24] and Wölfel–Bennison (summarised in [25]) who developed engineering mechanics models to determine the effective section modulus of laminated glass and the shear coupling between the glass plies, respectively. This Wölfel–Bennison approach has been adopted by both the American [26] and European [27] standards for the design of laminated glass.

The above-mentioned methods involve solving the differential equations, which is generally simple, but requires an a priori knowledge of the bending movement M and the shear force Q at the point of interest on the glass surface and they are therefore confined to statically determinate structures. Vallabhan et al. [13] proposed a method of wider applicability, for determining the flexural response of statically determinate and indeterminate laminated glass. This involves the derivation of five differential equations and their boundary conditions by minimising the potential energy in the glass plates and the interlayer. The differential equations are subsequently solved numerically by means of the finite difference method. More recently, Asik and Tezcan [18], Galuppi and Carfagni-Royer [25], and Foraboschi [19] used variational methods to develop exact mathematical models for the flexural response of laminated glass. These models are more complex, but they do not require an a priori knowledge of the bending moment and shear force and are therefore valid for statically indeterminate cases. Galuppi and Royer-Carfagni [12,25] also showed that the Wolfel-Bennison approach leads to significant errors when used for statically indeterminate laminated glass units.

In practise the flexural response of unusual or high-profile installations is determined by means of numerical models performed in commercially-available finite element analysis (FEA) software, but this still requires knowledge of the bulk material properties.

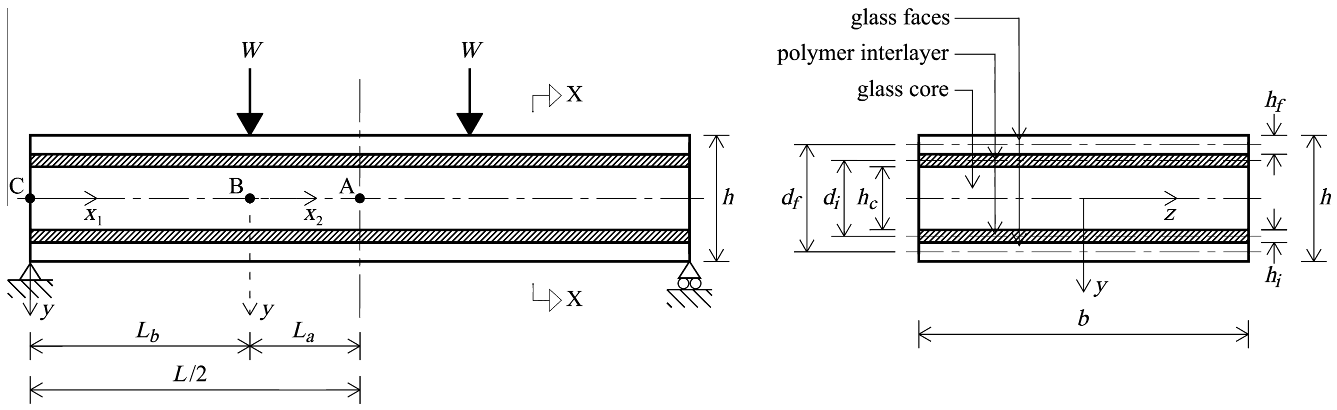

Fig. 1. Laminated glass unit in four point bending (4PB) test set-up.