



Experimental analysis of adhesion phenomena in fibre-reinforced glass structures



Emanuela Speranzini ^{a,*}, Stefano Agnetti ^a, Marco Corradi ^{a,b}

^a Department of Engineering, University of Perugia, via Duranti n. 93, 06125 Perugia, Italy

^b Department of Mechanical & Construction Engineering, Northumbria University, Wynne-Jones Building, Newcastle Upon Tyne NE1 8ST, UK

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ABSTRACT

Adhesion phenomena in hybrid glass structures made of glass and composite material are of critical importance in order to achieve high performance. As a contribution to the study of this topic, an experimental and analytical investigation was performed. It looked into the adhesion phenomena of two different composites, such as GFRP (Glass Fibre Reinforced Polymers) and SRP (Steel Reinforced Polymers), using different types of resins and various interface geometries. The experiment was carried out on samples subjected to shear traction tests, in order to examine the load transfer mechanism and the failure mode of the adhesive joint, to evaluate the optimal bond length and to perform a validation using substantiated theories. A formulation studied on the basis of the experimental results is also proposed herein to evaluate debonding resistance and the optimal bond length.

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1. Introduction

The designing of glass for structural use must provide structures that have good post-fracture behaviour and a suitable degree of residual strength to overcome the main obstacles in using glass as a structural material, such as fragility, low tensile strength and a high risk of spontaneous breakage even under low stress. It should also be stressed that glass breakage is dangerous to both people and objects, as it fragments into sharp pointed shards, which is another reason why glass is coupled with other materials i.e. laminated glass [1–6] or subjected to other processes (i.e. hardening, tempering) which modify the way in which it collapses [7–9].

Load-bearing glass elements which comply with the fail-safe design criterion can be made by pairing glass with materials that have good tensile strength to produce hybrid structural elements in which tensile stresses can be absorbed by the materials added, while the glass continues to support the compressive stress. The tensile strength of glass can therefore be exploited even further, provided that adhesion between the glass and the reinforcement material is guaranteed.

Recent studies have shown increasing interest in hybrid

structural elements, in which the purpose of the reinforcement material selected is to provide the element not only with greater strength during the pre-fracture phase, but also with a residual load-bearing capacity after the initial failure. The flexural behaviour of hybrid beams has been studied by several researchers, including systems coupled with steel bands [10], steel profiles [11] or steel fibres [12], glass fibres [13] and pultruded GFRP profiles [14,15].

Fibre preforms are often manufactured in sheets, and the adhesion between the glass and the composite material is especially important in these types of structural elements in order to create high performance systems. Glass is known as an amorphous material lacking a well-defined crystalline lattice. This makes the material difficult to bond chemically, and therefore these characteristics do not allow the interfacial stress to increase sufficiently after surface treatment to improve adhesion.

It should also be noted that it is difficult to find specific studies concerning glass adhesion with other reinforcement materials for structural applications. There has been a great deal of research on performance and adhesion between fibres and the more traditional materials of existing structures, such as steel [16], masonry [17–20], reinforced concrete [21–24], wood [25,26], glass fibre composites and carbon fibre composites. Adhesion tests for the latter are usually carried out in order to measure the tangential stresses shown by the two materials. Bonded connections in glass structures are a more recent development and include: steel-glass

* Corresponding author.

E-mail address: emanuela.speranzini@unipg.it (E. Speranzini).

connections using a range of adhesives [27], shear stresses and relative displacements among the glass-interlayer interfaces [28], structural performance of adhesively bonded connections compared with bolted connections [29], glass-to-glass connections using two-part modified epoxy [30], and the mechanical properties of glass butt joints [31].

In this paper the authors investigated the phenomena of adhesion between glass and composite materials which are able to increase glass performance when they work in synergy, for both the structural elements and the joints. The results of this experimental and analytical study are shown herein.

The purpose of this experiment was to study the adhesion of different types of composites and resins and various bonding geometries. All the samples tested were constructed using glass bonded to different types of materials: sheets of glass, GFRP and SRP. These were then subjected to shear tensile tests. Particular attention was given to investigating the load transfer mechanism and the failure mode of the adhesive joint, by evaluating the optimal bond length and by validating known experimental formulae in order to evaluate adhesion stress. In analogy to the design of the reinforcement of traditional fragile materials, a formulation was developed on the basis of the experimental results in order to evaluate debonding resistance and the optimal bond length that ensures the total transfer of the stresses between composite and support.

2. Debonding phenomena

The phenomenon of peeling of the reinforcement from the substrate is of particular importance in the bonding of different materials, since it leads to a drastic reduction in the load-bearing capacity and stiffness of the reinforced structural element. An effective reinforcement technique is based mainly on an efficient connection between the materials, established by means of the adhesion bond between the reinforcement and the support surfaces. It is guaranteed by the mechanical characteristics of the adhesive and by accurately carrying out all stages of the bonding process. Debonding usually depends on the stresses which develop in the adhesive, i.e. in the interface between the support and the reinforcement. However, they may involve the substrate surface to which the reinforcement has been bonded, or trigger the crisis as a result of debonding within the reinforcement.

The experiments on glass elements confirmed that debonding occurs mainly as a result of the reinforcement peeling from the support, i.e. in the interface between the support and reinforcement, as our experience gained from studying the phenomenon in other similar materials had suggested. Adhesion mechanisms consist mainly of the mechanical interlocking of the adhesive with the surface of the bonded material.

The tensile constitutive law of the bonding of the polymers used as structural adhesives is usually linear-elastic with fragile behaviour, which can be characterised simply by Young's modulus E and the ultimate tensile strength $\sigma_{\max}$. It should be noted that laboratory tests show that the adhesives' mechanical properties vary with temperature and load time.

Three different types of interface behaviour are instead shown under shear stress, all of which can be approximated to bilinear functions, which differ only in their behaviour in the post-elastic branch [32].

The first is defined by an elasto-plastic law [33] which can be linked to the behaviour of adhesives with low yield strength, such as non-thermosetting elastomers. Behaviour is univocally determined by the elastic shear modulus G , by the elastic limit of shear stress τ_s , and by the ultimate fracture deformation γ_F .

The second type is a non-linear interface law with a descending,

post-elastic branch, which describes the behaviour of the majority of adhesives, especially epoxy resins and thermosetting rubbers [34]. The slope G_p (negative) of the descending branch and the ultimate stress τ_F , which is less than τ_s , are needed in order to define this law, in addition to G , τ_s and γ_F . The third type is a non-linear interface law with the ascending, post-elastic branch, which characterises rubber hardened resins [35]. The behaviour of the material is defined by means of G , τ_s and γ_F and G_p .

The mechanical shear properties of adhesives depend greatly on time and temperature. The resistance values of an adhesive at elastic limit τ_s and at fracture of τ_F are determined by the mechanical properties of the joint materials, the characteristics of the contact surface, the presence or absence of internal forces, the geometry of the node, and the design details of the load mechanism of the node itself.

3. Materials properties

The samples to be tested were made of two glass sheets bonded using epoxy resins or reinforced with glass and steel fibre using resins. The mechanical properties of the materials are described in the following sub-sections.

3.1. Glass

All the test samples were made using sheets of 8 mm-thick float glass, specially cut in various sizes for the different types of tests. The annealed glass used complies with the EN 572 standard [36] (density 2500 kg/m³, Young's modulus 70 GPa, Poisson's ratio 0.2, flexural tensile stress 45 MPa).

3.2. Resins

Given the nature of the glass surface, the resin used to impregnate the fibres also acts as an adhesive, which is the reason for which it must not only have good impregnability, but must also have suitable adhesive requisites for the material to be reinforced. For glass, it is particularly important to apply the resin correctly; thus the substrate must be adequately prepared by removing any surface contamination, such as dust, foreign particles, grease and moisture. The efficiency of the adhesive bonding depends not only on the surface treatment, but also on the chemical composition and viscosity of the adhesive, the application technique and the hardening process or cross-linking action of the adhesive itself.

Two different bi-component epoxy resins were used for the glass-glass adhesion tests, with a single-lap joint. The two resins show similar mechanical characteristics, but differ in colour and viscosity. The first is a very fluid, transparent resin; the second is a pasty, light grey, thixotropic resin (Resins 1 and 2 in Table 1). They are both structural resins, commonly used to make FRP reinforcements.

Three resins were tested to assemble the test samples reinforced with GFRP and SRP: the two previously mentioned resins and a third, white, pasty, bi-component epoxy resin (Resin 3 in Table 1).

Resin 1 is aesthetically the most suitable because it is completely transparent. The other two resins are not only coloured, but are also denser than the preceding resin.

3.3. Glass fibres

The glass fibres used to make the composite consist of 320 g/m² unidirectional fabric (tensile strength 2857 MPa, Young's modulus 71.56 GPa, tensile elongation 4.11%) with an equivalent thickness of the sheet of 0.114 mm. The glass fibres are white and, contrary to glass, have a high tensile strength due to the processes they have

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