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Influence of the lamination on the redundancy of a horizontally layered glass element and analysis of the debonding of the adhesive interlayer

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ABSTRACT

It is now recognized that lamination enables to increase the redundancy of glass elements. This paper aims to quantify the possibilities of delamination between panes as well as the increase of redundancy for a horizontally layered glass element thanks to an analytical approach combined with a numerical modeling. From an analytical point of view, new procedures have been defined, taking into account the shear-lag effect as well as the mean curvature of the various adherents. The equilibrium of an infinitesimal element of the laminated structure has enabled to evaluate the interfacial stresses responsible for debonding phenomena. Based on this first approach and on the values of the interfacial stresses, a FE numerical simulation has been calibrated. This calibration is extended in two ways. First, the nonlinear behavior of the material is considered. A smeared crack approach is used to take into account the glass mechanical behavior. Then, a local debonding model involving the use of normal and shear springs is proposed at the interface between two glass panes. The mechanical behaviors of the springs are calibrated by simulating existing tension adhesion tests. Finally, by considering various structural cases, this work concludes that the debonding of the interface is a possibility and discusses its influence on the redundancy of the considered laminated structure.

1. Introduction

The brittleness of glass has largely contributed to give to this material a filling role (e.g in windows…), and has delayed its use as a structural material. However, glass has much more to offer in this regard due to its possibility to carry high compressive stresses and to its obvious aesthetical advantages.

It is now recognized that the strength, the robustness, and then the redundancy of glass elements can be considerably increased by laminating several panes to a composite action. As an interlayer, sheets of polyvinyl butyral (PVB) or Sentry Glass Plus® (SGP) are often used. Not only, does this interlayer enable the composite action to be developed, but also, when the first pane is broken, it may act as reinforcement for the remaining structure, leading to no catastrophic failure [1–3]. Preceding experimental research [4,5] has demonstrated that the SGP interlayer can be well exploited for bonding in laminated or hybrid glass beams. The shear strength and stiffness of the SGP interlayer is sufficient to transfer the forces between glasses to activate the reinforcement action once the glass is broken.

Laminated glass exhibits a complicated mechanical behavior because of the combination of a very stiff material (glass) and a very soft material (interlayer) [3,6]. A laminated glass pane is less stiff than a monolithic glass structure of the same dimensions, which leads to larger displacements. Furthermore, this increased structural integrity of a laminated glass element may be challenged by risks of debonding and/or by the breakage of the interlayer. Hence, it is important, for a safe and cost-efficient strength design, that the structural behavior in terms of displacements and stress distributions is accurately determined since previous design methods, such as analytical formulas, do not provide sufficient information to determine accurate stress and determine the load-bearing capacity of laminated glass [1,7]. Thus an increasing number of analytical or numerical works deals with this challenge [6–12]. The work of Fröling and Persson [12] presents one of the most accurate numerical studies and proposes an efficient numerical method using specific modified solid shell

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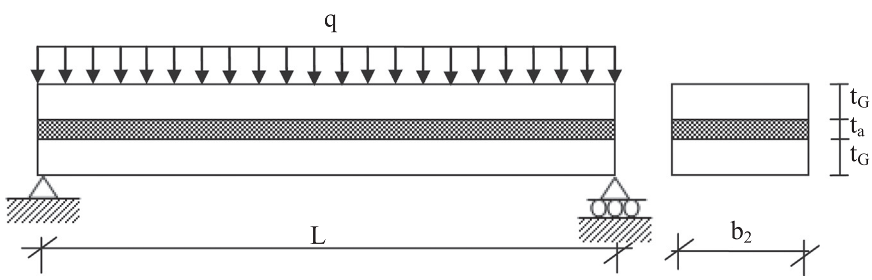

Fig. 1. Laminated glass element considered in the present study.

element. This study presents also a sensitivity analysis on the number of degrees of freedom and thus on the mesh fineness.

However, these previous advanced works do not address the problem from the angle of the adhesive layer, and do not focus on the interfacial stresses, which are of prime importance in the analysis of the debonding possibilities.

This work investigates this new aspect. First, an accurate analytical prediction of the interfacial stresses in the adhesive layer, responsible for debonding, is presented. Such an analytical modeling is a fundamental tool for analyzing composite structures in general. Then, and based on this first study, a Finite Element (FE) computation with ABAQUS (Version 6.9) is performed to investigate the behavior of a laminated glass element. The paper focuses on the necessity to well capture the interfacial stresses and aims to provide information for an efficient FE analysis of laminated glass structures. Thus, by means of a local debonding model involving the use of normal and shear springs, the appearance of interface debonding in such structures is discussed, and its influence on the overall behavior of the glass element is analyzed.

2. Theoretical background: analytical assessment of interfacial stresses responsible for debonding failure

2.1. Objective

Debonding failure in composite or hybrid structures is a consequence of too high shear and transverse normal stresses. Their accurate prediction is thus important for the design. Many studies have been conducted, both analytically and numerically, to predict these interfacial stresses. From this point of view, these studies have generally been conducted on strengthened Reinforced Concrete beams (among others: [13–18]), but some of them can be easily adapted to laminated glass structures.

Based on the solution given by Tsai [16], Tounsi [17] proposed a solution incorporating the effects of interfacial shear stresses on the strains in adherends, which were ignored by Smith and Teng [13]. The computed interfacial stresses are found to be considerably smaller than those obtained by the models neglecting the shear strains of adherends. However, all the studies mentioned are based on the assumption that both adherends have the same curvature. Krour et al. [18] have developed an improved theory which releases the improper restriction of the equal curvatures of adherends.

Starting from this last improved analytical model, the present study investigates first the interfacial stresses in a simple laminated glass element composed of two horizontally layered glass panes (see Fig. 1).

2.2. Main assumptions

The following assumptions are made:

- Simple beam theory is considered. Thus, the study is restricted to horizontally layered glass elements with a width b_2 significantly lower than the span (case of bridges for example). This assumption transforms a two-dimensional structural problem to only one-dimensional one.
- Glass is assumed to behave elastically, as well as the interlayer material. However the SGP Young modulus has two different values in function of the applied normal stress. This artifact is used to represent the hyperelastic behavior. This is one of the main novelties proposed in this paper: such a behavior has not been considered previously in the dedicated literature.
- Stresses in the adhesive layer do not change with the thickness unlike the model proposed by Rabinovitch and Frostig [19] where the stresses vary across the adhesive thickness.
- Contrary to some existing studies, the assumption that both adherends have the same curvature is not used in the present investigation. The adhesive curvature is assumed to be the mean of the two adherends curvatures. This assumption is simpler than the one made by Rabinovitch and Frostig [19] where higher order theory is used to describe the adhesive displacements.
- The component of shear deformation in the normal strain of the adherends has been included in the present theoretical analysis by assuming a parabolic distribution of shear stress across the thickness (shear-lag effect).
  This assumption has been used in Tounsi et al. [20] where the shear interfacial stress has to be continuous across the adherend section causing a lagging effect. The longitudinal displacement is assumed non-linear across the section following a cubic variation. This leads to a parabolic variation of the shear stress across the section.
- Since the section is bi-symmetrical, the neutral axis passes through the centroid, and the longitudinal normal stress is equal to $\sigma_N(x) = \frac{M_z(x)}{I_{eq}} y$ with M_z the applied bending moment and $I_{eq} = I_1 + I_2 + I_a + nS_1\left(\frac{t_G}{2} + \frac{t_a}{2}\right)^2 + nS_2\left(\frac{t_G}{2} + \frac{t_a}{2}\right)^2$ where $n = \frac{E_a}{E_G}$

where:

- S_1, S_2, I_1, and I_2 are respectively transversal sections and inertia moment of each adherend and I_a is the inertia moment of the adhesive,
- E_a, E_G, are respectively elastic moduli of adhesive and glass pane,
- y is the distances from the neutral axis.

2.3. Solutions procedure

2.3.1. Equilibrium of an infinitesimal element of a laminated glass floor

Let consider an infinitesimal element of a laminated glass pane. This element is at the equilibrium under the effect of forces and stresses presented in Fig. 2.

The equilibrium of adherends 1 and 2 implies following equations:

$$\text{Adherend 1}: \frac{\partial M_1(x)}{\partial x} = V_1(x) - b_2 y_1 \tau(x) \quad \text{and} \quad \frac{\partial V_1(x)}{\partial x} = -b_2\sigma(x) - q \tag{1}$$