ANALYSIS OF SHEAR DEFORMATION OF POLYMER ENCAPSULATES FOR LAMINATES

Holm Altenbach*, Konstantin Naumenko*, Stefan-H. Schulze** & Matthias Pander**
*Otto-von-Guericke-University Magdeburg, Institute of Mechanics, PF 4120, D-39016 Magdeburg, Germany
**Fraunhofer-Center for Silicon-Photovoltaics CSP Walter-Hülse-Str. 1, D-06120 Halle, Germany

Summary Laminated glass beams and plates are widely used in photovoltaic applications. One feature of these structures is a relatively thin and compliant polymeric layer for embedding solar cells. In this paper a three layered beam with glass skins and a polymeric core is applied as a model structure to evaluate the mechanical properties of encapsulant. Robust relationships between the maximum deflection, the transverse shear strain of the core layer and the applied force in a three-point-bending test of laminated glass beam samples are derived. Three-point-bending tests for laminated glass beams with core layers from different polymeric materials are performed. The experimental data for the maximum deflection are compared with the derived expressions.

INTRODUCTION AND MOTIVATION

Typical solar modules consist of a transparent front glass, a thin polymeric interlayer and a thin polymeric back sheet. One purpose for this back glass is to protect the photoelectric semiconductor against environmental influences, such as moisture. Since solar cells are usually made of brittle and thin silicon wafers, they are embedded in a compliant polymeric encapsulant. Materials like ethylene-vinylacetate (EVA), polyvinylbutyral (PVB) or thermoplastic silicon elastomer (TPSE) are examples of polymers that can be used for embedding solar cells [5]. Important parameters that influence the load bearing capacity are the thickness and the material properties of layers.

To examine the load transfer between the layers as well as the mechanical behavior of the encapsulant, a three-layered beam with glass skins and a polymeric core can be used as a model structure. In this paper we present results of structural and experimental analysis of laminated glass beams with core layers from different polymers applied in the photovoltaic industry. In addition to previous works [1, 4] we analyse laminated beams applying three structural mechanics models. We start with the first order shear deformation theory (FSDT) and derive expressions for the bending and the transverse shear stiffness of the beam. Then we develop a layer-wise theory (LWT) assuming that the deformation of layers can be described by the beam equations. We derive closed form solutions for the maximum deflection and the transverse shear strain of the beam under three-point bending. To verify the assumptions of FSDT and LWT we perform a finite element analysis with solid type finite elements. We perform the experimental analysis of beams with core layers from different polymers used in the photovoltaic industry including EVA, PVB and TPSE.

STRUCTURAL AND EXPERIMENTAL ANALYSIS

First Order Shear Deformation Theory

Consider a laminated beam, Figure 1 a). The maximum deflection is

$$w_{\max} = w(0) = \frac{Fa^3}{6B} + \frac{Fa}{2\Gamma} \tag{1}$$

The first term in Eq. (1) is the deflection according to the Bernoulli-Euler beam theory, while the second term is the contribution due to transverse shear deformation. The key step in the use of Eq. (1) is to compute the bending and the shear stiffness of the beam from the properties of the constituents. To designate the properties of the core and skin layers let us apply the subscripts c and s, respectively. Let E_i be the Young modulus, G_i the shear modulus and h_i the thickness of the layer i, $i = \mathrm{c}, \mathrm{s}$. The bending stiffness of the composite beam can be computed as follows [3]

$$B = \frac{bh^3}{12}\left[E_{\mathrm{s}}(1-\alpha^3) + E_{\mathrm{c}}\alpha^3\right], \quad \alpha = \frac{h_{\mathrm{c}}}{h}, \tag{2}$$

where $h = 2h_{\mathrm{s}} + h_{\mathrm{c}}$ is the beam height and b is the beam width. The transverse shear stiffness can be computed as [2]

$$\Gamma = \frac{1}{3}G_{\mathrm{c}}bh\frac{1-\alpha^3(1-\mu)}{\alpha(1-\alpha)} \tag{3}$$

Layer-wise type beam theory

For very low values of the shear modulus G_{c} and/or the thickness of the core layer, the first order shear deformation beam (plate) theory may fail to describe the deflection accurately. Indeed, if the shear modulus G_{c} approaches to zero for a fixed value of h_{c}, then according to Eq. (3) the shear stiffness of the beam approaches to zero and the second term in Eq. (1) tends to infinity. Let us discuss results applying a layer-wise type beam theory that includes the relative axial displacement of the glass layers as an independent degree of freedom. The maximum deflection can be computed as follows

$$w_{\max} = \frac{Fa^3}{6B} + \frac{Fa}{2\Gamma_L} + \frac{F}{2\Gamma_L\beta}\left(\frac{\sinh\beta(l-a) - \sinh\beta l}{\cosh\beta l}(1-\cosh\beta a) - \sinh\beta a\right), \tag{4}$$

[a)] Corresponding author. E-mail: holm.altenbach@ovgu.de

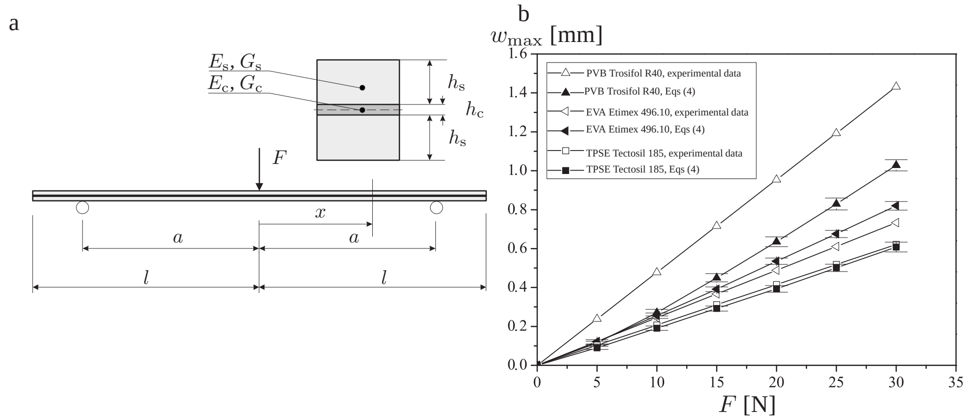

Figure 1. a) Geometry and loading of the beam; b) Measured and calculated maximum deflection

where

$$\beta = \frac{1+\alpha+\alpha^2}{\alpha(1-\alpha)}\sqrt{\frac{4}{3}\frac{\Gamma_c}{B}}, \quad \Gamma_c = \frac{\pi^2}{12}G_c h_c, \quad \Gamma_L = \frac{\pi^2}{9}\frac{G_c b h}{3\alpha}$$

The first two terms in Eq. (4) coincide with the solution according to FSDT (1) if $\Gamma_L = \Gamma$. Therefore Γ_L has the meaning of the transverse shear stiffness of the laminated glass beam. The value of Γ_L according to LWT is close to the value of Γ given by Eq. (3). The third term in Eq.(4) provides a correction to the FSDT for beams with low shear stiffness of the core.

Three point bending tests

In order to analyze elastic load-deflection behavior of laminated glass beams, flexural testing was performed for 10 specimens for each encapsulant material at room temperature. The support span was 384 mm and the radius of the supports and bending fins was 8 mm. Interlayer thickness was determined after lamination for each of the specimen. The laminate beams have been stored at room temperature for about 48 hours before testing. Flexural testing in the three-point bending mode was performed using a $Zwick\ Z050$ universal testing machine with a cross head speed of 10 mm/min.

In Fig. 1 b) load vs. deflection curves for the measurements and the calculated deflections from Eq. (4) are shown. While good agreement can be achieved for glass beams with relatively stiff EVA and TPSE interlayer, deflections for glass beams with soft PVB interlayer are overestimated. One explanation for this discrepancy is an essential rate dependence of the material behavior of amorphous PVB. Therefore, a viscoelastic material model should be used to describe both the tensile and the bending tests. In contrast, cross linked EVA and TPSE do not show strong viscoelasticity.

CONCLUSIONS AND RECOMMENDATIONS

The aim of this paper was to perform the structural and the experimental analysis of laminated glass beams with core layers from different polymeric materials. The outcomes are robust relationships between the maximum deflection, the transverse shear strain of the core layer and the applied force in a three-point-bending test of laminated glass beam samples. To analyze the deformation of beams with thin and compliant core layers the FSDT and the LWT are evaluated. The applicability ranges of these beam theories is determined by the parameter β. For beams with EVA and TPSE core layers the results of simulations agree well with the experimental data. For materials like PVB a viscoelastic material model and the LWT are required to predict the behavior of beams accurately. Further investigations to elaborate the rate dependence of the material behavior in both the tensile and bending tests should be performed. With the help of the derived expressions mechanical characteristics of polymeric interlayers in laminated glass can be determined. The results of provide a motivation for the use and further development of the layer-wise plate theories to analyze the deformation of the real solar modules.

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