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Mechanical behaviour of photovoltaic composite structures: A parameter study on the influence of geometric dimensions and material properties under static loading

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A B S T R A C T

Photovoltaic modules available on the market are subject to a wide variety of geometric dimensions and material properties. During their service life, they are exposed to, among other things, mechanical loads that can affect energy harvesting negatively through mechanically induced damages. Due to the high contrast in mechanical properties and geometric dimensions of constituting materials, classical structural analysis methods for such rather slender structures are unserviceable, what emphasises the necessity of alternative approaches. A potential candidate of that alternatives is the extended layerwise theory. In the present treatise, this theory is used to vary structural parameters in order to gain directions to optimal values of significant geometric and material ratios of constituents, whereby we stay in the range of characteristic parameters for terrestrial photovoltaic modules. The results of the present study constitute characteristic indexes useful in conceptual and design phase when developing photovoltaic modules.

1. Introduction

1.1. Motivation

A key aspect when designing photovoltaic modules is the variability of mechanical properties and geometric dimensions of components involved. Due to the composition, these components are the front and back cover (≙ skin layers) as well as the core layer, depicted in Fig. 1, which should be considered in design process. Engineers have a small but important range of possible materials and dimensions at their disposal. The choice of these parameters is important since it is directly correlated to mechanical failures, cf. [1]. Mostly, tempered glass is used for the front cover, a rubber-like material, e.g. the thermoplastic elastomer ethylene vinyl acetate for the core layer, and a plastic laminate or tempered glass for the back cover. However, as stated in [2], subsequent geometric ratios can be reported, resulting from market variability.

$$TR = \frac{h^c}{h^t + h^b} \approx 0.125 \dots 0.45 \tag{1}$$

$$LR = \frac{L_2}{L_1} \approx 0.25 \dots 1 \tag{2}$$

$$TLR = \frac{H}{L_{\min}} \approx 2 \times 10^{-3} \dots 1.4 \times 10^{-2} \tag{3}$$

Additionally, a typical ratio of shear modulus ($G = \frac{E}{2(1+\nu)}$ in case of isotropy where E is YOUNG's modulus and ν is POISSON's ratio) is in the following range [2].

$$GR = \frac{G^c}{G^s} \approx 7 \times 10^{-6} \dots 1.5 \times 10^{-2} \tag{4}$$

Due to the slenderness of photovoltaic modules ($L_1 \approx L_2 \gg H$), it is reasonable to use thin-walled structural theories for mechanical analysis whereby all calculations are reduced to the mid surface of the individual layer. This also includes theories for multilayered structures. Due to the vanishing shear stiffness of the core layer at photovoltaic modules, at least first-order shear effects have to be incorporated, where [3–6] are prominent examples of such models. Thereby, multilayered, layerwise, and equivalent single layer models are available [7,8]. However, since classical theories in this field fail due to the strong discontinuity of mechanical properties in transverse direction of photovoltaic modules expressed by GR, extensions were required, cf. [9]. Therefore, in [10] a so called the eXtended LayerWise Theory (XLWT) is proposed. Therein, a homogeneity postulate is introduced concerning the core layer, what enables to neglect the solar cells in global structural analysis. This postulate is confirmed in [11]. First investigations by applying the XLWT to structural analysis of photovoltaic modules were performed in [12]. In [2], the ability of XLWT to

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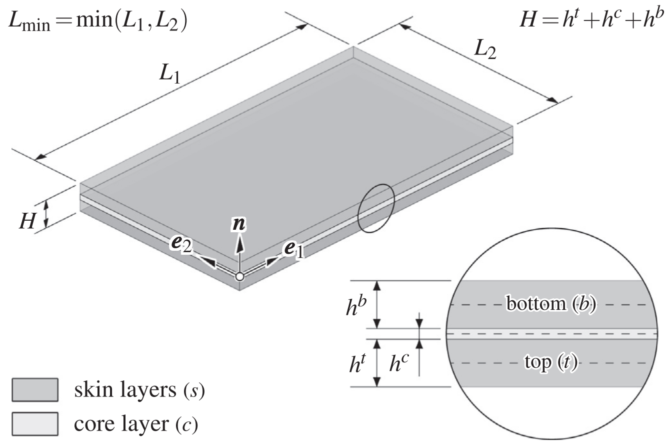

Fig. 1. Composition of a photovoltaic module for global structural analysis.

reproduce the zigzag nature of the displacements along the transverse direction is confirmed. In [13], the question about optimal parameters for photovoltaic modules has been raised. This vagueness will be enlightened whereby we draw attention to optima with respect to the aforementioned ratios.

1.2. Frame of reference

The theory of elastic surfaces serves as basis for XLWT. Such a surface comprises five degrees of freedom: two in-plane translational ($\boldsymbol{a} = a_1\boldsymbol{e}_1 + a_2\boldsymbol{e}_2$), one out-of-plane translational (w), and two out-of-plane rotational ($\boldsymbol{\varphi} = \varphi_1\boldsymbol{e}_1 + \varphi_2\boldsymbol{e}_2$). In the sequel, we make use of the direct tensor notation for the ease of description, whereby tensors of first, second, and fourth order are written as $\boldsymbol{c}$, $\boldsymbol{C}$, and $\mathbb{C}$. Furthermore, $\times$, $\cdot$, $:$, and $\otimes$ represent the cross product, the single contraction, the double contraction, and the dyadic product. ∇ is the Hamiltonian, $\nabla\boldsymbol{c}$ is the gradient of $\boldsymbol{c}$, and $\nabla^{\text{sym}}\boldsymbol{c}$ is the symmetric part of this gradient. Moreover, $\nabla\cdot\boldsymbol{C}$ is the divergence of $\boldsymbol{C}$. In the case of a geometrically linear theory, the deformation measures are thus $\boldsymbol{G} = \nabla^{\text{sym}}\boldsymbol{a}$, $\boldsymbol{K} = \nabla^{\text{sym}}\boldsymbol{\varphi}$, and $\boldsymbol{\gamma} = \nabla w + \boldsymbol{\varphi}$. The conjugate stress measures derive from a potential $W(\boldsymbol{G}, \boldsymbol{K}, \boldsymbol{\gamma})$ as $\boldsymbol{N} = \frac{\partial W}{\partial \boldsymbol{G}}$, $\boldsymbol{q} = \frac{\partial W}{\partial \boldsymbol{\gamma}}$, and $\boldsymbol{L} = \frac{\partial W}{\partial \boldsymbol{K}}$. They fulfil the following balance equations, whereby inertia is absent.

$$\nabla\cdot(\boldsymbol{N} + \boldsymbol{q}\otimes\boldsymbol{n}) + \boldsymbol{s} + p\boldsymbol{n} = \boldsymbol{0} \tag{5}$$

$$\nabla\cdot(-\boldsymbol{L}\times\boldsymbol{n}) + \boldsymbol{q}\times\boldsymbol{n} + \boldsymbol{m} = \boldsymbol{0} \tag{6}$$

Physically spoken, $\boldsymbol{N}$ is the membrane force tensor, $\boldsymbol{L}$ the polar tensor of moments, and $\boldsymbol{q}$ denotes the transverse shear force vector. The variable p denotes out-of-plane loads, while $\boldsymbol{s}$ denotes in-plane force fields, and $\boldsymbol{m}$ contains out-of-plane moment fields at the surface, cf. [2]. Since we restrict ourselves to symmetry in transverse direction concerning the coordinate origin, the elastic potential of the uncoupled but superposed surface continuum can be derived as follows whereby we use a description adapted from [14].

$$W(\boldsymbol{G}, \boldsymbol{K}, \boldsymbol{\gamma}) = \frac{1}{2}[\boldsymbol{G}: \mathcal{A}: \boldsymbol{G} + \boldsymbol{K}: \mathcal{D}: \boldsymbol{K} + \boldsymbol{\gamma}\cdot\boldsymbol{Z}\cdot\boldsymbol{\gamma}] \tag{7}$$

The membrane, bending, and shear stiffnesses $\mathcal{A}$, $\mathcal{D}$, and $\boldsymbol{Z}$ are given in [2] for isotropic materials. The above mentioned equations have to be considered for every layer separately, in the present case for three layers. Therefore, kinematic constraints have been introduced, cf. [10]. This includes the equality of all layer deflections. Since a virgin composite without delamination is considered, in-plane displacements and rotations are directly coupled at the interfaces between the layers. This description incorporates the straight line hypothesis [6] layerwise, whereat a straight line not necessary remains normal during the deformation process. A more detailed insight into the theoretical background and basic equations of the XLWT is given e.g. in [13], while we waive this description here to keep our presentation in the clearest manner possible. The model of an elastic surface for a three layered composite structure was implemented into the commercial finite element code ABAQUS using a user-defined quadrilateral element with quadratic shape functions for displacements, deflections, and rotations of all layers, cf. [12,13]. In context of the present study, we have parameterised our model of a photovoltaic composite structure within this subroutine to simplify geometry and material variations. However, the computational solution technique enables the analysis of a broad class of structural mechanics problems at photovoltaic modules since we are liberated from severely restricted boundary conditions of closed-form solutions, cf. [12].

2. Parameter study

To gain information of the behaviour at varying structural parameters, the study is confined to a simple loading case. The problem of a three layered composite structure under uniform and orthogonal loading conditions is considered, see Fig. 2 (left). Starting point for the present study is a photovoltaic module whose geometric dimensions and related material properties are specified in Fig. 2 (both boxes top right). For the sake of simplicity, we restrict ourselves to a symmetric composite so that $h^t \equiv h^b$, $E^t \equiv E^b$, and $\nu^t \equiv \nu^b$ holds true. The materials considered do not have any directional dependence. Considering the material data given, κ is the shear correction factor which is artificially introduced in $\boldsymbol{Z}$, considering the layerwise parabolic gradient of $\boldsymbol{q}$ along X_3. A moment-free support is used at all edges and the load at the composite is applied on the outer surface of the front cover in direction of the surface normal $\boldsymbol{n}$. This basis vector is depicted in Fig. 1. Details of the boundary conditions are given in Fig. 2 (bottom right). We renounce incorporating tangential loading. Due to the restriction of orthogonality and homogeneity of load applied, the load vector on the sun-facing side of the top layer reduces to $p\boldsymbol{n}$. In order to remain below a certain deflection threshold ($\frac{w_{\max}}{H} \approx 0.5$) which would be associated with departing from the scope of the geometrically linear theory (small displacements, small deflections, and small rotations), we limit our study to a relatively low loading intensity. For structural analysis, the finite element developed is used for discretisation, where a constant element edge of $h^e_\alpha = 10$ mm $\forall\ \alpha = \{1, 2\}$ is used at all subsequent studies to gain convergence. For comparison, identified ratios of our starting structure are: $TR = 0.15625$, $LR = 0.5$, $TLR = 9.136 \times 10^{-3}$, and $GR = 9.978 \times 10^{-5}$. However, geometric and material parameters stated in Fig. 2 are modified systematically to analyse the mechanical behaviour for variations of these ratios, at least up to the bounds reported in Eqs. (1)–(4). The deflection is used as evaluation criterion. For the ease of evaluation, the maximum deflection is used. In present case, this is given by $w_{\max} = w(\frac{L_1}{2}, \frac{L_2}{2})$. Following dependencies can be expressed concerning geometric dimensions and material properties.

$$w_{\max} = \mathscr{F}(L_\alpha, h^K, E^K, \nu^K) \quad \forall\ \alpha = \{1, 2\} \wedge K = \{t, c, b\} \tag{8}$$

To sum up, we have eleven parameters influencing the structural behaviour of the photovoltaic composite, in case of elastic isotropy. Since ratios have been introduced, it is sufficient to examine the dependencies of $w_{\max}$ with respect to the four ratios.

$$w_{\max} = \mathscr{G}(TR, LR, TLR, GR) \tag{9}$$

For the sake of comparability, the maximum deflection is normalised at all results, so that $0 \le \overline{w}_{\max} \le 1$ holds true.

$$\overline{w}_{\max}(\square) = \frac{w_{\max}(\square)}{\max[w_{\max}(\square)]} \quad \forall\ \square = \{TR, LR, TLR, GR\} \tag{10}$$

The advantage of using such normalisation with the ratios introduced in Section 1.1 is to achieve a general representation and universal implications as well.