Analysis
of Laminated Glass Structures
for Photovoltaic Applications

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Workshop

Impact of mechanical and thermal loads
on the long term stability of PV modules

November 5th, 2013
Hameln, Germany

OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG
MB FAKULTÄT FÜR MASCHINENBAU
DFG - Graduiertenkolleg
Micro-Macro-Interactions
of Structured Media and Particle Systems

Outline

1. Introduction and Motivation
2. Structural Model for Laminated Glass Beams
3. Conclusions and Outlook

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Acknowledgement

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Prof.Dr. Victor Eremeyev

Dr.-Ing. Stefan Schulze

Dr.-Ing. Ulrich Eitner

Dr.-Ing. Matthias Weps

Dr.-Ing. Matthias Sander

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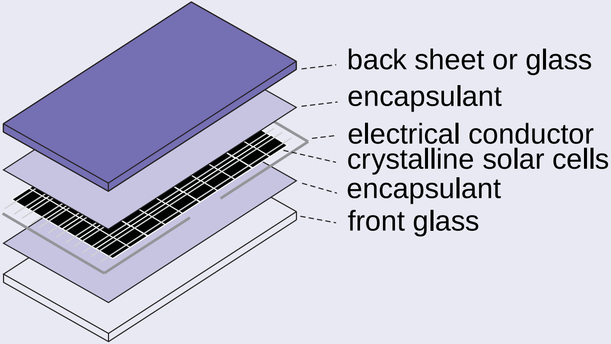
Introduction and Motivation

Introduction and Motivation

Components of Crystalline Solar Modules

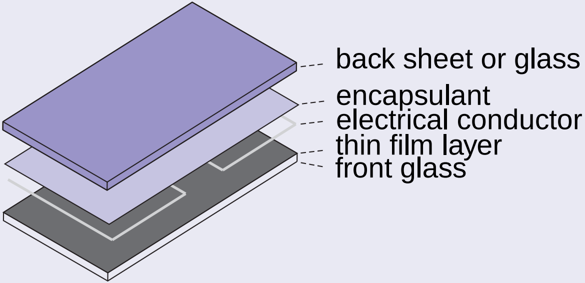


Reference:

Schulze, S.-H.; Pander, M.; Naumenko, K.; Altenbach, H.: Analysis of laminated glass beams for photovoltaic applications. - Int. J. Solids & Struct. 49(2012)15-16. - pp. 2027-2036

Introduction and Motivation

Components of Thin Film Solar Modules



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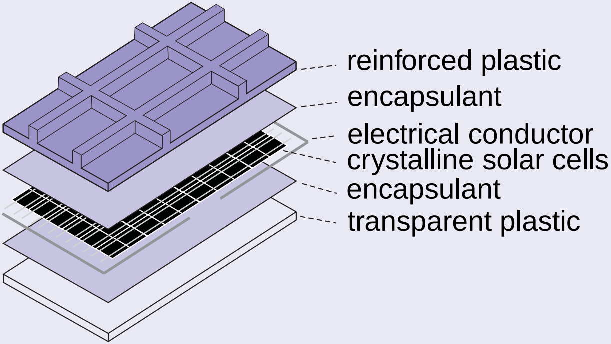
Introduction and Motivation

Components of Lightweight Solar Modules



Weps, M.; Naumenko, K.; Altenbach, K.: Unsymmetric three-layer laminate with soft core for photovoltaic modules. - Composite Structures 105(2013). - pp. 332-339

Introduction and Motivation

Environmental Influences

- Wind pressure, wind suction
- Snow and ice loads
- Ambient temperature changes (thermal cycles), hot spots
- Ultraviolet light, moisture

Damage Mechanisms

- Cracks in solar cells
- Delamination
- Interconnection and solder failures
- Ultraviolet and moisture degradation

After: IEC 61215 (2005), Eitner, U.: Thermomechanics of photovoltaic modules, PhD thesis, 2011

Introduction and Motivation

Benefits of Design

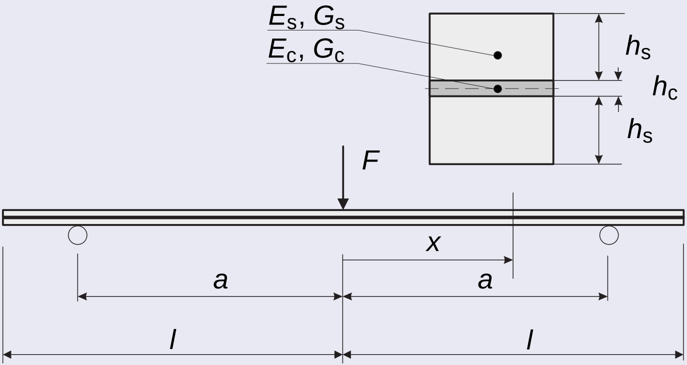
- Efficiency during guaranteed service life
- Cost reduction
- Reduced effort for analysis and testing

Problems for Mechanics

- Encapsulants are used to compensate mechanical and thermal strains of bottom and top layers and to minimize the loading of solar cells
- Encapsulant materials are EVA (ethylene-vinylacetate), PVB (polyvinylbutyral), PUR (polyurethane)
- Properties of encapsulants change after the lamination process or during the service.
- Robust plate theories are required to evaluate test results

Introduction and Motivation

Three-Point-Bending of Laminated Plate Strip



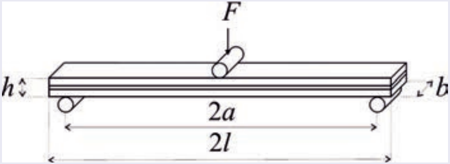
Material Properties of Layers

E_c/E_s is in the range of 10^{-5} and 10^{-2},
for example Glass: $E_s = 60 - 73 \cdot 10^3$ MPa, EVA: $E_c = 8$ MPa

Items under Investigation

- Development of a structural mechanics model for three-point bending tests on laminated glass beams;
- Comparison of the model with established methods;
- Application of the model for calculation of mechanical properties of the polymeric interlayer between the covering glass of the beam,
- Formulation of future tasks

3-Point-Bending Test



Aims of this Study

Approaches to Structural Analysis

Laminated Glass

Aşik & Tezcan (2005, 2006)
Biolzi et al. (2010)
Foraboschi (2012)
Galuppi et al. (2012)
Ivanov (2006)
Koutsawa & Daya (2007)

Photovoltaic Plates

Aßmus et al. (2012)
Corrado and Paggi (2013)
Eitner et al. (2010, 2011)
Sander et al. (2013)
Schulze et al. (2012)
Weps et al. (2013)

Development of a Theory for PV Plates - Requirements

- Layer-wise type theory
- Robustness and applicability of classical solution methods
- Accurate representation of transverse shear strains

Aims of this Study

Approaches to Structural Analysis

Laminated Glass

Layer-wise type theories: load transfer between the layers can be explicitly analyzed, experimental validation for three layer laminates

Photovoltaic Plates

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Photovoltaic Plates

Mechanical analysis by 3D (solid) finite elements: differences in properties of constituents, low thickness of layers ⇒ additional numerical effort

Development of a Theory for PV Plates - Requirements

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Outline

Basic Assumptions, Models

Features of Laminated Glass in Photovoltaic Applications

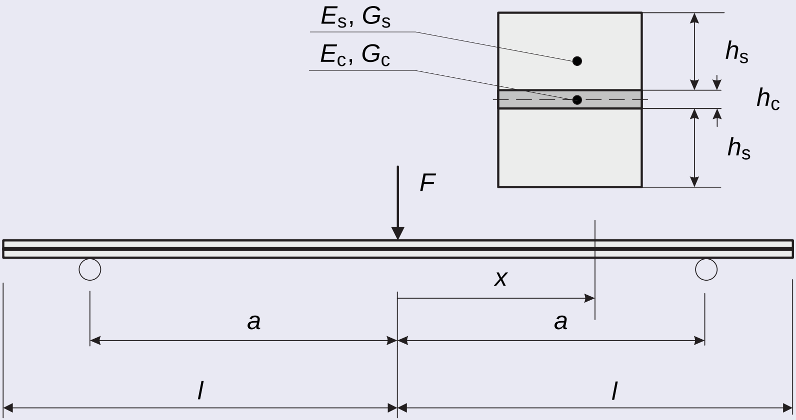
- layered composite,
- stiff skin layers and compliant core layer, if PVB (Polyvinyl butyral) as a core material: $\mu = 10^{-2} \dots 10^{-5}$, for classical sandwiches $\mu = 10^{-2} \dots 10^{-1}$ ($\mu = G_\mathrm{c}/G_\mathrm{s}$),
- thin core layer, relatively thick skin layers

Application of Three Structural Mechanics Models

1. First Order Shear Deformation Theory $\Rightarrow$ calculation of beam bending and transverse shear stiffness
2. Development of a Layer Wise Beam Theory (LWT) $\Rightarrow$ layer deformation is described by beam equations, development of closed form solutions
3. Application of finite element analysis (solid type elements) $\Rightarrow$ Verification of FSDT and LWT

First Order Shear Deformation Theory I

Geometry and loading of the beam



First Order Shear Deformation Theory II

Equilibrium for the Part of the Beam with the Length $a + x$

$$M(x) = \frac{F}{2}(a - x), \quad Q(x) = -\frac{F}{2}, \quad 0 \leq x \leq a$$

Constitutive Equations for the Stress Resultants

$$M(x) = B\varphi', \quad Q(x) = \Gamma(w' + \varphi), \quad (...)' = \frac{\mathrm{d}}{\mathrm{d}x}(...)$$

First Order Shear Deformation Theory III

Solutions for Rotation and Deflection

BC: $w(a) = 0$ and the symmetry condition $\varphi(0) = 0$

$$\varphi(x) = \frac{F}{4B} x(2a - x), \tag{1}$$

$$w(x) = \frac{F}{12B}(a - x)(2a^2 + 2xa - x^2) + \frac{F}{2\Gamma}(a - x), \tag{2}$$

$$0 \le x \le a \tag{3}$$

Maximum Deflection

$$w_{\max} = w(0) = \underbrace{\frac{Fa^3}{6B}} + \overbrace{\frac{Fa}{2\Gamma}}, \tag{4}$$

$$\underbrace{(...)} - \text{Euler} - \text{Bernoulli}, \overbrace{(...)} - \text{transverse shear} \tag{5}$$

First Order Shear Deformation Theory IV

Bending Stiffness

E_i - Young's modulus, G_i - shear modulus, h_i - thickness of the layer i, $i = \mathrm{c}, \mathrm{s}$

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

$h = 2h_\mathrm{s} + h_\mathrm{c}$ - beam height, b - beam width
With $E_\mathrm{c}/E_\mathrm{s} \ll 1$ the stiffness equation can be simplified to

$$B = E_\mathrm{s}\frac{bh^3}{12}(1-\alpha^3)$$

First Order Shear Deformation Theory V

Transverse Shear Stiffness

$$\tilde{\Gamma} = \frac{1}{3}G_\mathrm{s}h\lambda^2\left[1-\alpha^3(1-\mu)\right], \quad \mu = \frac{G_\mathrm{c}}{G_\mathrm{s}} \tag{6}$$

with

$$\sin\lambda\alpha\sin\lambda(1-\alpha) = \mu\cos\lambda\alpha\cos\lambda(1-\alpha) \tag{7}$$

First Order Shear Deformation Theory VI

Sandwich

Reissner's formula (1947): $\tilde{\Gamma} = G_c h$
For a laminated glass plate having a thin core layer with the low shear modulus the approximate solution of Eq. (7)

$$\lambda^2 = \frac{\mu}{\alpha(1-\alpha)}$$

Transverse stiffness

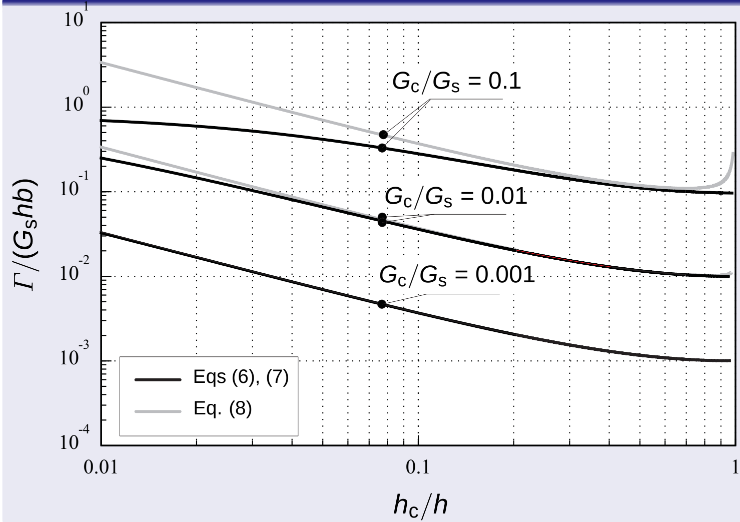
$$\tilde{\Gamma} = \frac{1}{3} G_c h \frac{1-\alpha^3(1-\mu)}{\alpha(1-\alpha)} \qquad (8)$$

Very Thin and Compliant Layers: $\alpha \ll 1$ and $\mu \ll 1$

$$B = E_s \frac{bh^3}{12}, \qquad \Gamma = \frac{G_c bh}{3\alpha} \qquad (9)$$

First Order Shear Deformation Theory VII

Shear Stiffness vs. Thickness of the Core Layer

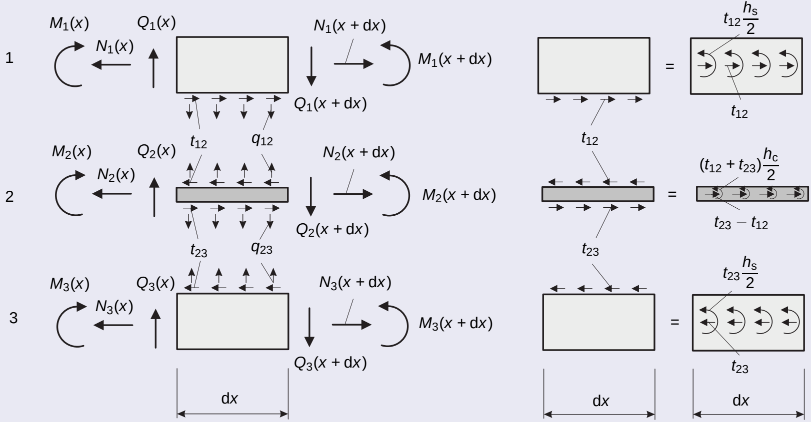


Layer-Wise Beam Theory I

Free-Body Diagrams for Layers with a Length dx

stress resultants and interaction forces

replacement of interaction forces by forces and moments



Layer-Wise Beam Theory II

Balance of Forces and Moments Applied to each Layer

$$N_1' + t_{12} = 0, \quad N_2' + t_{23} - t_{12} = 0, \quad N_3' - t_{23} = 0, \tag{10}$$

$$Q_1' + q_{12} = 0, \quad Q_2' + q_{23} - q_{12} = 0, \quad Q_3' - q_{23} = 0, \tag{11}$$

$$M_1' - Q_1 + t_{12}\frac{h_s}{2} = 0, M_2' - Q_2 + (t_{12} + t_{23})\frac{h_c}{2} = 0, M_3' - Q_3 + t_{23}\frac{h_s}{2} = 0 \tag{12}$$

Resultants of the Beam vs. Resultants of Layers

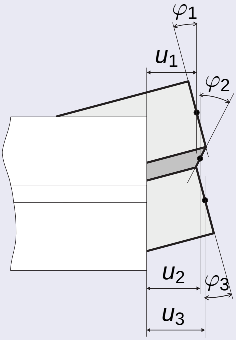
$$\begin{aligned} N &= N_1 + N_2 + N_3, \quad Q = Q_1 + Q_2 + Q_3, \\ M &= M_1 + M_2 + M_3 + (N_3 - N_1)\frac{h_s + h_c}{2} \end{aligned} \tag{13}$$

Layer-Wise Beam Theory III

Kinematical Relations

$$u_1 + \varphi_1 \frac{h_s}{2} = u_2 - \varphi_2 \frac{h_c}{2}, u_3 - \varphi_3 \frac{h_s}{2} = u_2 + \varphi_2 \frac{h_c}{2}, w_i = w \quad (14)$$

Axial Displacements and Cross Section Rotations



Layer-Wise Beam Theory IV

Constitutive Equations

$$\begin{aligned} N_i &= D_i u_i', & Q_i &= \mathit{\Gamma}_i (w' + \varphi_i), & M_i &= B_i \varphi_i', \\ D_i &= E_i b h_i, & \mathit{\Gamma}_i &= \kappa_i G_i b h_i, & B_i &= E_i \frac{b h_i^3}{12} \end{aligned} \qquad (15)$$

Assumptions

- the bending resistance of the beam is primarily determined by the skin layers,
- the skin layers are shear rigid

Layer-Wise Beam Theory V

Deflection

$$w(x)=\begin{cases}\dfrac{F}{12B}(2a^2+2xa-x^2)(a-x)+\dfrac{F}{2\Gamma_{\mathrm{L}}}(a-x)\\ +\dfrac{F}{2\Gamma_{\mathrm{L}}\beta}(\sinh\beta x-\sinh\beta a)\\ +\dfrac{F}{2\Gamma_{\mathrm{L}}\beta}\left(\dfrac{\sinh\beta(l-a)-\sinh\beta l}{\cosh\beta l}(\cosh\beta x-\cosh\beta a)\right),\\ 0\leq x\leq a,\\ \dfrac{Fa^2}{4B}(a-x)\\ +\dfrac{F}{2\Gamma_{\mathrm{L}}}\dfrac{1-\cosh\beta a}{\beta\cosh\beta l}(\sinh\beta(l-a)-\sinh\beta(l-x)),\\ a<x\leq l,\end{cases}\tag{16}$$

$$\Gamma_{\mathrm{L}}=\frac{4}{9}\Gamma_{\mathrm{c}}\left(\frac{1+\alpha+\alpha^2}{\alpha(1+\alpha)}\right)^2\tag{17}$$

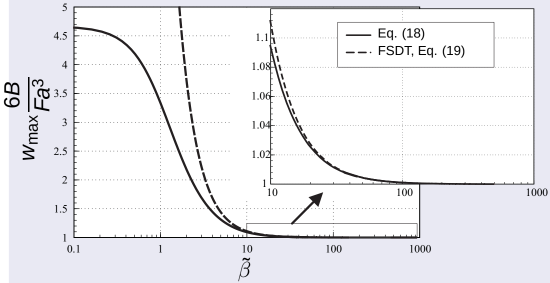
Layer-Wise Beam Theory V

Maximum:

$$
\begin{aligned}
w_{\mathrm{max}} &= \underbrace{\frac{Fa^3}{6B}}_{} \\
&+ \overbrace{\frac{Fa}{2\Gamma_{\mathrm{L}}}}^{} \\
&+ \underline{\frac{F}{2\Gamma_{\mathrm{L}}\beta}\left(\frac{\sinh\beta(l-a)-\sinh\beta l}{\cosh\beta l}(1-\cosh\beta a)-\sinh\beta a\right)}
\end{aligned}
\tag{18}
$$

Numerical Results I

Deflection vs. Parameter $\tilde{\beta}$ for $\zeta = 0.25$ and $\alpha = 0.05$

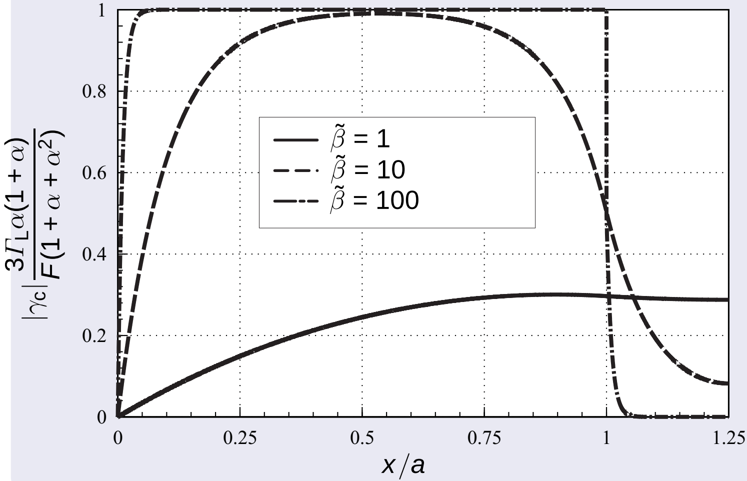


$$w_{\max} = \frac{Fa^3}{6B}\left[1 + \left(\frac{3(1+\alpha)}{\tilde{\beta}(1-\alpha)}\right)^2\right] \qquad (19)$$

$$\tilde{\beta} = \beta a = \sqrt{\frac{3\Gamma_{\mathrm{L}} a^2}{B}\frac{1+\alpha}{1-\alpha}}, \qquad \zeta = \frac{l-a}{a} \qquad (20)$$

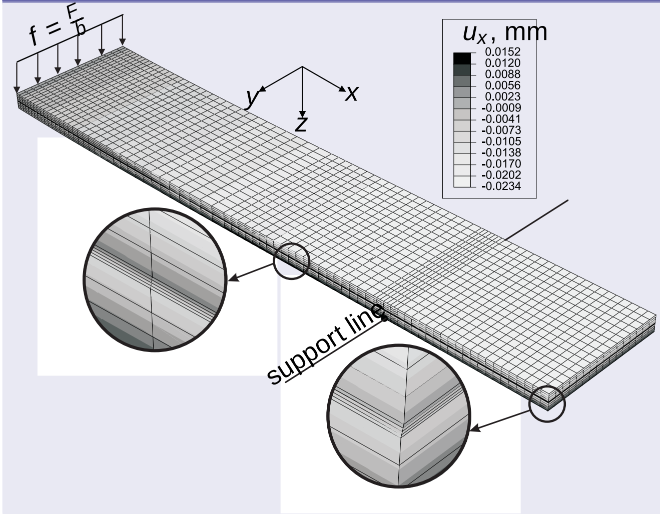
Numerical Results II

Shear Strain of the Core Layer vs. Axial Coordinate



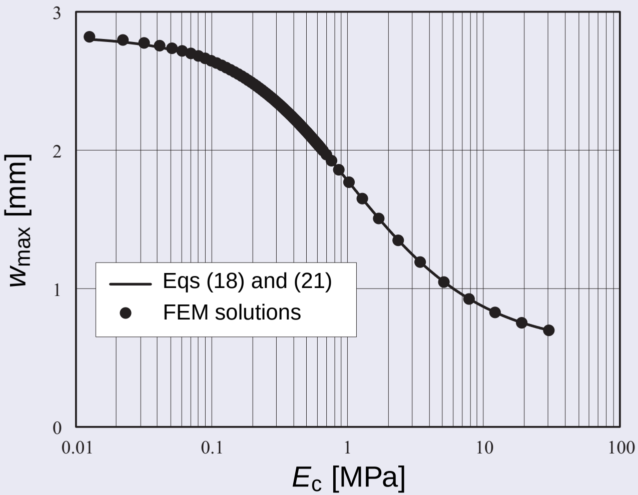
FEM I

FE Mesh and Axial Displacement u_x for $E_c = 3.5$ MPa



FEM II

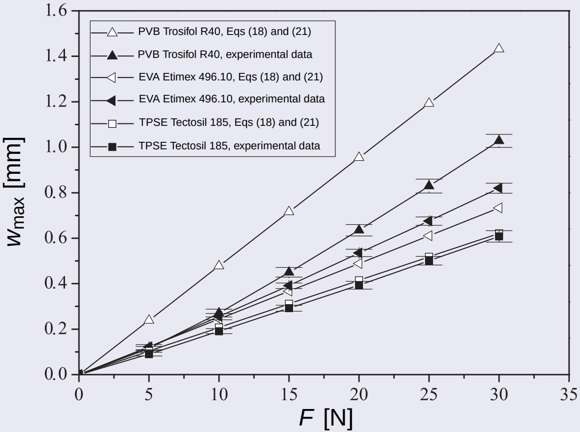
Deflection vs. Young's Modulus of the Core Layer



Experimental Proof

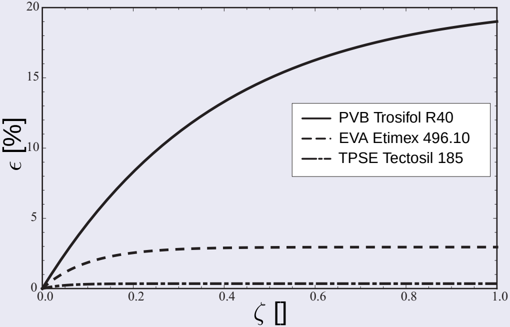
Measured and Calculated Deflection

$$\mathit{\Gamma}_{\mathrm{L}} = 4G_{\mathrm{c}}bh/9\alpha \tag{21}$$



Difference Beam Length to Support Span ζ

Difference in the Maximum Deflection ϵ vs. Parameter ζ



Material	$\tilde{\beta}$
PVB Trosifol R40	1.37
EVA Etimex 496.10	4.96
TPSE Tectosil 185	10.85

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Conclusions and Outlook

Formulation

- Layer-wise plate theory for PV-laminates
- Closed form solution for plate strip
- Verifications: comparison with FEA and experimental data

Conclusions

- The layer-wise theory reflects basic features of deformation and stress states for laminates with soft core

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Conclusions and Outlook

Current and Future Studies

- Solutions for plates with real boundary conditions (frames)
- Consideration of inelastic properties for encapsulant materials
- Thermo-mechanical analysis
- Analysis of damage and fracture processes

Thank You!!

Further questions:
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