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Stress analysis of a pinned wood joint by grey-field photoelasticity

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ABSTRACT

Pinned (bolted) joints/connections are a widely used, but difficult to analyze, component. Their bolt/hole interface stresses are typically unknown *a priori*. Structural failures often initiate at connections and their contact stresses can be the "Achilles' heel". Although such connections are extremely prevalent in wood structures, ability to determine the individual stresses in mechanical wood joints is aggravated by the material's orthotropy. Solutions to such non-linear problems that account for finite geometry, pin/hole friction and clearance are non-trivial. Many mechanical-joint analyses ignore friction for simplicity, but some contact friction is virtually always present. By applying a thin birefringent coating to the wood, the individual stresses and strains in the coating (and hence in the wood) are determined by synergizing grey-field photoelasticity, a stress function and boundary information. Full-field individual stresses are obtained in the wood, including at the contact boundary. Predicted strength based on the determined stresses is compatible with the connection failure.

1. Introduction

Bolted connections in orthotropic composite materials, including in wood, have received considerable attention over the years. Refs. [1–21] are representative of such studies. Structural non-linearity, and difficulties in determining the stresses on the contact area between the pin/bolt and fastened material, are among the challenges of such analyses. These difficulties can be aggravated if there is bolt-hole clearance, as frequently occurs in practice. In view of the above, the object of his study was to develop and demonstrate the ability to stress analyze a wood joint by bonding a thin birefringent coating to the wood and determining the stresses/strains in the coating using grey-field photoelasticity (GFP), Fig. 1. While applied here to wood, the technique is general and applicable with other orthotropic materials. Moreover, and although physical joint failure is compatible here with the evaluated stresses and wood properties, development of a data base for strength predications is beyond the scope of this manuscript.

As outlined in Fig. 2, individual strains in the isotropic coating, including their reliable determination at the edge of the contacted hole, are obtained photoelastically by using a stress function and boundary conditions. Considering the strains in the coating are equal to those in the wood, and using the orthotropic stress–strain relationship, the individual stresses become available throughout the wood (Red Oak), including along the pin-hole boundary. The present case is for pin-hole clearance. The approach utilizes some concepts of Ref. [17] where strain-gage data were combined with available boundary information to evaluate the coefficients of a stress function and thereby determine the individual stresses throughout a pinned aluminum connection.

2. Grey-field photoelasticity

A grey-field (GFP model 1200 by Stress Photonics, Madison, WI) photoelastic stress/strain analysis system is employed [22,23]. As with traditional photoelasticity, GFP is based on the fact that an optically isotropic, unstressed medium becomes optically anisotropic (i.e., birefringent) when stressed. The GFP 1200 utilizes circularly polarized light which becomes elliptically polarized in the presence of stress/strain, the amount of ellipticity being a measure of the magnitude of the maximum in-plane shear stress. The direction/isoclinic, θ_p, from the first principal strain (stress), ε_p, is $\pi/4$ radians away from the major axis of the ellipse. A rotating analyzer allows only that component of light to be transmitted in its direction. The intensity of the transmitted light is measured, with more light being transmitted when the analyzer is aligned with the major axis of the ellipse. The polariscope employs an achromatic white-light circular polarizing illuminator and the RBG camera captures all colors simultaneously. This highly-sensitive system

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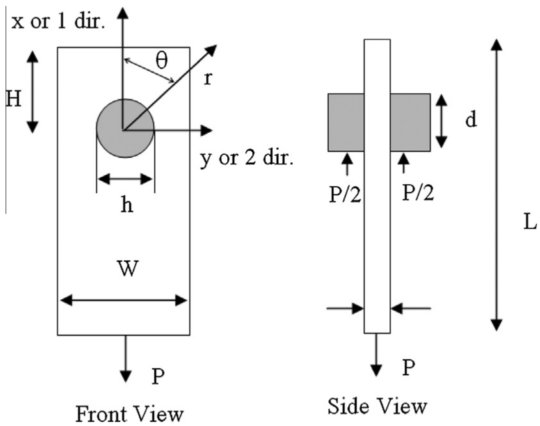

Fig. 1. Connection geometry (d = 25.4 mm, W/d = 2.5, H/d = 1.5, L/d = 8, t/d = 0.255, h = 25.591 mm and diametral clearance C = 0.191 mm).

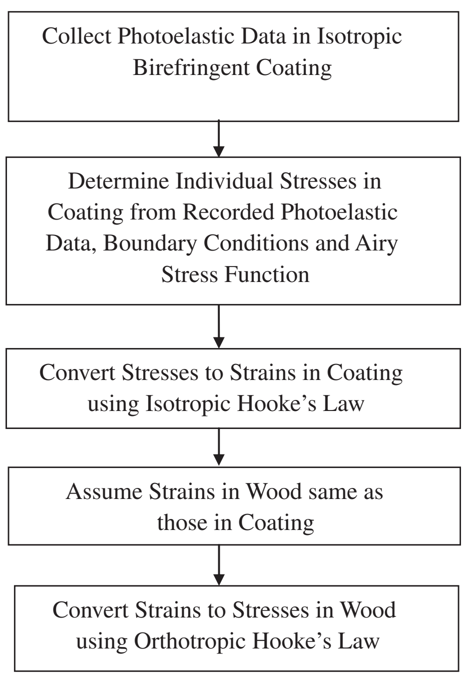

Fig. 2. Flow chart for evaluating the individual stresses in wood from recorded photoealstic data in bonded birefringent coating.

(records fractional fringe orders) circumvents the traditional tedious need to count fringes, and all data acquisition and processing are digital and accomplished with a computer. Resolution is on the order of 20 mircostrain, comparable to foil strain gages. Among the outputs available from this polariscope are full-field 320 × 240 pixels (from isochromatic, $\sigma_p - \sigma_q$, and isoclinic, θ_p, data and with reference to Mohr's Circle) of

$$\begin{aligned} &\sigma_{xy} = \frac{1}{2}\cdot(\sigma_p - \sigma_q)\cdot Sin(2\cdot\theta_p) \\ &(\sigma_{xx} - \sigma_{yy}) = (\sigma_p - \sigma_q)\cdot Cos(2\cdot\theta_p) \\ &\tau_{\max} = \frac{1}{2}\cdot(\sigma_p - \sigma_q) \\ &\theta_p \end{aligned} \quad (1)$$

where σ_p and σ_q are the principal stresses. The spatial resolution at the wood is 0.23 mm. Discrete photoelastically-measured values of $(\sigma_{xx} - \sigma_{yy})$ of Eq. (1) are synergized with differentiated information (stress expressions) from an Airy stress function to separate the strains in the bonded birefringent coating and thereby determine the individual stresses throughout the wood connection. Using photoelastic information in the form of $(\sigma_{xx} - \sigma_{yy})$, rather than just isochromatic data, to evaluate unknown coefficients of the stress function so as to determine stresses is advantageous in that only the linear, not non-linear, least-squares technique is necessary [23,24].

The GFP measured values of $(\sigma_{xx} - \sigma_{yy})$ of Eq. (1) in the thin (0.33 mm) epoxy (Devcon 2-ton epoxy, two-part system) coating bonded to the wood (i.e., reflective photoelasticity) were utilized to determine the individual strains throughout the coating. In-plane strains in the loaded structure are assumed to be identical to those in the coating. Before applying the epoxy coating, the wood was sprayed with Krylon (1403 dull aluminum) paint to help diffuse the transmitted light at the wood-coating interface. The value of the optical strain coefficient, K, of the coating was determined to be 0.05 from aluminum tensile specimens which were prepared and coated (with same thickness coating) simultaneously with the tested wood, where $(\sigma_p - \sigma_q) = N\lambda E_c/[2(1 + \nu_c)Kt_c]$ such that σ_p, σ_q, E_c, ν_c and t_c are the principal stresses, elastic modulus, Poisson's ratio and thickness for the coating, respectively, N is the isochromatic fringe order and λ is the wave length of the light [22,23]. The values of $(\sigma_p - \sigma_q)$ of Eq (1) were obtained from the center wavelengths of the three recorded colors and K, which is essentially independent of the wavelength. Reliability of the present hybrid photelastic-stress function pin-joint analysis was reinforced by verifying equilibrium and correlating with previous strain-gage and GFP based analyses [17,18,25].

3. Analytical considerations

The Red Oak is assumed here to be a 2-D orthotropic homogeneous material with constant properties in the two major material directions, parallel (1-direction) and transverse (2-direction – tangent to the growth lines) to the grain, Fig. 1. The individual stresses were determined throughout the coating. Utilizing 2-D, isotropic Hooke's law, the stresses in the coating were then converted into individual components of strain in the coating. Assuming the in-plane strains in the coating and wood are equal, the orthotropic stress–strain relationship (for the wood) was then employed to determine the full-field individual components of stress in the wood, Fig. 2. The expressions for the orthotropic stress–strain relationship are [26]

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{21} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{Bmatrix} \quad (2)$$

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{21} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \cdot \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} \quad (3)$$

$$\begin{aligned} &Q_{11} = \frac{S_{22}}{S_{11}\cdot S_{22} - S_{12}^2} \\ &Q_{22} = \frac{S_{11}}{S_{11}\cdot S_{22} - S_{12}^2} \\ &Q_{12} = Q_{21} = -\frac{S_{12}}{S_{11}\cdot S_{22} - S_{12}^2} \\ &Q_{66} = \frac{1}{S_{66}} = G_{12} \end{aligned} \quad (4)$$