Elastic Properties of Sandwich Composite Panels using 3-D Digital Image Correlation with the Hydromat Test System

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ABSTRACT

A method to determine elastic properties of sandwich composite panels by integrating digital image correlation analysis, plate bending experiments and numerical techniques was developed. Sandwich composite panels were evaluated as a simply-supported plate under uniform lateral pressure using a Hydromat test system according to ASTM D6416 standard method. The panel was modeled using sandwich composite plate theory with a Navier's solution.

A 3-D digital image correlation system capable of full field measurements of strains and displacements was utilized with the Hydromat test system. The experimental displacement and in-plane strain measurements were correlated to the sandwich composite plate solution. Based on this correlation, an inverse analysis technique was developed to compute elastic properties of the sandwich panel components (face sheets and core). A numerical optimization method based on non-linear least squares was utilized to minimize the error in the computation of elastic properties.

The relevance of this combined experimental-numerical method is that it could change the way composite materials are evaluated, since it may be possible to determine all the relevant elastic properties from one single plate bending test instead of several coupon tests. This approach reduces the testing effort required to characterize sandwich composite panels, while improving the reliability of the predictions.

INTRODUCTION

Sandwich composite panels are constructing by bonding thin high stiffness face sheets to a low stiffness but relatively thick core material. The theory behind sandwich construction is that the relatively stiff face sheets will carry most of the bending moments and axial loads while the core material will stabilize the face sheets and carry all transverse shear force. As the core material becomes thicker the sandwich plate becomes stiffer in shear and bending. Plate shear stiffness is directly proportional to the core thickness while bending stiffness is proportional to the thickness to the third power. Typical sandwich constructions exhibit a very high transverse stiffness when compared to materials with similar weight. The high stiffness to weight ratio makes sandwich construction a very attractive design option in weight critical structures.

Many test methods have been developed to characterize sandwich composite panels and their constituents. Structural ASTM tests for sandwich construction include Hydromat Test System (HTS), three-point and four-point beam bending. Additionally, ASTM test methods for determining properties of the sandwich composite constituents, such as tensile tests for face sheets and core shear tests are available. This paper presents a method to determine elastic material properties of sandwich composite panels and their constituents using HTS according to ASTM D6416.

HTS was developed as a structural test for simply supported sandwich composite panels under uniform pressure [1-3]. This test configuration matches the traditional Navier's plate solution allowing experimental data to be correlated with analytical modeling. HTS has proven accurate at creating the simply supported boundary conditions and uniform loading. This results in plate displacements within 1% and strains within 2% of predicted values when testing an isotropic steel calibration plate [4].

The method presented in this paper expands on the HTS method by using basic definitions from sandwich composite plate theory combined with powerful 3D digital Image Correlation (IC) techniques. Furthermore, full-field experimental data acquired through the IC system can be correlated to the analytical model using optimization techniques. This allows reliable computation of sandwich composite panel bending and shear stiffness coefficients.

DIGITAL IMAGE CORRELATION

All deformations of the central area of the sandwich composite panel during the Hydromat tests were determined by means of a 3-D digital image correlation system capable of full field measurements of strains and displacements using a non-contact digital IC technique. The IC method has been developed and used to measure deformation and strains of materials under various loading regimes with sub-pixel accuracy since 1980's [5-7]. It has been already successfully applied to determine strains in specimens of solid wood, individual wood fibers and papers [8-11], as well as resin films [12], fiber reinforced polymer composites [13], and concrete [14].

The method allows determination of displacements of selected points of the mesh on the surface of the deformed specimen by comparing successive images acquired during a test and cross correlating the gray intensity patterns of the direct neighborhood of the points (or the reference areas). In-plane strain values ε_x, ε_y, and γ_{xy} for deformation of specimen surfaces may then be obtained from analysis based on a triangular or rectangular network of points [13]. Detailed description of the method may be found in [5, 8, 14] and [6].

In addition, out of plane displacements may be accurately measured if two cameras are arranged in front of the same specimen area at an angle so that the displacements captured at the same instants of time by two cameras are correlated to provide stereoscopic information. Such capability is provided by the ARAMIS system by GOM, MbH, and has been successfully applied to a wide range of experimental problems. Detailed description of the 3-D measurement principles, system specifications, calibration procedures, and sample applications may be found in [15-18].

MATERIALS AND FABRICATION PROCESS

The sandwich composite panel face sheet was made of E-glass / vinyl ester. The fiber reinforcement was woven roving with a weight per unit area of 814 kg/m^2 (24 oz/yd^2) and the style was Vetrotex 324. The warp and fill directions have 55% and 45% respectively of the total fiber weight. The face sheet consisted of one layer of fabric reinforcement, where the warp direction correspond to the principal material direction 1 and plate coordinate direction x. The polymer resin was Derakane 8084, which is an elastomer-modified vinyl ester resin. The core material was end-grain balsa wood with a nominal density of 151 kg/m^3 and a thickness of 25 mm. The core style was Baltek D100 rigid sheet with AL600/10 coating for decreasing porosity and increasing bond strength. The core specified shear modulus was 157 MPa as determined by ASTM C273.

The sandwich composite panels were fabricated using the vacuum-assisted resin transfer molding (VARTM) process with the proprietary SCRIMP technology. Fabrication was conducted at ambient conditions with no postcuring process. In the VARTM/SCRIMP method the face sheets of the sandwich composite panel are infused and bonded to the core material in one step. Two panels with dimensions 610 by 1220 mm (2 x 4 ft) were fabricated. Each fabricated panel was cut into two square test panels with dimensions of 508.5 mm using waterjet machining equipment.

EXPERIMENTAL SET-UP AND PROCEDURE

HTS was implemented by mounting an aluminum fixture on a servo-hydraulic test frame (See Figure 1). The fixture was fabricated according to ASTM D6416 adjunct specifications. A 100 kN load cell was bolted to a t-slotted table and a reinforced glulam bladder support slab was utilized. The bladder consisted of 3-ply industrial belting with a metal frame. The bladder was filled with water. The maximum pressured allowed by the bladder was 0.90 MPa (130 psi). A pressure transducer (Setra 206) with a maximum capacity of 0.69 MPa was attached to the bladder. All testing and instrumentation equipment was calibrated as part of the AEWC Center laboratory standard procedures (laboratory certification is in compliance with ISO 17025).



Figure 1 – Hydromat Test System

The top and bottom edges of the test panel were supported by round journals attached to the fixture. To prevent uplifting of the test panel edges, and therefore enforcing simply-supported boundary conditions, the corner bolts were adjusted to a torque level of 6.8 Nm (60 in-lb). Crushing of the panel edges was prevented by the use of line-load diffuser strips. A neoprene membrane with a Teflon interface was applied on the bladder to provide protection from fiber splintering of the panel during the test. The bladder applies uniform pressure over a square contact area. The contact area dimension changes with the applied load and can be determined based on the load cell and pressure transducer measurements [19].

Two high-resolution (1280 x 1024 pixel) cameras were mounted on the HTS fixture (See Figure 1). The cameras were focused on the same region of interest in the center of the sandwich composite panels. The surface of the panel was painted white and then "randomized" by spraying a black speckle pattern, to enhance digital pattern correlation. Two 12 mm wide-angle lenses were used. The IC system automatically compensated for the wide-angle lenses distortion through a simple calibration procedure using standardized targets. A study on the accuracy and precision of the IC system is available in [20].

The HTS experiments were conducted in a temperature and relatively humidity controlled room. A monotonic load in displacement controlled mode was applied with a rate of 2.5 mm/min until panel failure. Voltages from the load and pressure transducer were recorded using the data acquisition system incorporated with the IC system. In this manner, each image was recorded with a synchronized load and pressure level. Digital images were acquired at 5 second intervals during the experiments.

After the tests post-processing of the image sets was conducted. The IC program assigned a regular mesh of approximately 6500 reference facets with dimensions of 15 x 15 pixels. Using the random speckle pattern each facet was triangulated in the image pairs obtained from the two cameras. The mesh interval or the distance between adjacent facets in the mesh was 13 pixels, which results in overlapping of facet areas. For each time step the program returns full 3-D displacement and in-plane strain components for each facet on the upper surface of the panel.

SANDWICH COMPOSITE PANEL MODELING

The test panel was modeled using sandwich plate theory based on first-order shear deformation theory (FSDT). The assumptions of the model are:

- The overall sandwich composite panel needs to be balanced and symmetric.
- The top and bottom composite face sheets need to be balanced.
- Composite face sheets are thin and they do not contribute to transverse shear stiffness.
- The transverse shear stress in the core is assumed to be uniform through the thickness.

According to Navier's solution for a simply supported plate with support span *a* under uniform pressure, *q*, the transverse displacement, *w*, and rotations in the x and y direction (ψ_x, ψ_y) are represented using Fourier series [21], as follows:

$$q(x,y) = \sum_{m=1,3\ldots}\sum_{m=1,3\ldots} \frac{16P\cdot\cos\frac{m\cdot\pi\cdot\phi}{a}\cdot\sin\frac{n\cdot\pi\cdot\phi}{a}}{\pi^2\cdot m\cdot n}\cdot\sin\frac{m\cdot\pi\cdot x}{a}\cdot\sin\frac{n\cdot\pi\cdot y}{a} \tag{1}$$

where *P* is the bladder pressure and ϕ is the distance from the support to the contact area.

$$w(x,y) = \sum_{n=1,3\ldots}\sum_{m=1,3\ldots} C_{mn}\cdot\sin\frac{m\cdot\pi\cdot x}{a}\cdot\sin\frac{n\cdot\pi\cdot y}{a} \tag{2}$$

$$\psi_x(x,y) = \sum_{n=1,3\ldots}\sum_{m=1,3\ldots} A_{mn}\cdot\cos\frac{m\cdot\pi\cdot x}{a}\cdot\sin\frac{n\cdot\pi\cdot y}{a} \tag{3}$$

$$\psi_y(x,y) = \sum_{n=1,3\ldots}\sum_{m=1,3\ldots} B_{mn}\cdot\sin\frac{m\cdot\pi\cdot x}{a}\cdot\cos\frac{n\cdot\pi\cdot y}{a} \tag{4}$$

where the explicit expressions for the series coefficients A_{mn}, B_{mn} and C_{mn} are presented in Melrose (2004).
In-plane strains are obtained from the panel curvatures, which are differentiated from the rotations in the x and y direction, as follows

$$\varepsilon_x = -z\cdot\frac{\partial}{\partial x}\psi_x \tag{5}$$

$$\varepsilon_y = -z \cdot \frac{\partial}{\partial y} \psi_y \tag{6}$$

$$\gamma_{xy} = -z \cdot \left(\frac{\partial}{\partial y} \psi_x - \frac{\partial}{\partial x} \psi_y \right) \tag{7}$$

Transverse shear strains in the core in the x and y direction, which represent shear deformation of the panel, are obtained as follows

$$\gamma_{xz} = \psi_x + \frac{\partial}{\partial x} w \tag{8}$$

$$\gamma_{yz} = \psi_y + \frac{\partial}{\partial y} w \tag{9}$$

The total elastic strain energy , U_T, stored in the panel during the load test is decomposed into a face sheet, U_F, and core component, U_C, as follows

$$U_T = \frac{1}{2} \int_0^a \int_0^a w(x,y) \cdot q(x,y) \cdot dx \cdot dy = U_F + U_C \tag{10}$$

where the core strain energy component is

$$U_C = \frac{1}{2} \cdot G_{13} \cdot h \cdot \int_0^a \int_0^a \gamma_{xz}(x,y) \cdot \gamma_{yz}(x,y) \cdot dx \cdot dy \tag{11}$$

The displacement, rotations and strain solutions are dependent on bending stiffness coefficients D_{11}, D_{12}, D_{22} and D_{66} and transverse shear coefficients A_{44} and A_{55} through the series coefficients A_{mn}, B_{mn} and C_{mn}

The transverse shear coefficients are defined as:

$$\begin{bmatrix} A_{44} & 0 \\ 0 & A_{55} \end{bmatrix} = h \cdot \begin{bmatrix} k_{23} G_{23} & 0 \\ 0 & k_{13} G_{13} \end{bmatrix} \tag{12}$$

where the shear correction factors k_{13} and k_{23} can be computed based on strain energy equivalence. However, in sandwich composite plate theory is typically accepted that $k_{13} = k_{23} = 1$ as shown by [21]. Then, the transverse shear moduli can be computed as:

$$\begin{bmatrix} G_{13} & 0 \\ 0 & G_{23} \end{bmatrix} = \frac{1}{h} \cdot \begin{bmatrix} A_{44} & 0 \\ 0 & A_{55} \end{bmatrix} \tag{13}$$

OPTIMIZATION APPROACH

A constrained non-linear optimization method was implemented using Matlab. The objective function for the optimization process computed the residuals between experimental data and analytical modeling. Each component of the objective function was normalized by the maximum absolute value for each experimental measured quantity. Normalizing the residuals weighs each component of the objective function equally. It is important to note that the objective function is a matrix with each column of the matrix containing a residual relating to an experimental quantity. Each row represents the measured experimental quantities at the point determined by the coordinates (*x,y*). Thus, when the objective function is minimized, the model is the best possible match to the experimental data set as a whole.

The optimization process varies the six stiffness parameters (D_{11}, D_{12}, D_{22}, D_{66}, G_{13} and G_{23}) that define the sandwich composite plate model until the magnitude of the residuals reaches a specific tolerance. The constraints applied to the stiffness parameters are that they are positive defined. By inspection of the problem, it was found that there were six unknown stiffness parameters and only four experimental quantities (w, ε_x, ε_y, and γ_{xy}). Therefore, this system was indeterminate. To ensure uniqueness of the solution, two additional experimental quantities were added by computing the gradient of the displacement field. By equating the number of experimental quantities to the number of unknown stiffness parameters, the optimization problem became determinate (i.e., 6 unknowns with 6 equations). The solution is valid for an orthotropic core;

however for the specific test panels presented in this paper the core was considered isotropic (i.e., G_{13} is equal to G_{23}). The flow chart shown in Figure 2 illustrates the optimization process.

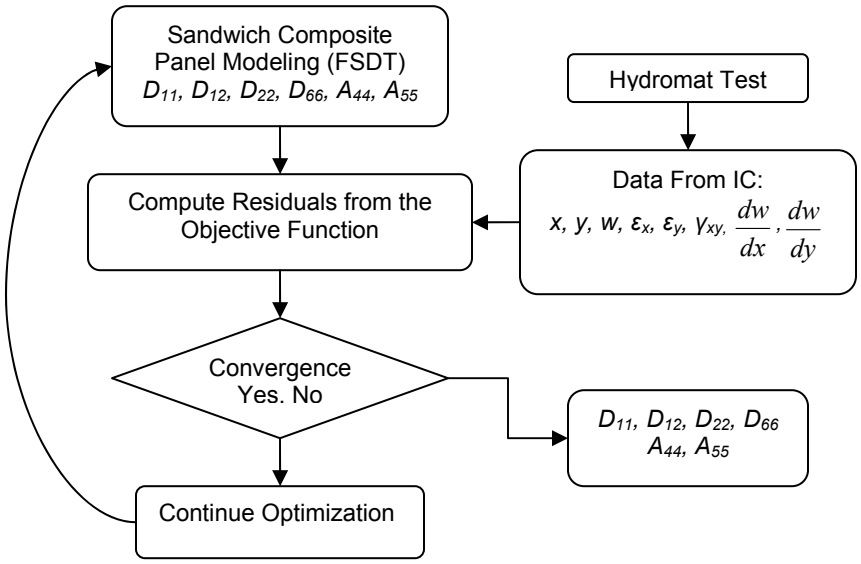
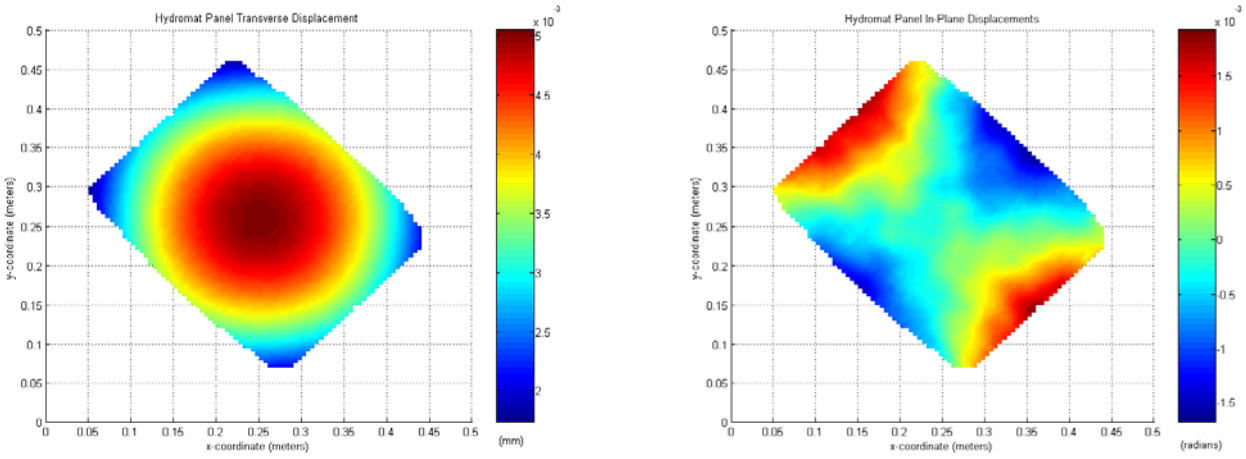


Figure 2 - Sandwich Panel Parameter Optimization Flow Chart

To evaluate the robustness of the optimization technique, full-field data was simulated using the sandwich composite plate model and perturbed by adding random noise. The optimization method consistently converged to the same solution for any level of reasonable noise (e.g., approximately 5% additive noise). The initial seed value was varied to ensure that convergence occurs independently of the quality of the initial approximation. Then, for typical initial stiffness values computed using micromechanics equations, which may differ up to 25% from actual values, convergence was observed.

DISCUSSION OF RESULTS

The field of view for the test panel is illustrated in Figure 3. The transverse displacement field measured through IC followed the expected trend predicted sandwich plate theory, as shown in Figure 3(a). The measured in-plane shear strain distribution in the field of view is shown in Figure 3(b). The peak in-plane shear strain occurs at the plate corners, which are outside the field of view. Optimally, the cameras should view the entire test panel. However, due to the HTS fixture configuration this was not possible.



(a) (b)

Figure 3 - Contour plots of hydromat panel: (a) Transverse displacements; and (b) In-plane shear strains

A set of initial seed values is presented in Table 1. These seed values are considered an “educated guess” based on a simple rule of mixtures approach.

Table 1 - Bending and Shear Stiffness Coefficients: Seed Value

Stiffness Coefficient	D_{11}	D_{22}	D_{12}	D_{66}	G_{13}	G_{23}
Units	N m	N m	N m	N m	MPa	MPa
Seed Value	6000	5500	500	500	140	140

The optimization routine was applied along with the IC measured fields as presented in Figure 3 to compute predicted stiffness values. Computed stiffness values for four different panels are presented in Table 2.

Table 2 - Bending and Shear Stiffness Coefficients: Computed Values

Stiffness Coefficient	D_{11}	D_{22}	D_{12}	D_{66}	G_{13}	G_{23}
Units	N m	N m	N m	N m	MPa	MPa
Panel #1	6175	5569	569	567	170	170
Panel #2	6099	5427	557	556	187	187
Panel #3	6045	5537	563	561	226	226
Panel #4	6232	5552	562	562	150	150
Mean	6138	5521	563	562	183	183
COV %	1.34	1.16	0.87	0.80	17.6	17.6

It was found that the coefficient of variation (COV) for the bending stiffness properties was very low, which implies that the computation was very reliable. The transverse shear properties exhibited higher COVs, which can be attributed two to factors. The first factor is the natural variability of balsa wood properties (i.e., shear modulus varies with density). The second factor involves the ratio of elastic shear strain energy to the total energy applied to the test panel. Based on equations (10) and (11), the face sheets of the sandwich composite plate sustained approximately 94% of the total energy applied to the plate. Thus, the face sheets dominate the behavior of the plate while the core has a relatively small contribution to the panel's response. As a result, the method is less sensitive to determine core transverse shear properties. The supplier specified balsa wood shear modulus is 157MPa based on ASTM C273. It was found that the mean computed transverse shear modulus is higher than the specified value.

For each panel, the sandwich composite plate model was evaluated with the stiffness properties reported in Table 2. There was excellent agreement between the computed and experimental strain and displacement fields. This confirms that the computed properties are an accurate estimate of the actual panel properties. The ratio between the bending stiffness coefficients D_{22}/D_{11} is 0.90. Using micromechanics equations based on the rule of mixtures (E_1 and ν_{12}) and Halpin-Tsai equations (E_2 and G_{12}) for supplier specified fiber and matrix properties, the predicted ratio between D_{22}/D_{11} is 0.89.

CONCLUSIONS AND RECOMMENDATIONS

A new method for computing stiffness parameters from a sandwich composite panel bending test is presented. The method combines digital image correlation with numerical optimization techniques to solve the inverse problem and generate reliable stiffness coefficients. The solution is unique because a determinate system is generated by using six different experimental data fields (transverse displacements, displacement gradient, and in-plane strains) to solve for six unknown stiffness coefficients.

The method is considered to be robust for two reasons. First, it was found that when random additive noise was introduced into simulated field data, convergence to the expected corrected solution was attained. Second, it was found that the solution converged for initial seed values containing significant error.

The proposed method has potential to be further enhanced with expected improvements in accuracy of digital image correlation techniques. Additionally, the basic method of matching full-field data to modeling can be used in a laboratory environment for a broad range of experimental applications.

The relevance of this combined experimental-numerical method is that it could change the way composite materials are evaluated, since it may be possible to determine all the relevant elastic properties from one single plate bending test instead of several coupon tests. This approach reduces the testing effort required to characterize sandwich composite panels, while improving the reliability of the predictions.

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