ANALYTIC SOLUTIONS FOR BIO-BASED RENEWABLE CONSTRUCTION PANELS MANUFACTURED WITH NON-RIGID BONDING

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ABSTRACT

Under the immense pressure of environmental, energy, economic, and other modern problems, many new materials have been scientifically developed. There is a wide range of renewable materials developed from natural and manmade resources as polymers and composites. Yet, the state of scientific advancements apparently lags behind their applications in the buildings sector. One may argue that there is a gap between the discovery of those materials and the state of residential construction. The needed knowledge about these materials for the engineering designs may shed light on that gap. To elaborate, structural insulated panels have been successfully used nationwide but why renewable components such as green adhesives and biodegradable foams have not been applied as load bearing elements in modular and panelized buildings?

This paper is the result of an in-progress effort to close the gap between the scientific development of materials and their applications. It will present accurate analytic models developed for panels manufactured with non-rigid bonding and subjected to various loads. The models are useful to ascertain the effects of the finite values of bonding stiffness on the performance and responses of the panels. Numerical and experimental results indicated that the customary assumption of perfect bonding should not be used beyond a certain level of stiffness. This discovery also provided an answer to what constitutes perfect bonding.

Keywords: Buildings, construction, laminated/sandwich panels, residential, SIP.

GENERAL

The demanding needs of the construction industry have inspired the creation of innovative building systems. Laminated and sandwich panels constructed from renewable products have been applied successfully in various construction projects (1 to 4, 6 to 8, and 10). They balance the engineering of light weight components with mechanical and thermal properties with the engineering of a useful system that possesses satisfactory properties while in service. Prominent organizations such as the EPA foster research in the area of alternative sustainable buildings made of composites from natural, biodegradable, and recyclable materials. The concept of combining different materials with different physical and chemical properties to produce products that are stronger than the individual components is not new. However, the use of cellulosic and synthetic fibers in new composite products is progressing at a very rapid pace. The new generation of products possess what the residential sector require in designs such as durability, high strength-to-weight ratios, energy saving, flexibility in design, and indeed became a category in the LEED system. The composite-based products are in each residence nowadays in varies applications including flooring and roofing, utility, bathrooms and kitchens, doors/windows/light panels, interior and exterior architecture as decking and fencing, HVAC, rain systems such as drains, etc. With this very wide popularity of composites in residential construction, their application in integrated load-bearing panels is not as noticeable. For example, green adhesives and biodegradable foams are available in the market but somehow not listed by the SIP as used materials.

Although the use of adhesives is unavoidable in manufacturing laminated and composite panels, the literature lacks adequate studies on their effects on the structural performance. The existing analytic and experimental methods of analysis laminated panels have invariably assumed perfect bonding between layers. Nevertheless, interlayer interactions occur because of the finite bonding stiffness; and environmental effects. These interactions may answer many unanswered questions related to problems such as delamination of renewable panels. This paper aims at the essential material in manufacturing these panels, i.e. the bonding. The broad impacts of this study include responding to the calls for construction systems that are recyclable; the reduction in construction demolition waste disposal in landfills; and the production of building materials with low hazardous impacts on the environment.

RENEWABLE PANELS IN THE HOUSING CONSTRUCTION

According to the EPA (10), residential and commercial buildings account for about 40% of the total annual energy consumption in the United States of America, they produce 35% of the total carbon dioxide emissions, and attribute 40% of landfill wastes. The building industry is also a large consumer of non-renewable materials and this trend has escalated dramatically over the past century. Building systems that included renewable materials have proven their potentials to reducing energy consumption, pollutant emissions and non-renewable material.

The rapidly rising and widely spreading of these materials in the buildings industry is pushing the boundaries in a heavily demanding markets towards residential composites systems. Structural panels composed of thick core bonded to two rigid sheathing materials are commonly applied in the residential construction for walls, floors, roofs, and foundations. The core is generally light weight foam, and the faces could be made a wide variety of materials such as oriented strand boards, plywood, composite panels, and of metal sheets.

The concept of such composite panels meet the functional and performance requirements of integrated designs such as structural, energy, acoustic, fire safety, constructability, maintainability, durability, aesthetics, and economy.

DESCRIPTION OF TECHNICAL PROBLEM

The effects of bonding on the structural response of renewable panels have been tackled using the fundamentals of theory of elasticity (9). Generally, equations are set up to define the equilibrium of the separate skins and of the core and to prescribe the necessary continuity between the faces and the core. The result is a set of differential equations, which may be solved for the quantities of interest as stress. Because this kind of analytic investigation is inherently complex and depends on the applied loading, only the edge loading case is presented here in details. The solutions of other cases could be obtained from the author of this paper. However, numerical results and the impacts of adhesives on the structural performance have been presented for various loading cases.

A Selected Formulation: Edge Loading

Consider a panel composed of three layers bonded together and made of orthotropic materials. The dimensions of the panel are a and b in the x and y directions, respectively. The faces or outer layers are of equal thickness t_f. The core or middle layer, of a thickness 2 t_c, has a modului of elasticity, E_{cx} and E_{cy} usually significantly less than those of the faces E_{fx} and E_{fy}. However, its shear modului G_{cxy}, G_{cxz} and G_{cyz} should be high enough to develop the interaction required between the layers. The adhesive between the faces and core has finite stiffness K_x and K_y. The extent of this kind of composite action depends on the relative stiffness of the constituent materials as will be shown subsequently. The stress state in the faces and core elements is shown in Figure 1. The equilibrium of the face element requires that

$$\frac{\partial \sigma_{fx}}{\partial x} + \frac{\partial \tau_{fyx}}{\partial y} - \frac{q_x}{t_f} = 0$$

$$\frac{\partial \sigma_{fy}}{\partial y} + \frac{\partial \tau_{fxy}}{\partial x} - \frac{q_y}{t_f} = 0$$

in which

σ_{fx}, σ_{fy}	=	Normal stress components in faces;
τ_{fxy}, τ_{fyx}	=	Shear stress components in faces;
q_x and q_y	=	Interlayer shear stress;
t_f	=	The thickness of the face;
f	=	Subscript denoting face;
x, y	=	Coordinate axes.

The state of stress in the core must satisfy the following equilibrium equations.

$$\frac{\partial \sigma_{cx}}{\partial x} + \frac{\partial \tau_{cyx}}{\partial y} + \frac{\partial \tau_{czx}}{\partial z} = 0$$
$$\frac{\partial \sigma_{cy}}{\partial y} + \frac{\partial \tau_{cxy}}{\partial x} + \frac{\partial \tau_{czy}}{\partial z} = 0$$

in which

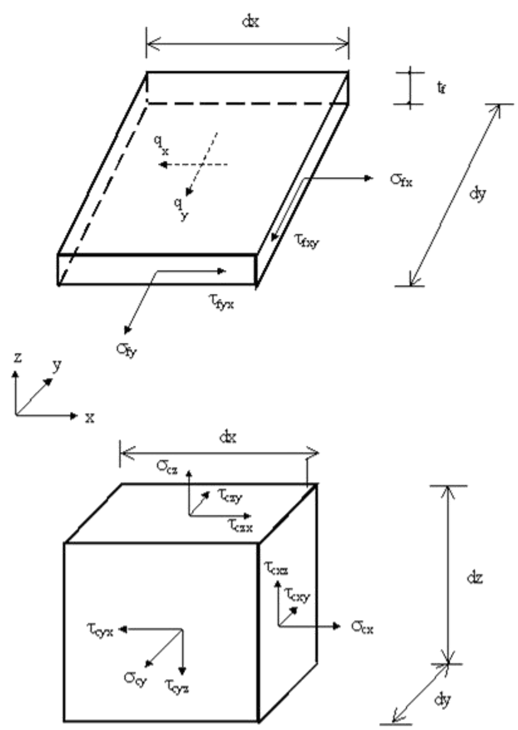

Fig 1. Stress State in Skin and Core

σ_{cx}, σ_{cy}, σ_{cz}	=	Normal stress in the core;
τ_{cxy}, τ_{cyz}, τ_{czx}	=	Shear stress in the core;
c	=	Subscript denoting core.

At the interfaces between the core and the skins, the stresses and strains must be compatible. The compatibility equations in terms of stresses are

$$q_x = \tau_{czx}\Big|_{z=\pm tc}$$

$$q_y = \tau_{czy}\Big|_{z=\pm tc}$$

In terms of strains, the compatibility equations are written as

$$\frac{\partial \Delta_x}{\partial x} = \varepsilon_{fx} - \varepsilon_{cx}\Big|_{z=\pm t_c}$$

$$\frac{\partial \Delta_y}{\partial y} = \varepsilon_{fy} - \varepsilon_{cy}\Big|_{z=\pm t_c}$$

$$\gamma_{fxy} = \gamma_{cxy}\Big|_{z=\pm t_c}$$

in which

ε and γ	=	Normal and shear strain, respectively;
Δ_i	=	Interlayer deformation in the i direction, where i = x or y;
	=	$\frac{q_i}{K_i}$;
K_i	=	Stiffness of adhesive in the i direction.

Solutions to the problem must satisfy the above equilibrium and compatibility equations, in addition to the following boundary conditions:

1. At the panel edges, no normal or shear stresses should exist in the core and the face normal stress must equal the applied in-plane stress, thus

   at x = 0, 2a $\quad \sigma_{fx} = \sigma_{fxo} \quad \sigma_{cx} = \sigma_{cxo}$
   at y = 0, 2b $\quad \sigma_{fy} = \sigma_{fyo} \quad \sigma_{cy} = \sigma_{cyo}$

2. For symmetrical loading about the panel middle plane and centerlines, the shear stresses vanish and no in-plane displacements occur, thus

   at x = a $\quad \tau_{fxy} = \tau_{cxy} = 0 \quad u_c = u_f = 0$
   at y = b $\quad \tau_{fyx} = \tau_{cyx} = 0 \quad v_c = v_f = 0$

   in which

   σ_{fxo} = p_{fxo} / t_f
   σ_{fyo} = p_{fyo} / t_f
   u and v = Displacements in the x and y directions, respectively.

A solution for normal stress components in the core satisfying the above boundary conditions is considered as (5 and 9)

$$\sigma_{cx} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} A_{mn}\, \phi_x\, S_x\, S_y + \sigma_{cxo}$$

$$\sigma_{cy} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} C_{mn}\, \phi_y\, S_x\, S_y + \sigma_{cyo}$$

Using these equations, expressions for the displacement of the core are derived from Hooke's law as follow

$$u_c = -\frac{1}{E_{cx}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \frac{A_{mn}\phi_x\, C_x\, S_y}{\alpha_m} + \frac{\nu_{cxy}}{E_{cy}} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{C_{mn}\, \phi_y\, C_x\, S_y}{\alpha_m} + (x - a)\left(\frac{\sigma_{cxo}}{E_{cx}} - \frac{\nu_{cxy}\,\sigma_{cyo}}{E_{cy}}\right)$$

$$v_c = -\frac{1}{E_{cy}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \frac{C_{mn}\phi_y\, S_x\, C_y}{\beta_n} + \frac{\nu_{cyx}}{E_{cx}} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{A_{mn}\, \phi_x\, S_x\, C_y}{\beta_n} + (y - b)\left(\frac{\sigma_{cyo}}{E_{cy}} - \frac{\nu_{cxy}\,\sigma_{cxo}}{E_{cx}}\right)$$

An expression for the shear strain and stress in the core are obtained by properly differentiating the above displacement equations; thus

$$\gamma_{cxy} = \frac{1}{E_{cx}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} A_{mn}\phi_x\left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx}\frac{\alpha_m}{\beta_n}\right) C_x\, C_y + \frac{1}{E_{cy}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} C_{mn}\, \phi_y\left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy}\frac{\beta_n}{\alpha_m}\right) C_x\, C_y$$

$$\tau_{cxz} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \int_{z=0}^{z} \phi_x\, dz\, A_{mn}\left[-\alpha_m + \frac{G_{cxy}}{E_{cx}}\beta_n\left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx}\frac{\alpha_m}{\beta_n}\right)\right] C_x\, S_y + \frac{G_{cxy}}{E_{cy}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \int_{z=0}^{z} \phi_y\, dz\, C_{mn}\, \beta_n\left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy}\frac{\beta_n}{\alpha_m}\right) C_x\, S_y$$

$$\tau_{cyz} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \int_{z=0}^{z} \phi_y \, dz \, C_{mn} \left[-\beta_m + \frac{G_{cxy}}{E_{cy}} \alpha_m \left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy} \frac{\beta_n}{\alpha_m} \right) \right] S_x C_y + \frac{G_{cxy}}{E_{cx}} \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} \int_{z=0}^{z} \phi_x \, dz \, A_{mn} \, \alpha_m \left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx} \frac{\alpha_m}{\beta_n} \right) S_x C_y$$

The continuity conditions require the interlayer stresses to be the same as the core shear stresses at the interfaces, thus

$$q_x = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} (A_{mn} \lambda_{gn1} + C_{mn} \lambda_{gn2}) \, C_x S_y$$

$$q_y = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} (C_{mn} \lambda_{gk1} + A_{mn} \lambda_{gk2}) \, S_x C_y$$

Similarly, the cores and face shear strains must be the same at the interfaces, thus

$$\tau_{fxy} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} A_{mn} \left[\frac{G_{fxy}}{E_{cx}} \phi_x \Big|_{z=t_c} \left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx} \frac{\alpha_m}{\beta_n} \right) + \frac{G_{fxy} \beta_n}{K_x} \lambda_{gn1} + \frac{G_{fxy} \alpha_m}{K_y} \lambda_{gk2} \right] C_x C_y + \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} C_{mn} \left[\frac{G_{fxy}}{E_{cy}} \phi_y \Big|_{z=t_c} \left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy} \frac{\beta_n}{\alpha_m} \right) + \frac{G_{fxy} \beta_n}{K_x} \lambda_{gn2} + \frac{G_{fxy} \alpha_m}{K_y} \lambda_{gk1} \right] C_x C_y$$

The obtained solutions for the face shear stress and interlayer stresses in conjunction with the equilibrium equations of the face element lead to the following expressions for the face stresses

$$\sigma_{fx} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} [A_{mn} \lambda'_{z1} + C_{mn} \lambda'_{z2}] S_x S_y + (\sigma_{xo} + \sigma_{cxo} \frac{t_c}{t_f}) \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{2}{a \alpha_m} \frac{2}{b \beta_n} S_x S_y$$

$$\sigma_{fy} = \sum_{m=1,3,..}^{\infty} \sum_{n=1,3,..}^{\infty} [A_{mn} \lambda'_{z3} + C_{mn} \lambda'_{z4}] S_x S_y + (\sigma_{yo} + \sigma_{cyo} \frac{t_c}{t_f}) \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{2}{a \alpha_m} \frac{2}{b \beta_n} S_x S_y$$

At this stage, A_{mn} and C_{mn} are the only unknowns. They were determined using the compatibility equations of interlayer displacements as

$$A_{mn} = \frac{\dfrac{\lambda_{y3}}{\lambda_{y2}} - \dfrac{\lambda_{y6}}{\lambda_{y5}}}{\dfrac{\lambda_{y1}}{\lambda_{y2}} - \dfrac{\lambda_{y4}}{\lambda_{y5}}}$$

$$C_{mn} = \frac{\dfrac{\lambda_{y3}}{\lambda_{y1}} - \dfrac{\lambda_{y6}}{\lambda_{y4}}}{\dfrac{\lambda_{y2}}{\lambda_{y1}} - \dfrac{\lambda_{y5}}{\lambda_{y4}}}$$

in which

$$\phi_x = \theta_x \,(2\,\theta_x \cosh\theta_x z + z\,\theta_x^2 \sinh\theta_x z - t_c\,\theta_x^2 \coth\theta_x t_c \cosh\theta_x z) - \frac{\alpha_m^2}{2} k_{\phi x} \cos\alpha_{\phi x} z$$

$$\phi_y = \theta_y \,(2\,\theta_y \cosh\theta_y z + z\,\theta_y^2 \sinh\theta_y z - t_c\,\theta_y^2 \coth\theta_y t_c \cosh\theta_y z) - \frac{\beta_n^2}{2} k_{\phi y} \cos\alpha_{\phi y} z$$

$$\lambda'_{z1} = \lambda_{z1}\,(1 - \frac{2}{b^2\,\beta_n^2}) - \frac{2\int_0^{tc} \phi_x\,dz}{t_f\; b^2\,\beta_n^2}$$

$$\lambda'_{z2} = \lambda_{z2}\,(1 - \frac{2}{b^2\,\beta_n^2})$$

$$\lambda'_{z3} = \lambda_{z3}\,(1 - \frac{2}{a^2\,\alpha_m^2})$$

$$\lambda'_{z4} = \lambda_{z4}\,(1 - \frac{2}{a^2\,\alpha_n^2}) - \frac{2\int_0^{t_c} \phi_y\,dz}{t_f\; a^2\,\alpha_m^2}$$

$$\lambda_{z1} = \frac{G_{fxy}}{E_{cx}}\,\phi_x\Big|_{z=t_c} \frac{\beta_n}{\alpha_m}\,(-\frac{\beta_n}{\alpha_m} + \nu_{cyx}\frac{\alpha_m}{\beta_n}) + \frac{\lambda_{gn1}}{\alpha_m}\,(\frac{G_{fxy}\beta_n^2}{K_x} + \frac{1}{t_f}) + \frac{G_{fxy}\,\lambda_{gk2}\,\beta_n}{K_y}$$

$$\lambda_{z2} = \frac{G_{fxy}}{E_{cy}}\,\phi_y\Big|_{z=t_c} \frac{\beta_n}{\alpha_m}\,(-\frac{\alpha_m}{\beta_n} + \nu_{cxy}\frac{\beta_n}{\alpha_m}) + \frac{\lambda_{gn2}}{\alpha_m}(\frac{G_{fxy}\beta_n^2}{K_x} + \frac{1}{t_f}) + \frac{G_{fxy}\,\lambda_{gk1}\,\beta_n}{K_y}$$

$$\lambda_{z3} = \frac{G_{fxy}}{E_{cx}}\,\phi_x\Big|_{z=t_c} \frac{\alpha_m}{\beta_n}\,(-\frac{\beta_n}{\alpha_m} + \nu_{cyx}\frac{\alpha_m}{\beta_n}) + \frac{\lambda_{gk2}}{\beta_n}\,(\frac{G_{fxy}\,\alpha_m^2}{K_y} + \frac{1}{t_f}) + \frac{G_{fxy}\,\lambda_{gn1}\,\alpha_m}{K_x}$$

$$\lambda_{z4} = \frac{G_{fxy}}{E_{cy}}\,\phi_y\Big|_{z=t_c} \frac{\alpha_m}{\beta_n}\,(-\frac{\alpha_m}{\beta_n} + \nu_{cxy}\frac{\beta_n}{\alpha_m}) + \frac{\lambda_{gk1}}{\beta_n}(\frac{G_{fxy}\,\alpha_n^2}{K_y} + \frac{1}{t_f}) + \frac{G_{fxy}\,\lambda_{gn2}\,\alpha_m}{K_x}$$

$$\lambda_{gn1} = \int_{z=0}^{z} \phi_x \, dz \Big|_{z=t_c} \left[-\alpha_m + \frac{G_{cxy}}{E_{cx}} \beta_n \left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx} \frac{\alpha_m}{\beta_n} \right) \right]$$

$$\lambda_{gn2} = \frac{G_{cxy}}{E_{cy}} \int_{z=0}^{z} \phi_y \, dz \Big|_{z=t_c} \beta_n \left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy} \frac{\beta_n}{\alpha_m} \right)$$

$$\lambda_{gk1} = \int_{z=0}^{z} \phi_y \, dz \Big|_{z=t_c} \left[-\beta_n + \frac{G_{cxy}}{E_{cy}} \alpha_m \left(-\frac{\alpha_m}{\beta_n} + \nu_{cxy} \frac{\beta_n}{\alpha_m} \right) \right]$$

$$\lambda_{gk2} = \frac{G_{cxy}}{E_{cx}} \int_{z=0}^{z} \phi_x \, dz \Big|_{z=t_c} \alpha_m \left(-\frac{\beta_n}{\alpha_m} + \nu_{cyx} \frac{\alpha_m}{\beta_n} \right)$$

$$\lambda_{y1} = \frac{\lambda'_{z1}}{E_{fx}} - \frac{\nu_{fxy} \lambda'_{z3}}{E_{fy}} - \frac{\phi_x \big|_{z=tc}}{E_{cx}} + \frac{\alpha_m \lambda_{gn1}}{K_x}$$

$$\lambda_{y2} = \frac{\lambda'_{z2}}{E_{fx}} - \frac{\nu_{fxy} \lambda'_{z4}}{E_{fy}} + \frac{\nu_{cxy} \phi_y \big|_{z=tc}}{E_{cy}} + \frac{\alpha_m \lambda_{gn2}}{K_x}$$

$$\lambda_{y3} = \frac{2}{a\,\alpha_m} \frac{2}{b\,\beta_n} \left[\frac{\sigma_{xo} + \sigma_{cxo} \frac{t_c}{t_f}}{E_{fx}} - \nu_{fxy} \frac{\sigma_{yo} + \sigma_{cyo} \frac{t_c}{t_f}}{E_{fy}} + \frac{\sigma_{cxo}}{E_{cx}} + \nu_{cxy} \frac{\sigma_{cyo}}{E_{cy}} \right]$$

$$\lambda_{y4} = \frac{\lambda'_{z3}}{E_{fy}} - \frac{\nu_{fyx} \lambda'_{z1}}{E_{fx}} + \frac{\nu_{cyx} \phi_x \big|_{z=tc}}{E_{cx}} + \frac{\beta_n \lambda_{gk2}}{K_y}$$

$$\lambda_{y5} = \frac{\lambda'_{z4}}{E_{fy}} - \frac{\nu_{fyx} \lambda'_{z2}}{E_{fx}} - \frac{\phi_y \big|_{z=tc}}{E_{cy}} + \frac{\beta_n \lambda_{gk1}}{K_y}$$

$$\lambda_{y6} = \frac{2}{a\,\alpha_m} \frac{2}{b\,\beta_n} \left[\frac{\sigma_{yo} + \sigma_{cyo} \frac{t_c}{t_f}}{E_{fy}} - \nu_{fyx} \frac{\sigma_{xo} + \sigma_{cxo} \frac{t_c}{t_f}}{E_{fx}} + \frac{\sigma_{cyo}}{E_{cy}} + \nu_{cyx} \frac{\sigma_{cxo}}{E_{cx}} \right]$$

$$k_{\phi x} = -\frac{\theta_x t_c}{\sinh \theta_x t_c} + \theta_x t_c \cosh \theta_x t_c \qquad k_{\phi y} = -\frac{\theta_y t_c}{\sinh \theta_y t_c} + \theta_y t_c \cosh \theta_y t_c$$

$$\theta_x = \alpha_m \sqrt{\frac{E_{cx}}{G_{cxz}}} \qquad \theta_y = \beta_n \sqrt{\frac{E_{cy}}{G_{cyz}}}$$

$\alpha_{\phi x} = \dfrac{m\ \pi}{2\ t_c}$ $\qquad\qquad$ $\beta_{\phi y} = \dfrac{n\ \pi}{2\ t_c}$

ν_{cxy}, ν_{cyx} = Poisson's ratio in the x plane and y-direction, and the y-plane and x-direction, respectively;

S_x, S_y, C_x, C_y = sin α_m x and sin β_n y, cos α_m x and cos β_n y, respectively;

α_m, β_n = $\dfrac{m\ \pi}{2\ a}$ and $\dfrac{n\ \pi}{2\ b}$, respectively, and m and n are integers;

σ_{cxo}, σ_{cyo} = Edge stresses in the core, if any, in the x and y directions, respectively. σ_{xo}, σ_{yo} are edge stresses in the skins;

m, n = Integers.

Effects of Adhesive on the Structural Performance

Case 1: Edge Loading

Consider a panel with the following properties: a = b = 20 in., t_f = 0.04 in.; t_c= 1.0 in., $E_{fx} = E_{fy}$= 10^7 psi, $\nu_{fxy} = \nu_{fyx}$= 0.33, $E_{cx} = E_{cy}$= 2 x 10^6 psi, $G_{cxy} = G_{cxz} = G_{cyz}$ = 10^4 psi, and $\nu_{cxy} = \nu_{cyx}$ = 0.20. Two loading cases are considered. In the first case, a biaxial uniformly distributed stress of intensity $f_{xo} = f_{yo}$ = 210 psi is used. In the second, case a uniaxial uniformly distributed stress of intensity f_{xo} = 210 psi is applied. In each loading case, the load is applied independently first to the face and core, and then concurrently to face and core. The face normal and shear stresses are calculated for a chosen range of bonding stiffness from $K_x = K_y = K = 10^3$-10^4 psi/in. The selected range for K-values covers a broad spectrum of adhesives from a non-rigid to excessively rigid for practical purposes. This range was needed for conducting a parametric study on the effects of adhesives. The normal stress in the faces at the panel center and the shear stress in the faces at the panel corner are shown graphically in Figures 2 to 7.

It is seen that the face normal stress shows greater sensitivity to the variation of bond stiffness value when the latter is in the lower range; and beyond a certain level of stiffness, the adhesive can be practically considered as rigid. A change in K-value for example from 10^3 to 2 x 10^3 psi/in induces a stress decrease almost 6 times in the uniaxial case and 5 times in the biaxial case greater than when K changes from 9 x 10^3-10^4 psi/in. The changes are 24% and 27% due to uniaxial core and combined edge loads, respectively, 32% and 22% due to biaxial core and combined edge loads, respectively. In all load cases, the face shear stress is practically independent of bonding stiffness.

This analysis has also detected an important point. By using existing theories, stress components in laminated panels may be determined only at high values of bond stiffness with a small margin of error, otherwise the K values must be included in the analysis.

Another important point was revealed by this analysis. By common sense, it can be felt that a very stiff adhesive would be unnecessary if the core was too soft, and the converse would be unwise. This is quantitatively shown in Figures 2 to 7 which show that the ratio of core stiffness to bonding stiffness is one of the main parameters influencing the behavior of laminated panels.

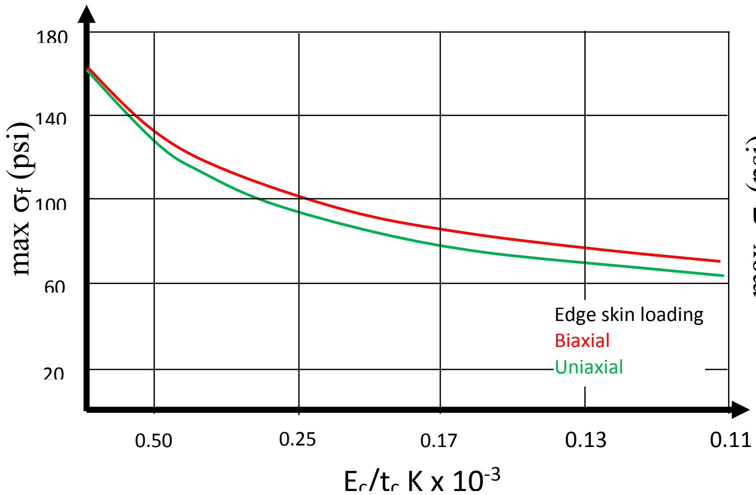

Fig. 2. **Effect of Bonding Stiffness on Skin Normal Stress Due to Skin Edge Loading**

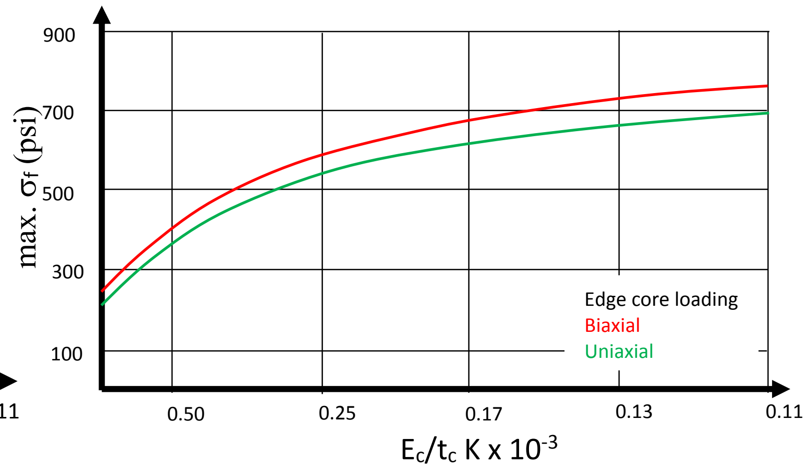

Fig. 3. **Effect of Bonding Stiffness on Skin Normal Stress Due to Core Edge Loading**

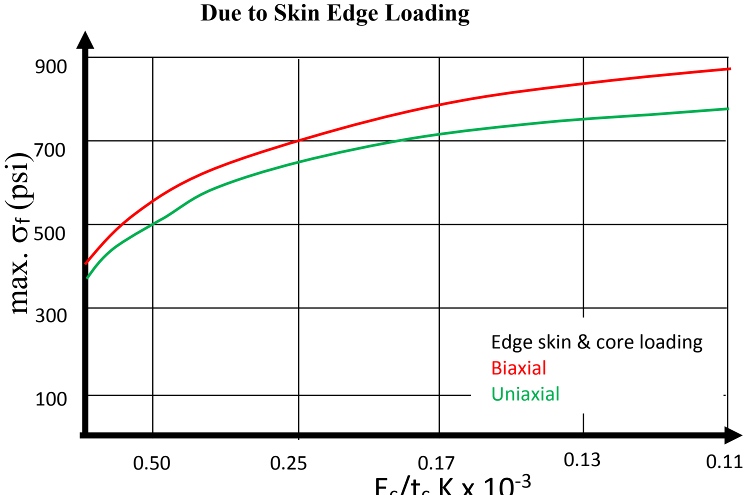

Fig. 4. **Effect of Bonding Stiffness on Skin Normal Stress Due to Skin and Core Edge Loading**

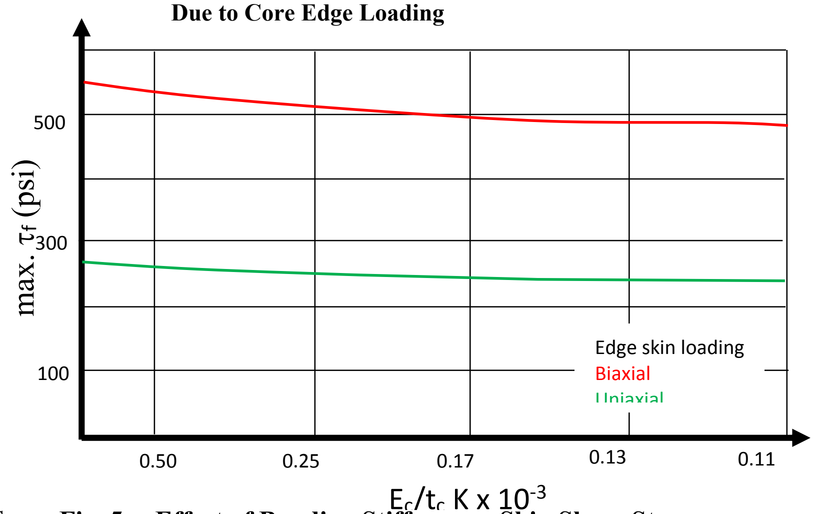

Fig. 5. **Effect of Bonding Stiffness on Skin Shear Stress Due to Skin Edge Loading**

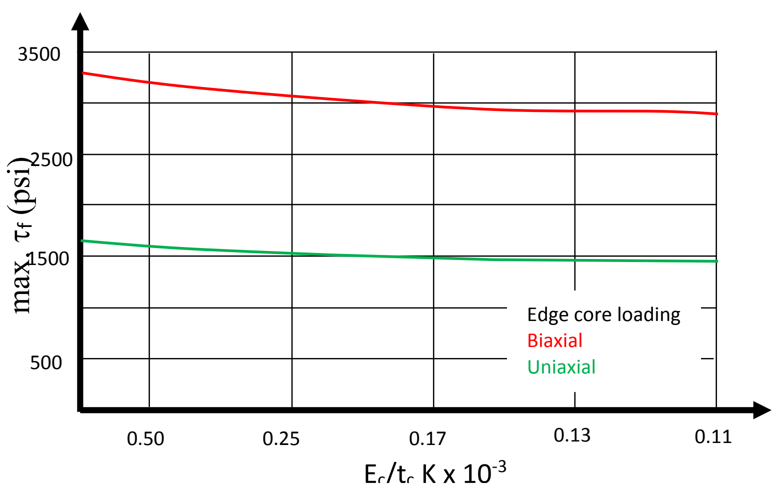

Fig. 6. **Effect of Bonding Stiffness on Skin Shear Stress Due to Core Edge Loading**

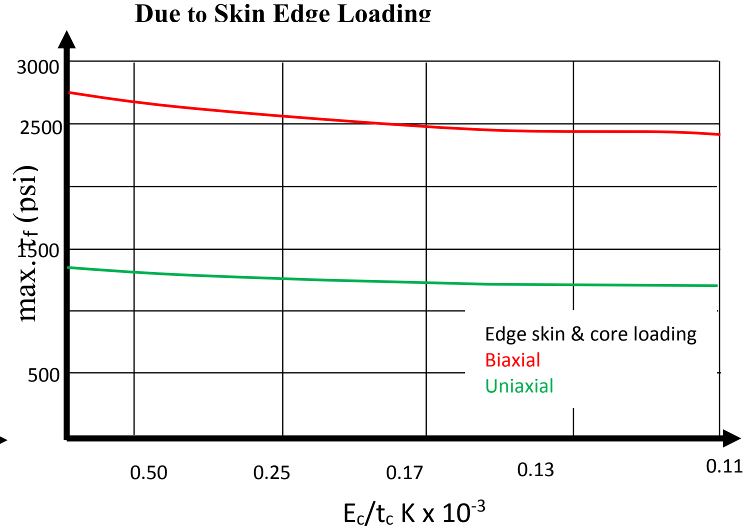

Fig. 7. **Effect of Bonding Stiffness on Skin Shear Stress Due to Skin and Core Edge Loading**

Case 2: Transverse Loading

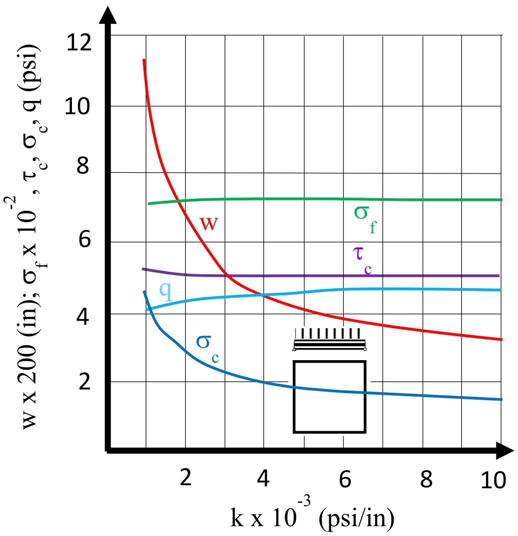

Fig. 8. Effect of Bonding Stiffness Due to Transverse Uniform Loading

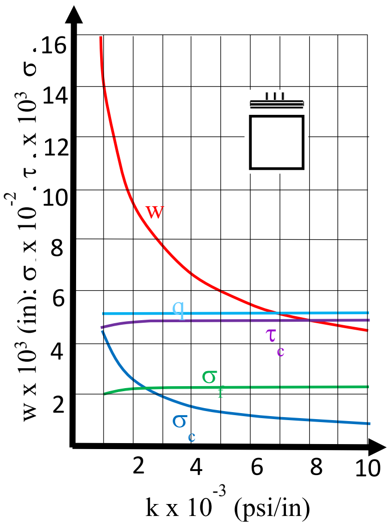

Fig. 9. Effect of Bonding Stiffness Due to Transverse Partial Uniform Loading

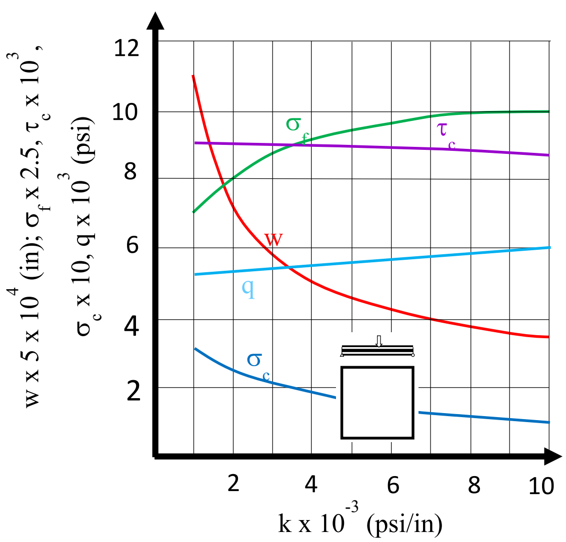

Fig. 10. Effect of Bonding Stiffness Due to Transverse Concentrated Load

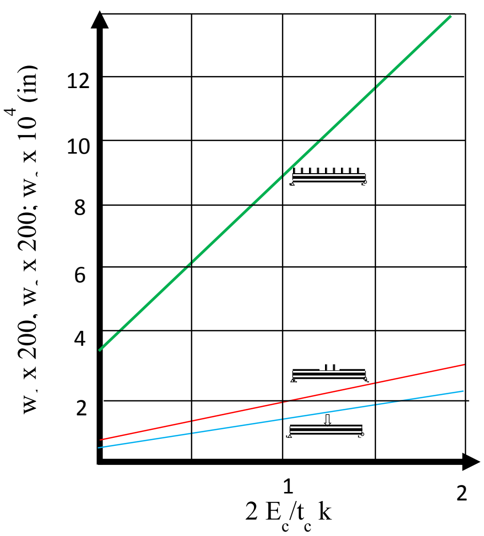

Fig. 11. Effect of E_c/t_c K on Maximum Deflection

To demonstrate the effects of bonding, three panels were investigated under three transverse loadings: uniformly distributed load, partial load on a central square area, and a concentrated load. In each case, the maximum normal stresses in the facings and core, the maximum in-plane shear stress in the facings, the maximum transverse shear stress in the core, and the maximum deflection were calculated for a range of bonding stiffness from 10^3-10^4 psi/in. The results are shown in Figs. 8 to 11.

It is seen that the deflection shows greater sensitivity to the variation of the K value when the latter is in the lower range; and beyond a certain level of bonding stiffness, the bonding can be practically considered as rigid. An increase in the K value is accompanied by a decrease in the normal stress of the core and an increase in the face's normal stress.

The results brought up an important point. By assuming perfect bonding, normal and shear stresses in the facings, and the transverse shear stress in the core may be determined using classic plate theories with a small margin of error. The bonding stiffness should be included in the analysis whenever the deflection is the quantity of interest.

Another important point has also been discovered. The results led to answer an un-answered question in the literature; i.e. what constitute perfect bonding? This question is best answered in terms of the ratio of the core stiffness to the bonding stiffness, rather than on the individual constituent material. By common sense, it can be felt that a very stiff bonding would be unnecessary if the core were too soft, and the converse would be unwise. This is quantitatively shown in Fig. 11, which shows that the ratio of core stiffness to adhesive stiffness is one of the main parameters influencing the behavior of the panels.

It should be noted that the complexity of the mathematical formulation and obtained solutions hinder their applications in real world practices. To resolve this problem, a knowledge-based computer client was developed using Windows architecture. In this way, any practitioner could easily analyze and design panels made of any materials.

SUMMARY AND CONCLUSIONS

In recent years, the world has experienced unprecedented environmental, energy, economic, and other challenges. To meet these challenges, a wide range of renewable materials developed from natural and manmade resources as polymers and composites. Yet, the state of scientific advancements apparently lags behind their applications in the buildings sector.

In the literature, very few papers have been published which deal with the effects of bonding on the structural response of laminated panels. Realistically, the core and bond in these panels are rigid enough to make a significant contribution to the overall structural integrity of the panels, yet flexible enough to permit shear deformations. In light the development of new biobased materials including adhesives and their applications in various industries including residential buildings, these deformations and their effects can't be ignored.

This paper presented an analysis of laminated panels taking into consideration the effects of the finite bonding stiffness. The solution satisfies the equilibrium equations of the face and core elements, the compatibility equations of interlayer stresses and strains, and the boundary conditions.

The numerical results have shown that the bonding stiffness, up to a certain level, has a strong effect on the structural response. Beyond that level, the usual assumption of perfect bonding is acceptable. The answer to what constitute "perfect" bonding is best answered in terms of the ratio of the core stiffness to the bonding stiffness, rather than on the individual constituent materials.

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