Modeling of Composites Constructed with Baypreg® F

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Abstract

Bayer MaterialScience has focused on developing new composite technologies combining a lightweight, low-density core together with fiber-reinforced polyurethane skins. A Bayer MaterialScience polyurethane chemistry, designated Baypreg® F, is ideally suited for constructing composites that require a high stiffness to weight ratio. The components of a composite made using these chemicals can be easily manipulated to allow part producers extensive freedom in manufacturing a wide variety of part designs and configurations.

This paper presents the development of a mathematical model for the prediction of composite properties. It specifically focuses on composites constructed with paper honeycomb as the core material and with glass fiber mat as the facing material. For typical composite applications, load-deflection behavior is the most significant indicator of performance. Subsequently, data accumulated from the testing of the core and facing materials individually is used to predict the load-deflection behavior of a composite constructed utilizing the polyurethane chemistry.   The theoretical predictions are compared directly to test data obtained from composites with specific constructions. A discussion of the model's predictive ability, focusing on part design to meet customer requirements quickly and efficiently, will be presented. Work targeted towards refining the model will serve as a conclusion to the discussion.

Composite Components and Production Process

A composite made with Baypreg® F chemistry is essentially two sheets of high-density, fiber-reinforced polyurethane separated by a lightweight core. The basic construction of it is shown in Figure 1. While the figure shows paper honeycomb being used as the core, a composite made with the two-component polyurethane system is not limited to using only this material.

Though this discussion focuses on the properties of the paper-cored composite and its modeling, several different low-density cores have been used to date in conjunction with the technology. These have included aluminum honeycomb, polypropylene honeycomb, balsa, and polyurethane foam.

The strength of the final composite is function of its three constituent components: facing material, core material, and polyurethane chemicals. The facing material is usually either a glass mat or natural fiber mat. The strength of the faces in a composite made with polyurethane is affected by the construction of the material used. In the case of glass fiber mats the construction options include E-glass, A-glass, chopped strand, continuous filament, and woven, to name just a few. However, the greater factor in strength is the amount of reinforcement in the facing material.   Higher area weights produce higher strength faces and subsequently stronger composite structures.

The choice of core material also will drive overall composite strength. Strength – in this case defined as load-bearing capability – is heavily controlled by thickness. A stiffer composite can be obtained by increasing the core thickness while maintaining the facing material construction. Choosing a stiffer core can also enhance the strength. For example, changing the core material from paper honeycomb to balsa wood will result in a composite capable of supporting greater loads. Core stiffness also can be increase by increasing the density of the specific core being used. The honeycomb products are available in several cell sizes and construction material weights.

The polyurethane chemicals are key to the composite construction process. They must efficiently bind the facing and core materials together to provide a high-strength, lightweight composite. This specific polyurethane system offers a long open time so the facing materials can be fully wetted in a spray operation. Once in a heated tool, the chemical reaction proceeds with very little foaming to ensure that a high-density face is created. The minimal foaming that does occur during the reaction process is sufficient to adhere the facing and core materials together. The polyurethane material itself is stiff and relatively brittle, but has high strength when incorporated in a composite structure with the glass mat facing.

A schematic of the production sequence is presented in Figure 2. The facing material is usually brought in as roll goods to take advantage of the economic benefits. The core material is received as flat sheets slightly larger than the final part dimensions. In most cases, the core is easily formed to a three-dimensional shape so there is no need to have pre-cut or pre-shaped cores.

A "sandwich" is assembled using these two components by wrapping the core with the facing material. The edges of the "sandwich" are closed with staples so the core will not shift while being moved through the rest of the process. The completed sandwich is transported robotically to a spray booth where both sides are coated with polyurethane. In a normal production scenario both sides of the sandwich would be sprayed simultaneously with the sandwich being moved between two fixed mix heads. The robot then places the wet sandwich into a hot tool where it is compressed into shape and the material is cured. After de-molding the part is trimmed and either packaged or sent on for final finishing.

Composite Physical Properties

Composites made with this two-component polyurethane system are targeted toward applications that require high stiffness to weight ratios. In the case where the component is not load bearing and must support only its own weight, a thin (4 - 5 mm) core with a light (225 - 300 g/m^2) facing material is all that is required. When the application requires that a significant weight be supported, then thicker cores and heavier weight-facing materials must be incorporated.

The data presented in Tables 1 and 2 are for composites designed to be used in load-bearing applications. The facing material is a chopped strand glass mat, Vetrotex M123, at an area weight of 600 g/m^2 in Table 1 and 900 g/m^2 in Table 2. Note that these area weights are per face. Consequently, the values must be doubled to obtain the total reinforcement weight present in the composite. The facings of composites made with this chemistry are designed to have approximately equal amounts of reinforcement and polyurethane. Therefore, determining the weight of reinforcement also will yield the weight of urethane required for a given construction.

The core material used in the specimens of Tables 1 and 2 is an untreated paper honeycomb. It is manufactured by SWAP in Europe and has a triangular cell configuration with dimensions of 5 mm per side. The density of the material is about 0.08 g/cm^3. The values listed under the "Nominal Thickness" column in the two tables are an approximation of the starting thickness of the cores used to make the specific test specimen.

Two aspects are of particular note from the data in Tables 1 and 2. One, the composite material made with the two-component polyurethane system offers significant stiffness at a very low density; and two, the gains afforded by a nominal increase in facing weight are quite dramatic in comparing the same thickness between the two tables.

One trend that requires additional explanation is the decrease in flexural modulus with increasing thickness. Flexural modulus is a commonly used property for describing structural materials, and is described by Equation (1). However, tensile modulus of the face, listed in Tables 1 and 2, is not influenced by thickness.

$$E = \frac{FL^3}{4\delta bh^3}$$

(1)

Where: E = Modulus
F = Force on the specimen
L = Span length
δ = Deflection under load
b = Width of the specimen
h = Thickness of the specimen

As this Equation (1) illustrates, flexural modulus decreases with the inverse cube of thickness. This trend is consistent with the data in Tables 1 and 2, but does not fully explain the differences in modulus. What this equation does not account for is that a sandwich laminate utilizes different materials of construction in the face and core. These materials can have very different properties, and can be varied independently.

Bending rigidity, listed in Tables 1 and 2 and defined as modulus times the moment of inertia, is a more descriptive property for sandwich composites than flexural modulus. Alternatively, bending stiffness, defined as the slope of the load/deflection curve is equally meaningful.

The load/deflection curves for the composite constructions in Tables 1 and 2 were measured using the following method. Test specimens measuring 178 mm x 610 mm were cut from plaque samples and were tested with open honeycomb edges. The test fixture had edge supports 12 mm wide along the 178 mm sides. Force was applied to the center of the specimen with an Instron Model 4602 tensile/compression tester. The results of the testing for the 600 g/m^2 and the 900 g/m^2 constructions appear in Figures 3 and 4, respectively.

Utilizing the force/deflection curves, it is now possible to compare different constructions with the same x-y dimensions. The thicker the composite made with this system, the better it performs. Because the core is made from a lower density material than the facer, a laminate that is twice as thick does not have double the mass. Therefore, laminate composites offer the ability to design a significantly stiffer part without a large weight penalty.

The ability to mathematically model the stiffness of the construction of a composite made with the two-component polyurethane system is of great importance. The end user often knows the size and shape of part and the amount of deflection that is required. However, it isn't always feasible to create a wide variety of mock ups to determine the exact type of construction that is required to meet the demands of the application. The ability to determine up front the construction with the highest probability of success allows for more efficient development.

Modeling Approaches

Accurate computer modeling of applications of composites made with the Baypreg[®] F polyurethane system requires an extensive set of material properties to be entered into commercial finite element analysis (FEA) software. Structural analysis of a composite made with this chemistry can be accomplished in a variety of ways. Two approaches with different assumptions and computational intensities are discussed. The first computationally efficient option is to treat the system as a composite laminate using only thin shell elements through the mid-plane of the part. This approach allows for an anisotropic, linear elastic representation using laminate theory. The top and bottom layers of the composite shell element assume a plane stress condition, and the core layers are treated as orthotropic with plane strain assumed. This approach is suitable for stiffness and deflection predictions, as long as a proper element formulation, which treats transverse shear as non-constant through the thickness, is used. Thin shell, reduced integration, element formulations available in ABAQUS [a] properly account for transverse shear effects.

The second approach is to model the layers discretely using thin shell elements for the faces and solid continuum elements in the core. This completely general although computationally expensive method uses the same material model assumption as the first approach. Sufficient element density through the thickness of the core will ensure proper treatment of bending and shear behavior. The face and core elements can then be tied together using common contact surfaces or node sharing. Failure of the face and core materials, or delamination between layers, is not considered in this study.

Component Characterization

The facing layer is comprised of single or multiple layers of glass mat impregnated with polyurethane. The tensile stress-strain characterization considered glass weights of 300, 600, 900 and 1200 g/m^2 of M123 chopped strand mats. Corresponding face thicknesses ranged from 0.4 mm to 1.6 mm. The glass content is consistently 50 – 60 percent of the total facing weight regardless of the glass weight used. The anisotropic, linear elastic material model requires the modulus of elasticity in the direction parallel to the mat roll direction, $E_{11, face}$, and the modulus transverse to the roll direction, $E_{22, face}$, using a coordinate system as described in Figure 5. Test coupons were cut from facing panels in the parallel and transverse directions for each of the four glass densities and tested in tension to determine $E_{11, face}$ and $E_{22, face}$. The average stress-strain response for both directions in the face is shown in Figure 6.

The modulus is relatively constant regardless of glass content since the face thickness must increase in proportion to the amount of glass. The average moduli were found to be $E_{11, face}$ = 12,700 MPa and $E_{22, face}$ = 9,700 MPa. The out-of-plane shear modulus, G_{13}, was calculated from a 4-point bending test per standard DIN 53293 shown in Figure 7. Since all three shear moduli were assumed to be equal, then $G_{12, face}$ = $G_{13, face}$ = $G_{2, face}$ = 2,200 MPa. Poisson ratio was assumed to be 0.3.

[a] Hibbitt, Karlsson, and P. Sorenson. 2002. *Analysis of Composite Materials with ABAQUS,* L5.9.

The core material is comprised of a paper honeycomb (SWAP Testliner II). As part of the orthotropic material model, the compressive modulus, $E_{33, core}$, of the paper core is determined from uniaxial testing on cores of various heights as shown in Figure 8. The compressive secant modulus was determined to be $E_{33, core}$ = 130 MPa. This testing was conducted with the faces intact, and shows the influence of core height on buckling strength.

The parallel and transverse moduli in the paper honeycomb core are assumed to be negligible, and therefore, $E_{11, core}$ = $E_{22, core}$ = 1.0 MPa. The out-of-plane shear moduli were determined in shear testing according to ASTM C 273. The shear moduli were found where $G_{13, core}$ = 59 MPa, $G_{23, core}$ = 33 MPa and an assumed $G_{12, core}$ = 1.0 MPa.

Beam Theory Calculations

Beam theory with consideration to shear effects can be used to estimate the stiffness of a sandwich construction. For a simply supported 3-point bend with a center load, the deflection taken from [b] is shown in Equation (2) as,

$$\delta = \frac{FL^3}{48E_f I} + \frac{FL}{4G_c A_c} \tag{2}$$

where F, L, E_f, I, G_c, and A_c are the force, span length, elastic modulus of the face, moment of inertia, shear modulus of the core, and shear area of the core, respectively. Equation (2) can be rewritten as,

$$\delta = \frac{FL^3}{24E_f bt_f h^2} + \frac{FL(h - 2t_f)}{4G_c b(h - t_f)^2} \tag{3}$$

where b, t_f, h, are the plate width, face thickness, and sandwich height, respectively. The modulus of face was taken to be the average between the parallel and transverse modulus, or E_f = 11,200 MPa. Calculated bending stiffness values, using Equation (3) are compared to test values in Tables 3 and 4, for two glass content levels (600 and 900 g/m^2) and three sandwich heights (10, 15 and 20 mm) using a plate width of 177 mm and a span length of 584 mm.

The beam theory calculation, in most cases, over predicted the bending stiffness compared to test values. The difference between calculated and actual stiffness ranged from 2 to 8 percent as shown in Tables 3 and 4. Equation (2) assumes the face thickness is thin compared to the sandwich height, and that the face material is isotropic. These assumptions are sources of error and are more noticeable at the smaller sandwich heights.

Finite Element Analysis Results

Both FEA modeling approaches described previously were evaluated by comparing force/deflection predictions to actual test results for the same plate and load conditions described in the last section. All cases were modeled using the thin shell approach shown in Figure 9, since this method is computationally inexpensive.

[b] American Society of Civil Engineers, 1984. *Structural Plastics Design Manual,* pp. 836

Only one case (10 mm sandwich height with 900 g/m^2 glass mat content) was evaluated using the thin shell and solid element approach as shown in Figure 10. Contact constraints and non-linear geometric effects were included in all FEA models. The 3-point bending test was conducted with the plate samples aligned so the glass mat roll direction, $E_{11,\ face}$ was parallel to the test span, or plate length direction. The predicted stiffness values from the FEA simulations are compared to the test stiffness values in Tables 5 and 6 for the 600 and 900 g/m^2 glass mat contents, respectively.

Force/deflection curves are shown in Figures 11 and 12. The difference between simulation and test results ranges from 0.6 to 8 percent. The thin shell and solid continuum element approach predicted a stiffness value within 8.5 percent of tested stiffness and is shown in Figure 12.

Summary and Future Work

Three approaches to predicting stiffness in a sandwich composite structure, which offered various levels of accuracy and effort, were presented. The beam theory calculation method is the simplest method and offers a reasonable estimate of stiffness, but is limited to isotropic faces and flat parts.

Of the two FEA methods, the thin shell method is a low-effort, high-accuracy approach due to the inclusion of the non-linear shear behavior through the thickness. This approach is recommended over the thin shell with solid continuum element method due to its simplicity. However, for tall sandwich heights where the height-to-span ratio exceeds 1/15, the hybrid modeling approach should be more accurate. Also, wall thickness changes can be modeled more closely with this approach.

Additional work is required to characterize and model alternative core materials, such as polystyrene, polypropylene or aluminum honeycomb. Also, rate-sensitive characterization for simulating impact conditions is needed, as well as damage and failure routines for determination of service life or durability.
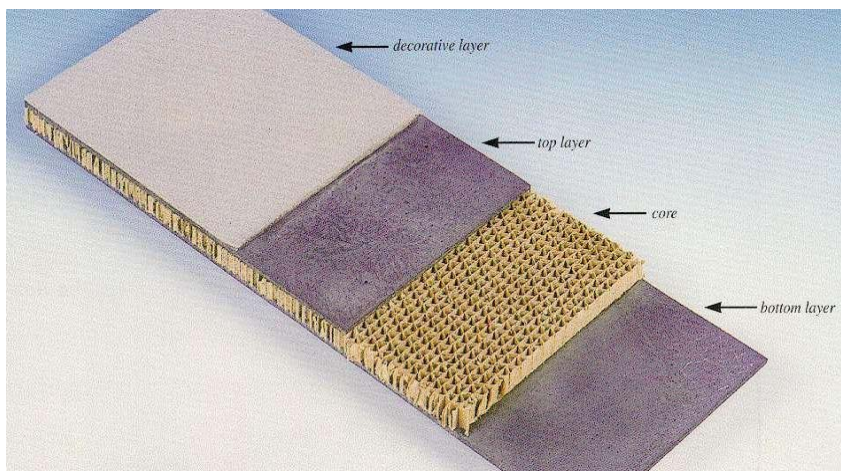
Data Tables and Figures

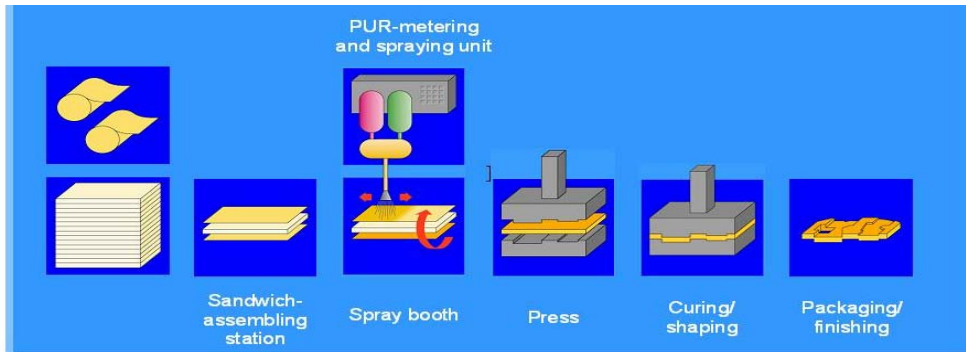Figure 1: Composite made with the Baypreg Chemical System

Figure 2: Production Sequence for Composites Made with the Baypreg Chemical System

Table 1: Physical Property Variation with Thickness – 600 g/m² Facing Weight

Nominal Thick. (mm)	Thick. (mm)	Density (g/cm³)	Tensile Mod.* (GPa)	Flex. Mod. (MPa)	Bending Rigidity (N-mm²) x10⁸
7	6.60	0.341	12.7	4840	0.4
10	9.25	0.312	12.7	5000	0.8
12	11.75	0.289	12.7	4010	1.2
15	14.40	0.258	12.7	3340	1.8
20	19.50	0.206	12.7	2550	3.1

* Face Material

Table 2: Physical Property Variation with Thickness – 900 g/m² Facing Weight

Nominal Thick. (mm)	Thick. (mm)	Density (g/cm³)	Tensile Mod.* (GPa)	Flex. Mod. (MPa)	Bending Rigidity (N-mm²) x10⁸
7	6.75	0.415	12.7	10,950	0.6
10	9.55	0.380	12.7	7350	1.2
12	12.30	0.345	12.7	4935	1.8
15	14.65	0.315	12.7	4720	2.6
20	19.60	0.250	12.7	3400	4.4

* Face Material
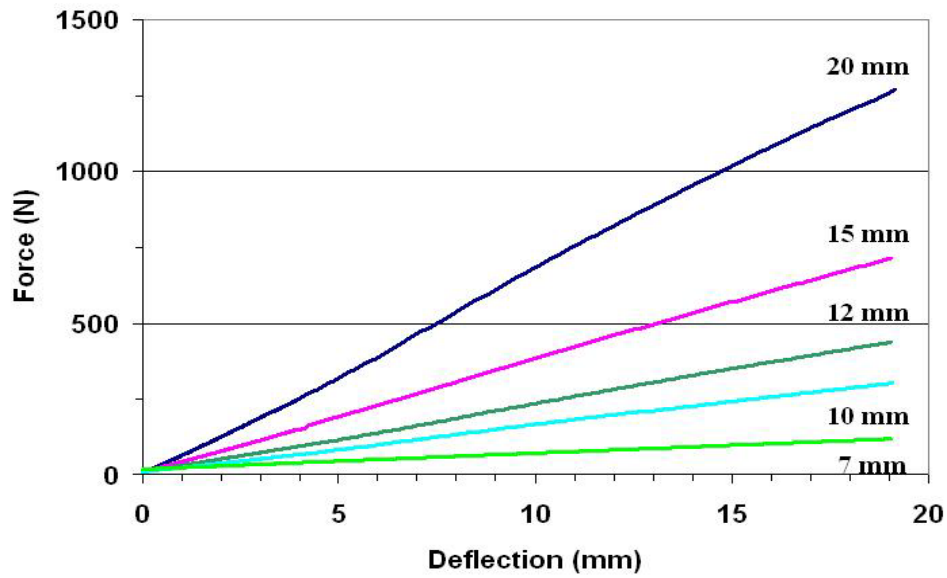
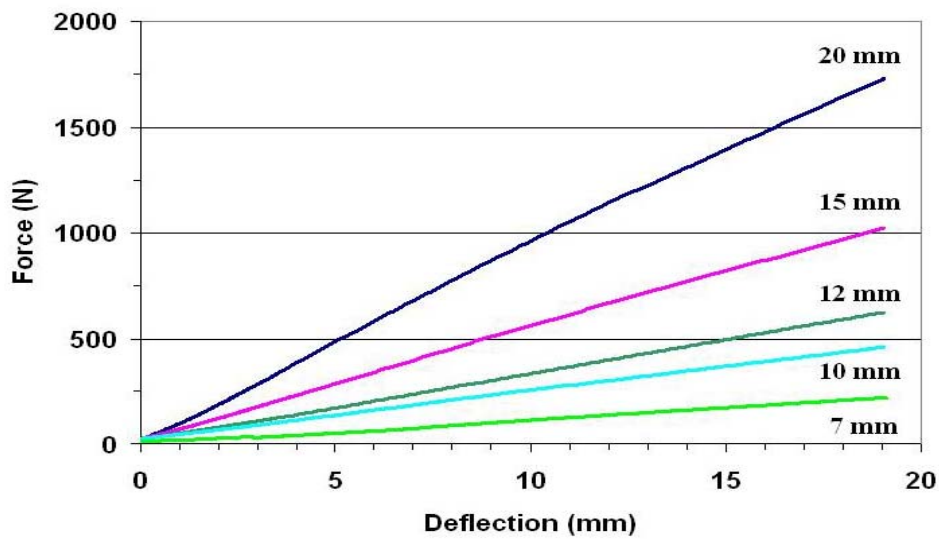*Figure 3: Force/Deflection 600 g/m² Facing Material*

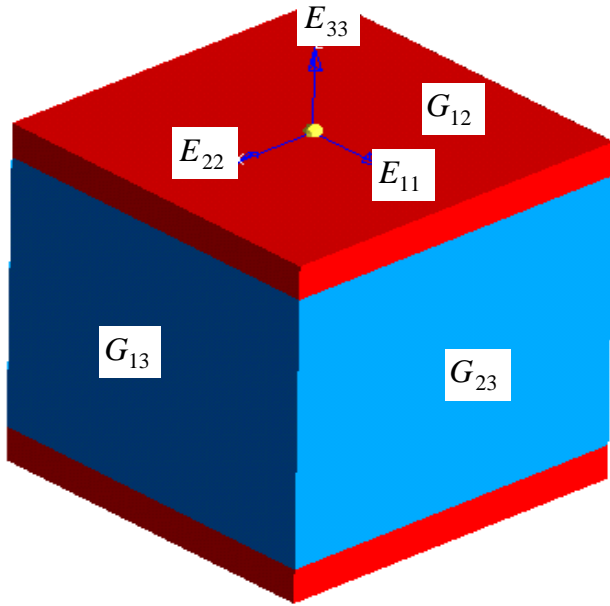*Figure 4: Force/Deflection 900 g/m² Facing Material*

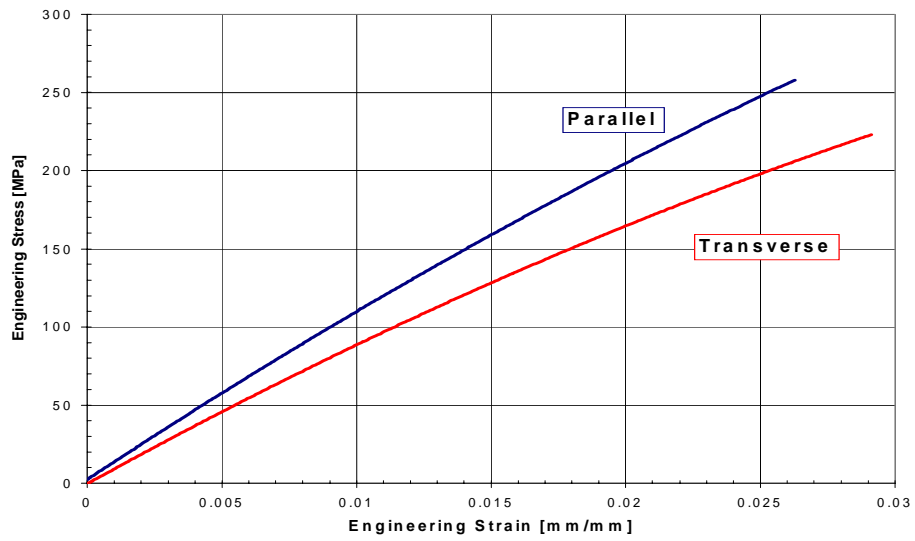*Figure 5: Sandwich Composite Coordinate System*

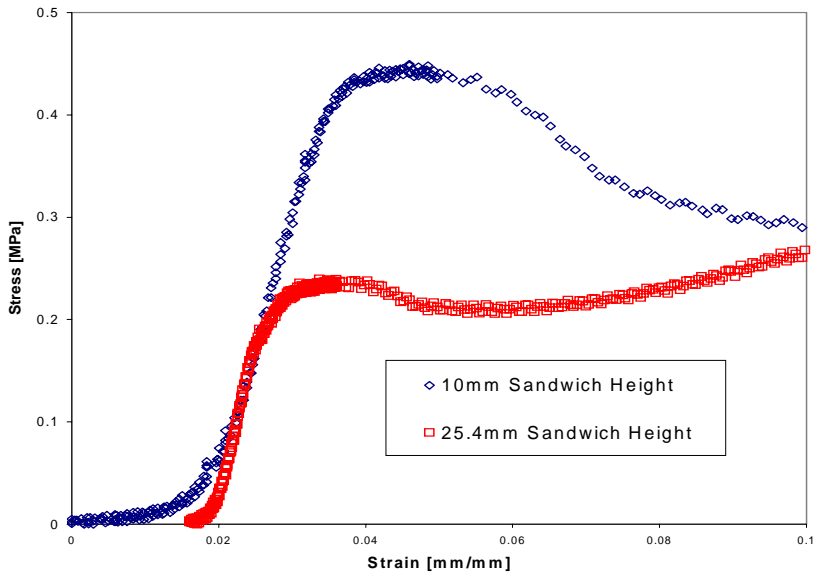*Figure 6: Average Tensile Stress-Strain Response of Faces*

Figure 7: Paper Honeycomb Compressive Behavior

Figure 8: 4-Point Bending Test

Table 3: Bending Theory Stiffness Comparison to Test (600 g/m², $t_f = 0.8mm$)

Nominal Thickness (mm)	Test (N/mm)	Bending/Shear Theory (N/mm)	Diff. (%)
10	15.9	17.0	-6.9
15	37.9	38.8	-2.4
20	68.9	66.4	3.6

Table 4: Bending Theory Stiffness Comparison to Test (900 g/m², $t_f = 1.2mm$)

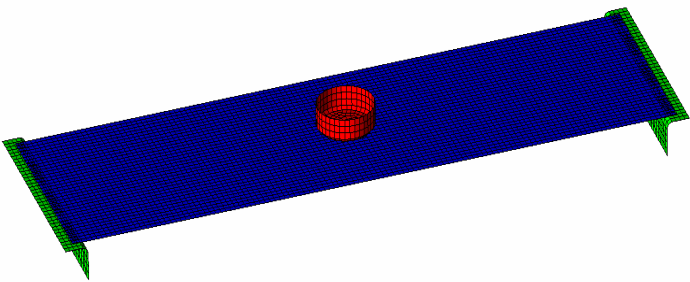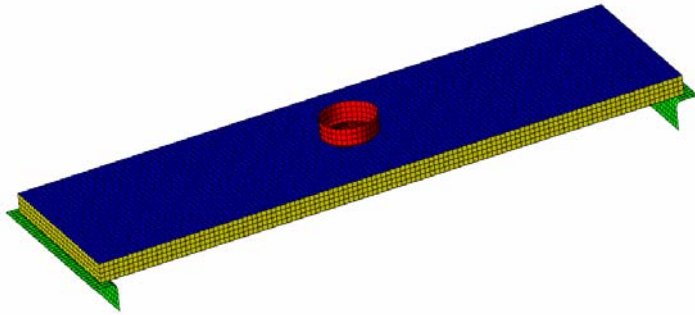| Nominal Thickness (mm)	Test (N/mm)	Bending/Shear Theory (N/mm)	Diff. (%)
10	23.4	25.2	-7.7
15	53.4	55.6	-4.1
20	92.2	95.2	-3.3

Figure 9: Thin-Shell Composite Sandwich FEA Model

Figure 10: Thin-Shell and Solid Continuum Composite Sandwich FEA Model

Table 5: FEA Stiffness Comparison to Test - 600 g/m²

Nominal Thickness (mm)	Test (N/mm)	FEA (N/mm)	Diff. (%)
10	15.9	15.8	0.6
15	37.9	39.0	-2.9
20	68.9	70.6	-2.5

Table 6: FEA Stiffness Comparison to Test - 900 g/m²

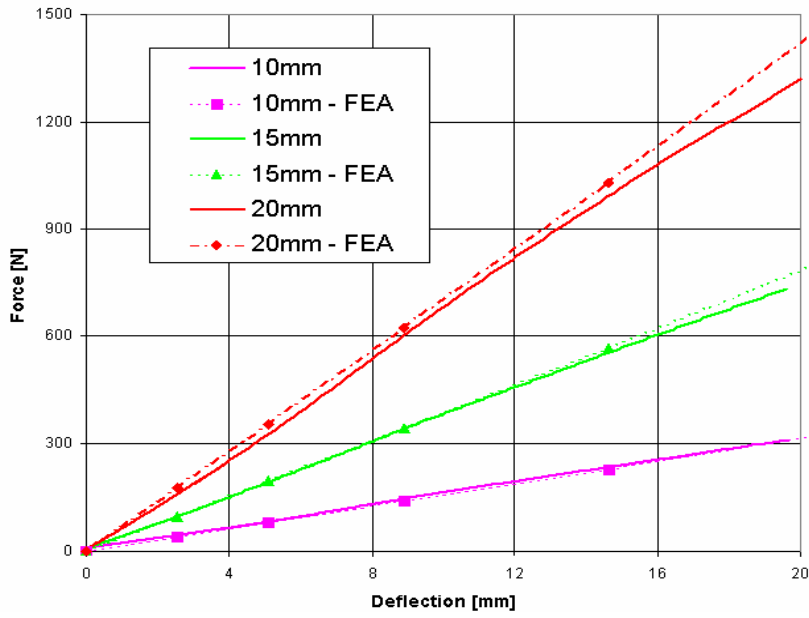| Nominal Thickness (mm)	Test (N/mm)	FEA (N/mm)	Diff. (%)
10	23.4	21.6	7.7
10*	23.4	21.4	8.5
15	53.4	54.3	-1.7
20	92.2	99.1	-7.5

* Solid Element Approach
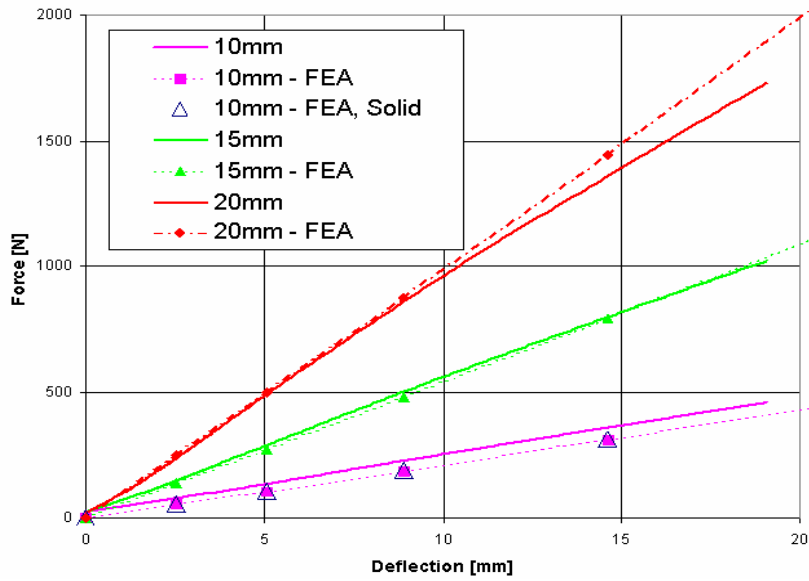
Figure 11: FEA Force/Deflection Comparison to Test - 600 g/m²

Figure 12: FEA Force/Deflection Comparison to Test - 900 g/m²