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Analysis of thermally induced stresses on the core node bonds of a co-cured sandwich panel

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Abstract

During process development testing of the ARES I composite interstage, large regions of node disbonds were observed in the aluminum honeycomb core. The sandwich panels were composed of carbon fiber/epoxy face sheets and one-eighth inch cell size aluminum core co-cured in an autoclave. Node disbonds were initially observed after cure with ultrasonic inspection and subsequently confirmed with X-ray inspection and cross sectioning. A stress analysis was performed on the residual thermal stresses resulting from post-cure cool down. Analysis indicated that the thermal stresses in the aluminum core are a function of foil thickness of the aluminum core. Thermal stresses are relieved through disbonding of the adhesive node. The node disbonds were shown to significantly reduce the shear capability of the sandwich structure. Funding was provided by the ARES I Upper Stage Project.

Keywords

Sandwich structure, induced thermal stress, node disbonds, carbon fiber composite

Introduction

Materials and processes

Process development panels representative of the ARES I composite interstage design were fabricated with two different face sheet thicknesses and lay-ups and with three honeycomb core densities. The higher stress regions of the interstage design incorporated higher density core and thicker face sheets. Table 1 identifies the configurations fabricated. Tool side face sheets (IM7/8552-1) were fiber-placed. Film adhesive (FM300K) and hexagonal cell aluminum core (MIL-C-7438G CRIII-1/8-5052) were hand-placed. Aluminum core was procured to a specification that uses the units pounds per cubic foot (pcf) for density. This nomenclature will be used throughout this text. The outer mold line, or bag side, was fiber-placed. Panels were vacuum bagged and cured in an autoclave by ramping to 179°C at 0.5°C to 2.7°C per min and holding for 120 min. An intermediate hold at 110°C was maintained for 60 min prior to obtaining the final cure temperature. Cool down rate was maintained between 0.5°C to 2.7°C. A higher than typical autoclave pressure was used because early process development work indicated a 379 KPa autoclave pressure provided improved consolidation of the outer mold line face sheet. Three replicates of each panel configuration were fabricated. To assess material variability, a different batch of core was used in each replicate.

Background

Other researchers have observed node bond failures. Most occurrences reported in the literature deal with disbonds associated with moisture intrusion, heating of the sandwich structure (such as in a repair), node bond degradation, or a combination.[1–4] Node bond failures due to the degradation of the node bond adhesive have been identified as a durability issue with metallic honeycomb cores. Node bond failures during heated repairs were attributed to moisture entry. Peel strength values of degraded node bonds were reduced by up to 90%.[5]

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Table 1. Configurations of sandwich panels fabricated for process development of interstage

Configuration	(0/45/90) degree plys (percent)	Face sheet thickness (cm)	Core density (pcf)/(kg/m^3)	Core foil thickness (cm)
Acreage	(55/22/22)	0.25	3.1/49.6	0.0018
Intermediate	(55/22/22)	0.25	6.1/97.7	0.0038
Buildup	(25/50/22)	0.81	12.0/192	0.0076

Rider[6] reported greater node bond peel strength in Alcore honeycomb than Hexcel over a range of temperatures. This increased capability may not be manufacturer dependant as the comparison was made between two different surface treatments with different node bond adhesives. The Hexcel CR3 core used a nitrile rubber adhesive. The Alcore phosphoric acid anodized (PAA) core used a fiber containing polyamide adhesive. Furthermore, the CR3 core has a chromium oxide surface layer, while the PAA material has a polyamide surface layer. Rider recommended further testing of both vendor products with the same surface treatments for a more direct comparison. One important observation in the Defence Science and Technology Organisation (DSTO) report is the higher peel strength of the Alcore PAA material at elevated temperatures.

Anomaly

Once the sandwich panels were fabricated, they were inspected with through transmission ultrasonic test (TTU). Anomalies were first detected on the panel using the third batch of high-density (12 pcf) core. Figure 1 illustrates the node disbonds as small black dots. The large black circles are two inch diameter regions of core potted with epoxy prior to lay-up and cure of the sandwich. It is known that node bond failures can be detected with X-ray (ASTM E2662 Radiologic Examination of Flat Panel Composites and Sandwich Core Materials Used in Aerospace Applications). Subsequent radiographic inspection corroborated the findings of TTU (Figure 2). Finally, an area was cross sectioned and examined, visually revealing the node disbonds (Figure 3).

A review of the other panels from previous honeycomb batches indicated far fewer instances of node disbonds, suggesting sensitivity to batch. A review of acceptance testing on the honeycomb core indicated that all batches met the requirements of MIL-C-3478, Military Specification for Core Material, Aluminum, for Sandwich Construction. No disbonds were found in inspection of the three batches of core that had not yet been used in sandwich construction. Thus, the disbonds occurred during the autoclave cure.

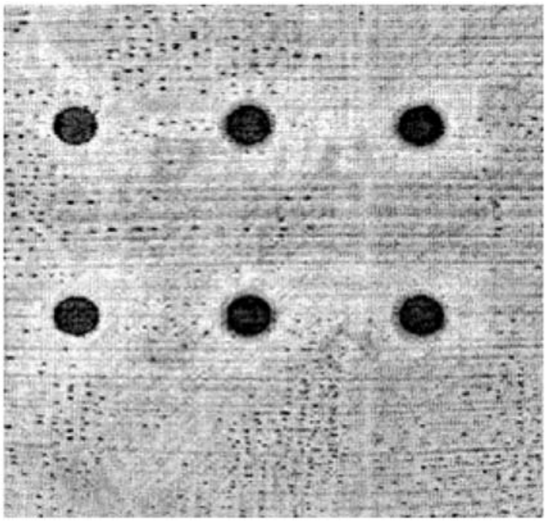

Figure 1. Ultrasonic image showing core node disbonds (dark circles are 5 cm diameter potted core).

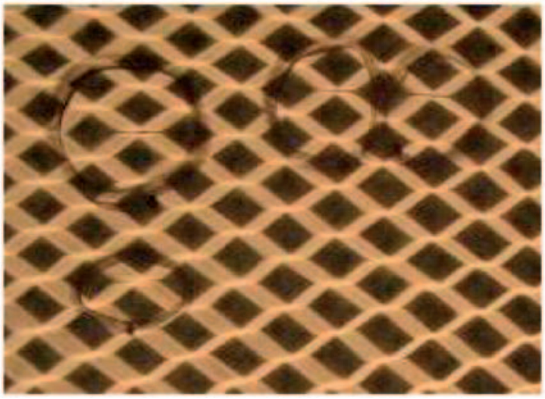

Figure 2. X-ray image showing core node disbands.

Test and analysis

Mechanical testing

Initial acceptance testing by the core vendor suggested no anomalies between the three batches. Mechanical properties all exceeded MIL-SPEC-3478 requirements. Core shear strength in the W direction was almost twice

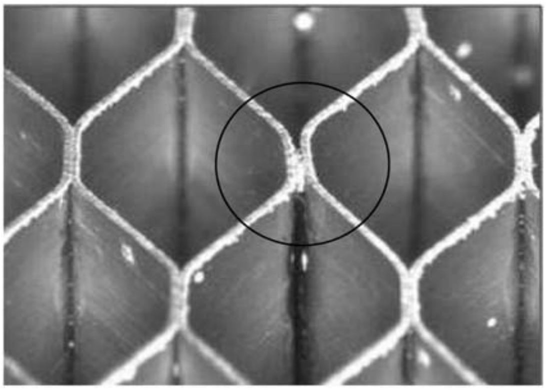

Figure 3. Cross section showing a core node disband.

the specification value. Similarly, delamination strength of the node bonds tested per MIL-STD-401 was more than twice the specification value. Table 2 shows the lot acceptance test results compared to minimum specification values. Shear tests are performed on 1.59 cm thick core. Delamination tests are on 1.59 cm thick core that is 12.7 cm wide by 25.4 cm long. During the investigation, another batch of 0.3 cm cell 193 kg/m^3 (12 pcf) core was procured from a different vendor. However, only the PAA treatment and not the CR3 treatment was available from the second vendor. Otherwise, this fourth batch was procured to the same specification. However, acceptance test results for the PAA-treated material significantly exceeded those of the CR3-treated material.

After the node disbonds within the sandwich were discovered by nondestructive evaluation (NDE), mechanical test coupons were machined from the sandwich panel. Four point bend coupons were tested in the W direction to determine core shear strength. Of the three batches of core tested, batch 1 had the greatest strength and batch 3 had the lowest strength. This strength reduction corresponds directly with the density of node disbonds detected by NDE. Table 3 shows the shear strength results. The room temperature specification minimum is 5171 KPa. It is apparent when comparing shear strengths in Table 2 and 3 that the co-cure affected the capability of the core and residual strength was batch-dependent.

Further evaluation of the node bond capability was performed with peel tests of the individual node bond. Ribbons of material were separated from the core that contained two strips of foil to isolate individual nodes (Figure 4). Three batches of CR3-treated 196 kg/m^3 (12 pcf) core were tested with three samples per batch and eleven replicates per sample. Analysis of variance rejected the hypothesis that the peel strengths in all three batches were equal. The fourth batch with a PAA treatment exhibited higher peel strength. Furthermore, the load displacement curves varied between the peel tests with different coatings. The nodes from CR3-coated core loaded to a peak followed by complete failure of the adhesive. The nodes from PAA-coated core loaded to a peak, relaxed as the adhesive began to peel, then failed (Figure 5). It is apparent from the two load displacement curves that the PAA-coated material had a greater toughness. This increased toughness could allow a greater relaxation of the thermal stresses prior to complete node bond failure.

Two-dimensional model

A two-dimensional (2D) model of the core displacement during cool down was performed. For the simplicity of a 2D model, the model assumed a thick core with no influence from the face sheets (coefficient of thermal expansion equal to zero) and constrained at distant in plane edges. Figure 6 is a schematic of the core after displacement due to thermal contraction. The original shape is represented by the blue lines of length L_1 and L_2. In order to balance forces, the foil must contract more along the double-foil cell wall than the single-foil cell wall. Thus, the intersection point must move to the right per Figure 6. Therefore, after cooling, theta is slightly smaller than the initial angle (assumed to be 60° for hexagonal core). F_1 can be expressed in component forces F_x and F_y as the following relationships:

$$F_y = F_1 \sin\theta \tag{1}$$

$$F_x = F_1 \cos\theta \tag{2}$$

Due to the small change in angle, the relationship between Δx and ΔL can be approximated by:

$$\Delta L \approx \Delta x \cos\theta \tag{3}$$

For the general case it can be shown that:

$$F_1 = \alpha\Delta TEA_1 + \frac{\alpha\Delta TEA_1 \frac{L_2}{L_1}\cos\theta[A_2 - 2A_1\cos\theta]}{2A_1\frac{L_2}{L_1}(\cos\theta)^2 + A_2} \tag{4}$$

A_1 and A_2 are the areas of the single and double wall of aluminum foil and E is the modulus of the aluminum foil. For the special hexagonal case where $\theta = 60°$, $L_1 = L_2$, and $A_1 = \frac{1}{2}A_2$:

$$F_1 = F_2 = \frac{6}{5}\alpha\Delta TEA_1 \tag{5}$$

Table 2. Honeycomb core acceptance test results

Test	Specification value	Batch 1	Batch 2	Batch 3	Batch 4
Corrosion coating		CR3	CR3	CR3	Phosphoric acid anodized
W Shear room temperature (KPa)	5171	Not tested	Not tested	Not tested	Not tested
W shear 177°C (KPa)	2241	4144	4089	4420	9866
Delamination room temperature (N)	222	516	601	578	1059
Delamination post boil (N)	44.4	338	373	422	427
Delamination 177°C (N)	111	267	258	254	400

Table 3. Sandwich four-point bend results

Core batch	Replicates	Density of disbonds detected	Failure mode	Average maximum shear stress (KPa)
1	5	None	Face sheet delamination	11404
2	5	Low	Core shear	6681
3	4	High	Core shear	4888

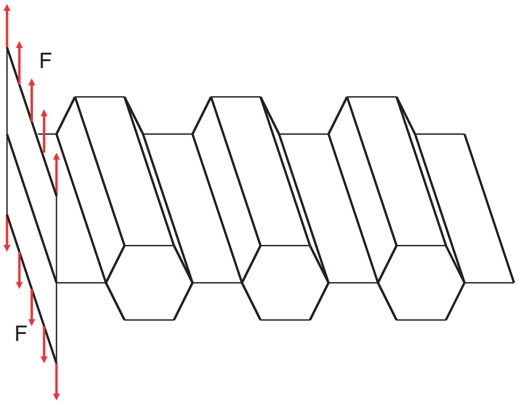

Figure 4. Node bond peel test.

Average tensile stress across the bondline is

$$\sigma = \frac{F_1 \sin\theta}{L_2 T} \tag{6}$$

Using average specification values and assuming hexagonally shaped core, one obtains $\sigma = 22.5$ MPa for 12 pcf core. However, the 12 pcf core with node disbonds was not quite hexagonal. The as-received 12 pcf core was under-expanded (Figure 3). Furthermore, the bonded node length L_1 was about 70% the length of the single ribbon of core (L_2). The aluminum foil supplier specification testing indicated the average foil thickness was 0.0094 cm.

Using the following inputs of the as-recieved core, where A_1 and A_2 are the areas of the single-foil and double-ribbon foil and ΔT is the change in temperature:

$E =$ aluminum foil modulus $= 68.9 \times 10^6$ KPa
$\Delta T = 158°\text{C}$
$\alpha = 23.8 \times 10^{-6}\,\text{cm/cm/°C}$
$L_1 = 0.112\,\text{cm}$
$L_2 = 0.079\,\text{cm}$
$T =$ core thickness $= 3.81$ cm
$t =$ foil thickness $= 0.0094$ cm
$A_1 = t \times T = 0.036\,\text{cm}^2$

One obtains $\sigma = 17$ MPa. Thus, it is apparent that changes in the geometry of the core have significant impacts to the calculated residual thermal stress on the core node bond.

Finite element analysis setup

The finite element analysis (FEA) runs of the composite cool down process were mechanical simulations driven solely by uniform temperature loading from an initial condition of 179°C to a final room temperature condition of 21°C as steady state models. Given the steady state nature of the analysis method, the main drivers of the node bond results are material stiffness and the difference in the coefficient of thermal expansion (ΔCTE) between the aluminum honeycomb core and the carbon fiber face sheet. The model inputs for material properties and geometry were the same as listed above for the as-received core. The 3D model included the effect of the face sheet CTE. The CTE of the face sheet was more than an order of magnitude lower than the CTE of the core; $1 \times 10^{-6}\,\text{cm/cm/°C}$ was used for the face sheet CTE.

A key conservative assumption made for the FEA is that during the cure process, as the autoclave temperature reaches 179°C, the aluminum core expands due to

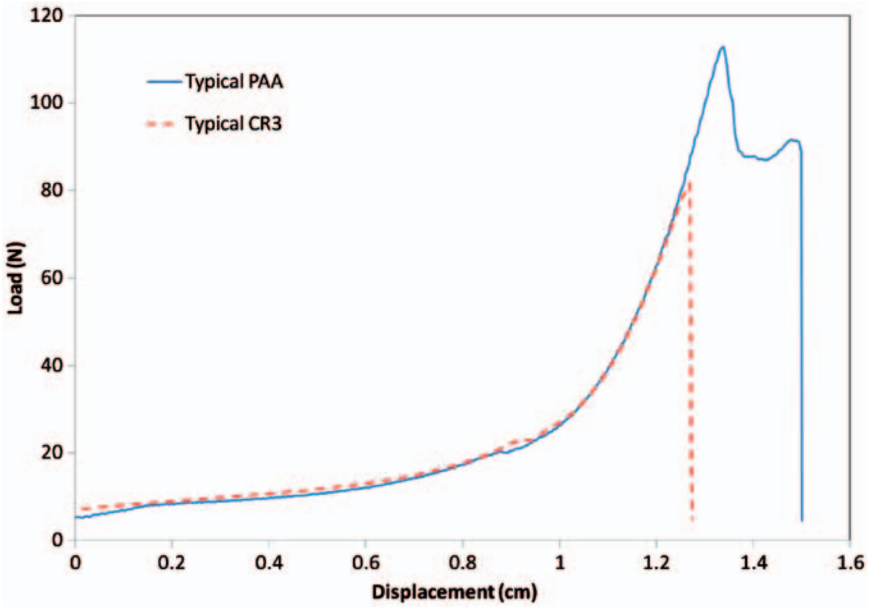

Figure 5. Typical load displacement curve of core node peel test.

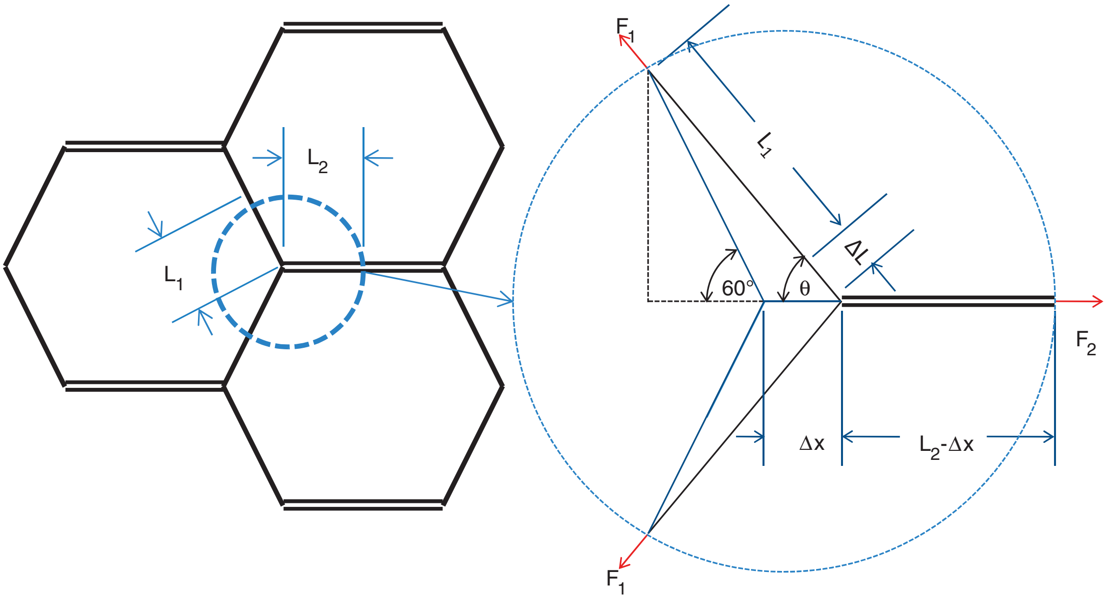

Figure 6. Free body diagram of core.

its coefficient of thermal expansion (CTE) and is stress free against the face sheet up to 179°C since the face sheet and film adhesive have yet to bond the core to the face sheet. For purposes of this analysis, a thermal assumption made is that the coupons cool slowly enough such that uniform temperature is maintained throughout and that the process results are steady state in nature. The final condition of the FEA is room temperature.

The finite element models (FEMs) of the composite coupons (Figure 7) were developed as 3D discreet models with 3D elements used for all of the sections. The nature of the uniform temperature loading and the rectangular perimeter of the actual coupons allowed for three planes of symmetry to reduce the FEM to convenient boundaries. ABAQUS v6.9-2 was used for the pre-processing as well as the finite element (FE) solver. For the FEM, ABAQUS incompatible mode solid elements (C3D8I) were used for two main reasons:

- To manage all of the discreet contact surfaces between the node bonds and face sheet bonds.
- When used properly, the incompatible mode solids provide good deformation accuracy even with a single element through the cross section.

A contact surface is defined in the FEM on each individual foil surface of the honeycomb core which opposes another foil surface; this creates each single honeycomb node. A contact pair is then defined for each of the opposing contact surfaces. These contact pairs are "bonded" together to create a bonded node, or a "joint", in the FEM.

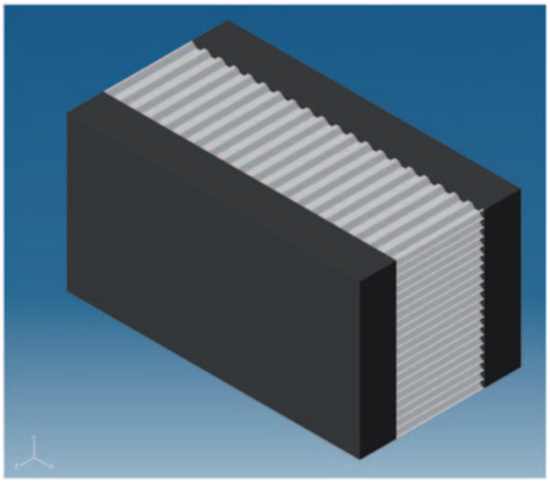

Figure 7. Full model of 6.6 cm × 12.7 cm coupon with 3.81 cm inch core.

During an FEA run, the bonded contact pairs tend to pull away from each other to produce tensile forces across the node bond boundaries. The force distributions provide the main output results which are then evaluated for the possibility of correlating node bond separation.

FEA results

The initial FEM validated that the honeycomb core cells tend to "pull away" from each other to produce a net tensile force between nodes due to ΔCTE and ΔT during the cool down. To accomplish this FEA validation, one of the internal node bonds in the FEM was purposefully unbonded initially to observe the natural deformation due to ΔCTE and ΔT. Figure 8 shows FEA output of the node pair that separated further during the FEA run at 1 : 1 deformation magnification.

The tensile forces were evaluated directly as a discreet output from the FEA in the form of contact force over the surfaces of the cellular nodes throughout the honeycomb model. The contact forces from the FEA were found at each node in the FEM and, hence, the distributions of contact (tensile) forces across the node bonds were evaluated during post-processing.

From the post-processing of the FEA results, it was found that the node bond force results were similar throughout the acreage of the model. The node bond force results were also found to be nearly uniform

Figure 8. Unbonded node analysis close-up view showing tendency to separate.

throughout the height of an individual foil surface of a bonded contact pair as shown by the contact force output (Figure 9).

Review of node bond tensile stress results revealed that there is a tendency for a high-edge stress to develop at either end of the node bond due to the added structural stiffness of the neighboring foils. Figure 9 also graphically shows typical contact stress output with the edge stress highlighted in red. Since it was found to be difficult to converge on a reliable edge stress, a method of evaluating results from the FEA output is the concept of average stress. With this concept, the tensile contact force output is summated over the entire contact area of the joint and divided by the total surface area to provide a simple "P/A" average stress. This average stress could then be used as a metric to compare one design to another, or to compare against simple mechanical test methods.

Initial FEMs were created without fillets applied to the cell geometry. However, the 12 pcf density core samples did show distinct fillets at the cell edges (Figure 3). FEMs for the 12 pcf core were thus developed with a fillet applied to the geometry. A 0.033 cm fillet was chosen from visual inspection of the samples although actual samples displayed a range of fillet radii.

When running the FEM to compare the "straight edge" results to the "fillet edge" results, the FEM with fillets exhibited a lower average stress across the node bonds by approximately 30%. An explanation for the reduced average node bond stress is that the system rigidity is reduced by adding the fillets, since the free foils outside of the node bond has more bending flexibility.

To compare the effect of the cell density to the node bond stress, the 6 pcf core design was run with the same method, load and boundary conditions, and material properties. Given that the 6 pcf core had a thinner foil thickness than the 12 pcf, the basic structural system stiffness was less. The FEA results of the average node bond tensile stress was found to be less than the similar 12 pcf model by approximately 52%. Table 4 provides the stress data from the FEA. With the same material property and geometric inputs, the results of the 3D model correlate well with the 2D model (16 MPA for the 3D, analytical model compared to 17 MPa for the 2D, numerical model that did not include the CTE of the face sheets.

Observations

Testing of the three batches of CR3-coated core and the fourth batch of PAA-coated core suggest the PAA-coated core node bonds are superior in strength to the CR3-coated core. Comparisons between the three batches of CR3-coated core suggested high variability in shear strength that correlated to the density of node disbonds. Thus, node disbonds within the core have a

Table 4. Finite element analysis (FEA) output of average contact (tensile) stress at node bond interfaces

Design	Edges	Average tensile stress
1/8-5052-.003 (12 pcf)	Fillet 0.033 cm	11 Mpa
1/8-5052-.003 (12 pcf)	No fillet	16 Mpa
1/8-5052-.0015 (6 pcf)	No fillet	8 Mpa

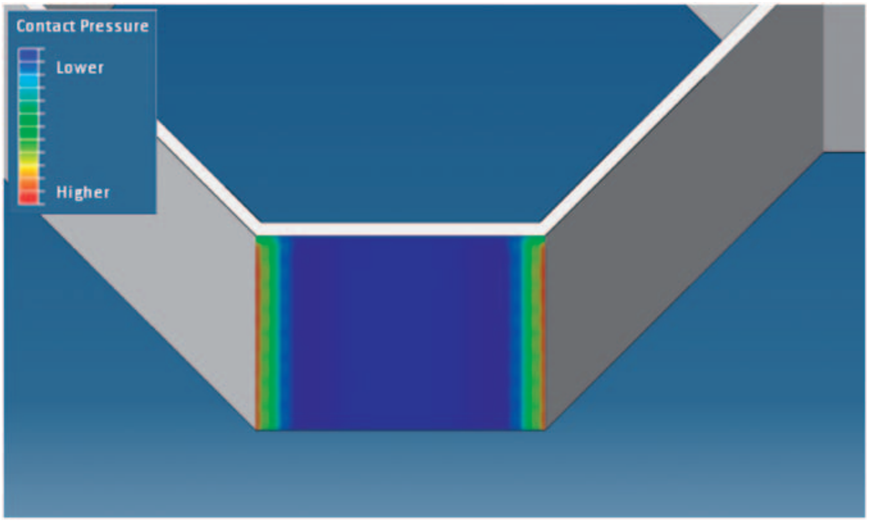

Figure 9. Node bond contact forces.

significant effect on the shear strength of a sandwich structure.

The 2D numerical analysis predicts similar stresses within the node bond as the 3D FEA. However, the predicted forces on the node bond are an order of magnitude higher than the capability demonstrated in mechanical testing. This suggests some of the initial assumptions used in the model are incorrect. Using the cure temperature as the stress-free temperature is a conservative assumption. Determining the stress-free temperature would provide for a more accurate model. Altering the honeycomb core cell size indicated the stresses developed within the aluminum core are highly sensitive to the geometry. Similarly, adding a fillet to the model further reduces the stress within the node bond, illustrating the importance of geometry. Furthermore, no yielding was assumed within the model. And lastly, adding a compliant layer of node bond adhesive would reduce the calculated stress. Critical improvements to the model would include (1) test and analysis to determine the stress-free temperature within the core and (2) determining the elastic properties of the node bond adhesive as an input to the model.

Conclusions

Mechanical testing and analytical models were performed in an attempt do understand processing anomalies during cure of composite sandwich structures. Node disbonds occurred during autoclave cool down within the aluminum honeycomb core. It was believed the disbonds were a result of a mismatch in CTE between the carbon fiber/epoxy face sheet and aluminum core. A 3D FEM was built to run simulations with various geometries. The 3D FEA was verified by 2D mechanics of materials type analysis. The model demonstrated high tensile stresses developed within the aluminum foil due to the temperature change and the mismatch in CTE between the core and face sheets. This created high stresses on the node bonds within the core. Mechanical testing performed on the node bonds did not correlate well with model results. The model predicted much higher stresses within the core than the capability determined by mechanical testing. Further refinement is needed within the model in order to predict the onset of node disbonding. Nevertheless, the model is useful for demonstrating the potential for high residual thermal stresses to develop within the honeycomb core. The model is also a useful tool during the design phase when evaluating stresses developed due to the choice of parameters such as core foil thickness, cell size, and cell geometry. Finally, this model has demonstrated the importance of process control, as small changes in geometry can affect the residual stresses with the honeycomb core.

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Conflict of interests

None declared.

References

1. Whitehead S, McDonald M and Bartholomeusz RA. Loading, Degradation and Repair of F-111 Bonded Honeycomb Sandwich Panels – Preliminary Study, DSTO-TR-1041, 2000.
2. Radtke TC, Charon A and Vodicka R. Hot/Wet Environmental Degradation of Honeycomb Sandwich Structure Representative of F/A-18: Flatwise Tension Strength, DSTO-TR-0908, 1999.
3. Cambell FC. Manufacturing technology for aerospace structural materials, London: Elsevier Inc., 2006, pp.396–398.
4. Davis, Max and Tomblin, John. Best Pactices in Adhesive-Bonded Structures and Repairs", DOT/FAA/AR-TN06/57, April 2007.
5. Davis MJ, Chester RJ, Perl DR, et al. Honeycomb Bond and Core Durability Issues; Experiences within CREDP Nations, Aging Aircraft Conference, Williamsberg, VA, Aug 31-Sep 02, 1998.
6. Rider, Andrew. The Durability of Metal-Honeycomb Sandwich Structure Exposed to High Humidity Conditions, DSTO-TR-1276, March 2002.