BENDING TEST OF THERMOPLASTIC COMPOSITE CONE

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1 Abstract
A composite tube bending test setup simulating pure bending condition has been developed to study bending and buckling behavior of composite conical shells under bending load. A 48-inch long thermoplastic composite cone made using automated fiber placement technique (AFP) was tested under bending load. Applied loads were measured using two independent load cells and then converted to bending moments. Experimental critical buckling moment was compared with the theoretical one and a very good agreement was obtained.

2 Manufacturing
The test specimen is a section of a helicopter tailboom (conical shape) and is a replacement part for the aluminum counterpart. It was made out of advanced thermoplastic composite material which has carbon fiber as reinforcement and Polyether ether ketone (PEEK) as matrix. The commercial name of the material is AS4/APC-2 from Cytec Engineered Materials and it was supplied as a slit tape with 0.25in width. The specimen was made at the Aerospace Manufacturing Technology Centre (AMTC) in Montreal using a 6-axis gantry-type AFP machine supplied by ADC Company (Figure 1). It is equipped with a thermoplastic head which accepts one tow at the time and has nitrogen Hot Gas Torch (HGT) as heating system. The mandrel used for manufacturing was a steel tool with internal heating system, and a temperature controller was used to maintain the tool temperature around 200°C. In order to achieve good in-situ consolidation, optimum process parameters were selected based on the results of modal analysis (stiffness criterion) and interlaminar shear strength test (strength criterion) obtained in [1] and [2]. The process parameters used in manufacturing of the thermoplastic composite cone are listed in Table 1. The layup sequence and dimensionless parameters of the specimen is tabulated in Table 2. Figure 1 shows the AFP machine laying down a 45° layer.

Table 1: AFP process parameters used in manufacturing of the thermoplastic composite cone

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
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<tr>
<td>Compaction force</td>
<td>40 Kg</td>
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<tr>
<td>Nitrogen flow rate</td>
<td>75 SLPM</td>
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<td>Processing speed</td>
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Table 2: Layup and dimensionless parameters of the thermoplastic composite cone

<table>
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<th>Parameter</th>
<th>Value</th>
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<td>Large radius/Total thickness</td>
<td>93.75</td>
</tr>
<tr>
<td>Semi-cone angle range (α)</td>
<td>1°-3°</td>
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</table>
3 Tube Bending Test Setup

Bending moment is the dominant load on cylindrical and conical shells in many applications (e.g., helicopter tail boom) and buckling due to bending is the main failure concern for these structures. However, experimental setups to study bending and buckling behavior of cylindrical and conical shells under pure bending load are rare. Moreover, experimental results for buckling of composite conical shells under bending are non-existent to the best of authors’ knowledge. Only two experimental setups to study cylindrical shells under pure bending have been found in the literature. The first one was developed by Fuchs, Hyer and Starnes [3] and sponsored by NASA Langley-Virginia Polytechnic Institute in 1992. Their investigation was limited to cylindrical shells. The second setup developed, more recently, in 2009 by Blom et al. [4]. They made a bending fixture installed on a MTS test bench which provides the loading power. The study was limited to a composite cylinder as well.

In order to study bending and buckling due to bending behavior of conical shells, a setup has been designed, manufactured and installed at Concordia Centre for Composites (CONCOM) laboratory. The setup shown in Figure 2 is composed of three main units including structural components, loading unit, and instrumentation. The structural components will be discussed in detail in upcoming sections.

The load is created by two hydraulic cylinders and converted to bending moment through the arms connecting the hydraulic cylinders to the main assembly. This bending moment, then, is transferred to the test specimen using a set of plates and rings. There are two mechanisms which transferred the load to the specimen: first, a series of radial bolts is inserted between the inner and outer ring and passes through the test specimen on the tension side. These bolts help to prevent the sample from slipping out of the rings during the test. Second, the specimen is potted with Low Melting Point Alloy (LMPA) which keeps the sample firm between the inner and outer ring and transfer the load smoothly to the specimen skin. LMPA is a Bismuth alloy which has a melting point of 75 degree of Celsius and can be melted easily and potted around the specimen.

![Figure 2: Composite tube bending test setup: 1-Hydraulic cylinders, 2- Test specimen, 3- Reaction frame, 4- Moment Arm assembly](image)

The loading unit has been designed in such a way to assure applying equal bending moment on both sides of the sample, even when the sample is not symmetric (i.e., conical shells).

Regarding the instrumentation, the tube bending test setup has been equipped with four digital cameras to measure full field strains and deformations using digital image correlation technique (DIC). Strain gauges were also installed to cover the test area which was not covered by DIC cameras.

The setup is able to handle samples with different lengths between 30 to 48 inches (adjustable length) and samples with different cross section shapes and dimensions from 1 to 33 inches.
3.1 Structural components

The structural parts of the set up are shown in Figure 3 and the description of its components comes after.

Figure 3: Structural parts of the bending test setup: 1- Moment Arm assembly, 2- Adaptor Plate, 3- inner and outer ring, 4- Vertical Support, 5- Reaction Frame, 6- Pivot Bracket, 7- Installation Spacer Beam

Moment Arm and Back-plate
The Moment Arm is the component that converts the vertical force generated in hydraulic cylinder to the moment, which is then transferred to the sample. It is composed of two plates held together with brackets to better distribute the load across the Back-plate. In order to display the connecting plates, one of the plates is shown as transparent in Figure 4. The Moment Arm is pinned from one side to the clevis joint of the hydraulic cylinder and bolted to the Back-plate on the other side using tapped holes in the Moment Arm and counter bored holes in the corresponding locations on the Back-plate. The selection of bolts to fasten the Moment Arm to the Back-plate rather than welding was because welds would cause warping of the Back-plate. This warping could prevent the Adapter Plate from resting flush against the Back-plate surface.
The Back-plate is a 1.5-in thick plate which transfers the load from the Moment Arm to the Adaptor plate uniformly. It has 33 inches height and 51 inches length which determines the cross section size limitation of the sample that can be tested by the setup.

Figure 4: Moment Arm

Adaptor Plate
The concept of adding an Adaptor Plate enables the setup to accommodate different sample geometrical shapes by using an appropriate set of Adaptor Plates. Another purpose of having the Adapter Plate is to ease installation and removal of the specimen once it has been fixed to the rings. Since the Back-plates are heavy and large, the use of smaller Adapter Plates allows easier manipulation of the sample once mounted between inner and outer rings. It also prevents the Low Melting Point Alloy (LMPA) from flowing out from between the rings. Using the Adapter Plate, the Back-plate has less bolt holes and consequently has more structural rigidity.

Vertical Support and Pivot Bracket
The Vertical Support is the component which supports the axis of rotation of the Back-plate. It is bolted from the bottom to the Reaction Frame and pinned from the top to the Pivot Bracket. The Vertical Supports are the links which transfer the load to the Reaction Frame and they are under high tension load during the test. The setup has four Vertical Supports of which two of them are affixed on the one side and the other two are movable and can be adjusted for different sample lengths. The Pivot Bracket is the connecting part between the Back-plate and the Vertical Support. It is designed in such a way that the axis of rotation of the setup is where the test specimen comes into contact with the Adaptor Plate. This way the entire test specimen (including the clamped ends) would be under bending load.
Due to high shear load (combination of torsion and transverse shear) on the Pivot Bracket, it is connected by four ¾-inch diameter shear pins to the Back-plate. Since it is also under bending, four 0.5-inch bolts are used to connect it to the Back-plate and to withstand this bending load. Welding is avoided because of possible warping that can occur on the Back-plate.

**Inner and outer ring**
The test specimen seats between two rings, called inner and outer ring. The bending load is transferred to the Low Melting Point Alloy (LMPA) through these two rings and then applied to the specimen. A cross section view of the rings and specimen is shown in Figure 5. The outer ring has one step toward the inside and the inner ring also has one step toward the outside. These two steps provide a self-locking mechanism and prevent the test specimen from sliding out of the rings during the test by getting benefit of the LMPA shear strength.

![Figure 5: Cross-section of the rings: 1- outer ring, 2- inner ring, 3- specimen](image)

**Figure 5: Cross-section of the rings: 1- outer ring, 2- inner ring, 3- specimen**

The inner ring is bolted to the Adapter Plate while the outer ring is bolted to both the Adapter Plate and the Back-plate. The outer ring has radial holes which allow for cross bolts to pass through the specimen and to be tightened to the radial bolt holes in the inner ring.

There is also a mechanism for centering the test specimen between two rings during installation which is basically three set screws mounted at 120 degree intervals.

**Installation Spacer Beams**
The test specimen is, first, installed on the rings and Adaptor Plates on the floor and then the assembly is installed on the setup. In order to make sure that the two Adaptor Plates attached to two ends of the specimen are parallel, Installation Spacer Beams have been designed to give the assembly structural integrity on the floor. Another important function of the Spacer Beams is to prevent the specimen from any unwanted pre-loading that may occur during installation and manipulation on floor. Installation Spacer Beams are basically four I-beams, two of which are installed on the top of the assembly and are connected by two plates. The other two I-beams are installed on the bottom of the assembly (Figure 6).

![Figure 6: Installation Spacer Beams inside the assembly](image)

**Reaction Frame**
Due to the high magnitude of the load and weakness of the concrete floor in tension, a Reaction Frame composed of five I-beam has been designed. The closed shape of the Reaction Frame (Figure 7) makes all the reaction forces stay on the frame and not to be transferred to the floor. So the only load acted on the concrete floor would be the weight of the setup which would be in compression and easily withstood by the floor.

Furthermore, the use of I-beams allows the frame to withstand the large moments and forces created by the application of the load. There are two longitudinal and three cross I-beams in the Reaction Frame. The longitudinal I-beams have been designed with slots on one end to allow the adjustment of cross I-beams when tests are being done on
specimens of different lengths. The reason for having three cross I-beams rather than two is to keep the structural integrity of the frame (perpendicularity and parallelism) while moving one of the cross I-beams to adjust the setup length.

4 Preparation of the sample for bending-buckling test

In order to prepare the thermoplastic composite cone for bending-buckling test, the following steps were taken:

4.1 Manufacturing end tabs

In bending-buckling test, the bending moment is applied to both ends of the test specimen. Two ends of the specimen are located inside the inner and outer rings and the load is transferred to the circumference of the specimen. In order to prevent the failure from happening inside the rings where it cannot be detected and be seen by cameras, extra layers of composite were added to the end of the thermoplastic composite cone. These layers were built in a stepwise manner, i.e., more layers were added at the end of the specimen and as it moved toward the center of the specimen, some layers were dropped until there was no extra layer. This would ensure smooth transition of the load to the specimen skin.

Furthermore, three composite rings were also manufactured at each end of the thermoplastic composite cone (Figure 8). The purpose of having these rings is to create a self-locking mechanism that prevents the specimen from sliding out of the ring during the test. Basically, the LMPA is entrapped between these rings and the steps made on the inner and outer rings and stop the tension side of the specimen from slippage during the test.

Figure 8: Tabs and rings manufactured by AFP on the thermoplastic composite cone

4.2 Applying random pattern

Since the Digital Image Correlation (DIC) system was to be used for deformation and strain measurement, the surface of the specimen should have enough texture to be recognizable by cameras. The surface of the thermoplastic composite cone was fairly black after manufacturing and did not have enough texture. So, to have maximum contrast, a white random pattern was applied on the surface of the thermoplastic composite cone using permanent markers.

4.3 Drilling radial holes

A series of radial cross bolts was designed to pass through the outer ring, test specimen and the inner ring. This would help the LMPA to prevent the test specimen from sliding out the rings during the test in tension side. In order to install these bolts, both ends of the thermoplastic composite cone were drilled by radial holes while it was fixed between the rings. These holes were drilled only on the tension side of the specimen as there was no concern of sliding on the compression side.

4.4 Applying strain gages

Twenty two strain gages were attached to the surface of the thermoplastic composite cone in 13 locations. The strain gage pattern, shown in Figure 9, was designed in such a way to have minimum interference with Digital Image Correlation system. The majority of strain gages were oriented axially...
(11 gages) while 8 strain gages were placed circumferentially and three gages were oriented at 45°. At three locations (i.e., mid-length and close to small end on tension side and close to small end on the compression side) three-arm rosette strain gages were placed which made it possible to read axial, circumferential and shear strain at these locations.

Figure 9: Strain gage pattern applied on the thermoplastic composite cone

Digital Image Correlation system (DIC) also was used to measure in-plane strains and out-of-plane deformation using two pairs of cameras (total four cameras). This measurement covered top surface (which was in compression) and side surface of the specimen.

4.5 Potting with LMPA and making the assembly

In order to pot the thermoplastic composite cone end into the space between the inner and outer ring using a Low Melting Point Alloy (LMPA), first the rings were mounted to the Adaptor Plate and then the assembly was put on a hot plate for several hours to reach about 100°C. The specimen was centered between the rings and while some LMPA was melting on the Adapter Plate (which was on the hot plate), some other amount of LMPA was melted in a separate pot and then poured around the circumference of the specimen in between the two rings (Figure 10). Once the one side of the specimen was potted, Installation Spacer Beams were installed and the assembly was rotated 180° on the hot plate and the same procedure was taken for the other end of the specimen.

Figure 10: Potting the specimen between the ring using LMPA: 1- LMPA, 2- radial cross bolts, 3- outer ring, 4- Installation Spacer Beam, 5- specimen

The assembly after potting procedure and installing the Installation Spacer Beams was brought to the setup using a gantry crane and mounted to Back-plates. The last step was to remove the Installation Spacer Beams from the bending test setup.

5 Bending-buckling experimental results

After calibrating the cameras and connecting all the gages to the data acquisition system, the test was started and the load kept increasing until a loud sound was heard and the load dropped drastically. The buckling due to bending occurred and led to final failure. A visible crack was observed on the top surface and near the small end of the thermoplastic composite cone (after tabs) as expected. The crack extended around the circumference of the cone. Looking at the failure section, one could clearly see the fiber and matrix breakage (see Figure 11). It was seen, also, that no slippage occurred between the specimen and the rings on the tension side, suggesting that the LMPA and cross bolts perfectly fulfilled their roles. The deformation, strain, and load results obtained are presented and discussed in the following sections.

Figure 11: Failure section of the composite cone
5.1 Deformation results (DIC system)

The contour plot of axial deformation ($U$) of the thermoplastic composite cone (top view) just prior to buckling is shown in Figure 12. As it can be expected, the small end and the large end of the specimen (right side) moved toward one another during the bending test and the top surface was contracted. As a result, the axial deformation of the small end (right side in Figure 12) was negative while the axial deformation of the large end (left side in Figure 12) was positive and the axial deformation was zero somewhere in between. The axial deformation pattern looks quite symmetric about the mid-plane and has a maximum magnitude of about 1.6 millimeter in the gage area, near the big end.

![Figure 12: Axial deformation (U) contour plot obtained by DIC system (top view)](image)

The contour plot of circumferential deformation ($V$) of the thermoplastic composite cone (top view) just prior to buckling is shown in Figure 13. It can be seen form Figure 13 that since the top surface of the specimen was under compression and consequently contracted in axial direction, it was expanded in the circumferential direction (Poisson effect). Figure 13 shows more deformation concentration close to the small end of the specimen where the failure happened.

![Figure 13: Circumferential deformation (V) contour plot obtained by DIC system (top view)](image)

The out-of-plane deformation of the specimen (top view) is shown in Figure 14 just prior to failure. As one can expect, the maximum deflection happened near the middle of the specimen (toward the small end) while the deflection decreased toward both ends. The maximum top surface deflection was recorded to be about 5 millimeters.

![Figure 14: Out-of-plane deformation (W) contour plot obtained by DIC system (top view)](image)

The contour plot of circumferential deformation ($V$) of the thermoplastic composite cone (side view) prior and after failure is shown in Figure 15. The maximum side surface deflection of 4.68 millimeter occurred at the middle of the specimen. Figure 5.32 also shows quite a symmetric deflection pattern prior
to the failure. After failure, the location of the maximum deflection moved from the middle to the location of the failure where the crack separated the top surface of the specimen. Although the specimen was ruptured at the top (where the failure happened) under compression load, the bottom surface of the specimen which was under tension was not ruptured completely and showed some resistance even after the failure.

Figure 15: Prior and after failure circumferential deformation (V) contour plot obtained by DIC system (side view)

5.2 Strain results (DIC system)
The axial strain obtained by two cameras looking at the top surface of the thermoplastic composite cone is shown in Figure 16. As can be seen from this figure, prior to failure, the whole top surface was under compression (negative strain) with the maximum strain of 7100 microstrain near the small end of the cone. The axial strain was not uniformly distributed on both ends of the specimen and more strain concentration could be seen at the small end. This was expected since the small end had less stiffness in comparison with the large end of the thermoplastic composite cone. From the axial strain distribution prior to buckling, one can predict the possible location of failure based on axial strain accumulation near the small end (see after failure image, Figure 16).

Figure 16: Prior and after failure axial strain ($\varepsilon_{xx}$) contour plot obtained by DIC system (top view)

5.3 Strain gages’ results
Twenty two strain gages (numbered from 1 to 22) were installed according to pattern shown in Figure 9. The axial strains recorded by gage 1 on the compression side and gage 13 on the tension side are shown in Figure 17. Both gages were located at the same section near the small end (see Figure 9). As can be seen from Figure 17, both axial strain graphs are symmetric about horizontal axis prior to the buckling. This behavior is well-known from classical beam bending theory in which the axial strain is proportional to the distance of the point from the neutral axis. Close to the point that buckling occurred, gage 1, which was located near the failure point, exhibited nonlinear strain behavior which could be interpreted as the start of the failure. After buckling occurred and the specimen failed, the strain at the compression side (gage 1) dropped almost to zero while gage 13 which was located at the tension side dropped first to about 2300 microstrain and then increased again to about 4000 microstrain. This could be attributed to the fact that while the compression side fell apart due the severe crack, the tension side still was bearing some load.
BENDING TEST OF THERMOPLASTIC COMPOSITE CONE

Figure 17: Axial strain at gage 1 and gage 13

Figure 18 shows the axial strain graphs for gage 10, gage 11, and gage 12 which were located at small end, mid-length, and large end, respectively. Although these three strain gages had the same distance from the neutral axis, but they were placed at different length location (see Figure 9) so that one can see the axial strain distribution over the length of the specimen. As one can see from Figure 18, prior to buckling, gage 10 (which is placed at small end) had the highest value at all time. Gage 11 (which was located at the mid-length of the cone) showed about 23% decrease in axial strain with respect to gage 10. Gage 12, which was placed at the large end, measured the axial strain by about 18% less than gage 11. This trend is logical since as one moves to larger section, stiffness increases and consequently, axial strain decreases. After failure occurred, the mentioned trend reversed; that is gage 12 recorded highest axial strain, gage 11 was at the second high value, and finally gage 10 showed lowest axial strains. This inverse trend could be explained by the fact that failure occurred at the small end and as a result, the drastic drop was associated with gage 10 (88% of value) while gage 12 which had the most distance from the failure location showed the least drop in strain value (70%).

Figure 18: Axial strain at gages 10, 11 and 12

Circumferential strains measured at small end of the specimen are shown in Figure 19. Strain gage 3, 6, and 15 were oriented in circumferential direction on the top surface (compression side), mid-plane (neutral axis), and bottom surface (tension side) of the cone, respectively (see Figure 9). Circumferential strain was almost zero at the neutral axis (gage 6), suggesting that no significant strain (and therefore stress) occurred at neutral axis as expected. Gage 3 located on the compression side of the specimen showed positive circumferential strain; that means although the top surface of the cone was under compression in axial direction, in the circumferential direction it was under tension all test time. On the other hand, gage 15, which was placed on the tension side of the cone, showed negative circumferential strain over test time, indicating that the bottom surface was under compression in circumferential direction (while was under tension in axial direction). As can be seen from Figure 19, strain graphs for gage 3 and 15 are symmetric about the horizontal axis and have quite linear trend except near the buckling point for gage 3 and after buckling occurred.
5.4 Force results obtained from the load cells
The graph of force versus time measured by two independent load cells is shown in Figure 20. Both load cells (right and left) recorded almost the same value for the force during the test that means the same moment was applied to both ends of the specimen. This was one the requirements in the design of the loading unit which was perfectly met. As can be seen from Figure 20, the load increases (in negative value) rapidly until 45 seconds passed from the test and reached to about 17500 lbf (critical load). After buckling occurred, the force measured by the left load cell, which was located at the small end of the specimen (close to failure section), decreased by 84% and the force measured by the right load cell decreased by 80%.

The applied moments on two ends of the specimen can be calculated from the force graphs (Figure 20) multiplied by the moment arm length. The results indicate a maximum moment of 402,052 lbf-in applied to the left side of the specimen and a maximum moment of 418,657 lbf-in applied to the right side of the thermoplastic composite cone prior to the buckling. So the experimental critical buckling moment of the thermoplastic composite cone would be the minimum of the above mentioned moment values which is 402,052 lbf-in.

Theoretical buckling moment of the composite cone under pure bending load was calculated using a shear deformation shell theory developed in [5]. Trefftz criterion was used to derive stability equations and Ritz method was applied to solve them [5]. After some mathematical manipulations, the critical buckling moment was obtained from the following equation:

$$\det[Z] = 0$$

$$[Z] = \left\{ \int_0^L \left[ ([\Phi]^T([B]^T[F][B] + [B_{bend}])[\Phi]) \right] r d\theta dx \right\}$$

where $[\Phi]$, $[B]$, $[F]$ and $[B_{bend}]$ are matrices defined in [5] and are not presented here for the sake of saving space.

Regarding the geometry, the tabs added to both ends of the specimen were not included in the analysis and consequently the gage area of the specimen was considered (which was the length between the end tabs). The dimensionless parameters and layup sequence used in theoretical analysis is shown in Table 3. The semi-cone angle is provided in a range as oppose to a specific value for the sake of confidentiality. Material properties of AS4/PEEK used in the theoretical analysis are listed in Table 4. Regarding the boundary condition, it was assumed that both ends of the thermoplastic composite cone were simply supported with axial degree of freedom allowed (S3-type).
Table 3: Dimensionless parameters and layup sequence of the specimen used in theoretical analysis*

<table>
<thead>
<tr>
<th>Layup sequence</th>
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<tr>
<td>Large radius/Total thickness</td>
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<td>Semi-cone angle range (α)</td>
<td>1° - 3°</td>
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*Real dimensions and the specific cone angle are not provided for the sake of confidentiality.

Table 4: Material properties of AS4/PEEK used in buckling under bending analysis

<table>
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<th>Property</th>
<th>Value</th>
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<td>$E_{11}$, psi (MPa)</td>
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<tr>
<td>$E_{22}$, psi (MPa)</td>
<td>1.31×10^6</td>
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<tr>
<td>$G_{12} = G_{13}$, psi (MPa)</td>
<td>0.44×10^6</td>
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<td>$G_{23}$, psi (MPa)</td>
<td>0.32×10^6</td>
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<tr>
<td>$v_{12} = v_{13}$</td>
<td>0.248</td>
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<tr>
<td>$\rho$, lb/in^3 (kg/m^3)</td>
<td>0.0596</td>
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</table>

The result of theoretical analysis and experimental approach in term of dimensionless critical buckling moment are tabulated in Table 5 for comparison purposes. The dimensionless critical buckling moment is defined as

$$\bar{M}_{cr} = \frac{M_{cr}L^2}{H^3E_{22}\pi R_p^5\cos(\alpha)}$$

(2)

where $M_{cr}$ is the critical buckling moment, $E_{22}$ is elastic modulus perpendicular to fiber direction, $H$ is the total thickness of the laminate, $\alpha$ is semi-cone angle, $R_p$ is the large radius and $L$ is the length of the conical shell.

The theoretical dimensionless buckling moment is provided for a range of semi-cone angle varying from 1° to 3°. Comparing the experimental dimensionless buckling moment with the theoretical one for the specific semi-cone angle of the thermoplastic composite cone, the difference less than 1% is achieved.

Table 5: Theoretical and experimental dimensionless buckling moment of the thermoplastic composite (AS4/PEEK) cone

<table>
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<tr>
<th>Experiment</th>
<th>Theory (for $\alpha = 1° - 3°$)</th>
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<tr>
<td>$\bar{M}_{cr}$</td>
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<tr>
<td>$\bar{M}_{cr}$</td>
<td>3380.1 - 2985.2</td>
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7 Conclusions

The thermoplastic composite cone made using AFP was tested on the unique pure bending test setup (which was designed and developed at Concordia Centre for Composites (CONCOM) laboratory) and critical buckling moments was obtained experimentally. This experimental critical buckling moment was then compared with the theoretical result obtained from theory developed in [5] and a very good agreement was observed.

Acknowledgements

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References


