THE ROYAL INSTITUTION OF NAVAL ARCHITECTS

Design, Verification, and Forensic Correlation of Composite Yacht Structures

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Figure 1: “Stars and Stripes” IACC USA-77

SUMMARY

High performance marine composite structures are common in many competitive arenas. This paper highlights the lessons learned through analysis, testing and post-failure review of some of the composite structures used by Team Dennis Conner during the 2003 America’s Cup. Materials were almost exclusively carbon fibre/epoxy prepreg laminates cured at elevated temperature and pressure. Specific research topics included resin/fibre content, full-scale testing of portions of the deck and rig and forensic analysis of the rig and hull. A side note includes a discussion of another post-accident structural analysis. The primary structural analysis tool was finite element analysis, which was seen to be reliable. Computational fluid dynamics combined with historical on-board data were used to generate many structural loads.

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Stringent weight criteria driven by the need to maximize righting moment required low safety margins and the elimination of uncertainties in the reliability analysis. This led to the decision to implement a limited testing and analysis program. This paper discusses aspects of that program including a deck panel test, an evaluation of compressive strength versus resin content, and mast tube tests. The last two included full-scale prototype testing on a 2.2 MN compression tester to calibrate the finite element analysis (FEA) tools. Post-failure analysis of the first mast and the second hull also validated the FEA tools.

1.1 FEA TOOL

All finite element analysis was conducted using the COSMOS/M package donated by Structural Research and Analysis Corporation of Los Angeles, California. The PC-based code was run on laptops so that it was easily transportable to meetings, manufacturing facilities and even on-board the vessels. Typical run times of less than five minutes for the linear models meant quick turn around of results. All models were tested for mesh density effects. The shell elements had additional checks made by switching from four-node to eight-node elements until acceptable convergence levels of 1% variation were achieved. For the composite materials analysis all laminates were detailed ply-by-ply using laminated shell elements. The built-in Tsai-Wu failure criterion [2] was supplemented by a user-developed, post-processed Hashin criterion [3].

2. DECK PANEL ANALYSIS AND TEST

IACC yachts are in many ways like a longbow that is being pulled back for firing. The arrow is the mast, the fore and back stays the bowstring, and the hull the longbow. Due to the large tension in the stays the mast experiences large compressive forces and the deck is in compression as the bow and stern bend upwards. The near loss of the IACC yacht "Young America" identified the sidedeck (Figure 2) as one of the critical components.

No published report identified the failure mode, however due to the compressive forces the failure was likely either compressive material yield or buckling, with delamination a possible contributing factor. In this area the partial side decks transition to a full-width foredeck near the area of maximum global bending moment. The IACC rules require the minimum thicknesses as: upper deck skin - 1.2 mm, lower deck skin - 0.9 mm, core - 14 mm. Additional uni plies are often added longitudinally to stiffen the hull. These can be added on either skin with the trade-off that adding them to the upper skin beneficially places them farther from the vessel's neutral axis while negatively unbalancing the laminate.

Figure 2: "Young America" suffering deck failure during the 2000 America's Cup

The TDC test program consisted of a global finite element model of the yacht combined with a local model of the deck. Global boundary conditions were transferred to the local model via force mapping [4]. To achieve the global stiffness goal while maximizing deck strength, various combinations of six additional 300 gram unidirectional plies were split between the upper and lower surfaces. Compressive yield and critical buckling loads were calculated using both linear and nonlinear material and geometric analysis. With the fine mesh density (90 x 25 on the local model) the results were similar for the methods and linear buckling was used due to the significantly shorter run times.

In addition to a full suite of coupon tests to determine the primary material properties, a full-scale test deck panel was built by the boatbuilder and tested at the U.S. Naval Academy's Ship Structures Lab. Figure 3 shows the panel in the test jig, just after failure. As the test rig's boundary conditions were different from the vessel's due to the absence of the topsides, the local model was adapted to duplicate the test. Figure 4 shows the results. The squares show the FEA predictions and the diamond shows the test results. "0 Add'l Plies" means that all six plies were added to the lower skin. The best result was achieved with two of the six plies added to the upper skin, bringing the laminate closer to full balance.

Figure 3: Deck panel test jig showing buckling failure

The actual value observed in the test was 12% below that predicted by the FEA. Two likely reasons caused the discrepancy. First, the failure initiated about 45 mm from the predicted failure location. This was at the edge of a 3 mm indention, 155 mm square caused by the vacuum bag breather pick up. Secondly, the end rotation boundary conditions were modelled as rigid. In reality the ends were potted in epoxy resin filled with 10% short glass fiber. COSMOS/M does not at present allow for elastic foundations in buckling analysis (although it does in other analyses). The next step would be to construct in the model artificially elastic foundations. Additional studies in this program included the effects of different close-out geometry with a cored closeout showing significantly higher buckling loads.

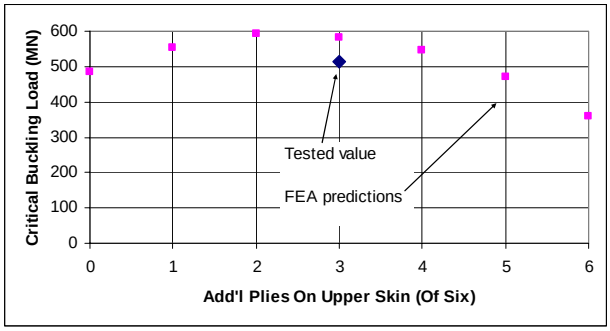

Figure 4: Ply distribution on buckling load

3. MAST TUBE PROGRAM

The mast on an IACC yacht is roughly 35 m tall and the primary load is compression with superimposed fore and aft and transverse bending. The maximum compressive load is on the order of 0.6 MN and the shroud base (distance from mast to shroud) is on the order of 1.5 m. In the IACC Rule the fore and aft and transverse mast dimensions as well as the materials are limited, but the skin thickness is not limited and the mast walls may be cored. The overall rig weight must be over 820 kg, including all the shrouds and stays. The minimum vertical centre of gravity is also defined. Performance criteria drive toward a mast tube that is minimum weight, low centre of gravity, maximum stiffness, and high reliability. Typical failure modes of the mast tube include panel buckling between the spreader and shroud attachment points, wall buckling and localized crushing.

A modification of the IACC Protocol after 2000 forced each syndicate to specify their mast designs rather than rely on the dedicated designers of the mast manufacturers. TDC first approached the new requirement by reverse-engineering an existing successful mast to determine baseline operating limits. Additional detailed loads were provided by North Sails using their proprietary FLOW and MemBrain codes. Based on the goal to maximize fore and aft stiffness two projects were developed. The first was to determine the minimum possible resin content in the prepreg. This would allow additional fibers to increase stiffness at the expense of damage toughness. The second was to minimize the sidewall thickness, allowing for more material on the fore and aft walls. The danger was decreased critical wall buckling loads and reduced damage tolerance.

3.1 RESIN CONTENT TESTS

Standard resin contents (by weight) for ambient cure marine composites are as high as 65% but are more commonly in the 40-50% range. Common values for unidirectional carbon/epoxy marine prepregs are in the 34-36% range. Due to the bleed off and other manufacturing issues, a reduction in the resin content by 2% in the rig could mean a weight savings of 10-20 kgs. If the minimum weight was already achieved, this could be added as additional fore and aft plies, giving an increase in stiffness of 0.5-4% depending on the initial laminate.

TDC and Southern Spars worked closely with the prepreg supplier, Newport Composites of Irvine, California to develop a product with the minimum resin content for mast construction while retaining toughness. Initial consideration looked at three resins, but preliminary tests showed one resin, while exhibiting slightly lower modulus, had higher compressive strength and toughness values. Figure 5 shows the resulting compressive strength versus resin content. Newport was comfortable with a 4% manufacturing variation, and the drop off near 28% led to a resin content specification of 30+/-2%. As the outer plies were more susceptible to resin bleed and abrasion, on later masts those plies were specified with 33% resin content.

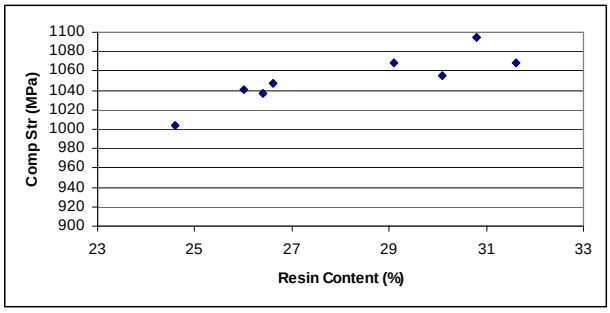

Figure 5: Compressive strength versus resin content

3.2 GENERAL RIG ANALYSIS APPROACH

Traditional FEA of IACC masts used nonlinear beam elements to size rigging, determine mast tube capabilities and improve deformation characteristics. Two problems exist with this approach. First is the uncertain loads imparted by the sails along the span, including the significant stabilizing effects of the mainsail. Second is the absence of detailed stress output for the tube design.

TDC adopted a different approach for 2003 to address these issues. Load determination and initial sizing (rigging, spreader locations and panel moment of inertias) were developed by JB Braun of North Sails using MemBrain and FLOW. FLOW is a panel-based CFD code that determines the sails' loads, which are fed to MemBrain for rig analysis [5]. MemBrain takes the loads and using linear beam elements analyzes rig deformations, with an additional step determining whether rigging goes slack. An iterative loop between FLOW and MemBrain converges the sail shape and rig deformations. Run times on a laptop were typically less than an hour, giving the sailmaker a rapid method of improving sail/rig combinations. Limit load cases and geometry from MemBrain were then loaded into a full geometric and material nonlinear COSMOS/M model constructed of laminated shell, truss, and beam elements. This model was used to check for crushing, attachment design, panel and wall buckling. Initial verifications between the two FEA codes showed displacements within 8%. The final COSMOS/M global rig models included elastic or forced boundary condition displacements determined through mapping the displacement and stiffness of the global hull model. As with the hull program, the rig program also featured global and local models.

3.3 BUCKLING TUBE TESTS

The large compressive loads in IACC masts can lead to global or wall buckling failure modes, therefore early on the TDC team used these and a torsion limit as design criteria. The final 2000 TDC rig provided a known lower limit for acceptable panel EI and wall buckling resistance. Initial TDC research led to the selection of a three-spreader "X-rig" as the baseline, with significantly higher fore and aft dimensions. The shorter panel lengths in the X-rig and the higher fore and aft EI meant that panel buckling fore and aft was no longer a limiting case, but the desire to move material from the sidewall to the front and back meant that transverse panel and sidewall buckling were possible.

A parallel research program looking at low drag mast section shapes was undertaken by Joe Laiosa of South Bay Simulations using 2-D and 3-D CFD codes. Candidate shapes were developed by various team members in consultation with the sparmaker to ensure manufacturability. Based on the results of previous research, roughly a dozen new shapes were evaluated by the two groups and luckily the same shape was at the top of each list! As this shape was significantly different from the 2000 section, and as a goal was to minimize the side-wall thickness, two test programs were implemented. The first looked at verifying the FEA tools for buckling and the second looked at the resulting damage tolerance.

With the section shape determined, various studies looked at sidewall thickness variations from 3-6 mm, ply weights from 125-300 gram, stacking sequence variations, coring and ply orientation percentages. With up to 300 plies in a laminate a large number of choices were possible. These were initially screened using an Excel spreadsheet and solver programmed with micromechanics, classical lamination theory and laminated buckling theories. Two final structural concepts representing the most probable and the most risky tube designs were built and tested. Test sections 2.5 m long that were heavily reinforced at the ends were constructed by the mast manufacturer using their proposed fabrication methods for the full mast.

Figure 6 shows the global and a section of the local FEA mast models. The local model has two noticeable asymmetries in its results. These reflect the final calibration of the model to the test pieces and jig and the nature of the laminate. In addition to gravity, the boundary conditions were not exactly square, and the travel of the piston was not perfectly axial. The laminate was not perfectly symmetric and balanced due to an odd number of off-axis ply pairs.

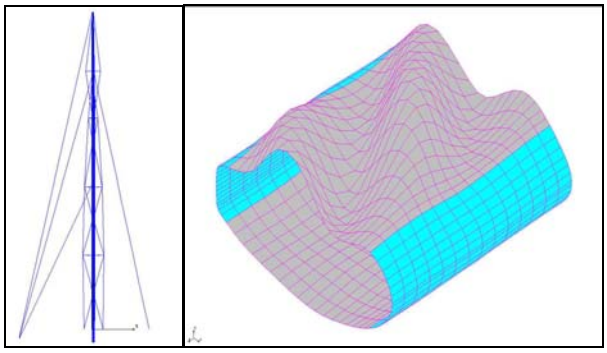
Figure 6: Global rig and local mast models

The two tubes failed at 1.63 and 1.57 MN. Both failed in buckling in the same mode predicted by the FEA. Initial correlation between the model and tests had the tubes failing at 71% and 72% of the predicted values. Matching the actual tests' boundary conditions (loading varied as much as 7% from uniform) increased the correlation to 85%, and matching the tube as-builts brought the correlation to 89%. Figure 7 shows the failure of one tube. Failure initiated at the seam running longitudinally up the tube. The scarfed seam was not explicitly modelled however, but was included as a laminate thickness variation.

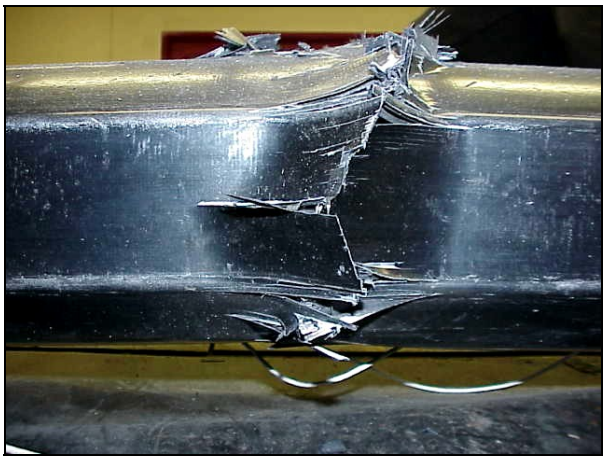

Figure 7: Failure of mast test section

3.4 IMPACT TUBE TESTS

The increase in wall buckling resistance from the 2000 to the final 2003 tube was mostly accomplished through wall curvature variation and careful laminate stacking. This led to a dramatic decrease in wall thickness and the concern that other operational conditions could precipitate mast failure. In particular, crew members are frequently hoisted aloft to adjust rigging, free tangled gear, look for wind shifts and facilitate sail handling. While aloft the vessel's rolling can cause large impact loads between the crew member, their equipment and the mast.

TDC's rig team discussed the potential consequences with crew members, who enthusiastically supported the proposed tests. The crew provided pictures and samples of the gear and the potential likely operating conditions which would maximize the impact loads. These were translated into energy values and an impactor was designed to simulate the crewmember and their gear. Two 1.2 m tubes were built and tested. The tubes were loaded to 120% of the maximum design load and the impactor was dropped onto the thinnest portion of the laminate, adjacent to the longitudinal seam. The "most probable" design showed minor damage, while the "risky" design was punctured but did not otherwise fail. Figure 8 shows the damaged section. The longitudinal seam is clearly seen. Production models had wet laminated carbon cloth covering the fasteners and seam.

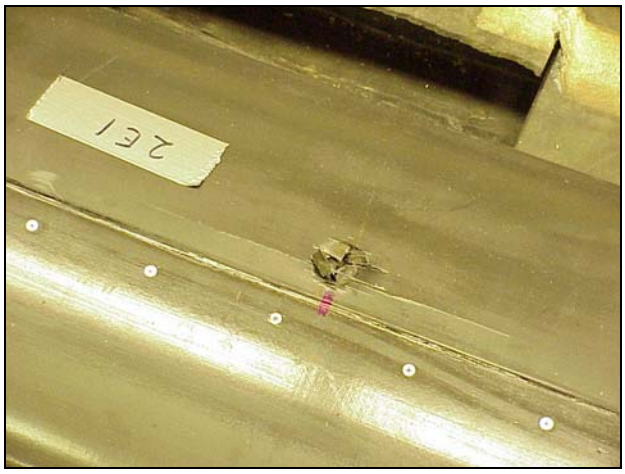

Figure 8: Puncture due to impact

With confidence in the FEA tool and the resulting sidewall to post-impact strength, the final masts were designed. With a narrower shroud base the masts were subject to higher compressive loads, yet the final mast tubes were approximately 2.5 times as stiff fore and aft, 1.25 times stiffer athwartships, 1.2 times stiffer in torsion and 5% lighter than the 2000 tube.

4. FORENSIC ANALYSIS

In any leading edge design project the risk of failure is high and in the America's Cup it is not uncommon. The evaluation of failed structures usually provides insight into the engineering uncertainties. During the 2003 campaign TDC suffered two significant structural failures; the first mast came down and the second boat sank. The mast was repaired but not used again, and the second boat was repaired and raced.

4.1 MAST 1 FAILURE

In spite of all the research and analysis the first mast failed during its third outing, breaking just above the deck. Weather conditions at the time were winds of 14-17 knots and smooth seas; well within the design envelope. On board sensors recorded rig loads just prior to failure. The damage around the failed region was extensive, preventing an absolute determination of the failure. A team put together by TDC and the mast manufacturer developed a number of possible scenarios, including insufficient reinforcement at the deck, missing adhesive in the seam, too low a resin content and a stress concentration caused by a hydraulic fitting.

Each scenario was carefully analyzed using the global rig model and with the loads provided by the on-board sensors and crew records. Only one case of the eight possibilities showed a significant loss in capacity. By modelling the seam as free of adhesive over a 100 mm length by using gap elements and overlapping shells of reduced thickness, the predicted factor of safety reduced to 1.03. The immediate consequence was to heavily reinforce this area for the masts in production and take a

weight increase to ensure reliability. Increased quality assurance and greater faith in the latter masts allowed for the removal of the extra reinforcement with no further in-service problems.

4.2 USA-77 SINKING DAMAGE

Just prior to shipping the boats to New Zealand from Long Beach, California, USA 77 sank during practice (see Figure 1). Luckily it was in relatively shallow water and she was recovered in remarkably short time. While the cause was quickly determined, the bigger question was the extent of damage and the required scope of repairs.

To estimate the damage the global hull FEA model was used. Witnesses and pictures provided estimates of the contact angle, locations, accelerations and complicating factors. In particular, an air bag was inflated in the bow, causing the deck to carry hydrostatic pressures when submerged. By the time the boat was hauled and blocked, a FEA run using the probable grounding load conditions was accomplished. Within a day of the sinking the FEA model showed probable damaged areas.

The laptop accompanied the engineer and shipwright on the damage inspection tour. Of the more than three dozen damaged areas the FEA model predicted every one! Only one discrepancy between the model and damage was noted. The model predicted light damage in the keel box area, but none was seen. Later however it was found that the model had not been updated with the as-builts, which included more reinforcement than initially modelled. In spite of the high bending moment when the bow hit the bottom, the deck portion in the area of the earlier design study did not suffer any damage.

The FEA model was then updated to reflect the damaged areas and was used to design temporary repairs so the vessel could be floated over to the ship for transport to New Zealand. Permanent repairs were performed in New Zealand and the FEA model was used to help determine the cut lines and the forces for the lap joint designs. Lightweight repairs were performed and the vessel was returned to a competitive condition.

4.3 S/V CASCADIA

Proprietary agreements limited the amount of detail available to publish in the forensic analysis of the TDC structures. As another data point however, FEA was also used in the design and forensic analysis of the S/V Cascadia, a 24 m vessel designed by the late Carl Schumacher. Launched in April 2003, she ran aground at high speed on a rock ledge in Alaska in early July. Hitting at an estimated 10 knots, she saw severe damage to the bulb and cracking of the hull shell. Nonetheless, only minor weeping was experienced.

Her structural design included cold-moulded cedar veneers, balsa core and carbon fabrics in a latent cure wet layup epoxy resin. Figure 9 is a picture of the damaged area and Figure 10 shows the corresponding FEA prediction. Again the correlation between the observed and predicted damage was excellent. In this case however the model did not predict damage in one area that did show damage. During excavation of the area it was found that the local reinforcement did not extend to the dimensions in the model. When the two were calibrated the model predicted damage.

Figure 9: Damaged areas on “Cascadia”

The model also predicted slight damage in the off-axis cedar plies in the topsides adjacent to the keel. This was not seen in the vessel however. Two possibilities exist for the discrepancy. First is the uncertainty in material properties. Shear tests for the laminated cedars were not performed, so conservative material properties based on short beam shear tests of free lumber were used. As wood often fails by fibre breakout, and the cold-moulding process restricts this somewhat, it may be that the actual material strengths were significantly higher than estimated. The second issue is with the aft boundary condition. It was modelled as a compliant foundation in tension, but how far the stern rises and the bow sinks during a grounding at the tip of a 3 m keel is difficult to model, yet can significantly effect the results.

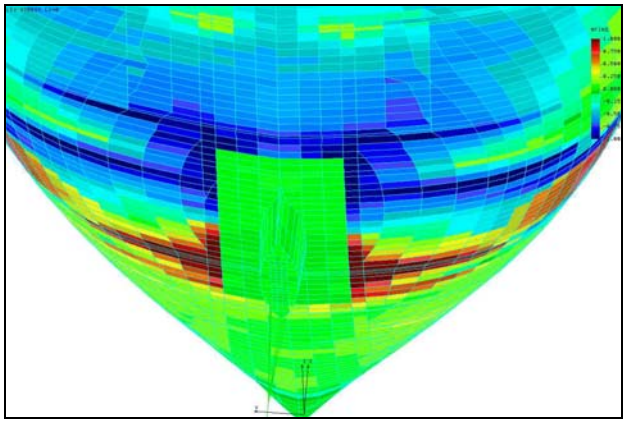
Figure 10: FEA predicted damaged areas on “Cascadia”

5. CONCLUSIONS

With composites use in the marine industry growing, the engineering challenge of predicting their performance increases. Few areas push the limits of marine composites more than the America's Cup competition. Research, design and forensic analysis of test coupons and in-service components for the 2003 Team Dennis Conner program indicate that carefully applied finite element analysis can predict within manufacturing tolerances the performance and strength of advanced composite structures. Although unfortunate, the in-service failures of the TDC mast and hull and the S/V Cascadia grounding provided extremely valuable verification of the FEA tools. On the competitive side, the failures forced the engineering team to focus on cause and solution rather than performance improvements. This was a lost opportunity that clearly detracted from the team's potential for success.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. America's Cup Class Rule, Version 4.0, Challenger of Record and Defender, October 19, 2000

2. TSAI, S., and HAHN, H., *Introduction to Composite Materials*, Technomic Publishing, Lancaster, 1980, p. 280

3. HASHIN, Z., 'Failure Criteria for Unidirectional Fiber Composites', *ASME Journal of Applied Mechanics*, Vol. 47, 1980, p. 329-334

4. RANSOM, J and KNIGHT, J., 'Global/Local Stress Analysis of Composite Panels', *NASA technical report*, 1989.

5. RICHTER, H. and BRAUN, J., 'Computational Fluid Dynamics for Downwind Sails', *Proceedings of the 16th Chesapeake Sailing Yacht Symposium*, 2003

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