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COMPOSITE MATERIALS APPLIED ON GAS TURBINE'S INLET SYSTEM

Bartłomiej Armański[1], Pierenzo Morriello[2], Pierluigi Tozzi[3]

Baker Hughes contractor: Łukasiewicz Research Network – Institute of Aviation, Aleja Krakowska 110/114, Warsaw, Poland, +48 221253956, bartlomiej.armanski@bakerhughes.com[1]
Baker Hughes, Via F. Matteucci 2, Firenze, Italy, +39 3468430459, pierenzo.morriello@bakerhughes.com[2]
Baker Hughes, Via F. Matteucci 2, Firenze, Italy, +39 0554233883, pierluigi.tozzi@bakerhughes.com[3]

ABSTRACT

A new inlet plenum made of composite material – glass fiber reinforced plastic (GFRP) was designed and manufactured for a Baker Hughes gas turbine. The invention described in this paper is patent pending. Flow optimization, new technology introduction, material tests, and structural analysis were performed in order to execute this project. Composite material description and its advantages are described, followed by the project stages details and manufacturing process description. Moreover, the material tests and benefits of this new technology introduction are presented.

INTRODUCTION

Gas turbine inlet system (Figure 1) is used to guide the air towards the compressor of a gas turbine. It consists of inlet duct, filters, silencers, inlet plenum, and FOD screen.

The shape and size of those components determine the quality of the intake flow, and contribute to the performance and stability of the whole engine. Inlet plenum, being the closest part to the compressor, has a big impact on the air flow entering the compressor. In most cases, inlet plenum changes the direction of the flow 90°, which is a source of distortions, and degrades the quality of the flow. To optimize the air flow, it is necessary to change the shape of the inlet plenum from simple box to more smooth and complex shape with better aerodynamics.

Inlet plenum made of steel is heavy. In order to reduce mass, it is necessary to change the material to a lower density one.

Cost reduction is another important goal when designing new parts, and the cost can be reduced by changing the mass, material and manufacturing process.

Although the materials used are known in other industries, the application in oil & gas is a novelty. Composites were not used as a material for gas turbine flowpath components before. The shape and aero design is also a novelty for an inlet plenum.

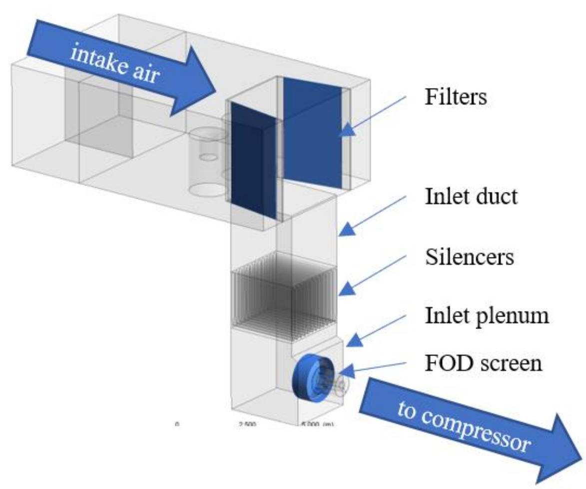

Figure 1. Inlet system of a gas turbine

NOMENCLATURE

Inlet system – a group of components guiding the intake air towards gas turbine compressor, consisting of inlet duct, plenum, spacers, silencers, FOD screen, etc.
Inlet plenum – a box used to collect the air from inlet duct, and guide it towards gas turbine compressor
FOD screen – foreign object damage protection screen
GT – gas turbine
IGV – inlet guide vane at the compressor entrance
Composite material – a material composed of two different materials (e.g. polymer resin and fiberglass)
Tsai-Wu criterion – composite material failure criterion
GFRC – glass fiber reinforced composite
GFRP – glass fiber reinforced plastic
FVF – fiber volume fraction – volumetric percentage of fiber content in composite material

Zone 2 ATEX – a place in which an explosive atmosphere consisting of a mixture with air of dangerous substances in the form of gas, vapour or mist is not likely to occur in normal operation but, if it does occur, will persist for a short period only
BH – Baker Hughes (formerly known as: Baker Hughes, a GE company; GE Oil&Gas)
NTI – new technology introduction process
CFD – computational fluid dynamics – analysis of air flow
HDT – heat deflection temperature
MMC – metal matrix composite
CMC – ceramic matrix composite
PMC – polymer matric composite

STATE OF THE ART

In the last 30 years, the number and importance of the applications of composite materials have grown exponentially. Those innovative and unconventional materials has been used in many mechanical constructions.

The success of composite materials is essentially due to their exceptional physical and mechanical properties.

The use of composites has led to a reduction of the overall weight of the structures by offering higher specific stiffness. It has also offered better corrosion resistance properties, and reduced the operational costs.

Nowadays, the applications of composite materials concern innumerable fields, and passing through the automotive industry and aerospace applications, has also arrived in oil & gas industry where composites are mainly used to manufacture pipes and tubing, pressure vessels (Figure 2), tanks, and in secondary applications such as in the grids and gratings, handrails, cable trays, ladders, decking, and flooring of offshore platforms.

Figure 2. Typical oil & gas composite applications (Duoline piping, Brine King Tanks vessel)

Despite all the benefits that composites offer, the oil and gas industry has not been using composite solutions extensively.

The development of materials that combine two or more homogeneous ones and that allow the best properties of each constituent to be used synergistically, has given the opportunity to think about more complex solutions never used in the past.

For above reasons, an enormous opportunity for the adoption of composites in inlet systems design was observed. It could allow to realize very complex shapes, not so easy to produce with steel metal sheets as done in the last 50 years, and reach good results in optimizing cost and performance of gas turbines of different sizes.

Composites would also be quite useful in all offshore applications where they could be a helpful alternative to traditional materials, and change maintenance practices reducing impact on offshore fields operations.

Considering the delay in introducing composite materials in oil & gas industry with respect to other sectors such as aerospace, automotive, and construction, where composites have been widely used for decades, the main challenge was to reduce the lack of relevant performance information to compete with standard steel parts.

COMPOSITE MATERIAL

Composite materials are made by combining two or more dissimilar materials such as resins (matrix) and fibers (reinforcement) to create a product with exceptional structural properties not present in the original materials.

Matrix, which could be metal (MMC), ceramic (CMC) or polymer (PMC), is the continuous phase of composite and has the purpose to transfer stress to reinforcement phases and to protect them from the environment.

Reinforcement (typically fibers of various materials) is the structural phase of composite, and has the purpose to provide strength to the laminate. Glass and carbon fibers are the most commonly used for PMC like GFRP, in the form of fabric woven roving, unidirectional continuous or chopped strand mat (Campbell, 2010).

When designing composite, it must be considered that they are usually anisotropic (properties are not the same in all directions) and heterogeneous materials. Mechanical properties of reinforcement (Figure 3) and matrix need to be evaluated individually, considering their relative concentration and interaction.

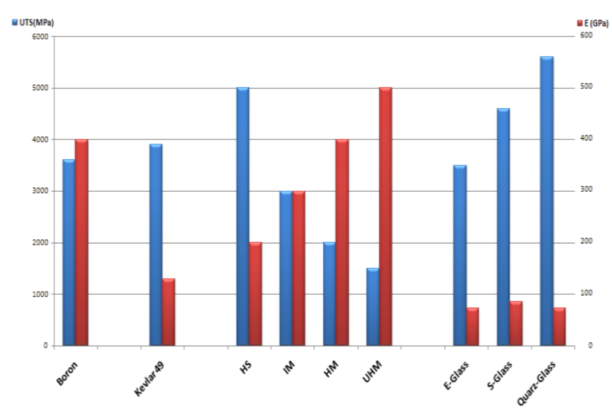

Figure 3. Comparison of fiber strength

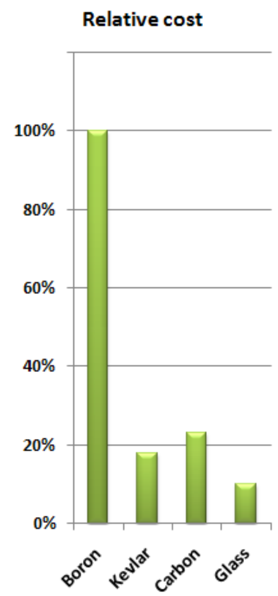

Figure 4. Relative cost of different fibers

For a gas turbine inlet systems, E-Glass fiber reinforcements have been chosen together with vinyl epoxy resin system as the best compromise between cost (Figure 4) and required performance, ensuring good mechanical properties and resistance to a wide range of medium aggressive chemicals. Moreover, when Zone 2 ATEX certification is required, design is performed considering laminate auto-ignition, assuring low electric charge accumulation and controlling self-burning behaviours due to environmental conditions mainly by selecting adequate fire-retardant solution (i.e. with specific gelcoat to be applied on component surface).

In GFRP, the resin can be added to the reinforcement using several manufacturing processes. Some of them are hand layup and resin infusion, which do not require much tooling investment.

Hand layup is the most basic method, in which the wetted fiberglass is applied by the operators manually on the mold.

Resin infusion has been preferred for example for Inlet plenum of PGT25+. In this process, resin is infused into the fiber material once the vacuum has been applied. The positioning and number of the resin infusion points depend on the size and shape of the part. For a given lamina, different values of FVF can be obtained depending on resin infusion parameters. If compared with other processes, resin infusion is able to guarantee higher and more uniformly distributed FVF values inside the material thanks to vacuum pressure consolidation of layers, allowing the resulting composite material to have higher mechanical properties.

INTRODUCTION INTO GAS TURBINE INLET SYSTEM

Fiberglass inlet plenum introduction was a complex enterprise which required a lot of effort and tests in order to develop a robust product and reliable manufacturing process.

At the time of starting the project all existing plenums in the BH fleet were made of metal – carbon steel or stainless steel. This was limiting the optimization of the shape as manufacturing of aero shapes would be much more expensive than simple flat walled shapes.

The introduction of GFRP composite materials in oil & gas applications had the objective to reduce weight (mainly for offshore applications) and overall costs. Moreover, it allowed to realize geometries that were not easy to be obtained by classical manufacturing techniques using steel metal sheets as raw material. Also, for inlet plenum application, it is representing a good solution to operate gas turbines in corrosive environment since it is not prone to rust. Thanks to the use of resin with higher heat deflection temperature (HDT), the component can also face high operating temperature with peaks of 113°C.

With the potential introduction of composite material, which manufacturing cost is not so dependent on shape, it was possible to keep manufacturing cost low and optimize the shape in order to get better aero parameters of the inlet flow.

The first project, which introduced this material in gas turbine, was to replace the existing PGT25+ steel inlet plenum (Figure 5) with the composite version (Figure 6), changing the shape of the flow, while keeping the interfaces with other components unchanged.

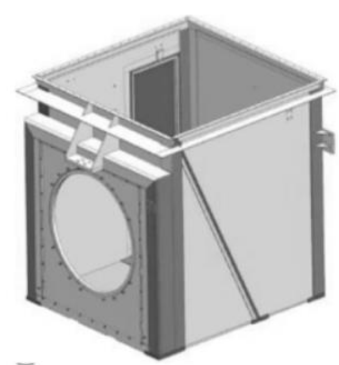

Figure 5. PGT25+ steel inlet plenum

Figure 6. Composite inlet plenum

Patent

The design described in this paper is protected by United States Patent US 2016/0076447 A1 and International Patent WO 2014/177658 A1. Figure 7 shows the state of the art plenum in box shape made of steel, which was a starting point for the invention. Figure 8 shows the invented new fiberglass inlet plenum assembled with gas turbine.

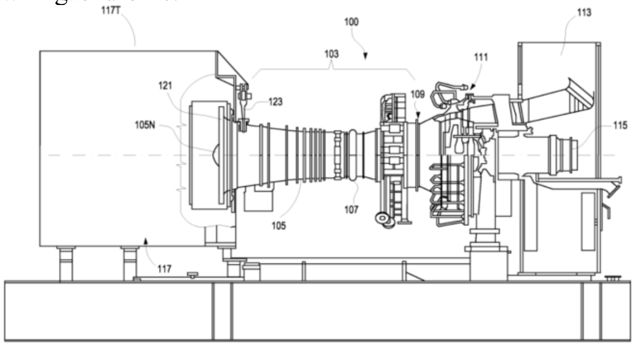

Figure 7. Steel inlet plenum with gas turbine (Merlo et al., 2016)

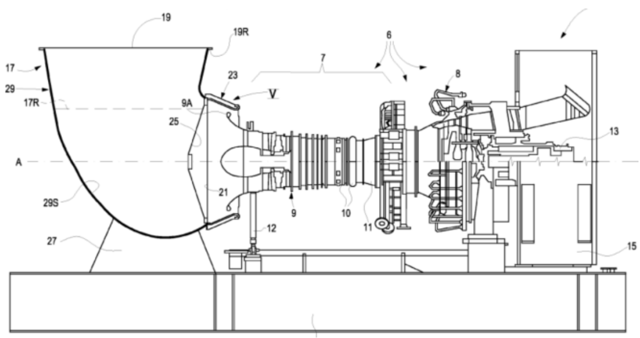

Figure 8. Fiberglass inlet plenum with gas turbine (Merlo et al., 2016)

Special requirements

Inlet plenum is a part of an internal combustion engine, therefore its design needs to meet some special requirements.

<u>Electric conductivity</u>

In accordance with ZONE2 area classification of gas turbine enclosure and ISO 14692-2 requirements, composite inlet plenum shall not be an ignition or spark source as consequence of electrostatic charge accumulation. Both constituents of GFRP are dielectric, so to fulfil that requirement, the component is coated with a conductive gelcoat and equipped with earth connections.

<u>Fire resistance</u>

In order to check fire resistance, a test was conducted based on ISO 5660-1. This cone calorimeter test was performed using composite panels with and without gelcoat. The samples were subjected to 60 seconds of heat flux to simulate fire conditions. The test allowed to determine the key fire parameters as ignition time and heat release rate. The test results are presented in Figure 9.

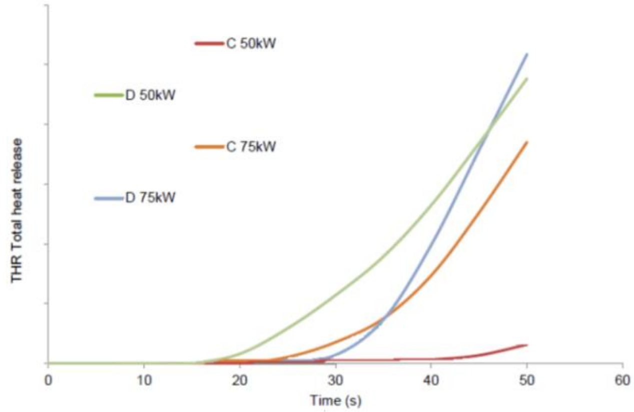

Figure 9. Total heat release at various heat impact (C – with gelcoat, D – without gelcoat)

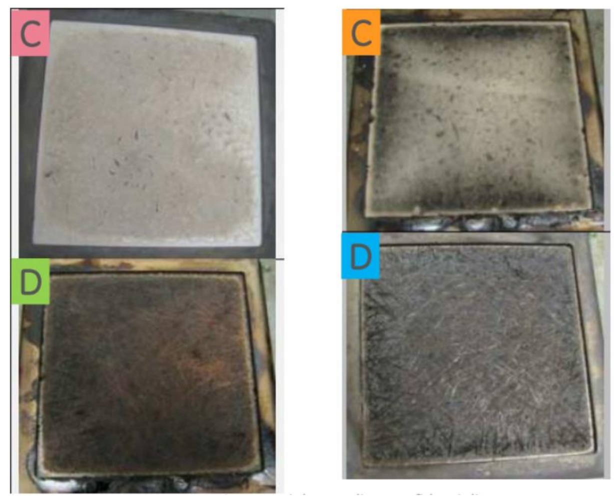

Figure 10. Composite samples after heat impact test. (C – with gelcoat, D – without gelcoat)

The result of this test has shown that the sample with the gelcoat applied performs better during fire scenario than the one without gelcoat (Figure 10), so the gelcoated composite configuration was chosen as the final one.

Special requirements described above has led to special solutions that would be suitable for the use inside gas turbine enclosure.

New technology introduction process

At the end of 2012, it was decided to introduce composite material and fiberglass composites on inlet system of one of the gas turbine PGT25+. Main goal, at that time, was to reduce weight of entire package, and also revise maintenance and full train cost structure. For this purpose, a dedicated NTI program was started.

The goal of the NTI project was to select and validate a commercially available glass fibers (fabric, uni/bi directional, random) and suitable resins.

The validation program covered all mechanical aspects, variability and manufacturing processes, and resulted in a design practice that was used as guideline for next designs of composite inlet plenums.

The selection criteria of materials (glass fiber + resin) were based on:

- rapid prototyping for wrapping simulations and ply definitions,
- risk scorecards,
- manufacturing and laboratory tests,
- environmental impact.

All special tooling used for production was validated by specific qualification programs that involved several tests for molding resistance and life estimation.

The selected materials had to satisfy also the following specific requirements, in particular:

- corrosion resistance not worse than stainless steel,
- operating temperature range with attention to arctic environment,
- life of components above 20 years,
- internal erosion and corrosion resistance,
- aggressive environment resistance.

Apart of inlet plenum, other potential applications for this technology were investigated and specific programs were launched on:

- ventilation ducts,
- inlet ducts first stages,
- filter house frames,
- gas turbine baseplate.

Design of composite inlet plenum

The design process of composite parts is different than the one for stainless steel ones. The difference is the material itself, as well as the form that the composite components can take. The composite plenum can be shaped in a different way than the one made of steel, with use of more rounded corners, smooth transitions of curvature and thickness. Structure of the material is anisotropic with multiple layers having different material properties, thickness, and orientation of the fibers. This makes the design more complex, but gives the possibility to provide an aero shape, reduce the volume without increasing pressure loss, optimize the strength and stiffness by locally changing the number and directions of layers.

<u>CFD analysis</u>

In order to develop an optimized aero shape, several CFD iterations needed to be run and assessed.

Firstly, the steel box plenum standard inlet configuration (Figure 11) was checked to establish a baseline performance.

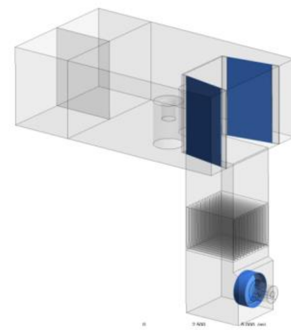

Figure 11. Standard steel box plenum inlet configuration

The results were showing non uniform total pressure distribution in IGV plane view (Figure 12) and significant swirl angle value (Table 1).

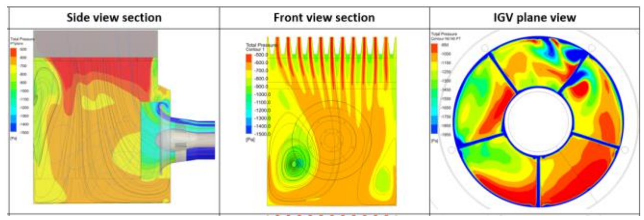

Figure 12. Original steel plenum total pressure CFD results

The next step was to prepare concepts of aero shape which, according to current experience, would provide better flow parameters. New CFD models with inlet duct and modified plenum shapes were prepared.

The final shape was developed by several iterations of optimization thanks to CFD analyses which were showing the difference in the flow parameters between each shape.

Considering the manufacturability limits, the best flow path geometry was chosen, which was then represented in the final design of the component (Figure 13).

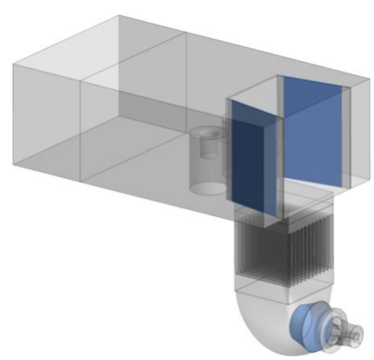

Figure 13. Final fiberglass plenum inlet configuration

More uniform total pressure distribution (Figure 14) and significantly lower swirl angle (Table 1) can be observed at IGV plane. Those parameters are important to ensure stability of the flow at different working conditions and are one of the important criteria checked during design phase for every new product.

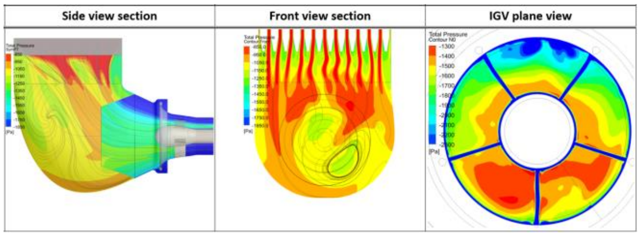

Figure 14. Final shape of plenum total pressure CFD results

Inlet configuration	Relative swirl angle
Standard steel box plenum	1
Final shape of plenum	0,33

Table 1. Swirl angle comparison

Structural analysis

In order to develop a robust component, a structural analysis was performed considering many load cases representing different working, shipping, lifting, and seismic conditions. The analysis was made using ANSYS software for composite materials. For evaluation of the results, the Tsai-Wu failure criterion was used. Each layer of fiberglass is specified in the analysis and Tsai-Wu strength index indicates whether the ply strength is below or above failure limit.

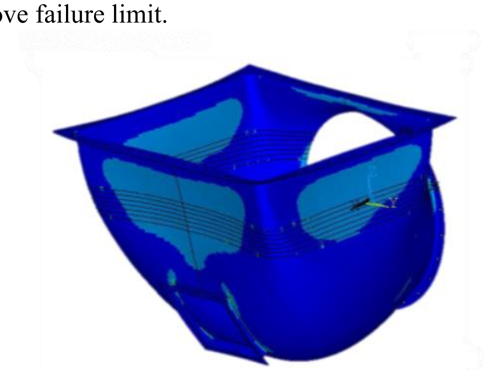

Figure 15. Structural analysis of plenum design

The analysis highlighted areas which needed to be reinforced because of the stiffness and strength criteria. Thanks to fiberglass technology advantages, only necessary regions were reinforced, so that no additional weight was added to the design.

In the design, the composite shell is equipped with stainless steel inserts, bushings etc. To fix them to the composite walls, the adhesive connection was used, which was never done before in inlet plenum design. Also composite shells of main body and supports were bonded with adhesive. Those connections needed to be verified in the structural analysis as well.

With the final design of the part (Figure 16) a mass saving of 83% was achieved. The manufacturing cost of the component was reduced by 30% with respect to the original steel version.

Figure 16. Final design of composite inlet plenum

Manufacturing

After finishing the design, the manufacturing phase has started. First piece production was a very important moment for the technology introduction, as it allowed to validate the manufacturability of the design and technology restrains.

Mold

The mold for the plenum was made using roughly shaped styrofoam blocks. After coating with a tooling paste, the mold was precisely machined to its final shape. The finished mold was coated with a release agent.

Figure 17. Mold for the composite plenum

Hand layup

For the first piece, the hand layup technique was used. Sheets of fibreglass wetted with resin were applied manually by the operators according to the lamination schedule (Figure 18). The part was post cured in high temperature in order to increase heat deflection temperature (HDT) of the material. To provide electric conductivity, surface was covered with a conductive gelcoat.

Figure 18. Hand layup of fiberglass

Resin infusion

The improved manufacturing method – resin infusion – was chosen for next products. It uses a vacuum bag to evacuate air from the fiberglass layup and resin channels to infuse dry reinforcement with resin (Figure 19). As in hand layup technique, the part was post cured and covered with conductive gelcoat. The infusion technique provided more compacted composite with better fiber volume fraction.

Figure 19. Resin infusion technology

Bonding metal to fiberglass

The metal parts were bonded to the composite shell using polyurethane adhesive, which was found to be not strong enough and was later replaced with a more robust adhesive of methyl methacrylate (MMA) type.

Figure 20. Metal insert bonded to plenum shell

Material test campaign

The data needed to perform structural analysis was acquired during material test campaign, as no specific data was available for the materials chosen. Initial test results were used for design purpose, to set up material models in Ansys. During manufacturing of the component, other samples were prepared and tested in order to check if the manufactured part was in line with the assumptions made during the design phase.

Additionally, cryogenic test campaign was conducted, to verify composites behaviour in low temperature environment (-60°C). Positive results (Figure 21) has permitted to select these materials also for arctic applications.

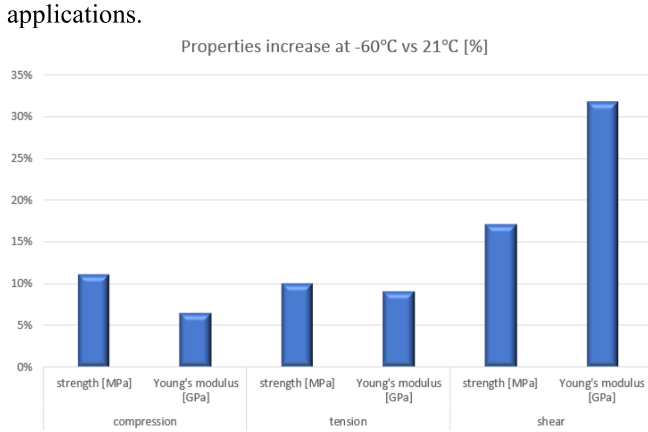

Figure 21. Mechanical properties increase at low temperature

The tests were made according to ASTM standards:

- tension – ASTM D3039/D3039M-17
- compression – ASTM D6641/D6641M-16e1
- v-notched rail shear – ASTM D7078/D7078M-12
- constituent content – ASTM D3171-15
- in-plane shear – ASTM D3518/D3518M-13

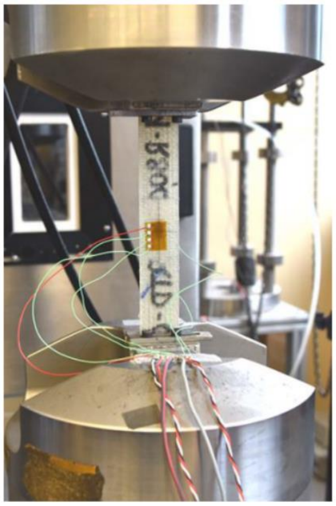

Figure 22. ASTM D3039/D3039M-17 tension test

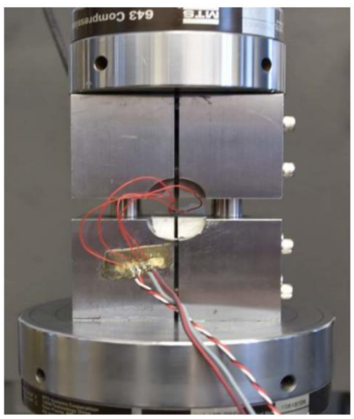

Figure 23. ASTM D6641/D6641M-16e1 compression test

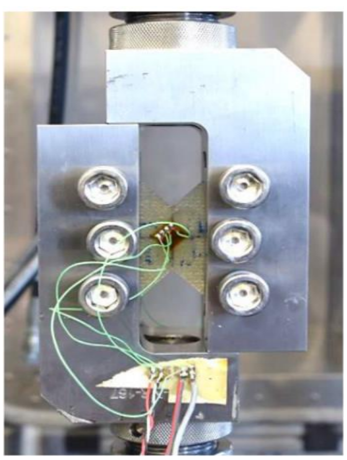

Figure 24. ASTM D7078/D7078M-12 v-notched rail shear

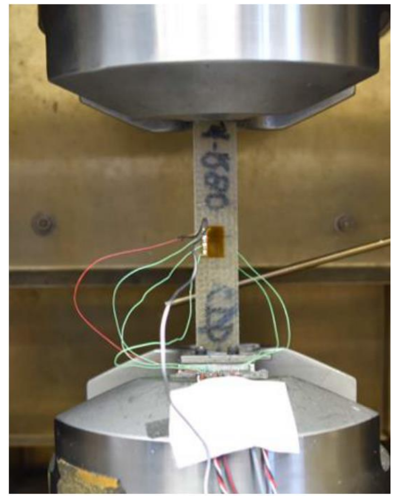

Figure 25. ASTM D3518/D3518M-13 in-plane shear

The results were showing strength and stiffness increase in resin infusion technology compared to hand layup.

CONCLUSIONS

The introduction of composite inlet plenum proved to be a profitable process. With reduced cost and mass, optimized flow parameters thanks to aero shape, reduced inlet plenum volume, a better inlet system could be designed. Lower values of swirl angle contribute to better compressor stability. The new advantages affect also other components of gas turbine, like package, auxiliaries, instrumentation, as reduced volume leaves additional space for other systems located close to inlet plenum.

With the right selection of material, special requirements of electric conductivity and fire resistance can be met. Fiberglass is an optimal material for this application, as it provides good strength and stiffness for a reasonable price. Using more advanced reinforcement, like carbon fiber or aramid fiber would offer higher strength but the resulting cost increase would be not acceptable for this type of component.

To ensure good quality product, a close cooperation with the supplier is needed to develop certain manufacturing standards and procedures suited for the part, which may be slightly different for every design depending on the shape, materials used, laminate thickness, and other design features.

Material tests are both the starting point for the design and validation step of the manufacturing, firstly to acquire the material data for the structural assessment, then to validate if the manufacturing quality is sufficient and in line with initial assumptions.

Fiberglass has reduced overall gas turbine weight, facilitated assembly and disassembly of inlet plenums, and reduced time to market. A lighter and stronger product results in lower costs for shipping and storage.

ACKNOWLEDGEMENTS

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