INTEGRATED HIGH PERFORMANCE JOINT IN COMPOSITE VESSELS

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Abstract

The paper presents an experimental and computional investigation of a high performance integrated joint (IHPJ). The first type are multi loops joints, which are used in high pressure vessel applications. The next type are adhesive joints.

Experimental and numerical stress analysis is described on specimens of a single loop of different material and geometrical parameters. Finite element method (FEM) and analytical calculation methods are in good agreement to calculate the maximal tangential stress in the loop.

A static failure criterion was then proposed for engineering design procedure. Fibre Bragg Grating (FBG) sensors and in-wound strain gages were tested through experimental investigation.

Finally, a carbon nano tube modified resin was applied to increase the strength of the joint.

1 Introduction

Composite products are being increasingly used and composites are becoming important engineering materials for a wide range of applications such as the aerospace, athletic and recreational equipment, transportation, infra-structure, military, electronic and chemical industries. The composite material of interests is the composite of long fibers and polymer matrixes. We focus on so-called high performance structures made by filament winding technology. The presented filament winding technology system including axial fibre placement and laying process was developed at the company CompoTech PLUS Ltd Sušice, Czech Republic with close collaboration from the Czech Technical University in Prague. The original feature of this technology is the possibility of axial fiber orientation (0 degree winding angle) allowing a significant increase in the stiffness and strength of tubes with different sections. The other advantage of this technology is the possibility of integration of connection elements directly in the composite part. The custom computer software for design of filament wound composite beams and some other optimization methods has been developed at CTU Prague [1], [2].

2 Composite Material Application

2.1 Pressure Vessel

The above described technology has been used for development and production of high pressure vessels with applications as linear hydraulic motors. The body of high pressure vessels is an all composite carbon fibre/epoxy construction. The vessels have multilayered structure with hoop and off-axial layers for overtaking radial pressure and axial layers for overtaking axial load, generated by pressure acting on the vessel ends areas.

2.2 Pressure Vessel Joint to Alloy End

The widely known problem of successful application of composite parts into real structures is a joint between the composite part and typically a part composed of isotropic material. Isotropic material (steel and aluminum alloys) is often used for load implementation in to composite part or structure thanks to its resistance to point load and/or wear resistance. There are generally three types of joints used in composite engineering: adhesive joint, bolted joint and so called integrated joint. Attention is focused on the third type of joints – called high performance integrated joints (IHPJ).

3 Integrated High Performance Joint

3.1 IHPJ Principles

Most common examples of applications are described in [3]. The main principle in the case of filament winding is that the fiber tow is wrapped directly around the shape of the alloy pin or tapered rod part. By this method the load is implemented directly in to the composite structure, avoiding cutting of the fiber or adhesive shear load. Multilayer loops were developed. They were composed the high modulus or high strength fibre tows to obtain optimal stress distribution.

Fig. 1. IHPJ with multi pin loops

3.2 IHPJ and Adhesive Joint Comparison

In order to evaluate the advantage of the IHPJ on the pressure vessel application, the adhesive joint (of equivalent parameters has been built and examined see Fig. 2).

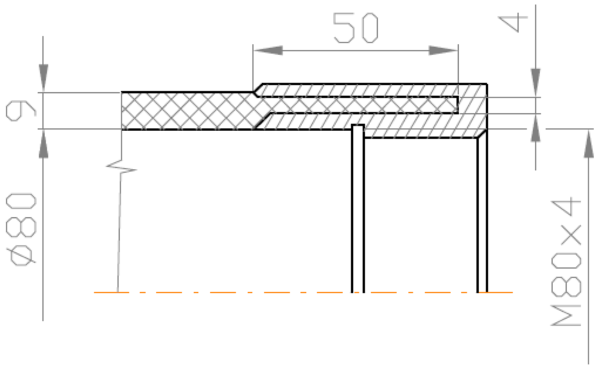

Fig. 2. Equivalent adhesive joint scheme

Analytical and FEM calcualtions of adhesive joints have been compared. Comparison of several resulting parameters provided satisfaction that IHPJs perform better than equivalent adhesive joints. This has been validated by practical testing of vessels for the marine industry. Vessels with adhesive joint achieved a burst strength of 32 MPa pressure and vessels with IHPJ achieved an 81 MPa oil pressure.

3.3 Carbon Nanotube Application at IHPJ

In order to further increase the performance of the IHPJ joint, a carbon nano tube modified resin has been applied. Such resin has been developed by Jyväskylä University Nanosience Center, [4] and it increases the strength of a carbon composite via chemical linking between the carbon nano tubes and the matrix and fibres, as shown in Fig. 3. The technology of applying such a resin was developed and results have been experimentally verified.

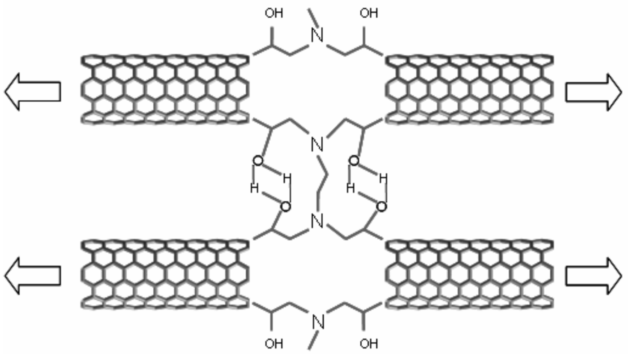

Fig. 3. Carbon nano tube adhered to resin structure, [4].

Verification tests were performed using a three point bending scheme in order to achieve maximum compression strength in the axial carbon fibre layer. Specimens were tubes made by CompoTech fibre laying technology. The laminate consisted of three layers with 90, 0 and 21 degrees with multi axial layers but with 80 % of the fibres in the axial direction. The compression strength increase over the standard epoxy resin system is significant (see Fig 4.)

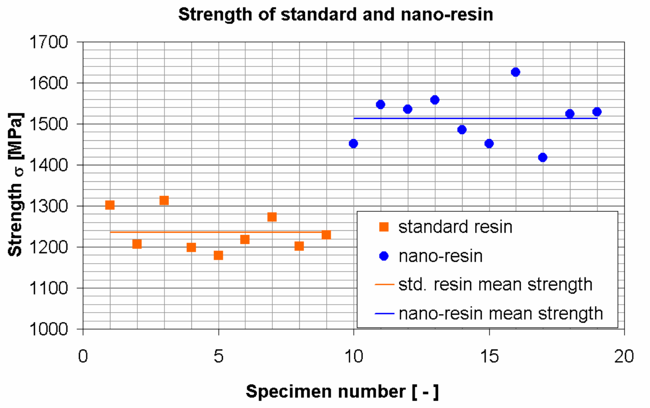

Fig. 4. Comparison of strengths of standard and nano-resin.

4 Experimental and computational analysis of IHPJ

Different methods of strain and stress analysis and failure damage process in the pressure vessel body and in the IHPJ were used. Static tensile tests of many different shapes of carbon fibre composite connection loops were performed. Strain gauges were applied on the surface as well as inside between the layers of the tested composite loops. Strain measurement methods based on fibre optic sensors (Bragg grating sensors) were applied and tested as well. Both methods were used to verify strains between the different layers of the multilayer loops. New analytical proposals and different numerical FEM models of multilayer IHPJ with different number and stiffness of layers were calculated and tested [5].

4.1 Experimental investigation of IHPJ multi pin loops properties

To optimize the dimension parameters of IHJP multi pin loops (see Fig. 1), several batches of single loops of different dimensions were made at CompoTech PLUS company for testing (see Fig. 5, Table. 1 and Table 2).

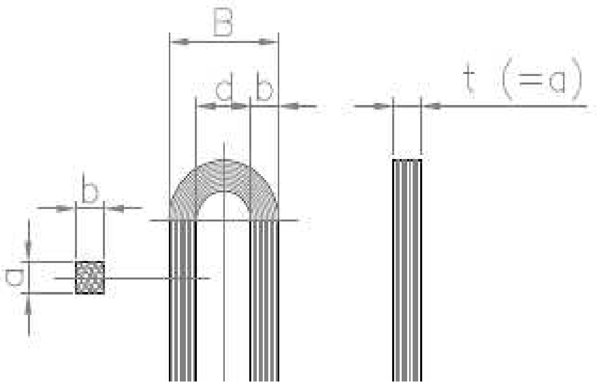

Fig. 5. Detail of the loop sample

Two PAN carbon fibers were used, HTS5631 of Tenax and T700 of Torayca, both impregnated in a matrix of LG120 epoxy resin and EM100 hardener.

The loops were wound manually on a special frame separated by agent and the volume fraction of the fibers was of 56 to 70%. After winding, the loops were pre-cured in 25°C for 6 hours, then in 40°C and then put into the curing oven for the standard 12 hours long curing cycle with a maximal temperature of 100°C. When the curing completed, the frame was remounted and the loop samples were numbered, frays removed and actual dimensions of the samples measured (the values varied around set mean values according to fiber volume ratio).

Table. 1 Nominal dimensions of loops made of HTS5631 fiber

diameter	active pin length	thickness	ratio
d [mm]	h [mm]	b [mm]	D/d [-]
10	5	3.5	1.7
10	5	5.0	2.0

Table. 2 Nominal dimensions of loops made of T700 fiber

diameter	active pin length	thickness	ratio
d [mm]	h [mm]	b [mm]	D/d [-]
10	5	1.0	1.20
10	5	1.5	1.30
10	5	2.0	1,40
10	5	2.6	1.52
10	5	4.4	1.88
10	5	6.0	2.20

Mechanical tests were performed in the laboratories of the Faculty of Mechanical

Engineering of CTU in Prague as shown in Fig 6. The sample loops were loaded by a tensile force until failure. The testing machine head displacement was adjusted to be 0.5 mm/sec. The displacement and tensile force were recorded as well as initializing and localization of the failure.

Two types of boundary conditions were tested – so-called free loop on the pin and the loop with washers tightened on the sides of the loop, thus enforcing an axial force (from the view of the pin). Typical loading behaviour of sample loops are presented on Fig. 7 and Fig. 8. Although only samples of T700 carbon fiber are shown, the HTS5631 samples’ behavior was very similar because of similar mechanical properties of both types of fiber.

The obtained results i.e. the strength values of the loop samples, were evaluated as absolute values and then also as the ratio of the absolute value and the nominal value of calculated strength of they straight part of the loop (see Fig. 9).

When all the data are plotted in a graph, the character of dependence curve shows that fiber strength utilization for loops of higher thickness is lower than for loops of lower thickness and also loops loaded by pin without side washers has significantly lower load capacity than with the washers (for comparison see Fig. 7 and Fig. 8).

Fig. 6. Loop sample gripped in testing machine

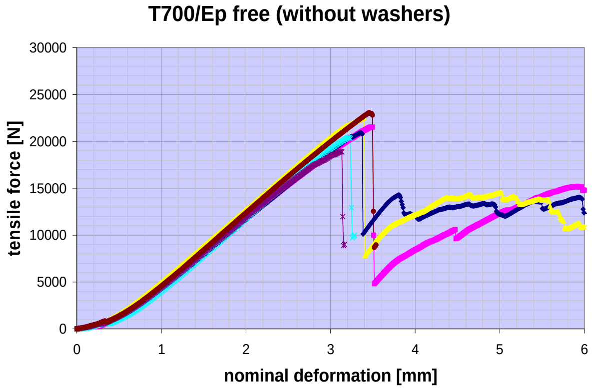

Fig. 7. Loading of free loop samples

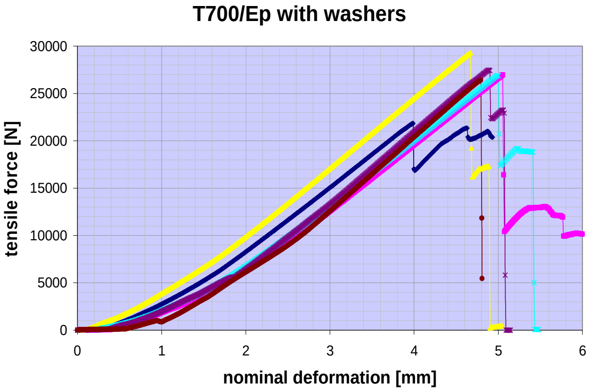

Fig. 8. Loading of loop samples with washers

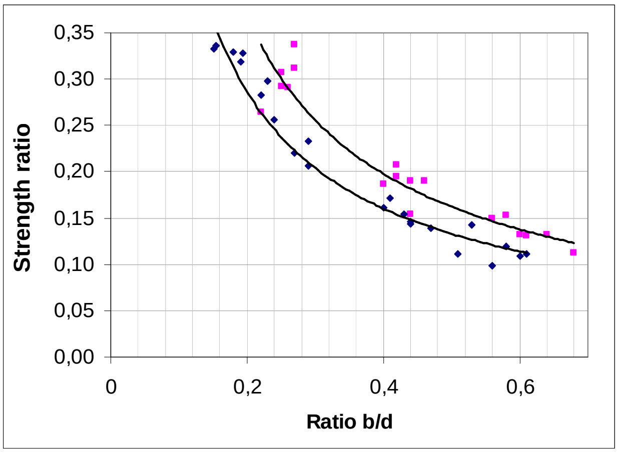

Fig. 9. Tendencies of loop samples (upper curve is for loops on pin with washers, the lower one for free loops

Fibers in tested loop samples failed by 10% to 33% of nominal of calculated strength of straight part of the loop as apparent on Fig. 9. When lowering the thickness of layer, the strength of the loop increases significantly.

In reality, most of fiber load capacity was not used. The main reasons for this are the irregularity of loading in the fibers within the loop and the decrease of longitudinal strength because of the transversal press. Specimens after failure are shown in Fig. 10.

Fig. 10. Two loop samples after test with washers

Selected samples were also examined by fractography analyses depicted in Fig. 11. Observations indicate that failure initiated in the corners of the inner diameter surface.

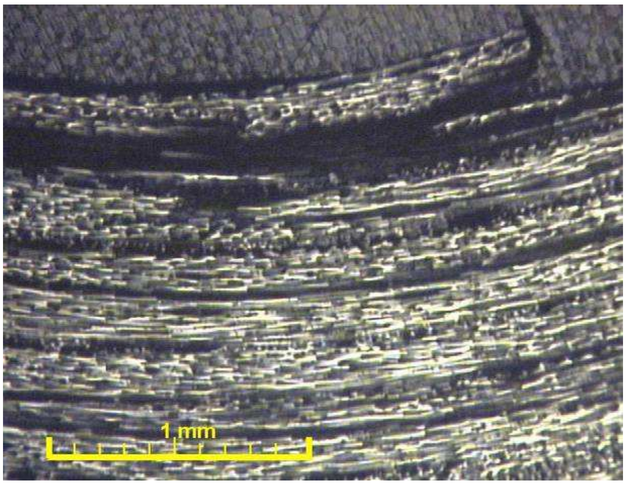

Fig. 11. Delamination on inner diameter of sample

4.2 Integrated sensors

For the first experiments with strain gage sensors embedded into composite loops, common strain gauges were used. In order to have strain gages perfectly isolated from carbon fibers, the connecting wires were from varnished copper wire, soldered onto the gage with tin. The strain gauge was placed between two layers (upside down), separated by a teflon film from the bottom layer, so glued by epoxy resin to bottom face of upper layer of loop (see Fig. 12).

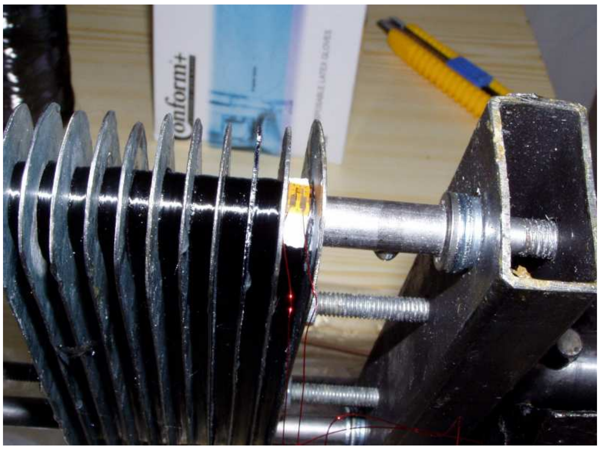

Fig. 12. Manufacturing process of loops and placement of strain gauge

This is the expected location of peak tangential stress. Completed specimens were tested and compared with common loops without integrated sensors. But the results achieved from the integrated gauges (measured on four loops with integrated sensors) were, at of the time of this writing, not consistent with expectations and there are continuing studies to further investigate this.

It seems, that the best way of monitoring the strain and stress inside the specimen, are fiber optic sensors. Mountable strain sensors MS-01 with Bragg gratings with fiber a diameter of 250 micrometers and an Ormocer coating (see Fig. 13) were used. They can be easily embedded into loops during the manufacturing process (specifically in the straight part for tensile strain sensing) without relevant influence to the strength of the basic composite material (longitudinal axis of fiber is parallel with carbon fibers).

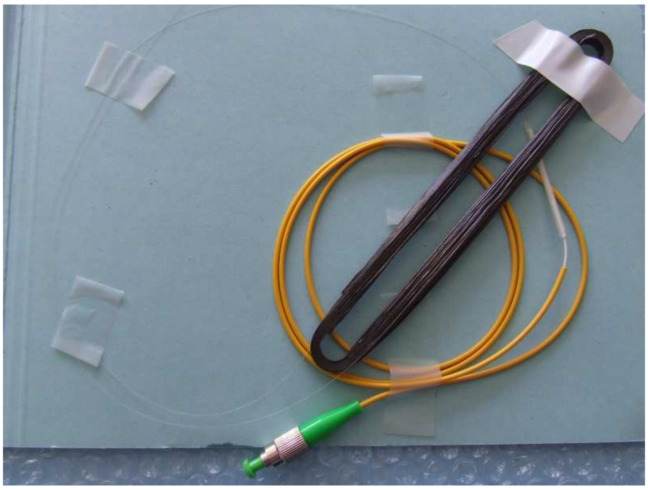

Fig. 13. Specimen with integrated FBG sensor

Future research will be focused on the integration of FBG sensors into different layers of loop for sensing of tangential strains inside the loop head. Another aim is to have FBG sensors integrated into IHPJ during the manufacturing process of the whole composite vessel for its structural health monitoring.

4.3 Numerical calculations of pin loops

FEM calculations were made using Abaqus 6.6 Standard solver. Loops were modeled as a 3-D continuum and for composite material an orthotropic material model was used based on the known properties of E_1, $E_2=E_3$, $G_{12}=G_{13}$, G_{23}, $\nu_{12}=\nu_{13}$, ν_{23}. Loops were in contact with the tensile-loaded pin. The pin was created as an analytical rigid body. Contact between the pin and loop was modeled using normal hard contact and tangential contact with friction.

Results for the loop made from T700 carbon fibers with loop thickness b=2.7 mm are shown in Fig. 14 and Fig. 15. Tangential and radial stress distributions in the lug is similar to the stress distribution in thin or thick pressure vessels depending on the loop thickness (see Fig. 16 and 17). Numerical sensitivity analysis was made by varying the loop thickness to receive information about a ratio dependency of maximum tangential stress in the loop head to stress in the straight part (stress concentration factor). The results are shown in Fig. 18.

Analytical solutions were made to provide the possibility of quick solutions and loop optimization. The theory of thick pressure vessels was employed as an analytical model. The comparison between the analytical and FEM results of the tangential stress on the inner loop surface is shown in Fig. 19

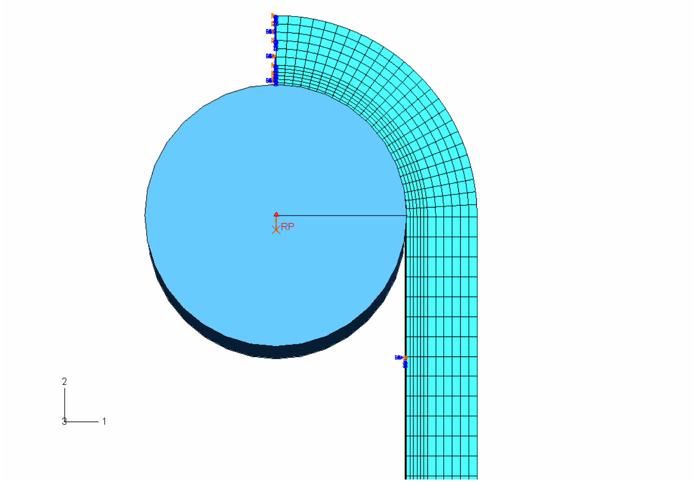

Fig. 14. Pin-loop assembly

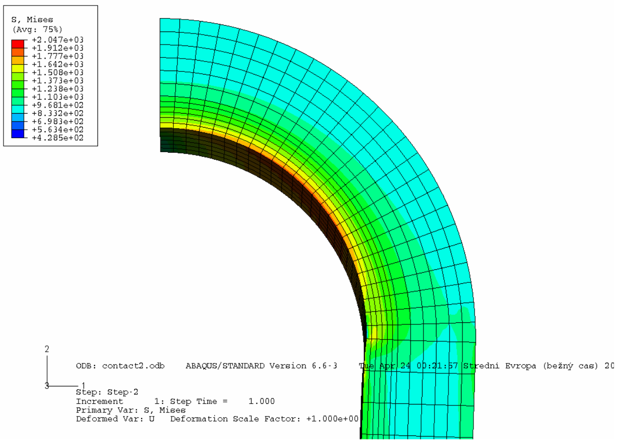

Fig. 15. Mises stress distribution in the head of loop by tensile force 26 600 N which is corresponds to the rupture force in an experimental test

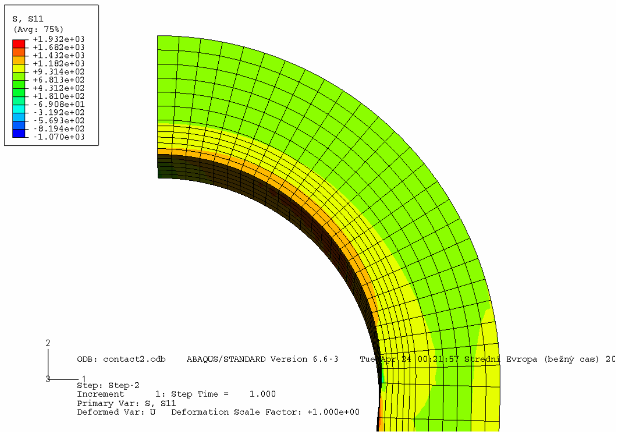

Fig. 16. Tangential stress distribution

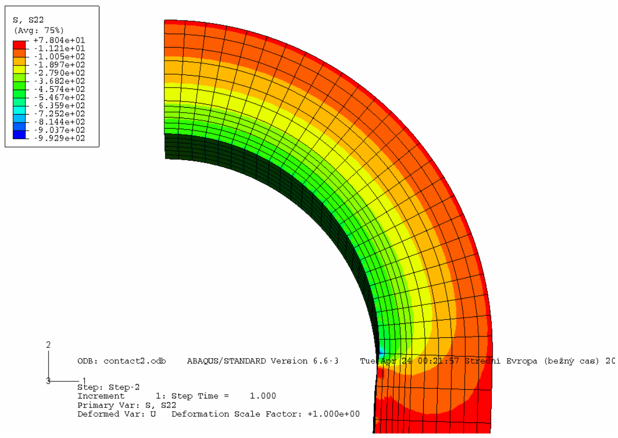

Fig. 17. Radial stress distribution

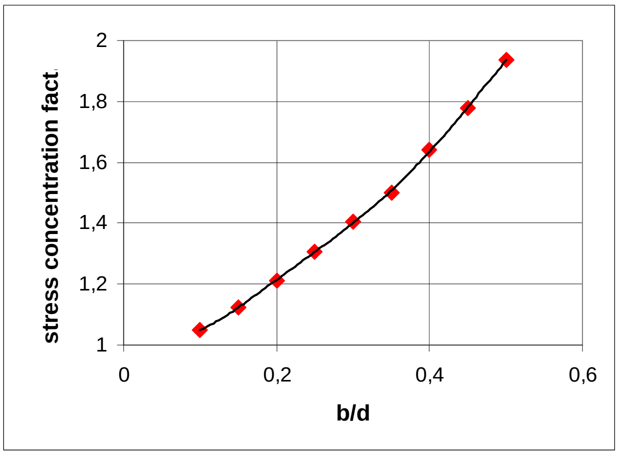

Fig. 18. Ratio of maximal tangential stress in the loop head to nominal stress in the loop (stress concentration factor)

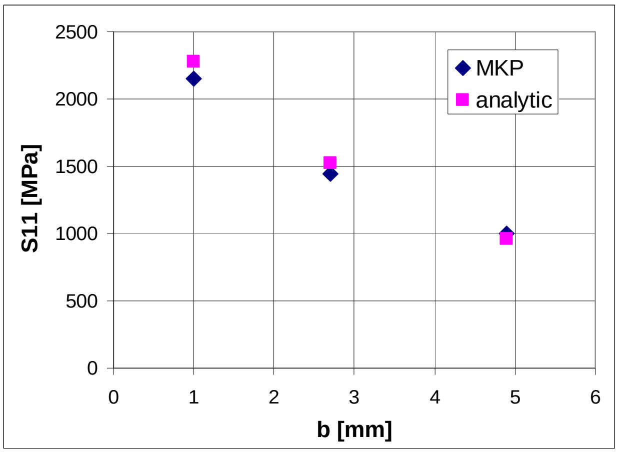

Fig.19. Comparison between analytical and FEM results

4.4 Strength criterion of the pin loop

To design an optimal IHPJ multi pin loop, a failure criterion under static and cyclic loading in the working condition should be derived. As the first step, a static criterion using results of the previously mentioned tests was proposed.

FEM results of Mises stress were used for such a criterion, because of the multiaxial stress state in the loop. Through, multiplication of the nominal strength value in the straight part of the loop by the stress concentration factor, (see Fig. 18) the maximum of stress in the loop head can be estimated. In such a way, stresses in other points of the ruptured cross section were calculated for different thicknesses of the loop. The results for loops made from fibre T700 are shown on the Fig. 20.

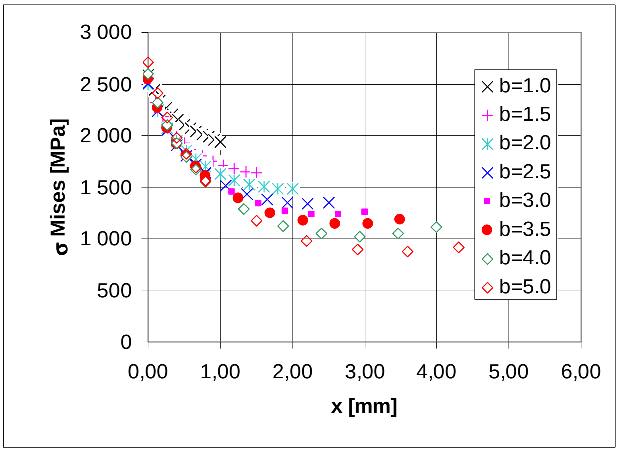

Fig.20. Reconstruction of the stress distribution across the ruptured cross section for loops for different thickness

The picture shows that increasing the thickness leads to a rising stress gradient and higher maximal Mises stress in the inner radius of the loop. So the criteria of Mises extreme stress couldn’t give good accordance with the experimental results. Mises stresses in a different constant distance *x*=*a* from the point of maximum were calculated and depicted in the Fig. 21.

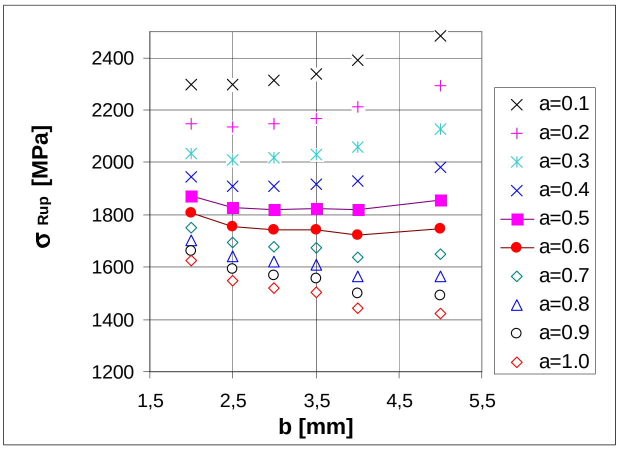

Fig.21. Mises stresses in a different constant distance *x*=*a* from the point of maximum

Some parameters give increasing dependence and the others a decreasing dependance. Rupture stresses in the distance between *a*=0.5...0.6 mm are very similar. A critical rupture stress of a pin joint made from T700 carbon fibre in this point is about 1790 MPa. It is approximately 50 to 55 % of the nominal stress value in the straight part of the loops, when the loops failed.

5 Conclusions

The main focus of the IHPJ research program is to develop a simple to use engineering criterion such that the IHPJ concept could be applied to a wider area of applications. The pressure vessel application was the first to be developed because of the relatively simple axial load case. But the same technique can be use for other load cases of joining like torsion or bending moment. Especially bending moment where the load can be split into axial and compression/ shear forms the next step of application. Advantages of IHPJ have been demonstrated in this paper. In spite of the latest developments in adhesives [2], it is possible to find applications were IHPJ, based on principle of fibre wrapped around the pin, outperform the adhesive joint by maximum strength/weight performance.

Experimental investigation of single loops showed that fiber strength utilization for loops of higher thickness is lower than for loops of lower thickness and in addition, loops loaded by a pin without side washers have significantly lower load capacity than with the washers. Fibers in the tested loop samples failed by 10% to 33% of the nominal calculated strength. The stress concentration factor of the loops and the stress gradient increase with the ration of loop width to diameter of pin (b/d).

An engineering failure criterion was also determined. It predicted a rupture of the pin connection by achieving 50 % of the nominal strength of fibre tow in the critical point, which is approximately 0.5 mm under the inner surface of the lug.

Damage should be monitored through the use of optical fibers and FBG sensors, and will be developed in future.

Acknowledgment

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