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ADHESIVE JOINT DESIGN OF A FULL COMPOSITE, ULTRA-LIGHT STRUCTURE FOR HIGH ENERGY PHYSICS

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Abstract

This note describes the activities done to design, optimise and qualify the glued joints of the composite support structure (stave) for the sensitive elements of the ATLAS Pixel Detector to be installed in the new Large Hadron Collider at CERN (Centre Européen pour la Recherche Nucleaire, Genève, Switzerland) 1). About 150 staves will have to be produced. The series production issues have been addressed and the manufacturing process has been set up.

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1 INTRODUCTION

Adhesive bonding is a well known and assessed practise to join composite structures. However, a comprehensive qualification program is always necessary in case of severe operating conditions and when the reliability becomes a vital requirement. This is the case of the stave [2)], where an omega-shaped carbon fibre profile has to be longitudinally glued underneath a carbon-carbon tile (see fig. 1), to form a cooling channel. Such a design allows for the maximum reduction of material and provides excellent thermal/structural performances. Therefore a special care has been devoted to their qualification, and a long and comprehensive test program has been performed.

The stave structure features two types of glued joint, where the same adhesive is employed on different geometry: the longitudinal joint between the omega profile and the carbon-carbon tile, and the joint of the PEEK (Polyetheretherketone thermo-plastic resin) hydraulic terminations inside the cooling channel, at its ends (see fig. 1). The first one, on account of its unavoidable geometry, is essentially subject to a peeling stress due to the coolant pressure, and then doesn’t work in a structurally optimised condition. The second one is subject to a complex load condition coming from the combination of the coolant pressure and the action of the interconnecting cooling pipes.

2 SPECIFICATIONS

The requirements of the glued joints of the stave can be summarised as follows:

- Radiation hardness: the stave is the supporting structure of the sensitive elements of the pixel detector, the innermost part of ATLAS detector, that is the closest one to one of the interaction points and will be exposed to the maximum radiation dose. The glued joints don’t have to show any significant degradation of their performance even after being irradiated up to the maximum dose collected during 10 years of operation (50 Mrad).
- Lifetime: the reliability of the structure, and then of the joints, should allow for an operating life of 10 years.
- Fluid compatibility: the baseline coolant for the pixel detector is C_3F_8 [3)] which will boil off flowing along the stave to efficiently remove the heat produced by the on board electronics. C3F8 will enter the stave partially evaporated and will leave it almost in dry-out conditions. The glued joints will have to withstand both chemical (dilution) and mechanical (erosion) actions. Furthermore the cooling fluid will be subject to decomposition due to irradiation and even if continuously filtered, possible residual aggressive compounds could attach the glued joints.
- Operating temperature: the structure should be cooled down to –25°C from room (assembling) temperature.

- Temperature cycles: the structure is a part of a system that is expected to be started up and shut down on a weekly basis; therefore, around 600 thermal cycles from room to operating temperature could be foreseen for the lifetime of the component.
- Operating pressure: the joint will have to withstand an operating pressure, inside the channel, in the range 2-4 bar abs, while, in fault condition, the peak pressure should reach 8 bar abs. The design pressure of the joint will be 10 bar abs.
- Pressure cycles: as for the temperature, the stave will be subject to a maximum of about 600 cycles from atmospheric to operating pressure. Furthermore, high frequency cycles of roughly 0.5 bar of amplitude are expected around the operating pressure, due to unavoidable instability of the cooling circuit control system.

3 ADHESIVE SELECTION

Due to the specific design issue of the stave longitudinal joint, high peeling strength adhesives have been looked at. Past experience and recommendation of suppliers led to focus on two CIBA Araldites (AY103 and 420 A/B). Table 1 shows the typical properties of the two selected adhesives. The two selected adhesives, both epoxy based, have been fully tested and qualified.

4 PEELING TESTS

Pseudo-peeling test (fig. 2) has been performed on small samples of the stave reproducing the actual geometry of the structure and of the longitudinal glued joint.

The tests allowed for the estimation of the adhesive peeling strength as function of the expected actions during operation: irradiation, operating temperature and coolant exposure. C_6F_{14} fluid has been used instead of C_3F_8 because it is liquid at room temperature and from the chemical point of view it should have a very similar behaviour.

Three specimens for each test case have been used. The results of the peeling tests (figg. 3 - 4) show very little dispersion of peeling strength values around 10 N/mm for CIBA AY103 and around 13 N/mm for CIBA 420 A/B.

These data have been found to be in a fairly good agreement both with the actual stress conditions due to an internal pressure in the stave of 26 and 33 barg (respectively for AY103 and 420 A/B) and with the pressure tests performed on different stave specimens.

The glue joint peeling strength doesn’t seem to be sensitive both to the irradiation, to the coolant exposure and to temperature (in the expected operation range). CIBA 420 A/B adhesive has been adopted due to its higher peeling strength.

5 LONG DURATION TEST - LONGITUDINAL JOINT

To assess the adhesive performances of the selected adhesive (CIBA 420 A/B), further tests have been performed to check the longitudinal glued joint strength against the action of static pressure (creep tests) and pressure cycles (pseudo-fatigue tests).

Tests have been performed on 300 mm long specimens obtained by a full stave prototype. The specimen has been tested with pulsing pressure (from 0 to 8 barg) up to a given number of cycles (fatigue test) and then kept at a constant pressure (creep test) of 8 barg.

The specimen overcame 115000 cycles and then 2440 hours at constant pressure without showing any important leak increase. As during the test the applied pressure was a factor of 3 above the maximum expected operating pressure, we considered the achieved test duration to be enough representative of the whole required operating life of the part.

6 LONG DURATION TEST - HYDRAULIC TERMINATIONS

To assess the performances of the selected adhesive while employed on the geometry of the hydraulic terminations, a series of 10 specimens reproducing the end of the stave have been manufactured and submitted to a test program.

The first test campaign submitted 5 specimens to 2500 cycles, where an axial traction and a transverse force, applied to the PEEK termination, varied respectively from 0 to 40 N and from 0 to 4 N. The other 5 specimens overcame the same load history, but after receiving a radiation dose of 50 Mrad. The values of the applied forces were roughly 2 times those expected during operation because of the combined action of coolant pressure and tubes restrained thermal displacements. Such loads have been calculated by a finite element simulation of the interconnecting cooling pipe.

None of the specimens showed significant leak increase after the test.

7 DESTRUCTIVE TESTS

Destructive pressure tests have been performed to validate and normalise the results given by the peeling tests. Two tests have been performed on two specimens, 300 mm long, obtained from different full stave prototypes. Both tests were made gradually increasing the pressure inside the omega channel until the specimen broke.

The first specimen broke at 30 barg, the second one at 22 barg. This difference is due to a slightly different geometry of the two samples and is well correlated with the expected different stress conditions: in both cases the ultimate tensile stress was 1.8 MPa.

It is important to underline that in both cases the failure mode of the structure is by delamination of the carbon fibres layers of the omega (see fig. 5): the strength of the structure is given by the peeling strength of the carbon fibres. The safety factor on the maximum expected pressure in case of fault of the cooling circuit is around 3. The agreement between the peeling tests and pressure tests was found to be fairly good.

8 MANUFACTURING

As the bonding of the omega to the carbon-carbon tile is one of the most crucial operations in the assembling of a part to be produced in a series of around 150 items, a considerable effort has been carried out to set up and assess a suitable gluing procedure. The manufacturing process should guarantee the required performances maximising, at the same time, the yield and overcoming the influence of the individual skill of the operator. The critical points we have addressed are discussed here after:

- Surface treatment: this is widely known as a key-point for the strength of a glued joint. Roughness and cleanliness of the surfaces must be controlled. As the previous operation on the carbon-carbon tile is a dry milling (without coolant), both the above mentioned parameters are under control, provided that proper handling and storage of the part are implemented. Simple acetone cleaning was specified, just for safety. On the contrary, the carbon fibre profile comes out from a forming process on a graphite mould, where a special wax is put on to help the removal of the part after curing in autoclave. Therefore the omega-gluing surface has to be properly prepared in order to remove any contaminants and to achieve the expected glue joint strength. The adopted cleaning procedure has to be reliable and “soft” in order not to damage the fibres (weakening the structure and causing uncontrollable distortions). A semi-automated gritblasting process did not lead to successful results: the induced distortions on the omega turned out to be unacceptable and no combination of the process parameters was found to be useful to minimise the effect. Therefore, only a manual light sandpaper scratching was found to be viable. Though heavily depending on the skill of the operator, we never had evidence that such a process could reduce the strength of the joint (see paragraph 8).
- Components mixture: special tool and mixing and dispensing procedures had to be implemented in order to have an homogeneous mixture in the prescribed ratio of the two components. This way we could avoid as well to have air bubbles trapped in the glue ribbons leading to local weak point (mainly from the leak point of view) on the glue joint.
- Glue dispenser: the amount of glue, as well as the ribbon position, have been optimised through an extensive set of trials. The goal was to achieve a glued joint that uniformly bonded the “wings” of the omega profile to the carbon-carbon tile, then ensuring both reproducible strength and sealing of the channel. The right set up of the relevant parameters should have also allowed the glue to form a rounded fillet inside the channel (to reduce both the hydraulic losses and the peeling effect of the pressurised coolant to the joint), with a reasonable excess of glue outside. Due to the length of the parts to be bonded (800 mm), the small distance between the two glue ribbons (8 mm) and the small ribbon diameter (1.5 mm), a custom-designed automated machine have been assembled. A glue dispenser is installed on a motorised, computer controlled, high precision slide, while a pneumatic piston displaces transversally the glue outlet orifice. The process optimisation went through the set up of the relevant parameters (dispenser pressure, slide speed, orifice diameter and orifice distance from the surface of lay up). During the manufacturing of a pre-series of parts, we had evidence of a good repeatability of the process.

- Gluing mould: measurements on prototypes showed that a bad alignment of the omega profile on the carbon-carbon tile results in a poor stability behaviour of the assembly when cooled down, with axial torsion. To align the carbon fibre profile to the design position on the back of the carbon-carbon tile, a two-shell mould has been designed and manufactured. Such a tool features a graphite basement (to minimise the geometry errors and stresses due to different expansion coefficients) that accurately replicates the "shingled" geometry of the upper face of the carbon-carbon tile. The omega carbon fibre profile instead is centred in a grove machined in the aluminium cover; the cover, on its turn, is centred on the graphite base by means of reference planes, and axially positioned by means of a central dowel pin, that let it free to expand its ends. The mould is then closed and vacuum-bagged.
- Curing: the parts are kept at 60°C for 90 minutes, as specified by the Supplier. Nor a pre-curing period at room temperature, neither extensions of the curing period and increases of the relevant temperature produced noticeable variations of the strength of the joint or of the final shape of the assembly.

9 CONCLUSIONS

Tight requirements and reliability concerns suggested to carefully select the glue type and to investigate the behaviour of the glued joints. The extensive test campaign on specimens and prototypes allowed to choose the glue type, to optimise the design and to check that such a joints can meet the requirements, with large safety margins. The optimisation went through the set up of a complete manufacturing process that, after the production of several full-scale prototypes, proved to be ready for the mass production.

10 REFERENCES

(1) ATLAS Technical Proposal - CERN/LHCC/94-43, CERN, Switzerland, Dec. 15 1994.
(2) ATLAS Pixel Detector Technical Design Report CERN/LHCC/98-13, CERN, Switzerland, May 1998
(3) Fluorocarbon Evaporative Cooling Developments for the ATLAS Pixel and Semiconductor Tracking Detectors ATLAS-INDET-99-01618, CERN, Switzerland, Sep. 1999.

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TAB. 1: typical properties of the selected adhesives

SUPPLIER	**TYPE**	**N° OF COMPONENTS**	**CURING TEMP.**	**CURING TIME**	**B PEEL STRENGTH**
			[°C]	[min]	[N/20mm]
CIBA	AY103	2	70	180-300	-
CIBA	420 A/B	2	60	90	150

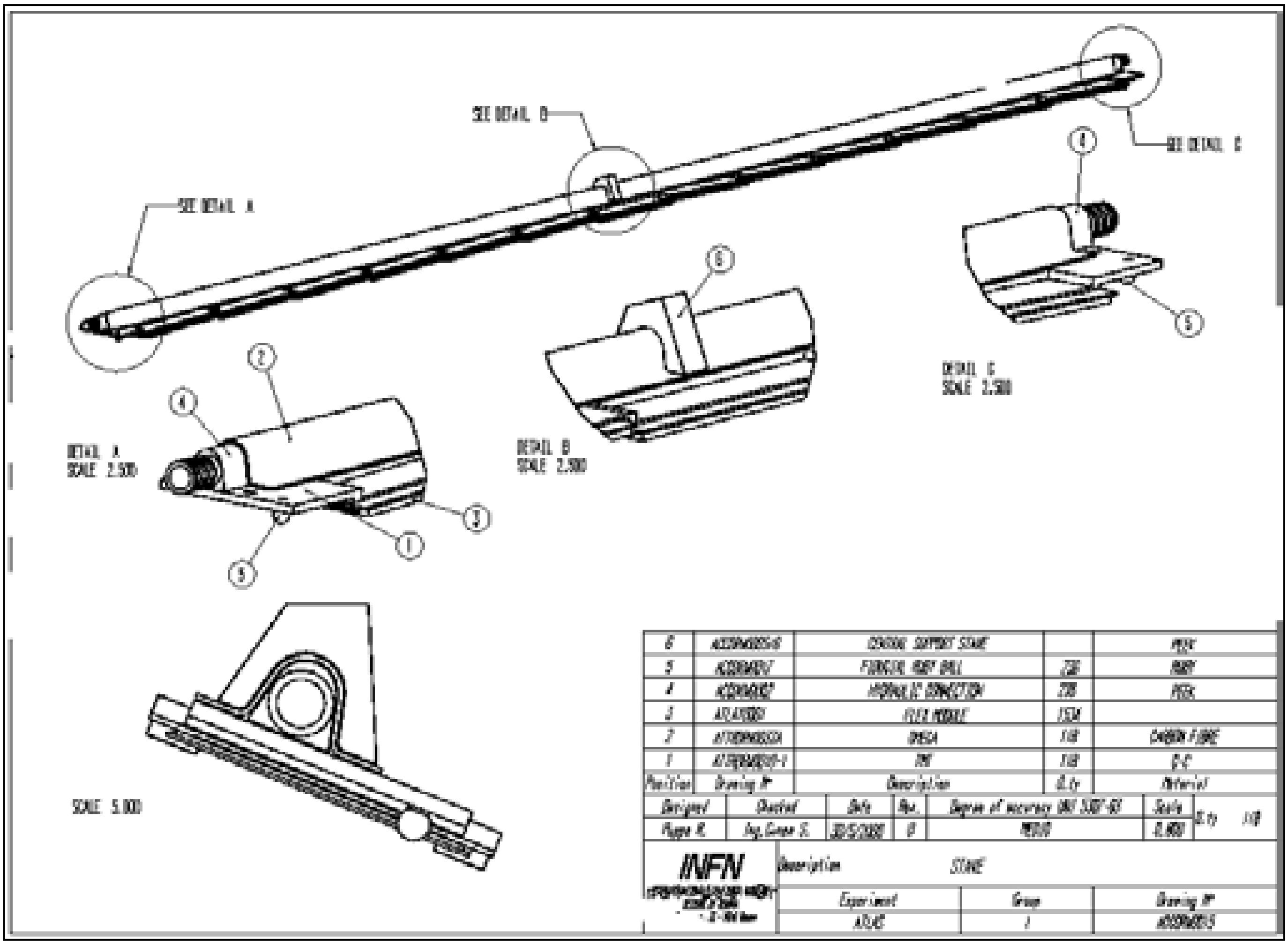

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FIG. 1: stave assembly

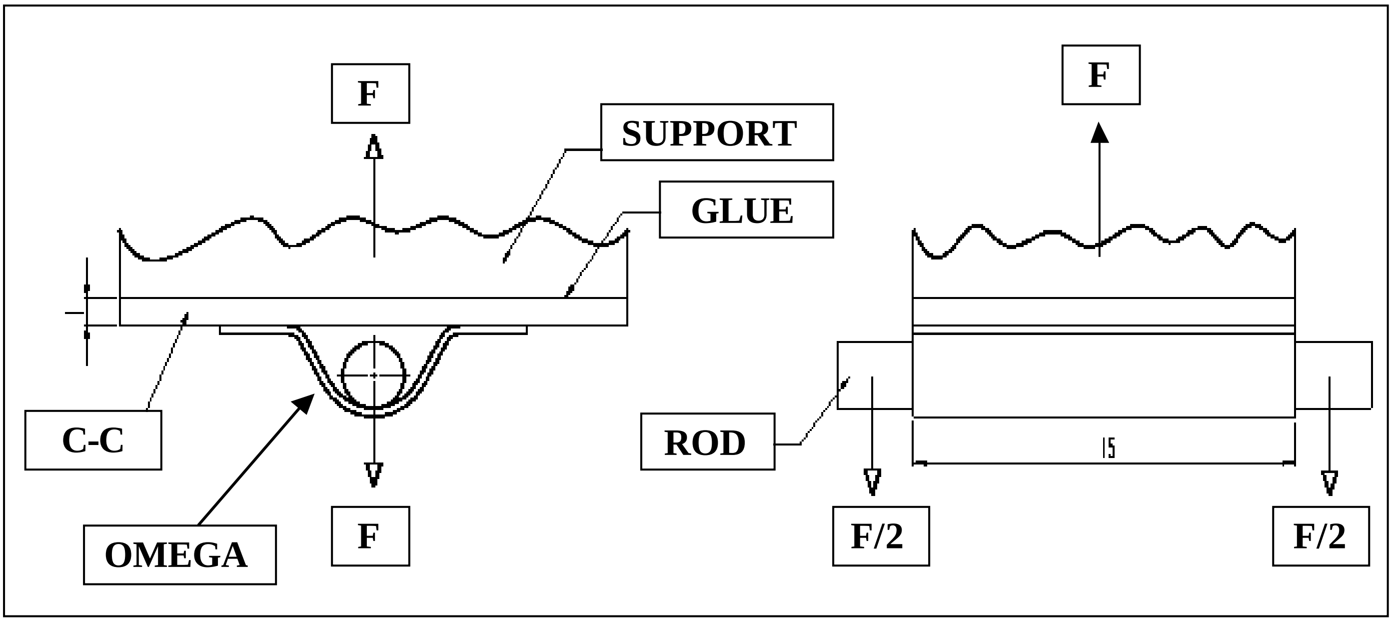

FIG. 2: peeling test specimen set-up

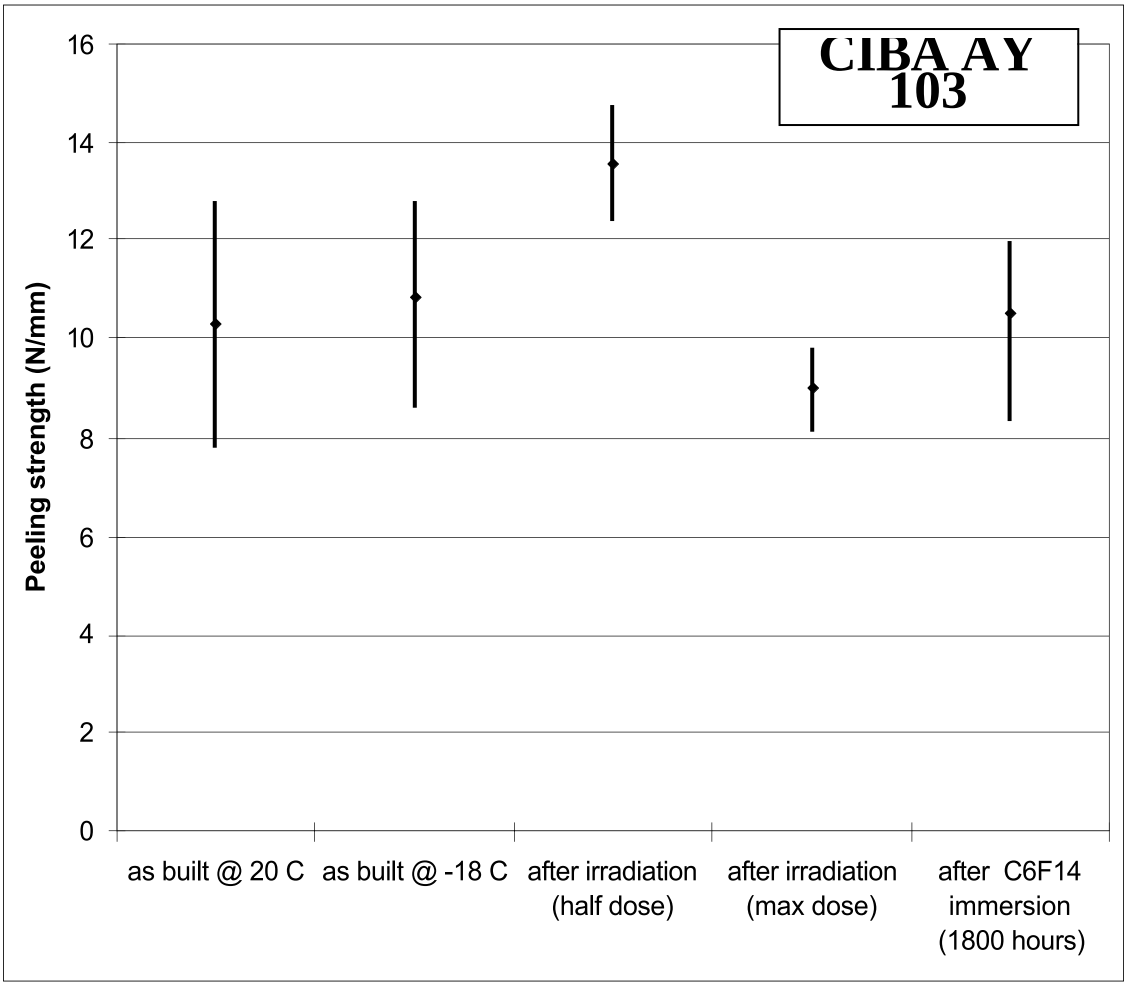

FIG. 3: peeling test results with CIBA AY 103

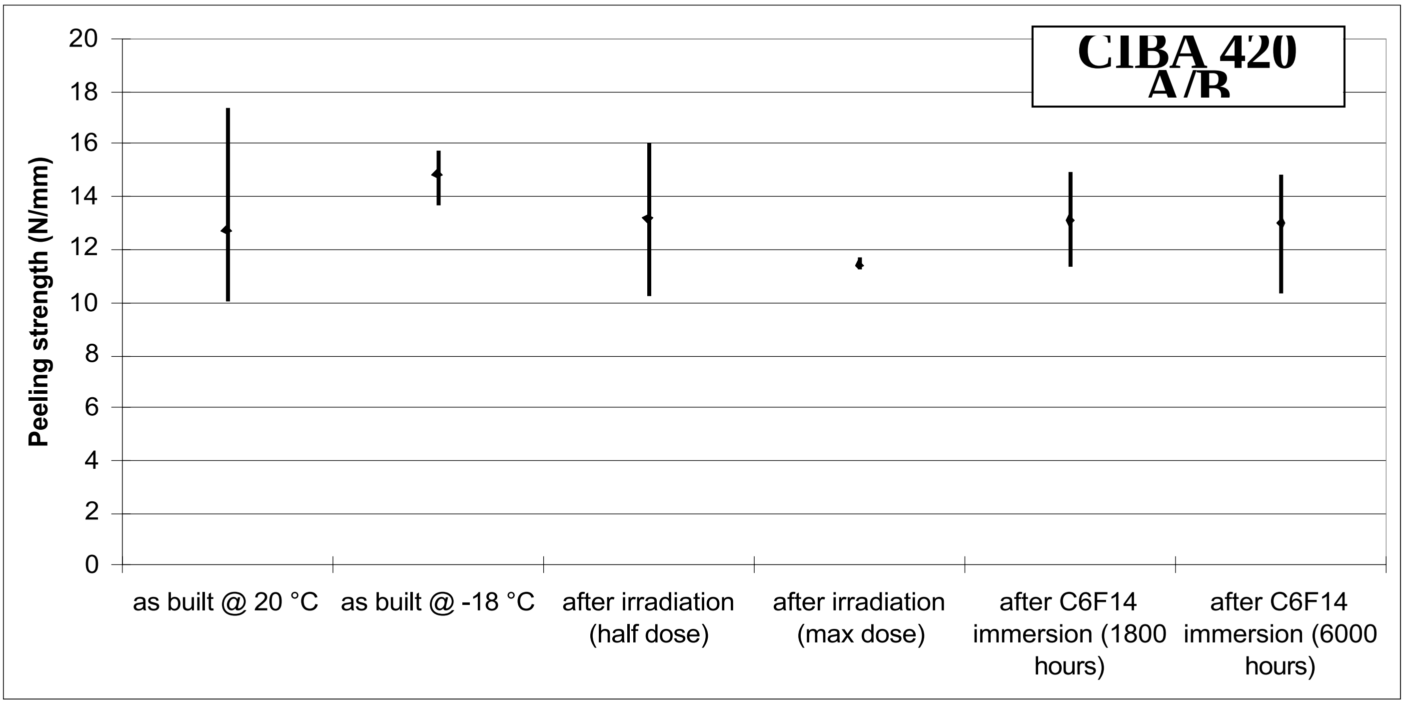

FIG. 4: peeling test results with CIBA 420A/B

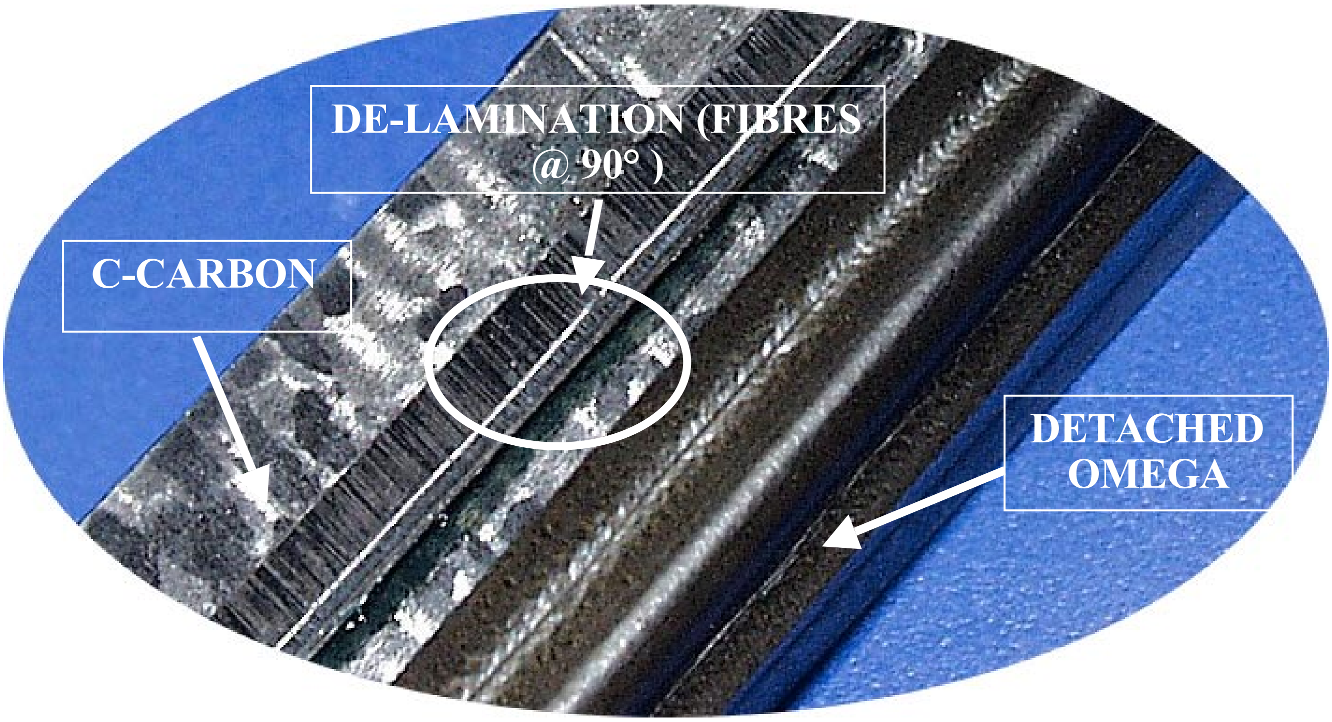

FIG. 5: carbon fibres de-lamination after destructive pressure test