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FIBRE OPTIC DAMAGE DETECTION IN COMPOSITE STRUCTURES

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Abstract

A system of thin, light conducting fibres, which was integrated into a composite structure during its manufacturing process, can serve as a reliable, automatic and remote working long-term monitoring device for structural damages. Fractures, cracks, or delaminations in a structure area destroy the optical fibres installed here and thus interrupt the light flow. Various examples of applications in GFRP and especially in CFRP aircraft components are described. The outline of a complete Fibre Optic Nervous System (FONS) for big Airbus CFRP components shows, how fibre optic damage detection can contribute to future aircraft maintenance and inspection philosophies: Following the example of other aircraft systems as engines, computers etc., the structure too can be included in the permanent and automatic working Central Fault Detection Systen (CFDS).

I. Introduction

Numerous methods have been developed to detect cracks in components after manufacturing or during their life time. Yet, most of these methods are for inspection purpose, which means in general, that the operation of the structure has to be interrupted, accessibility for test personal and equipment must be given, and sufficient time for a piece by piece, sometimes even rivet by rivet inspection, must be available. In many technical fields these conditions either cannot be fulfilled or it would represent a tremendous advantage concerning time, cost and saftey to overcome them. So in aircraft fatigue testing and operation, but also in other fields as wind power plants etc., the demand came up for automatically, realtime and remote working long-term crack detection systems.

A classical solution to this problem is to bond crack detection wires onto components. Cracks contacting the wire will interrupt the sensor current and thus monitor the crack. This method has a couple of serious disadvantages due to corosion of the wire, low sensitivity to fine cracks, electrical problems and frequently a great difficulty to localize a fine crack along the path of the wire.

To improve this situation, the Test Department of MBB in Lemwerder is developing a new fibre optic crack detection system called FORS (Faser-optischer Riss-Sensor).

II. Principle of Operation

The basic principle is shown in Fig. 1. Thin optical fibres with diameters from 30 to 200 μ are bonded to the surface of structural components. Illuminating one end of the optical fibres reveals, that the structure is sound, if all fibres transmit light to the opposite edge of the component. If the structure contains a crack or a rupture, the fibre will break and the lack of light transmission will target the site of the damage. The crack position along a fibres path can be easily found just by looking for the light being emitted here out of the fibre. The damage of a fibre, caused by a structural flaw, is irreversible; even if the load is taken off from the component and the crack per-

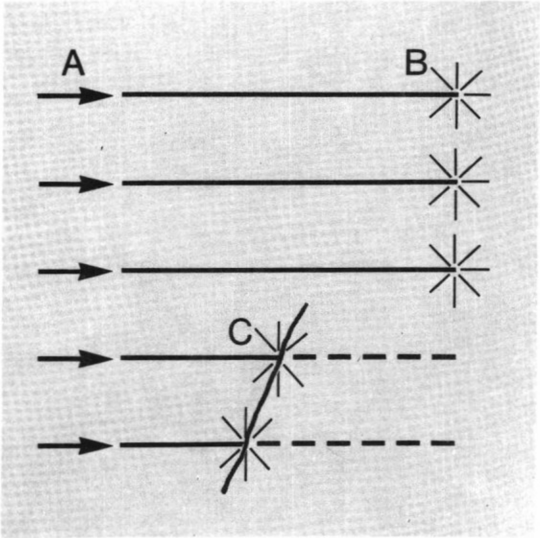


Fig. 1: Functional principle of fibre optic damage detection. Light conductive fibres attached to the component surface break immediately upon contact with a crack. The light coupled in at (A) does not reach its outlet (B) but is emitted at the crack (C).

fectly closes, the light transmission through the fibre remains interrupted. Fig. 2 shows an aluminium specimen with 8 fibres of 100 µ diameter attached on its surface. The growing of two cracks starting at the middle of the specimen was achieved by about 100.000 cycles of tensile load. The cracks are very fine and cannot be recognized visually. However the fibres break immediately upon contact with the cracks and mark the cracks path by light spots.

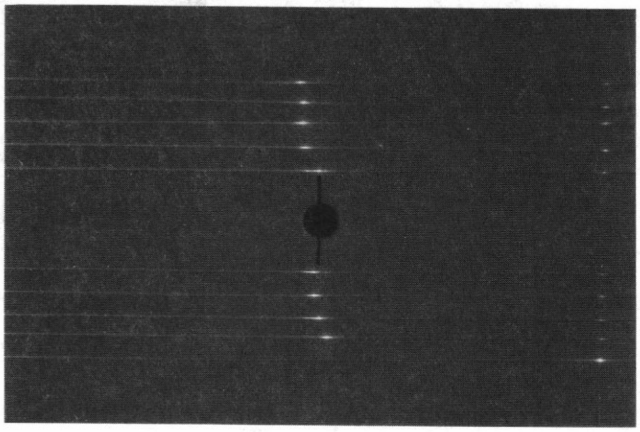


Fig. 2: Optical fibres, bonded onto an aluminium specimen, indicate two cracks.

This principle of crack detection can be used in three modes of operation (Fig. 3). Mode 1 is a pure inspection mode. Nothing else is installed on the structure but the fibres with marks at their ends. The system is used from time to time, light is coupled in manually and the opposite fibre ends are observed visually. Mode 2 is an active real-time monitoring mode. All fibres are connected to one or more light sources. At each fibre exit, a photodetector is installed giving its signal to a monitoring electronic unit. Most applications in aircraft fatigue testing are performed in this mode. If numerous fibre channels are to be installed, it is sometimes difficult and unpractical to equip each fibre with a separate photodector, so an optical scanning mode (mode 3) is preferred. All fibres end at one photodetector and light is coupled into the fibres in cyclic way, as it can be done for instance by a laser scanner.

First applications were performed at various aluminium aircraft components (Airbus) as frames, stringers, rivet rows of the skin etc., and at the 35 m long steel rotor blades of a 2 MW wind power plant.

The sensitivity of an optical fibre for crack detection, that means the minimal crack opening, which is needed to break the fibre, depends on the properties of the adhesive and on the fibres fracture strain. The fracture strain can be influenced by chemical treatments of the fibres surface and thus be adapted to a large variety of crack detection problems.

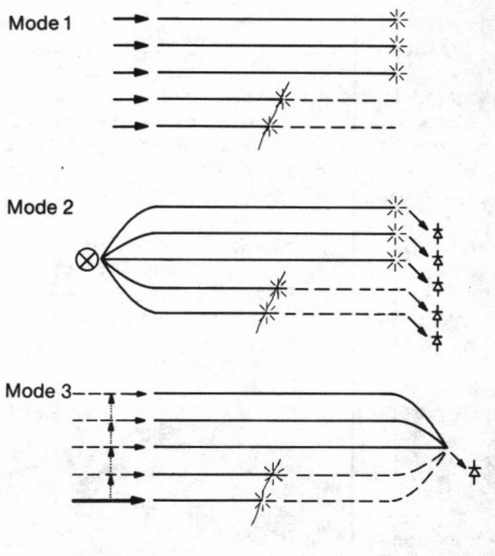


Fig. 3: Modes of operation: 1. Inspection mode. 2. Realtime monitoring mode 3. Scan mode.

III. Applications in GFRP

Applications of this type on metal surfaces just were the beginning of the FORS-development. It soon turned out, that composite materials like Glassfibre Reinforced Plastic (GFRP) or Carbonfibre Reinforced Plastic (CFRP), both materials which are used more and more in aircraft design, represent as well a large field of application for fibre optic damage detection. Composite materials and the way how they are manufactured offer the possibility to install optical fibres not only at surfaces, but also inside the laminat. Fig. 4 shows a GFRP plate, which was built up in the usual way by laying one sheet of thin prepreg material onto the other, until the desired thickness is reached. In this process it is easily possible to install between arbitrary layers of prepreg any configuration of optical fibres. The following curing process at high pressure and temperature will not destroy the fibres, which, in effect, do not represent a foreign body in the laminat. The only difference between the GFRP-fibres (about 10 µ) and the FORS-fibres (20-100 µ) is the diameter.

Fig. 5 gives a simple example of fibre optic damage detection in laminats. 8 FORS-fibres are integrated in the center plane of the about 2 mm thick specimen. Intensive laser light, coupled into the fibres, makes their path clearly visible even through 1 mm of GFRP laminat.

During the application of strain cycles, a damage inside the specimen starts to spread around the region of the hole. One fibre after the other shows multiple breaks as the damage area grows. After 70.000 strain cycles only one fibre remains intact. The damaged area indicated by the broken fibres is far bigger than the visible damage at the surface.

An example of application to GFRP constructions is the railroad undercarriage structure shown in Fig. 6, which is currently under development for a new german high speed train.

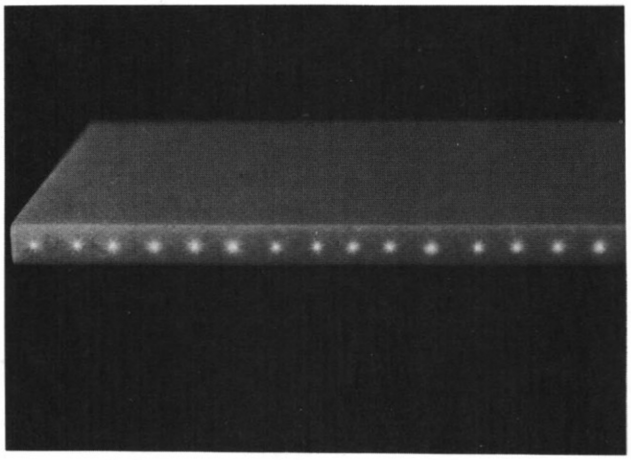


Fig. 4: GFRP laminat with integrated optical fibres.

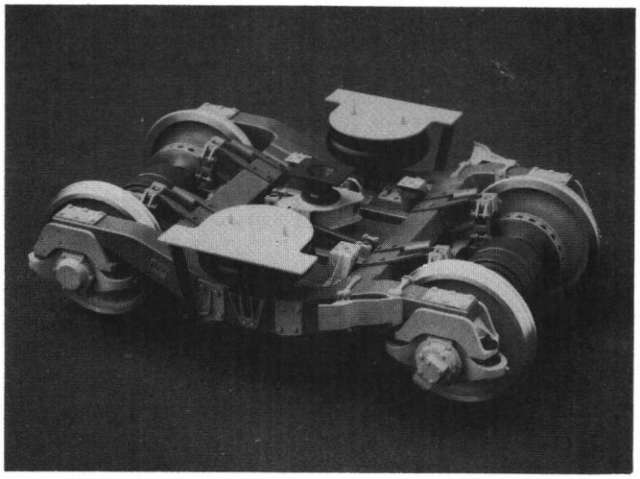


Fig. 6: GFRP undercarriage structure for a new german high speed train.

The main GFRP components are 3 m long and relatively thick, with a rather complex internal laminat configuration. As far as inspection of this complex structure during its life time is concerned, the only Non-Detructive-Test method applicable could be computer-tomography, which requires a very high effort in cost and time. So the demand was for a quick and simple inspection tool to check at least the most vulnerable areas at certain inspection intervalls with no need to take the train waggon out of operation and to disassemble it.

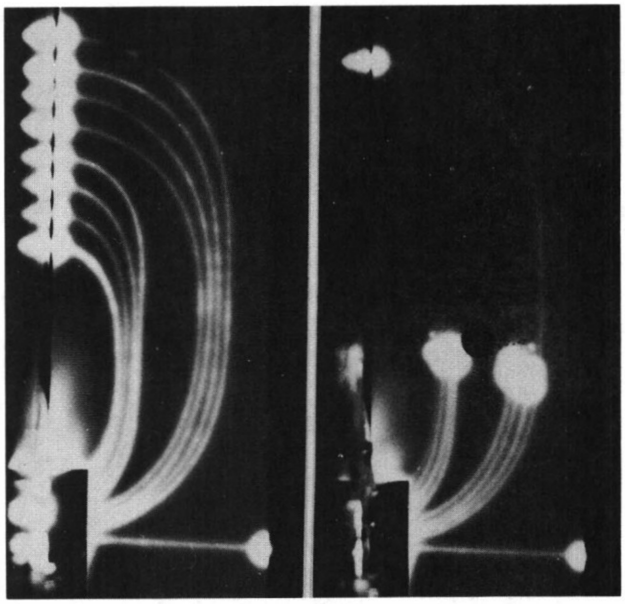


Fig. 5: A tensile test specimen made of GFRP with 8 optical fibres incorporated between two center laminate layers made visible by laser.
The left-hand photo shows the specimen in a perfect condition, the right-hand photo reveals the condition after fatigue test. The fibres indicate interior damage to the laminate long before any external damage becomes visible.

The solution to this problem was a fibre optic damage detection system, consisting of numerous fibres being routed in various layers through the component, ending at the well accessible front and back sufaces. The manufacturing process made use of GFRP prepreg ribbons, so the integration of the 3 m long sensitive light conducting fibre bundles could easily be done by off-line production of prepreg pairs, with the fibres integrated in between (Fig. 7). These optical prepregs could be handled and installed just as the ordinary ones. The check of the complete structure is easily done by illuminating one structure-side with a common light source and observing the completeness of light spots at the opposite end.

IV. Applications in CFRP

In aircraft design, the demand for weight reduction leads to a rapid increase of components made of Carbon Fibre Reinforced Plastic (CFRP). Nowadays operating Airbus planes are equiped with spoilers, airbrakes or the fin manufactured in CFRP technology. For future Airbus generations it is planned to design major parts of the

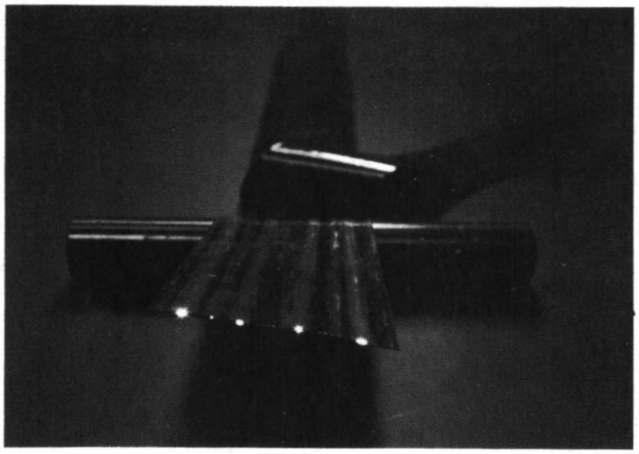


Fig. 7: Prepreg tape with integrated bundles of optical fibres (Each bundle consists of 30 fibres of Ø 30 μ)

airframe entirely in CFRP. Therefore at MBB a development program is running where typical components of a future CFRP airframe (Fig. 8) are designed, manufactured, and tested. The new material CFRP instead of aluminium implies a change of the inspection methods during the life time of an airframe. Most traditional methods for metal planes fail or work with serious restrictions at CFRP. Here again, optical fibres as integral parts of the composite structure offer the possibility of a simple and quick check, if desired even permanent and automatical. The idea is, to integrate a widely spread system of FORS-fibres into all vulnerable or inaccessible areas of the airframe, to interface this system with the on-board computer and thus to realize a Fibre Optical Nervous System (FONS), giving information in realtime about site and dimensions of a damage.

The development of such a FONS started with the test components of Fig. 8. Some examples are given here, how optical fibres can be integrated into components and what their benefit is.

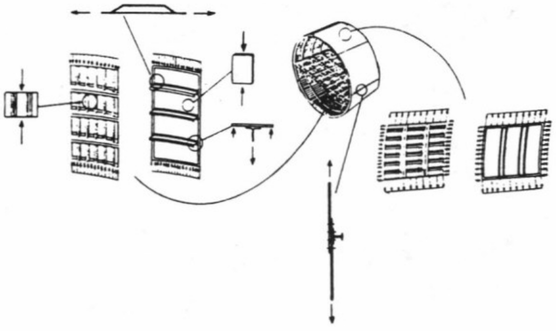


Fig. 8: Overview on development activities for an Airbus CFRP airframe

Fig. 9 shows a part of the plane's skin with two frames on it. The specimen undergoes static pressure tests, which cause the frames to delaminate. During the manufacturing process, optical fibres have been integrated between skin and frame into the wet prepreg material. Numerous

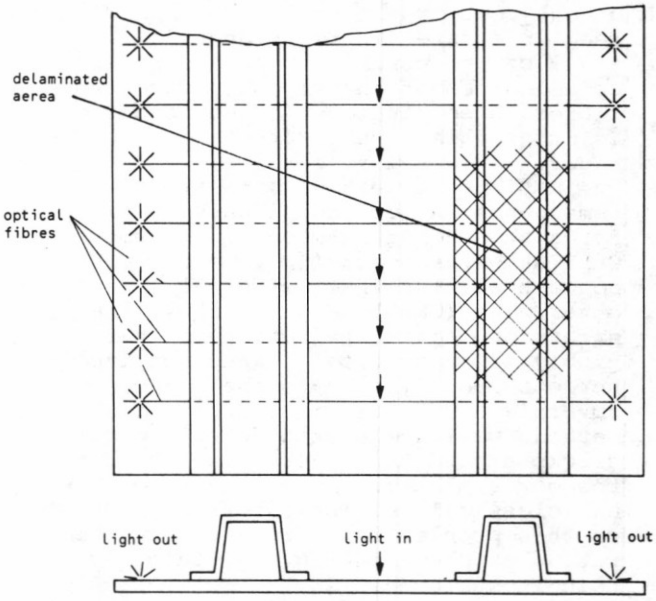


Fig. 9: CFRP specimen (skin and frames) with integrated FORS fibres used as delamination detectors

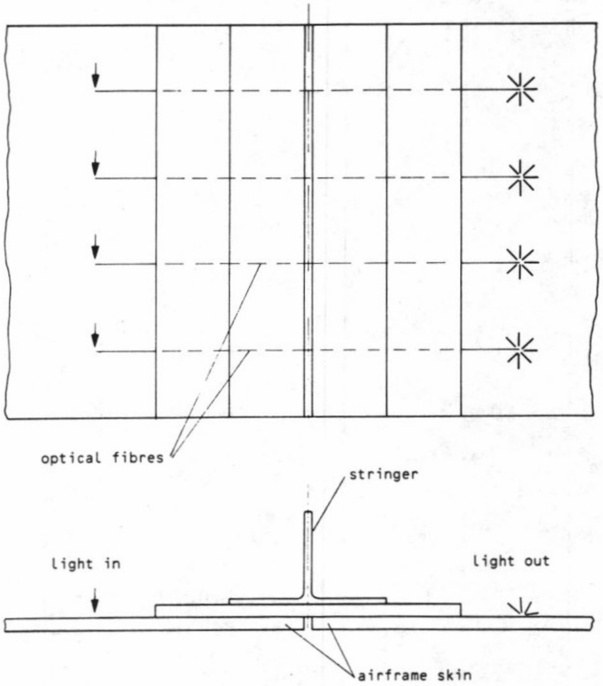


Fig. 10: CFRP specimen (bonded skin joint with integrated FORS fibres used as debonding detectors)

tests with such specimen showed, that all fibres running through delaminated areas were destroyed, and thus represent a reliable and remote sensing detector for frame delaminations. Another example is a skin joint as shown in Fig. 10. The joint is bonded, with FORS-fibres embedded in the bond layer. Again a debonding of the connection destroyed the fibres. A third example (Fig. 11) is a stringer on a honeycomb type of skin. FORS fibres have been integrated in two planes, on both sides of the stringer base and again any delamination of the stringer destroyed the fibres. A conclusion of these experiments is, that this type of system can be considered as a reliable tool to detect delaminations between various structural components. A more complicated example is a skin joint between aluminium and CFRP skins, as occurring in a new wing concept with an inner wing (Alu) and an outer wing (CFRP). Fig. 12 shows the construction. Later inspection of this highly safty critical connection imposes serious problems due to the titanium coverplates. On the aluminium side NDT methods will be able to detect important cracks around the rivet holes through the cover plates, on the CFRP side however all classical NDT methods fail. A solution to this problem is a fibre optic configuration as shown in Fig. 12. Each rivet hole is surrounded in the depth of the laminat structure by a fibre circle, in a distance of 2-3 mm from the rivet hole. Damages around the hole thus will be detected in an early stage. A first manufacturing of such a component was performed successfully, static and dynamic testing will follow.

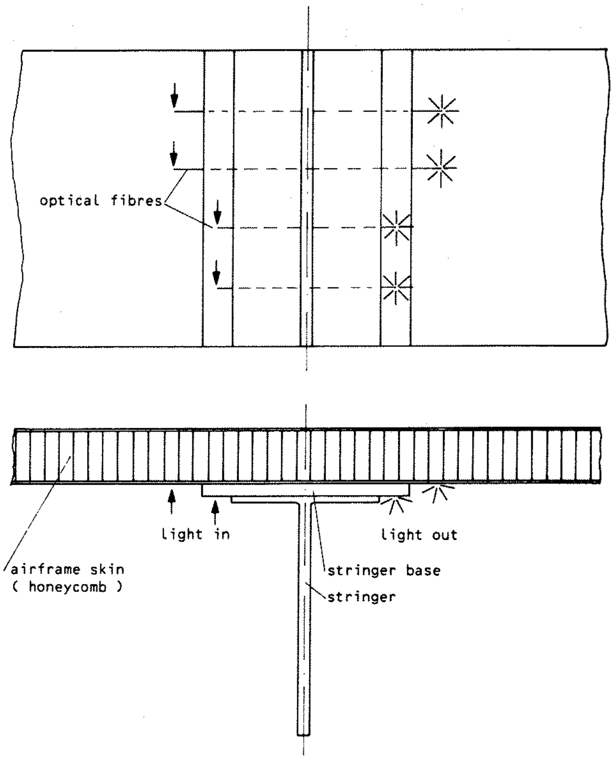
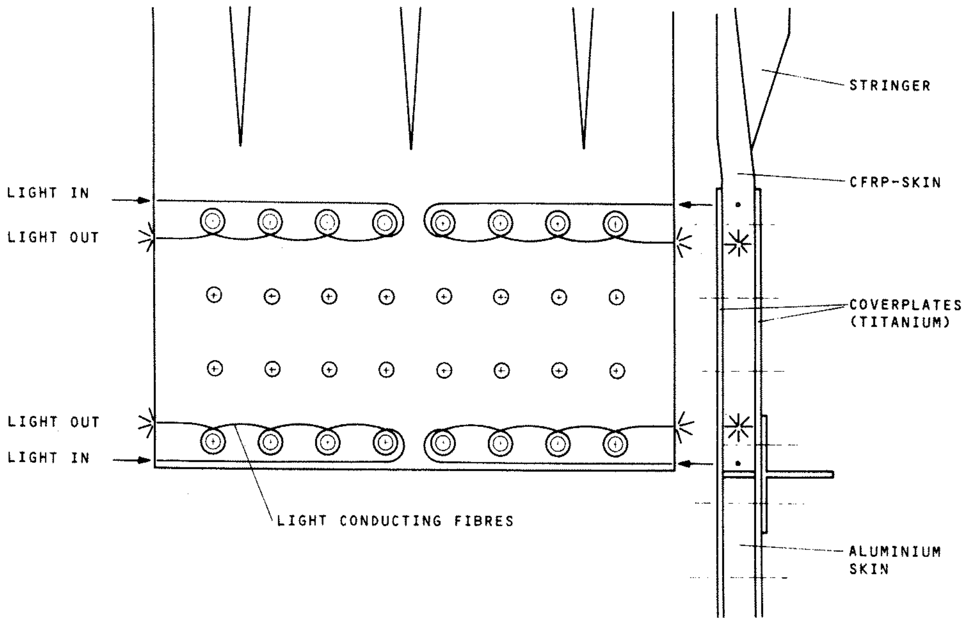


Fig. 11: CFRP specimen (Honeycomb skin with stringer) with integrated FORS fibres used as delamination detectors

Fig. 12: Skin joint between inner wing (Alu) and outer wing (CFRP). CFRP rivet holes are monitored by integrated optical fibres.



There is one strange property of CFRP, which needs special attention in aircraft design and inspection. Fig. 13 shows a flat CFRP - specimen exposed in a test situation to the impact of a high speed steel bullet. This is a simulation of impacts as they can happen to airplanes, for instance during start or landing, when stones on the runway are thrown by the wheels to the planes structure. The surprising effect is, that the front side, where the bullet hits, remains in many cases completey undamaged with no visible marks at all (Fig. 14A), whereas the backside, which is at a real aircraft unvisible and often unaccessible, shows severe damage (Fig. 14B). This effect means a serious difficulty for visual inspection of CFRP airframes. With aluminium all impacts are visible from outside by dents or holes, with CFRP the effect is inside, unvisible. To detect damages of this type, CFRP test specimen, with optical fibres integrated on the back surface and under the first layer of laminat (Fig. 13), were built up. The test results show (Fig. 14), that just the fibres in the damaged area are broken. The missing of the surface fibres 1.5 and 1.6 (Fig. 14c) indicates a damage with about 3 cm lateral extension and the intact inner fibre 2.5 gives the information, that the second layer is not affected.

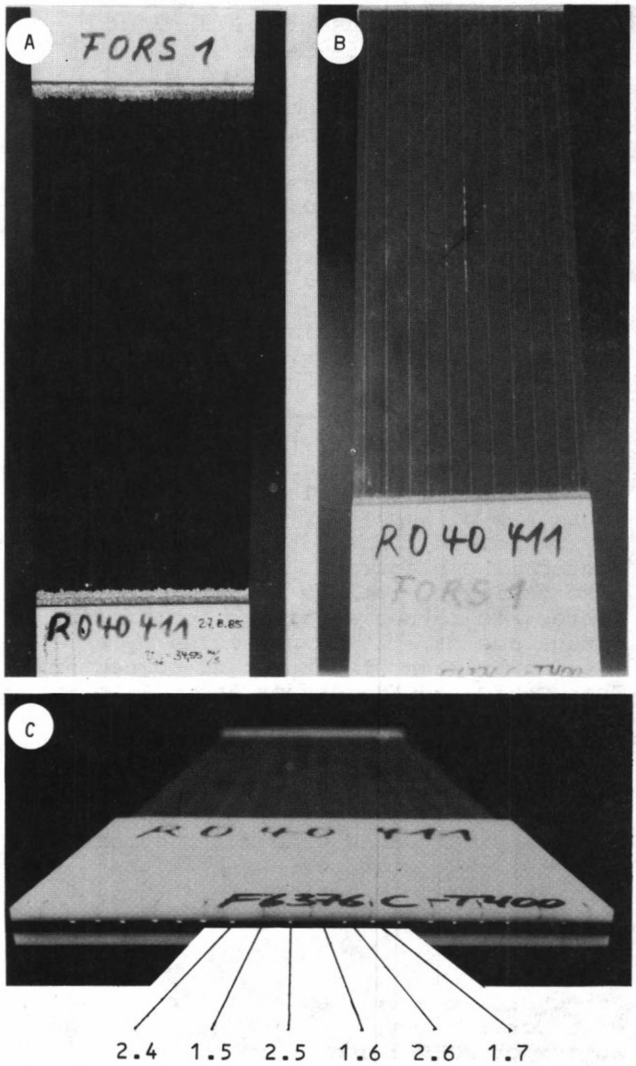


Fig. 14: Impact test specimen (CFRP):

A: View at undamaged frontside
B: View at damaged backside
C: View at integrated FORS fibres

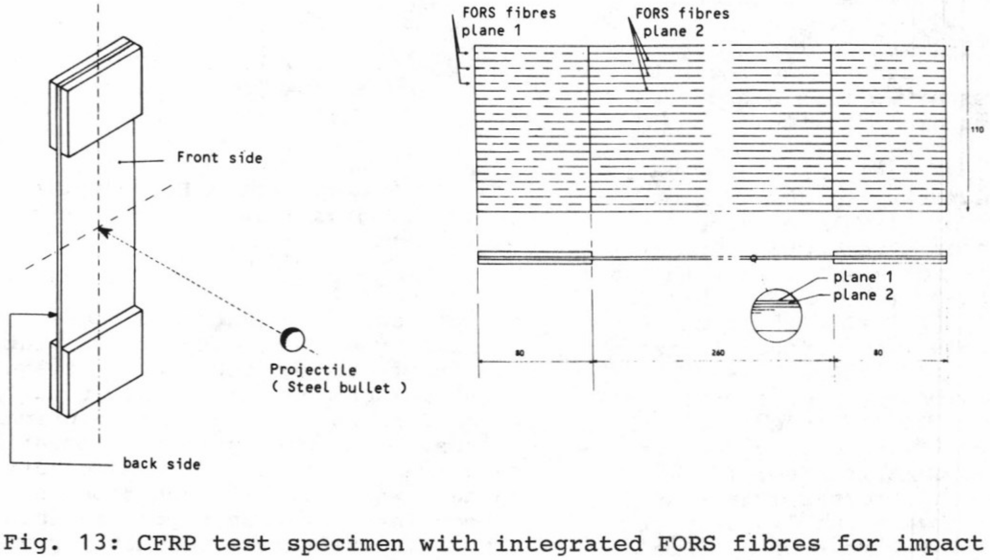


Fig. 13: CFRP test specimen with integrated FORS fibres for impact tests

V. A Fibre Optic Nervous System for CFRP Airbus Structures

All applications in composites presented so far have been of the inspection type, which means, that all fibres simply end at accessible surfaces and are inspected visually by an operator. Professional aircraft applications however, being characterized by numerous and frequently inaccessible or hardly accessible areas, demand for an automatic check procedure with the results displayed in real-time at the available cockpit facilities.

To achieve this, all ends of the integrated fibres (primary fibres) are conducted out of the composite structure and equipped with optical connectors. Thus, the primary fibres are coupled to ruggedized fibre cables, which are routed like electrical cables to optoelectronical units. The thin primary fibres are rather sensitive to mechanical damage and have to be protected by a tube in between structure and connector. The tubing penetrates for about 1 cm into the structure and is installed before curing the composite. The photo in Fig. 15 gives an example of a primary fibre, consisting of a bundle of 30 fibres (each Ø 30 μ), being connected to an optical cable with Ø 200 μ core diameter. The test set-up shown in in Fig. 15 was to monitor in real-time the delamination of frames from the skin.

Structur surveillance in an Airbus type of aircraft clearly will require a high number of FONS-channels in various regions of the plane. Fig. 16 shows a general concept for a FONS, spreading into various structure regions like the wings, airframe skin joints, the bulkhead etc. The multiple fibre channels in each region are adapted to their specific purpose like detection of cracks, delaminations, debondings or impact damages and are all connected directly or via secondary fibres to an optical multiplexer. Only few optical connections are needed to the cockpit, where the neccessary optronic and data processing units are installed.

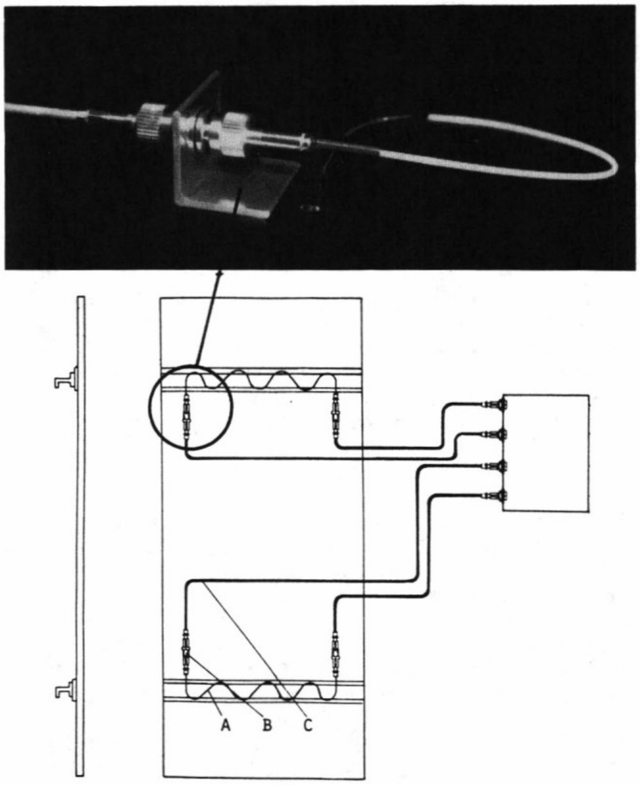


Fig. 15: Test set-up for permanent monitoring of CFRP components.

A: FORS fibres, integrated into CFRP
B: Optical connector
C: Light conducting cable

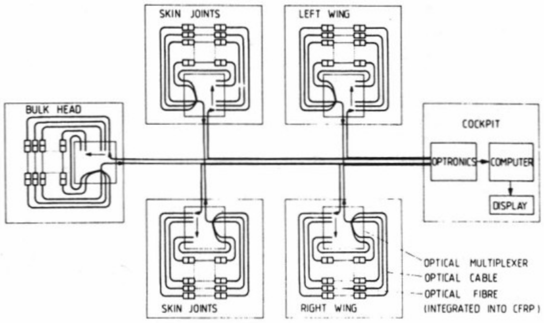


Fig. 16: Concept for a Fibre Optic Nervous System (FONS) for in-flight structure surveillance

A FONS-laboratory model with 50 fibre channels of lengths up to 20 m, integrated into a typical CFRP component, is currently under development. The in total 100 fibre-ends are routed with suitable protection tubes to a fibre optic scanner (Fig. 17). Without using optical connectors, the primary fibres are bonded into the Ø 200 μ holes, arranged in two concentric circles on the scanner disk. The process of polishing 100 fibre end-surfaces is done in one working step on this disk. The mechanical scanning process is achieved by a rotating arm with one light input fibre, scanning the circle with fibre inputs, and one light feed back fibre, scanning the fibre outputs. The latter transports to the cockpit a pattern of light pulses containing the status information about all installed primary fibres. Each scan cycle is initiated by a small, flight qualified electric magnet, whose linear excursion is transformed into rotation of the scanning arm. This mechanical scanning principle is completely insensitive to electromagnetic interference, offers an extremly low cost, weight and volume solution to handle 100 optical fibre interfaces, and is ruggedized enough to withstand the environmental conditions.

Fig. 18, a system diagram of the FONS laboratory model, shows the functional principle of the scanner, its interface to the composite structure and the interface via 2 optical and 1 electrical line to the cockpit. A FONS control unit in the electronics bay provides all neccessary functions like scan initiation, interpretation of scanner data,detection of broken fibres by missing pulses, judgment of criticality,if several neigbouring fibres are broken, generation of maintenance and warning data. All relevant maintenance data is transmitted to the Central Fault Detection System (CFDS), which is accessible to flight and maintenance personal via two CRT displays as shown in Fig. 19 for Airbus A320. Pressing the button "FONS" will initiate a software menue, presenting in any desired detail all status and history information of the installed fibre channels. Thus a clear and deep inside look at the corresponding structure is possible without even looking at it.

Important damages, which are judged by the FONS control unit to be saftey critical, can be displayed spontaneously on the ECAM displays (Fig. 19). (Electric Central Aircraft Monitoring).

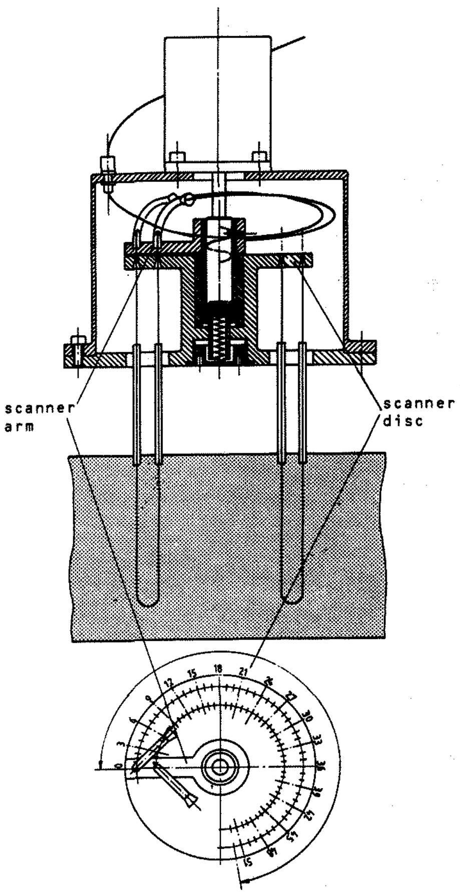


Fig. 17: A mechanical fibre optic scanner for 54 fibre channels

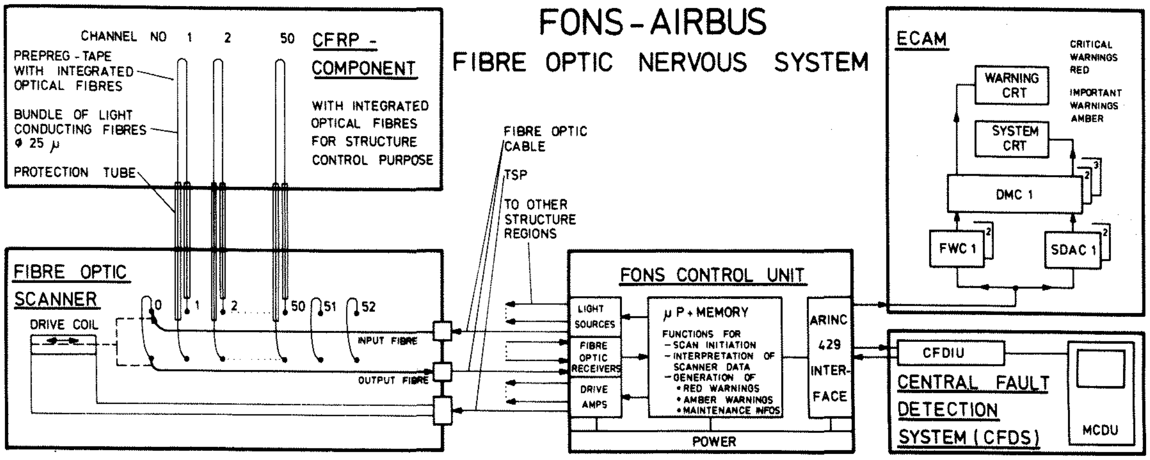


Fig. 18: System diagram for a Fibre Optic Nervous System (FONS) to monitor impact damages at CFRP Airbus structures.

VI. Conclusion

Fibre optic damage detection offers the possibility to change with a moderate effort in weigth and cost the inspection and maintenance philosophy for modern compound structures in the same way, as done already for other aircraft systems like engines, electrical systems and computers. Regular routine inspection can be reduced or even deleted because of the continous availability of up-to-date status informations. Physical system access will only happen upon automatic fault indication.

A welcome side-effect of fibre optic structure monitoring is the experience with optical data transmission on board of civil aircrafts, which can be of advantage when doing the step from the "Fly-by-Wire" to the "Fly-by-Light" technology.

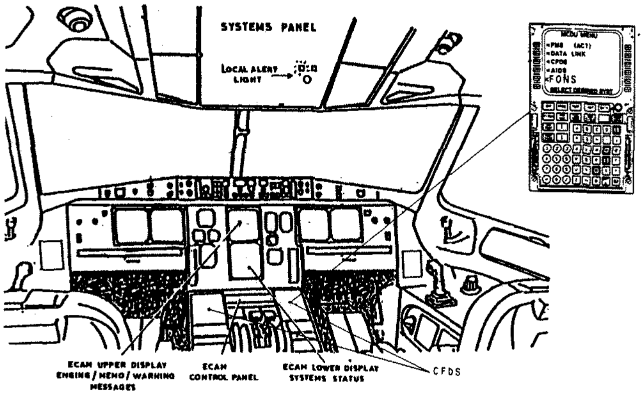


Fig. 19: FONS status information will be available in the cockpit at the CFDS-display (Central Fault Detection System). Safety critical damages can be displayed spontaneously on the ECAM displays. (Electrical Central Aircraft Monitoring)