VERIFYING THE POTENTIAL OF FIBRE OPTIC SENSORS TO MONITOR STRAINS AND CRACKS IN FIBRE COMPOSITES

Ivo Cerny[1]*, George Jeronimidis[2], Jinping Hou[2], Rayner Mayer[3], Albert Bruns[4], Eli Voet[5]

[1]*SVUM, a.s., Areal VU – Bechovice, Podnikatelska 565, CZ-190 11 Praha 9, Czech Republic*
[2]*University of Reading, School of Construction, Management and Engineering, Reading RG6 6AY, UK*
[3]*Sciotech Projects, Sciotech Office, Engineering Building, University of Reading, Reading RG6 6AY, UK*
[4]*NOVACOM Verstärkte Kunststoffe GmbH, Bergstr. 26, 52068 Aachen, Germany*
[5]*FBGS International, Bell Telephonelaan 2H, B-2440 Geel, Belgium*
**Ivo.Cerny@seznam.cz*

Keywords: glass fibre sensors, RTM moulding, thick fibre composites, NDT technique

Abstract
The potential of embedded fibre optic sensors to monitor strains and delamination cracks, especially in thick fibre-reinforced composites has been investigated by moulding beams up to 115 mm in thickness and 3 m in length. In selected beams, optical fibre sensors with high tensile strength have been moulded within 10 mm of the tensile surface. Within the whole experimental programme, the beams have been loaded in 3 point bending to loads up to 160 kN and strains of 1.5%. The immediate observation is that the moulding, curing or post curing does not affect the condition of the optical fibres nor do the fibres affect the strength of the beams. On loading these beams there is a good correlation between the output of the mechanical gauges bonded to the tensile face and the embedded fibre optic sensors, taking into account the difference in strains between the two locations. These observations will enable the monitoring in service use of thick GRP beams for which no other non-destructive test method is suitable.

1 Introduction
For fibre composites to be used with confidence in primary load bearing structures, methods of monitoring strains in service use are essential. However for glass reinforced plastic (GRP) beams with thicknesses greater than say 40 mm, no suitable non destructive test technique is available which limits the range of applications for these materials. So the partners in the Eurobogie project (E!1841) have investigated the potential of fibre optic (FO) strain sensors with high tensile strength, i.e. Draw Tower fibre Bragg Gratings (DTG®s), to monitor strains for components moulded by different methods. Part of this investigation has been to develop a methodology of inserting the sensors and moulding the beams so that neither the fibre's properties are affected by the moulding process nor the beam's mechanical properties by the insertion of multiple optical fibres and DTG®s. The other part was to correlate prediction and measurement making use of mechanical strain gauges. The fibre sensors were manufactured by FOS&S (now FBGS) and are 'draw tower' type gratings, which are fibre Bragg gratings (FBG's) with high tensile strength (~5GPa).

2 Design & testing of hand lay up beams

A series of test plates was manufactured using a leaky mould and laying up each glass fabric layer by hand. Finally two beams were moulded 1000 mm long, 100 mm wide and 80mm thick using 67 layers of a unidirectional glass fabric (OCV Unimat 1136/100) and a high temperature polyester resin (Scott Bader Crystic 199) with Trigonox 44B (Akzo) as catalyst. Three optical fibres were embedded and tensioned using a thermoplastic polyester powder on the 8th layer above the tensile face. The beams were tested in 3-point bending (Figure 1), one beam without a flaw and the second with a piece of polythene sheet 60mm long in the mid centre of the neutral axis to simulate a delamination crack.

Figure 1. Three point bend test of thick beam

A Finite Elements Analysis of the intact and delaminated beams was carried out using Strand 7 FEA Software and the results are summarised below. This was done in order to determine the "best position" for the optical fibre sensors and the changes in bending strains in the longitudinal direction "seen" by the optical fibre sensors as a function of delamination length. All simulations have been carried out for a vertical load of 200 kN. Because of the loading, the FEA calculations have been done using plane stress, 2D 8-noded quadrilateral elements with anisotropic properties. The beam thickness is subdivided into 34 elements (each 2.7 mm thick, corresponding roughly to two layers of unidirectional glass tape) and its length into 40 elements 12.5 mm long.

FEA of loaded intact beam – At 200 kN the predicted central deflection of the beam is 20.97 mm, which is close to the theoretical displacement of 18.8 mm. The difference may be due to additional deformation under the loading points which is not considered in the theory. At this load the maximum bending strain (tensile or compressive) is of the order of 1.25% -1.5%. In reality, the bogie maximum allowable strain is limited to 1%. The maximum interlaminar shear stress obtained from the FEA model is about 19 MPa.

FEA of beam with delamination crack – Figure 2 shows the distribution of bending strains in the beam for delamination lengths at the centre of the beam at mid-thickness of 25, 75, 125 and 175 mm. There are two calculations for a delamination of 125 mm, one using contact elements to prevent the "closure" of the delamination [Delam 3 (125 mm) C in the legend of

Figure 2] and one without [Delam 3 (125 mm)_NC]. In all cases the delamination is modelled with a separation between the elements of 0.9 mm in the delaminated region. It is clear from Figure 2 that when the delamination "appears" the bending strain across the thickness of the beam changes showing a jump at the delamination discontinuity. The jump increases as a function of delamination length. Modelling the delamination with or without contact elements between the delaminated surfaces seems to have a negligible effect.

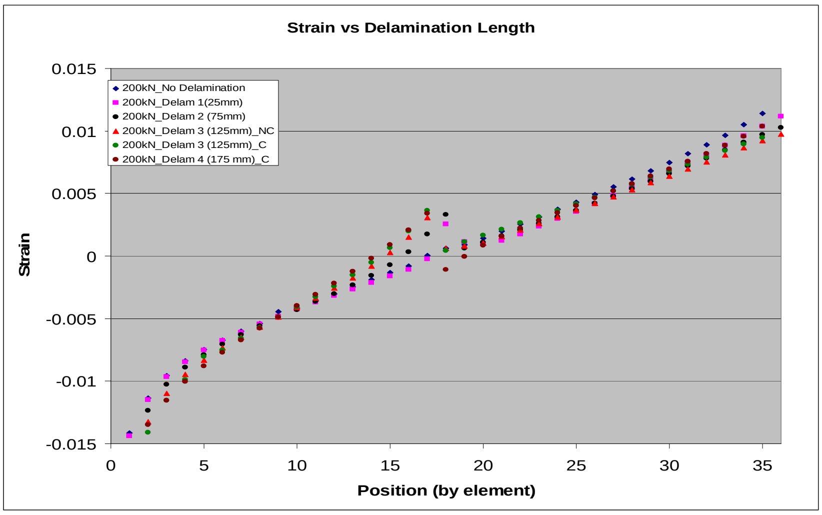


Figure 2. Bending strain distributions across beam thickness in the delaminated beams. Beam mid-plane corresponds to element 17

Assuming that the optical fibre is located 8 glass layers below the surface on the tensile side of the beam in bending (about 10 mm from the surface), the simulated change of strain measured by the optical fibre sensor in this location is shown in Figure 3. This shows that at the position of the optical fibre there is a change of strain of about 800 microstrains going from the intact beam to the beam with a 25 mm delamination (under the same load). As the delamination increases, the change with respect to the intact beam increases but only slowly. The biggest change is between intact and 25 mm delamination. These results suggest that two optical fibre cables per beam should be sufficient to measure the response of the optical fibres in the intact and delaminated beams and a neutral axis delamination of 50 mm at the centre of the beam should provide enough difference in strain to be measurable.

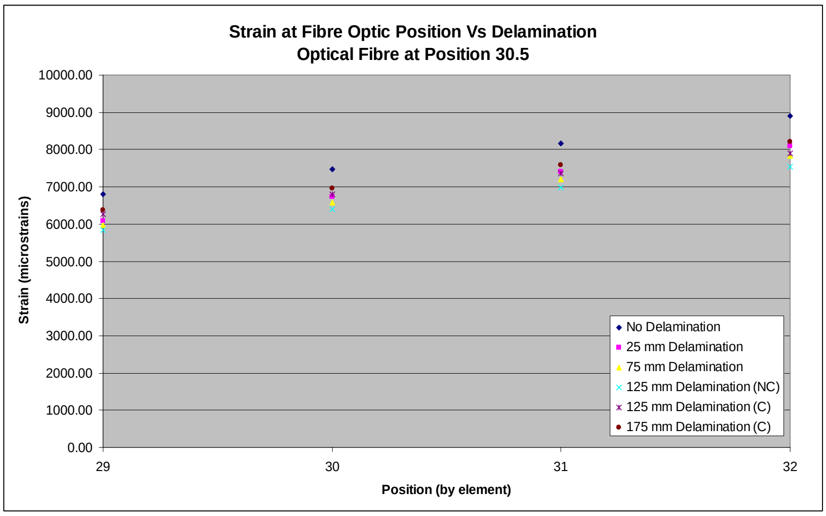


Figure 3: Simulated bending strain changes at the position of optical fibre as a function of delamination length

3 Modelling the side arms of the bogie frame

MARC/MSC software was used to carry out a similar analysis on the side arms of the lower GRP bogie frame (Figure 4) to determine the best location of the optical fibre sensors and to estimate the strain change introduced by a delamination at the centre of the beam. Figures 5a and 5b show location of the maximum interlaminar shear strain without and with delamination near the wheel set.

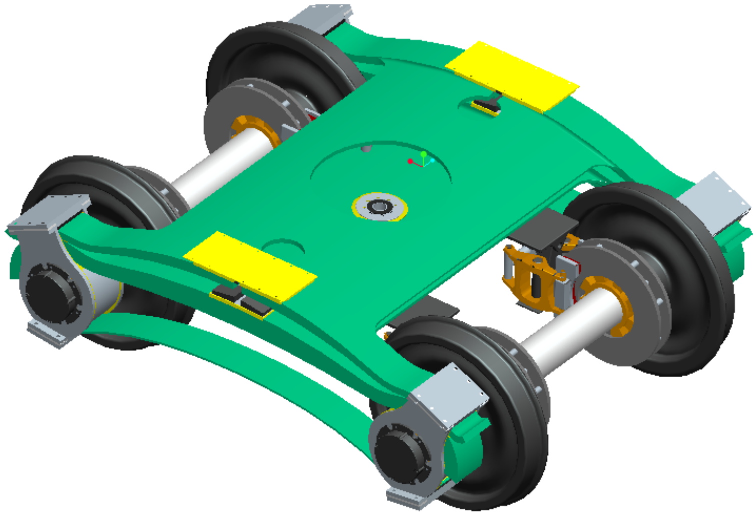
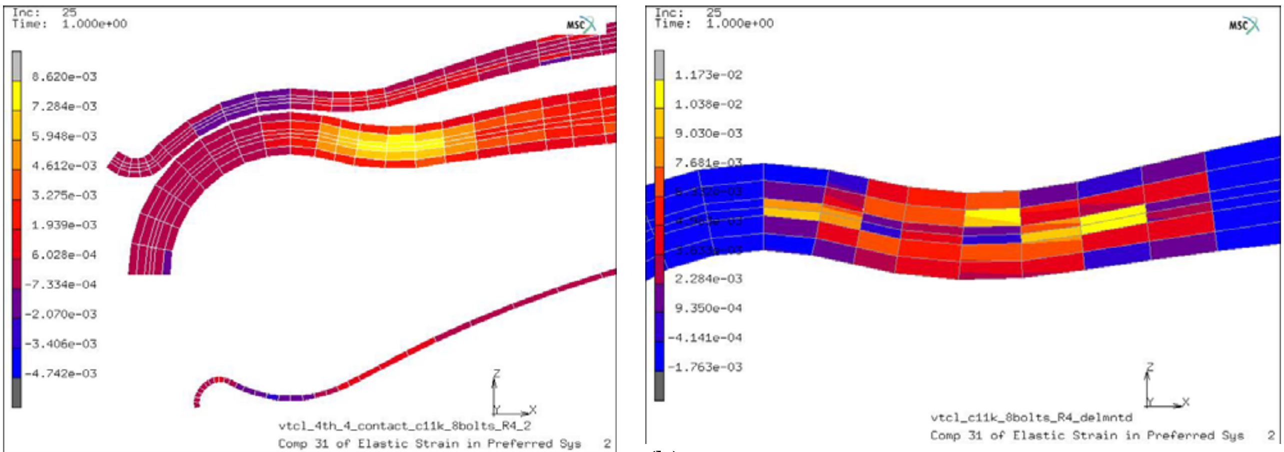


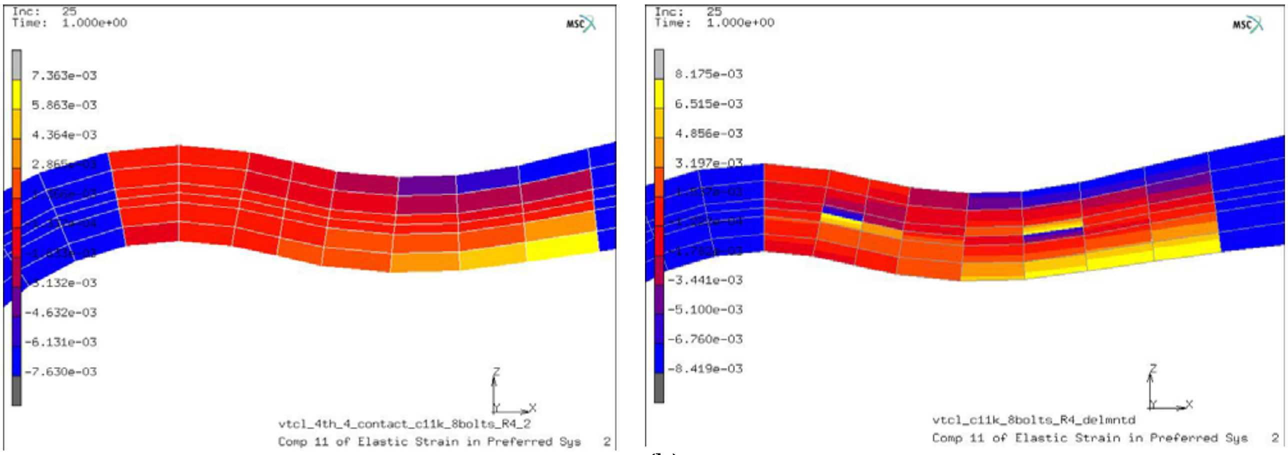
Figure 4. Fibre glass bogie frame



(a) (b)

Figures 5a & 5b: Location of the maximum interlaminar shear strain of the bogie under vertical load without (a) and with (b) delamination.

The maximum shear strain changes significantly with the introduction of the delamination which is about 100 mm long. Figures 6a and 6b show the distribution of normal strains across the thickness of the bogie side-frame beam without and with delamination, respectively.



(a) (b)

Figures 6a & 6b: Distribution of normal strain parallel to the fibre direction of the bogie without (a) and with (b) delamination under vertical load.

What is important is the change of normal strain due to delamination at the planned location of the optical fibres 10 mm from the tensile surface. Figure 7 shows the change in normal strains before and after delamination near the top surface of the bogie frame beam. The change in normal strain is of the order of 300-500 microstrains, sufficient for the optical fibres to be able to register.

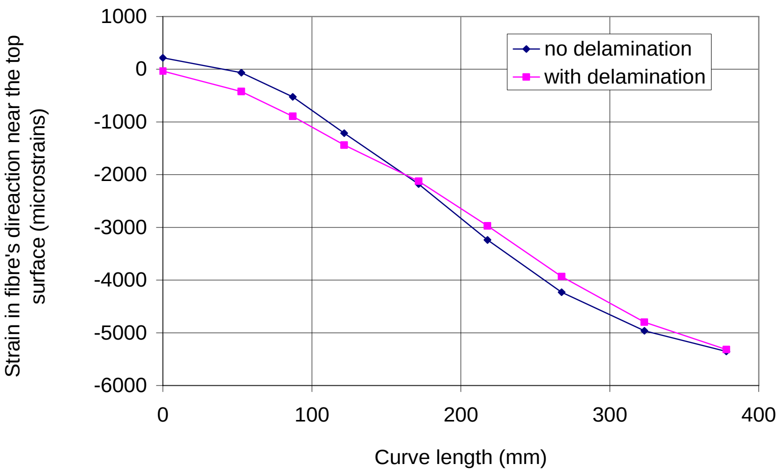


Figure 7 Comparison of normal strains close to the top surface of the bogie with and without delamination

4 Moulding and testing the side arm of the lower bogie frame

The side arms of the lower GRP bogie frame (Figure 4) are 3.0 m long, 192 mm wide with a thickness tapering from 115 mm in the centre to 75 mm adjacent to the wheel sets. Some 104 layers of uni-directional glass fabric were successively laid up laid up inside a dedicated 4 part mould. As with the hand lay up beams, 4 optical fibres were tensioned on the 10th fabric layer from the tensile surface and then the remaining 94 glass layers added. The out coming (egressing) FO cables were then wrapped in a protective polystyrene box, the mould closed and catalysed resin injected and cured. The 84 kg beam was then demoulded and post cured up to 120 C. After post curing, the FO sensors were checked to ensure that the moulding and subsequent curing had not induced change in the condition of the sensors. Like with the hand laid up beams, no change was detected.

The side frame sub-assembly was completed by adding the side arms of the upper frame, the two axle boxes with their stub axles and the axle tie. The sub assembly was then bolted together and placed inside a reaction frame which allowed the stub axles to rotate on a rail each side of the assembly (Figure 8) so enabling the span to vary from 2000 mm at no load to 2040 mm at 200 kN. The loads were applied to the top of the upper side arms via a servo-hydraulic actuator.

Figure 8. Side assembly bogie side undergoing testing

Foil mounted strain gauges (SG) mounted along the lower (tensile) surface of the beam were compared with FO sensors (DTG®s) at 230 mm and 750 mm from centre (Figure 9) – that is SG2 & SG5 with FO4b; SG 4 with FO4a; SG 7 with FO2b and FO3a.

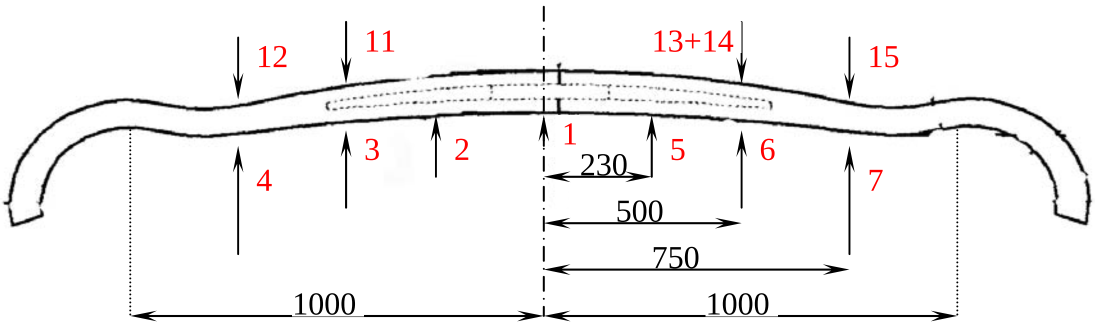


Figure 9. Side arm beam with position and number of strain gauges

There is a linear response to load of both sets of sensors for varying loads up to 160 kN depending upon the location of the gauges/DTG®s along the length of the beam. For similar located gauges/ DTG®s, the strains, as expected, are somewhat lower for the FO sensors located 10 mm inside the beam than at the surface where the foil SGs are located (Table 1).

Load (kN)	SG2	FO4b (μstrain)
40	1050	1000
50	1300	1250
60	1600	1500

Table 1. Strains measured by SG and FO gauges/gratings located 250 mm from beam centre

The strains are always greater near the centre of the beam than at the ends which are supported by the axle boxes (compare Table 1 and Table 2). The strains in the beam are asymmetric because initially there were more visible delamination cracks along the left hand side of the beam than on the right hand side (Table 2).

Load (kN)	Left of centre SG4	FO4a (μstrain)	Right of centre FO1b	SG 7 (μstrain)
40	800	600	430	(-200)
50	960	730	500	
60	1150	800	550	600

Table 2. Strains at 700 mm either side of centre for SG and FO gauges/gratings

However when the load was increased above 65 kN, the existing delamination cracks along the neutral axis lengthened and further delamination cracks grew beneath the neutral axis (see Figure 8). This resulted in all FO strains increasing but particularly to the right of centre where the delamination crack on the neutral axis extended beyond the axle box.

5 Discussion

A method has been developed of tensioning and embedding FO sensors into glass reinforced plastics in a way that neither affects the performance of the sensors nor that of the component. The strain output of the FO sensors correlates very well with that of bonded foil strain gauges. However subsequent fatigue tests showed that the FO sensors are more rugged and better able to withstand cyclic fatigue because they are fully bonded around their circumference to the resin matrix whereas the mechanical strain gauges are only bonded on one face.

Of equal significance is the ability to burn up to 10 DTG®s along a 3m length of fibre optic cable so enabling the strain distribution to be measured along the length of the beam. This is of particular importance for delamination cracks which can arise anywhere along the length of the beam and do not necessarily grow symmetrically as illustrated above.

The difference in strains between left and right hand side of the beam indicate the presence of a delamination cracks which were also observed visually because the critical crack length is in excess of 100 mm in these beams. The strain differential in Table 3 is about 600 to 700 μstrain which is of a similar magnitude to that predicted by the finite element analysis.

Load (kN)	Left of centre (FO4a) (μstrain) before	after	Right of centre (FO1b) (μstrain) before	after
40	600	820	430	1460
50	730	1100	500	1650
60	800	1200	550	1830
100		1300		2080
130		1380		2000
160		1400		1900

Table 3 Strains at 700 mm either side of centre for FO gratings at loads below 65 kN and after increasing the load to above 130 kN

What we have yet to demonstrate is that the same set of FO sensors can be used to monitor the flow of resin along the length of the beam during the resin transfer moulding and then to record the distribution of the exothermic temperature rise during subsequent cross linking and curing of the polyester resin. For very thick components, our results show that the exothermic temperature rise has to be kept below 60 C. Such an outcome would enable the quality of each moulding to be assured.

This study is of critical importance to the successful development of our glass fibre bogie as by embedding such glass fibre sensors inside the side arms of the bogie frame, it will be possible to monitor strains in service and so detect delamination cracks below the critical crack length.

6 Conclusions

Our results demonstrate the potential of fibre optic sensors with high tensile strength to monitor both strains and the growth of delamination cracks in primary load bearing components manufactured from glass reinforced plastics. This will enable such materials to be introduced into the railway industry which has lagged behind all the other transport sectors in securing the benefits of reducing mass.

This potential can only be realized by further demonstrations of the type that are being undertaken within the Eurobogie project and an industry and society willing to invest in introducing new suitable NDT technology.

7 Acknowledgements

The authors wish to acknowledge an R & D grant from the UK Department of Trade and Industry (now administered by the Technology Strategy Board).