EVALUATION OF THE STRAIN FIELD IN A COMPOSITE – METAL ADHESIVE JOINT WITH AN OPTICAL BACKSCATTER REFLECTOMETER

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Abstract
Knowing the strains and stresses in an adhesive joint is critical for the understanding and proper modeling of adhesive joints. To find a good method for measuring this has been a part of the work done by FP7 Co-Patch research program. Since the adhesive is sandwiched between the adherents the strains in the joint areas are difficult to measure. Movements of the entire joint can be measured with displacement transducers or crack opening can be measured with clip gauges. But these methods only allow an indirect evaluation of the conditions in the adhesive joint.

1 Introduction
Most large steel engineering structures will develop some cracks during their lifetime. Usually these cracks are repaired by welding, but in some cases the hot work associated with welding makes the welding repair unattractive. Examples are Floating Production and Storage Offshore units (FPSO) or tank ships, where hot work could cause fire and explosions [1,2]. Welding can only be done if production is shut down and all oil and gas is removed. Similarly electrical cables or other coatings on cruise ships may suffer from the hot work. Infrastructures like bridges are also often difficult to weld.
A method to avoid welding is patching with composite laminates. In this case the crack or corroded area is bridged by a patch made of a composite laminate. Stresses are transferred around the defect by the laminate, preventing the crack in the metal from growing further. The patch repair can be done without any hot work. A schematic of a patch repair is shown in the upper part of Figure 1. The crack in the metal is bridged by the composite patch. An adhesive layer lies between the composite patch and the metal. If the patch is made of carbon fiber composite the adhesive layer is usually called a galvanic corrosion protection layer. It is filled with a glass mat, ensuring that there is no electrical contact between the carbon fibers and steel that could lead to galvanic corrosion.
The main technical challenge is designing and producing a strong and durable adhesive joint between the steel and composite. The joint studied here was a carbon fibre laminate patched over a cracked metal I-beam. This type of test has been used successfully before to characterize joints [1,2] and it has been adopted recently in DNV´s recommended practise for composite patch repairs [3].

Getting a better understanding on how adhesive joints work and eventually fail will be essential for wider use of this technology, especially long term use in critical application. A good method is needed to measure strains in the adhesive joint system during an experiment. These measurements can be compared to stress analysis done by the finite element method allowing improvement of modeling techniques leading to better designs. The strain measurement system investigated here is an optical fiber coupled to an Optical Backscatter Reflectometer (OBR). The optical fibre was glued onto the top surface of the patch, and embedded inside the patch between the galvanic protection layer and the carbon fibre laminate. Strains could be measured continuously along the entire length of the optical fiber.

2 Strains in an adhesive joint

It is well known that adhesive joints work by transferring shear through the adhesive layer from one substrate to the other. The shear stress has typically a stress concentration at the edges of the adhesive joint and lower shear stresses in the middle [4,5]. The shear stress distribution is often referred to as the “bathtub curve”. In the case of a patch repair stress concentrations are also present at the mouth of the crack in the metal, as shown in Figure 1. The system can be seen as two adhesive joints in series with two “bathtub” curves.

It is not possible to measure shear stresses directly. But the shear stresses cause axial stresses and strains in the adhesive interface and the composite patch laminate. These axial strains can be measured by the optical fiber, as shown on the bottom of Figure 1. Any change in the shear stress distribution due to damage development will result in changes of the axial strain. It is also important to note that the axial strains will change through the thickness of the laminate. Adhesive joint models analyze typically the stresses right at the interface. Going away from the interface towards the surface of the patch the strain concentrations will be reduced due to redistributing stresses by interlaminar shear.

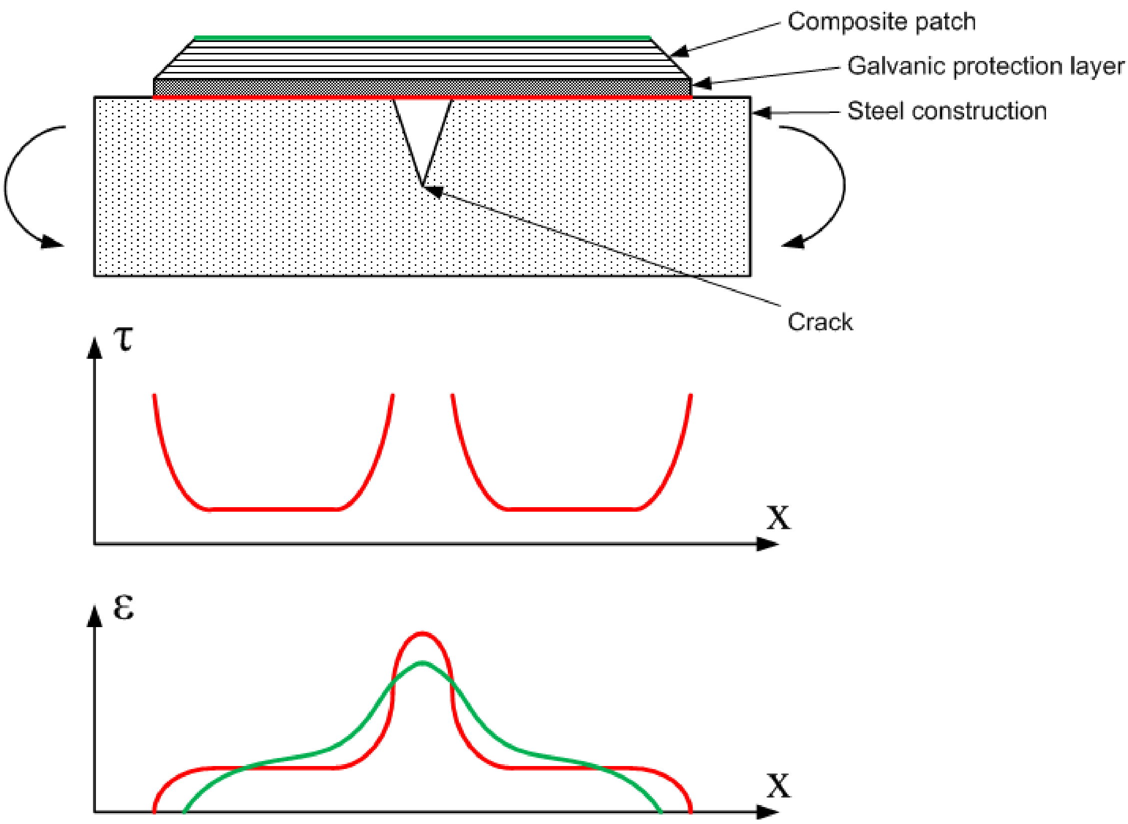

Figure 1. Shear and strain stress distribution between the galvanic layer and composite patch.

3 Optical Backscatter Reflectometer

Fibre bragg grating (FBG) and especially electrical strain gauges are well known and acknowledged methods to measure strains locally on a structure or specimen. It is difficult to decide where to place the strain measuring points. The strain concentrations shall be evaluated and compared to smooth far field strains. However, it is not known in advance where the strain concentrations will be if damage develops and moves them. The system used here allows continuous strain measurement along the optical fibre making the placement much easier.

The system is called Optical Backscatter Reflectometry (OBR) and consists of a tunable laser source and an Optical Frequency Domain Reflectometer (OFDR), used to measure the Rayleigh backscatter, in an interferometry setup [6]. Interferometry enables the system to measure the amplitude and the phase of the Rayleigh backscatter and with the help of Fourier transform [7] they are able to get information about changes in the backscatter profile and the position along the length of the fibre [8]. The use of multiple wavelengths in swept wavelength interferometry (SWI) enables the system to achieve high spatial resolution of the measurements.

The Rayleigh backscatter profile of fibre optic cables is a result of a heterogeneous reflective index, randomly distributed along the length of the fibre. This is a result of the manufacturing of the fibre and is unaltered until any external stimulus (like strain) causes a temporal and spectral shift locally in the backscatter pattern [6]. These shifts are used to calculate the changes in strain along the length of the cable when compared to the unstrained reference state.

4 Experimental method

Four point bend testing was used to measure the strains in the patch. An IPE100 beam was tested with a composite patch repairing a pre-made crack in the top flange. The loading span was ½ of the support span. The width of the support span was 800 mm and the load span was 400 mm (see Figure 2). The shear web will achieve low shear stress and constant moment between the load span.

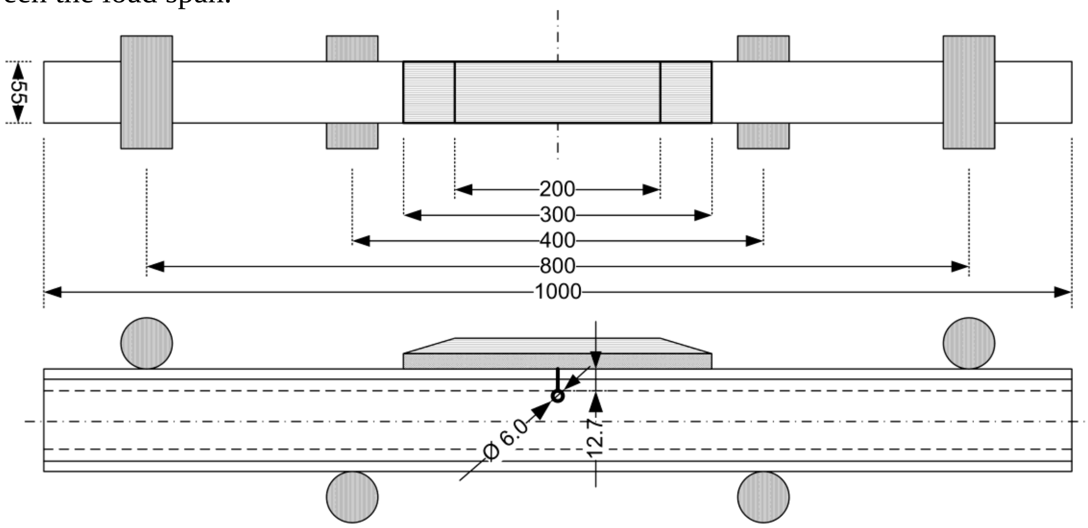

Figure 2. Experimental setup for a 300mm patched IPE100 beam with four point bending and 1/2 loaded.

The thickness of the carbon laminate was calculated to achieve the same stiffness as the cracked flange. The laminate was tapered at both ends to reduce peel stresses. The stresses will be highest near the opening of the crack in the metal beam. The fiber direction of the laminate was unidirectional, with the fibers running along the long axis of the beam.

The fiber optic cable was embedded between the carbon laminate and the galvanic protection layer, and it was attached to the surface of the patch. In addition, four electrical strain gauges were attached to the surface of the patch to compare the strain at these positions with the strain measured by the fiber optic cable.

Figure 3. Experimental setup at NTNU Fatigue lab of the patched IPE100 beam.

5 Materials

5.1 I-Beam

The beam used for the experiment is a 1m long PE100 beam with steel grade S355J2 [9]. A 20 mm long crack was machined in the middle of the top flange, i.e. 500 mm from the side. The crack passes through the top flange, and barely into the shear web, where it is terminated by a 6 mm diameter hole. A broach was used to reduce micro cracks around the hole.
The bonding area of the patch was cleaned according to ISO procedure [10], and grit blasted with a surface quality of SA 2½. The surface roughness was 136µm.

5.2 Patch

The grit blasted area was coated with a chopped strand matt (CSM) right after the surface treatment. This coating works as a galvanic protection layer, and the fiber optic cable for the OBR is applied at the middle of the flange over the whole patch length (300 mm). The patch was applied with a vacuum assisted infusion process.

6 Finite element analysis

A numerical model of the patch repaired I-Beam was done in Abaqus 6.11-1. Linear Hexahedron C2D8R elements were used over the whole model, and the maximum element aspect ratio was below 9. Standard material properties were used for the I-Beam with plasticity characteristic from the I-Beam material certificate. The CSM was modeled with engineering constants without plasticity, and the carbon laminate with ply property engineering constants measured by the Co-Patch project according to the standards [11-14].
Constraints between the three parts, I-Beam, CSM and patch are made with tie constraints. The parts are sharing the nodes, and parts are sectioned at the same places. Number of elements in patch are 13 440, galvanic protection layer 4560 and I-Beam 75 136, this gives a total of 93 136.
Symmetry plane for the I-Beam is over the area yz-plane in the shear web and neighboring surfaces in same plane. Also under crack ligament in the shear web to the bottom flange,

patch and galvanic protection surfaces in z-direction have the symmetry over the yx-plane. The load span is fixed by the nodes in y-direction, and support span contribute with displacement in negative y-direction. A stress distribution in the length direction is shown in Figure 4.

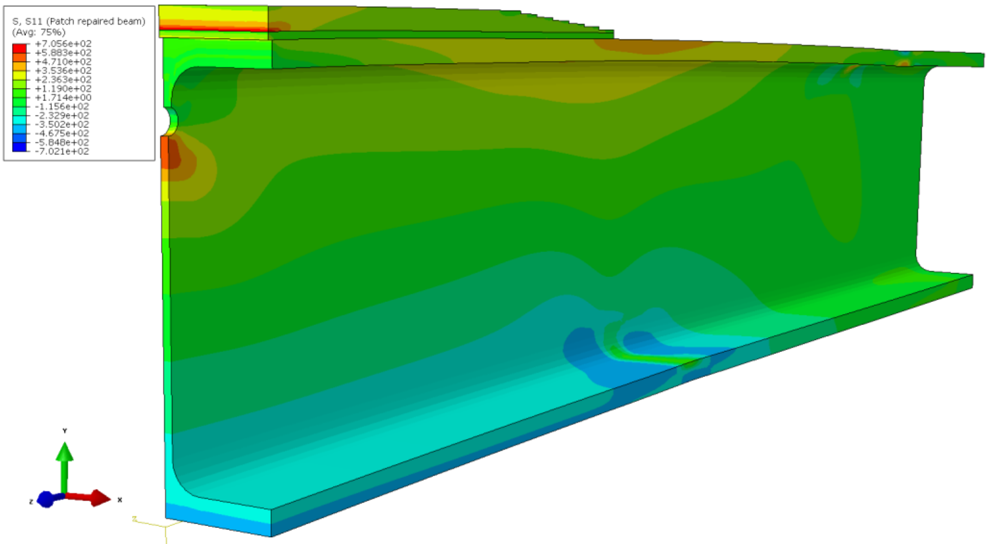

Figure 4. Numerical model for the patch repaired I-Beam. S11is stresses in z-direction.

7 Results

Testing of the I-Beam was done with 0.3 mm/min in displacement control. With this displacement speed, it was possible to do measurements with the OBR without holding the test. Measurements were done with the OBR every 10kN. Presented here is the comparison of measurements at two load levels: one within the linear elastic area, and one closer to failure and plastic behavior. Measurements done with strain gauges are presented live during the loading of the test, but results from the OBR are ready after some post processing.

7.1 Reading at 71 kN

The strain measurements from the optical fibre on the surface of the patch coincide well with both the FE-analysis and the electrical strain gauge readings. The strain gauge value at the crack is slightly higher than both the FE-analysis and the optical fibre. A reason for this is the 5mm gauge length of the strain gauge, which reads the average value over the length, compared to the 1mm “gauge length” achieved with the OBR. The top surface of the patch was displaced by 5 - 10 mm, hence the measurement with the optical fibre has an offset compared to the symmetrical FE-analysis. The positions of the strain gauge values are according to the placement on the patch surface measured from the center of the crack.

The embedded optical fiber corresponds well with the FE-analysis, except directly over the metal crack.

High strain gradients are a measurement challenge for the OBR. Too big changes will cause the cross-correlating algorithms for the spectral shift to fail. The result of this is sometimes an unrealistic value, seen as noise, but also entails uncertainty in the accuracy of the absolute value of the measurements at high stress concentrations. Improvements are achieved by post processing, but for the purpose of this comparison it is more interesting to evaluate the strain gradient leading up to the crack.

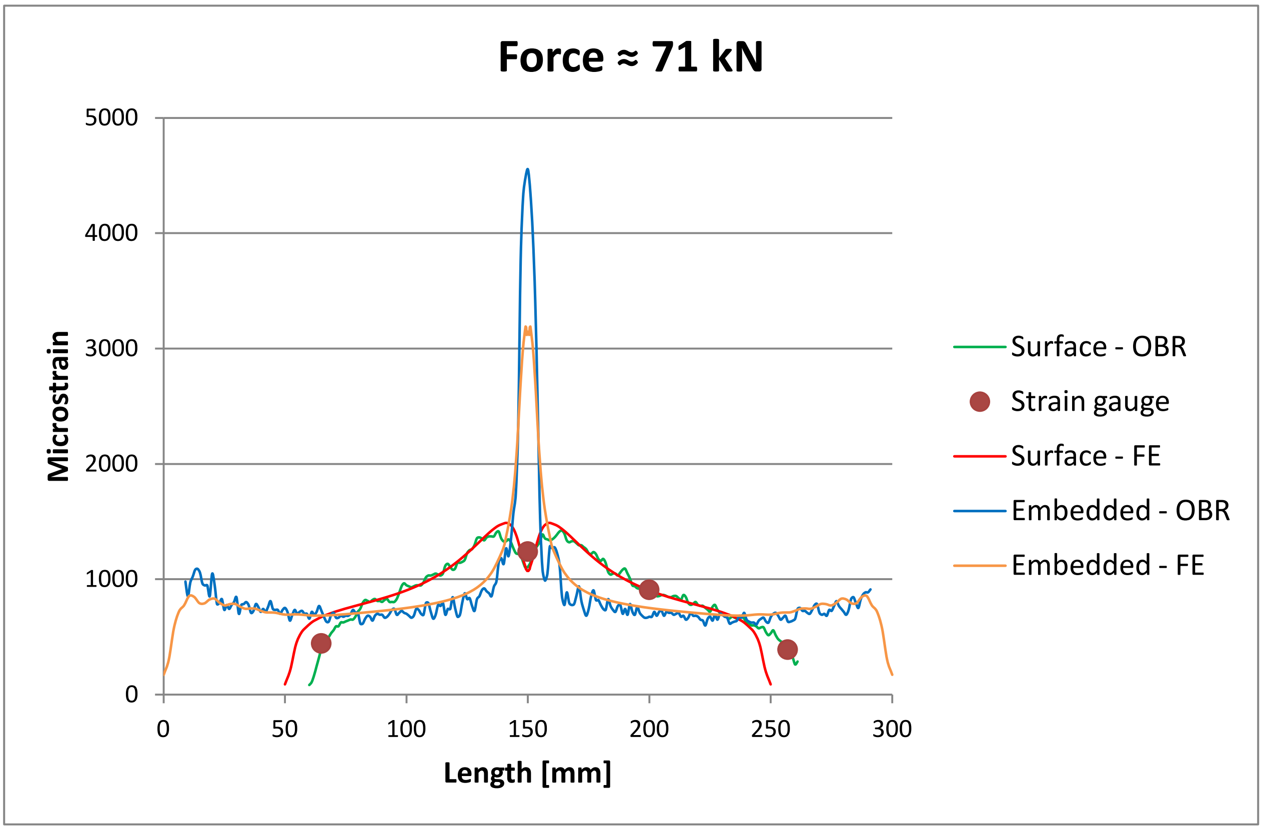

Figure 5. Strain in the patch at 71 kN.

7.2 Reading at 138 kN

The strain measurements of the optical fibre on the surface of the patch agree also here well with the strain gauge readings. However the FE-analysis deviates from the measured strain on the surface. The FE-analysis did not take into the account the possible degradation or cracking of the patch at the metal crack which is expected to happen at this high load. The spatial misalignment between the FE-analysis and the measurement by the fiber optic cable and the electrical strain gauges is probably due to a displacement of the patch, where the patch center is to the right of the crack.

The strain field of the embedded optical fibre is wider than the FE-analysis. This is due the effects of damage appearing at the crack tip, which has not been a part of the FE-analysis.

Future work will look into nonlinear FE analysis using progressive failure analysis to simulate damage growth. This should help to explain how the strain field changes with damage development. However, it is already clear now, that the optical strain field measurement can be used to monitor damage development.

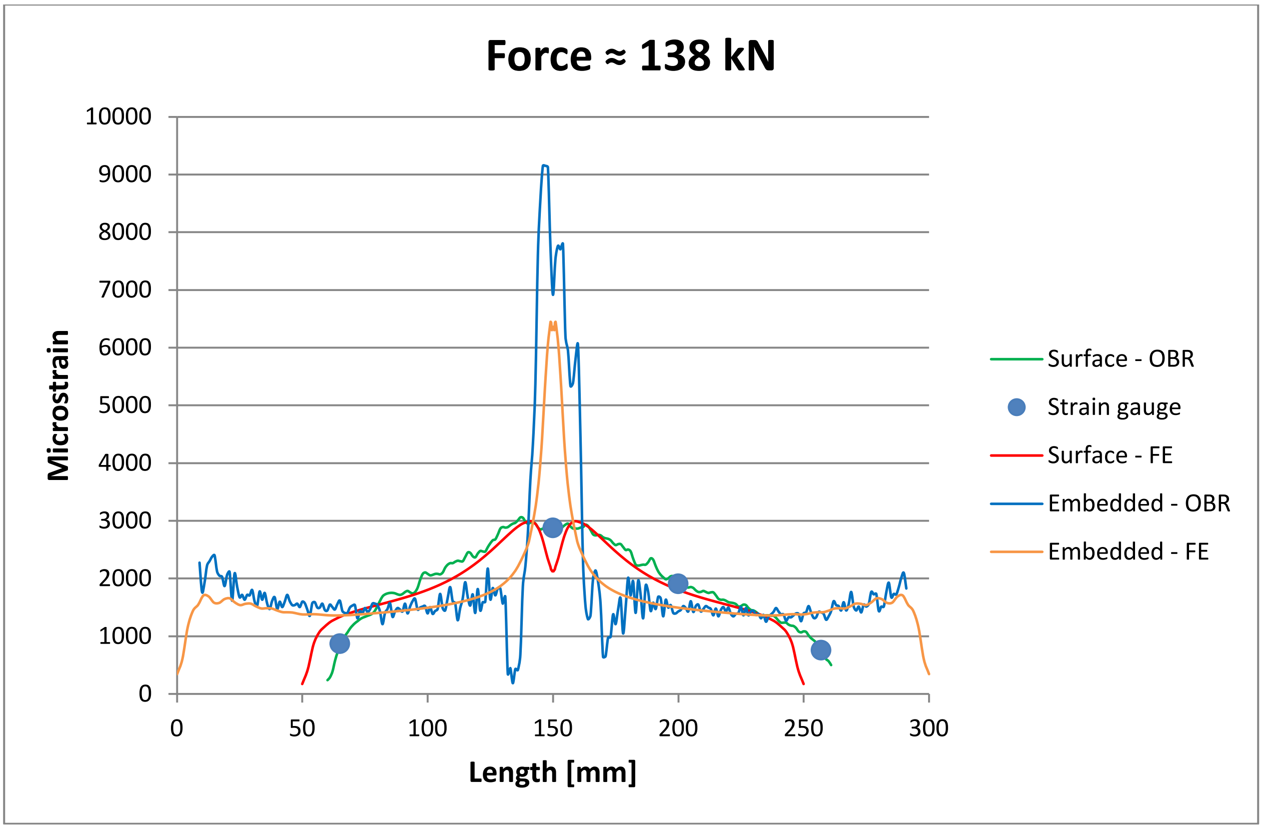

Figure 6. Strain in the patch at 138 kN.

8 Conclusion

The four point bend test has successfully been used to evaluate the repair of a cracked steel beam with a composite patch. The strain on the surface of the patch could be measured continuously with the optical back scatter method. The optical strain measurements agreed with local strain data obtained from classical electrical strain gauges. Strain could also be measured along the length of the sample with an embedded fiber inside the repair laminate at the interface between the load bearing patch and the galvanic protection layer. The strain measurements show that strains differ inside and outside the patch indicating that a 3-D analysis of the stress state in the patch is important.

The strains at low loading obtained from the simulations agreed well with the measured strains both inside the joint and on the surface. At high loads the shape of the experimentally measured strain field changed. The changes are understood to be caused by damage developing in the composite. This damage was not modeled by the linear finite element analysis. Progressive nonlinear failure analysis will most likely be able to relate damage development and observed changes in strain.

It is encouraging that the strain measurements pick up changes in the strain field. This method should have a good potential to be used as an early warning of damage developing inside the patch that could eventually lead to failure.

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