ID-1270

MODELLING AND EXPERIMENTAL ANALYSIS OF THICK CFRP BOLTED JOINTS

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SUMMARY A 24 mm thick CFRP laminate, representative of the root section of a large wind turbine blade, was built and tested. Joining the thick laminate to the steel flange is very critical for the design of the blade. A conventional approach was used concerning lay-up sequence, hole diameter- pitch ratio, and other design parameters for the bolted joint. Scaled specimens were tested first, to obtain empirical design values, such as bearing strength and stress factor, according to the Hart-Smith approach. A bearing failure mode was ensured by design. Two full scale experiments were done, the strain fields was predicted by a FEM analysis, and measured by BG optical fibre sensors, placed inside the joint, at the vicinity of the holes. Good agreement is found at the linear region, up to the initiation of the internal cracking, detected as an audible noise and as the initiation of large non-linear compressive strains. A 50% of overload margin exist from the initial cracking to the final failure, giving enough confidence to the design. These experiments demonstrate the validity and usefulness of fibre optic strain sensors for the experimental analysis of composite structures.

KEYWORDS: bolted joint, bragg grating, strain measurements

INTRODUCTION

The connection between highly loaded primary composite structures and other parts by means of bolts is a complex problem and holes are critical areas. Out-of-plane loads modify its strength and stacking sequence is of great importance. Distance between holes and clearance between hole and bolt affect not only strength but also failure mode.

Tests were carried out to check the correct design of a joint, since composite materials like carbon fibre reinforced plastics (CFRP) are brittle and any mistake may lead to catastrophic failure (net tension or shear out). Preferred failure mechanism for most applications is bearing, that is, local compression, since it is a progressive degradation of the local mechanical properties at the holes and an increase in their diameter.

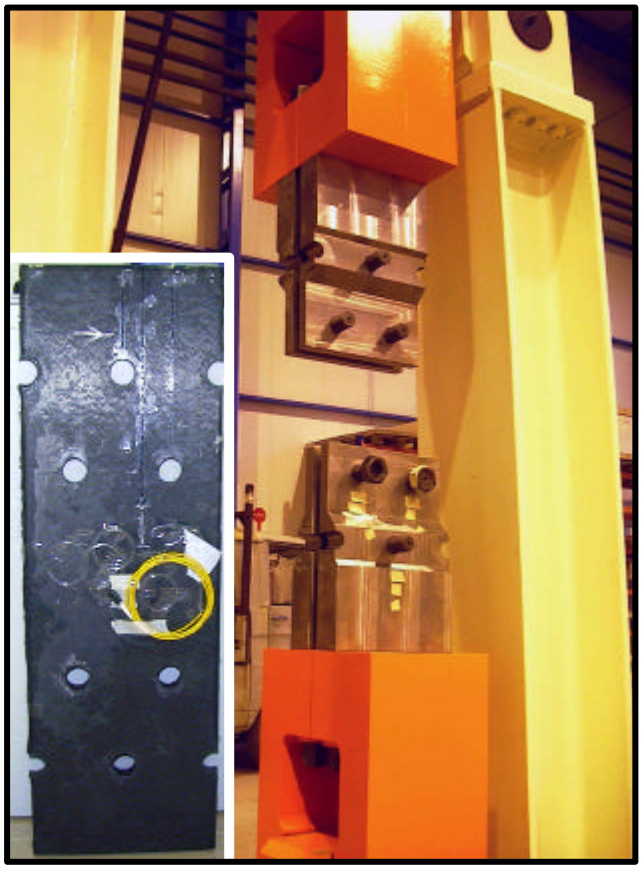
Design of laminate and distance between holes are mainly based on empirical data. Multiple rows of bolts show a complex pattern of load transfer. Some studies (1) show that first row is usually more loaded than second in a double-row joint. Nevertheless, load at any bolt is highly dependent on fabrication tolerances, adjust of bolts to holes and plastic deformation of bolts (since composite is initially too brittle and only under high loads deforms pseudo-plastically to achieve fitting). Several different laminate configurations were tested in flat plates.

In order to measure the strain at the vicinity of the different rows of bolts, and as the interesting material is CFRP and it is completely adjusted to its metallic support, Bragg gratings were used, to take advantage of their tiny size. Demodulation scheme for backreflected light is based on a Fabry-Pèrot scanning configuration. Results are reported, and compared to those from resistive strain gauges at the free surface of the test coupons. Finite Element Modelling was also performed.

TEST ARRANGEMENT

Two 30-mm thick flat plates corresponding to two different lay-up configurations were manufactured and 6 holes were drilled on each one. These laminates were bolted to metallic grips and were instrumented and tested under static axial load up to 1.5 x 10^6 N in a test machine (Fig. 1). Three uniaxial strain gauges and 3 rosettes were externally bonded to the free surfaces of the laminate and metal grips. Four Bragg gratings were located in small grooves in each laminate near holes on both first and second rows. One grating was located at the bottom of the hole at the compression area and another grating was placed 90º from it, at the maximum tensile stress expected location (Fig. 2).

Every grating was centred at 1318.4 nm. All of them were connected through a mechanical switch to the demodulation equipment. Measurements were made on every channel in 10-point batches (10 Hz) and changes from one channel to next took 0.5 seconds.



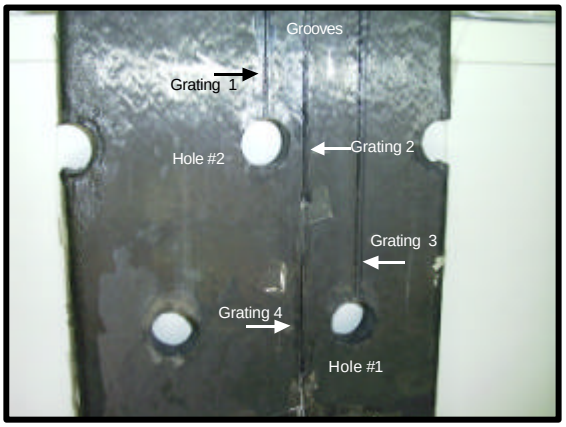


Figure 2. *Location of holes and Bragg gratings.*

Figure 1. *Test machine with steel grips and composite plate with holes.*

Demodulation scheme was developed at the UPM and is shown in Fig.3. It is based on a broadband LED and a scanning Fabry-Pèrot filter. Control and synchronisation of the filter and signal acquisition and display are performed by specifically designed Labview™ software. Switch control is also Labview™ based. This system has been working properly for several years and it has been proved in different measurements in civil engineering structures. Although only time multiplexing capability was used for these tests (all the gratings were centred at same wavelength), the demodulation equipment has also wavelength multiplexing capability. All 4 gratings could have been written in a single optical fibre at different wavelengths to improve measurement rate, but this would have complicated the paths between grooves to place that single fibre.

RESULTS

Some results are shown in Fig. 5 for gratings and one strain gauge (the one located at the centre of the free area of the composite coupon) for second test. Location of the gratings was sketched in Fig.2. Gratings #1 & #3 were loaded under compression while gratings #2 & #4 were under tension and at different distances from the edges of the holes. One pair, Bragg gratings # 1 & #2 was near the outer row hole and the other, gratings #3 & #4, close to one hole at the inner row. Equivalent maximum applied load was 150,000 Tons.

From 100,000 Tons up, crushing of the composite part was audible in both tests. None of the coupons broke under net tension failure, but some extent of failure in bearing mode happened. It was visible after the end of the tests as some surface delamination near the holes in the compression zone and some ovality of the holes. Mechanical tests were successful.

Measurements from conventional strain gauges showed that free surface between grips did not overpass 4000 $\mu\varepsilon$. Strain at the side of the first row hole (hole #1, grating #4) follows perfectly strain variation of the free area with time. Values from grating #2 are lower than those from grating #4.

Compression measured by grating #1 is lower than grating #3. A peak value of –8100 $\mu\varepsilon$ was reached at the bottom of hole #1 and only –3000 $\mu\varepsilon$ in hole #2 . Non-linearity, typical of this kind of contact problems with failures in bearing mode, can be seen clearly from 100 tons upwards, coincident with the beginning of sounds from cracking of the matrix of the composite and fibres (beginning of bearing failure).

Results from the other coupon (test #1) behave similarly Slight permanent strain after load release appeared, showing the pseudo-plastic deformation of composite and change in the shape of the holes.

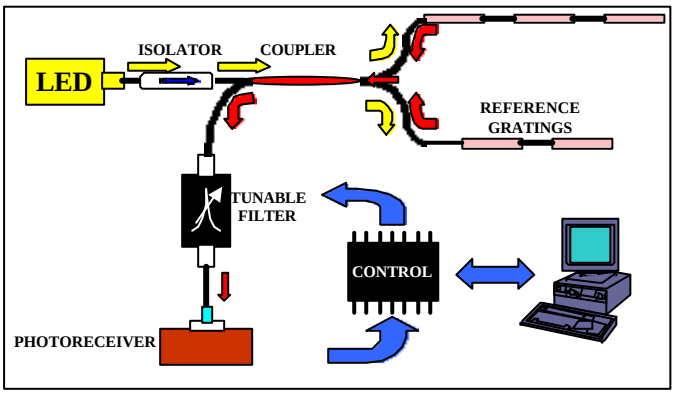


Figure 3 *Bragg Grating Interrogation System.*

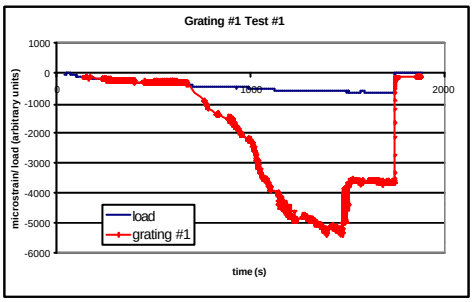


Figure 4. *First test measurements for grating #1 and load (arbitrary units) showing non-linearity.*

Second test (shown in Fig. 5) maximum compressive measured strain was –8100 με for hole #1, but some release of strain before unloading took place. First test showed a maximum compression of –5300 με for hole #2, and a more severe release of strain even while increasing load. Measurements were jumping back and forth from –3700 με to –5300 με for a while, due probably to the occurrence of a strain gradient along the sensor length (two different wavelength peaks appeared) and finally the lower value (-3700 με) remained stable (Fig. 4). Some authors (3) have analyzed the behaviour of Bragg gratings in two-dimensional fields, and two peaks can also appear due to transversal loading (promoting a change in effective refractive index in that direction). This happens inside thick laminates and the two peaks detected in these tests are not likely to have been produced for this reason.

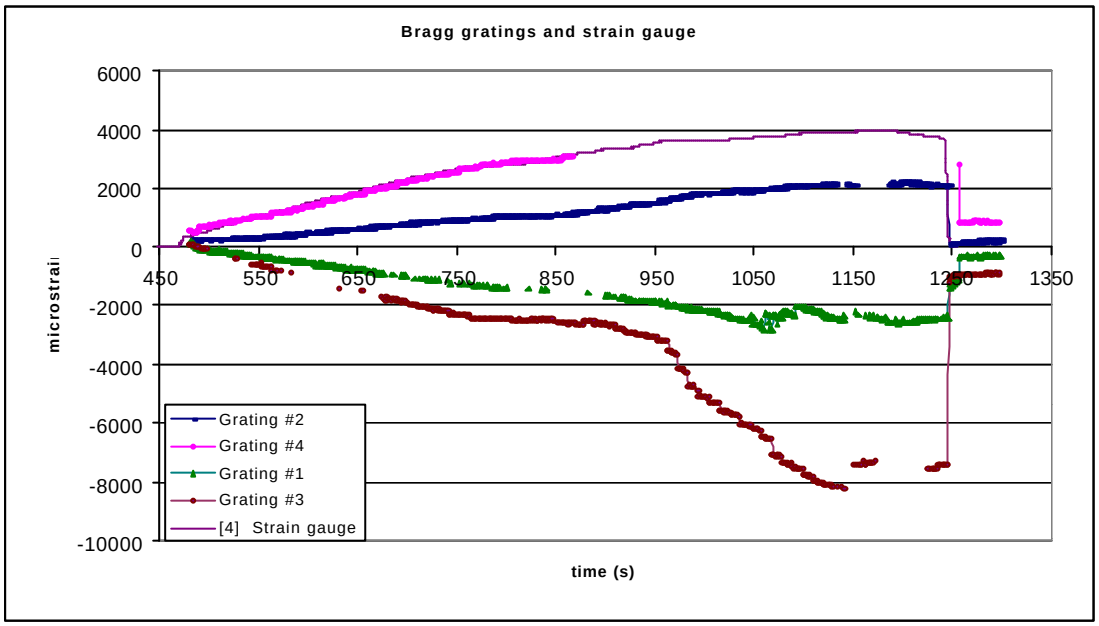


Figure 5. *Bragg gratings and strain gauge measurements in second configuration test.*

Differences between values of grating #1 in both coupons depend mainly on the different stacking sequences of laminates and load transfer. Grating #1 of second test measured a lower value (-3000 με) than in first test (-5500 με) showing differences in clearances and some improvement in the behaviour as the stacking sequence was modified. Maximum tension strain at the side of hole #1 is about 1.8 times greater than near hole #2 and they are about the same distance (13 mm vs 17 mm).

Results were essential for a better understanding of the load transfer in this kind of joint and will help to better designs.

FINITE ELEMENT MODELLING

Previous modelling of the joint was carried out and results can be compared to measurements from tests. Fig. 6 shows the evolution of stress at holes as load increases, for the following load values: 3.8 kN, 5.2 kN, 6.5 kN, 7.7 kN, 9 kN, 12.6 kN. Damage, showed in yelow colour, initiates as a local bearing damage, and corresponds to the first nonlinearities. At load levels near 10 kN per hole, damage grows as a transverse crack. At Refs. 4 to 7 appear clear discussions on damage progression, which may explain the results from our analytical models.

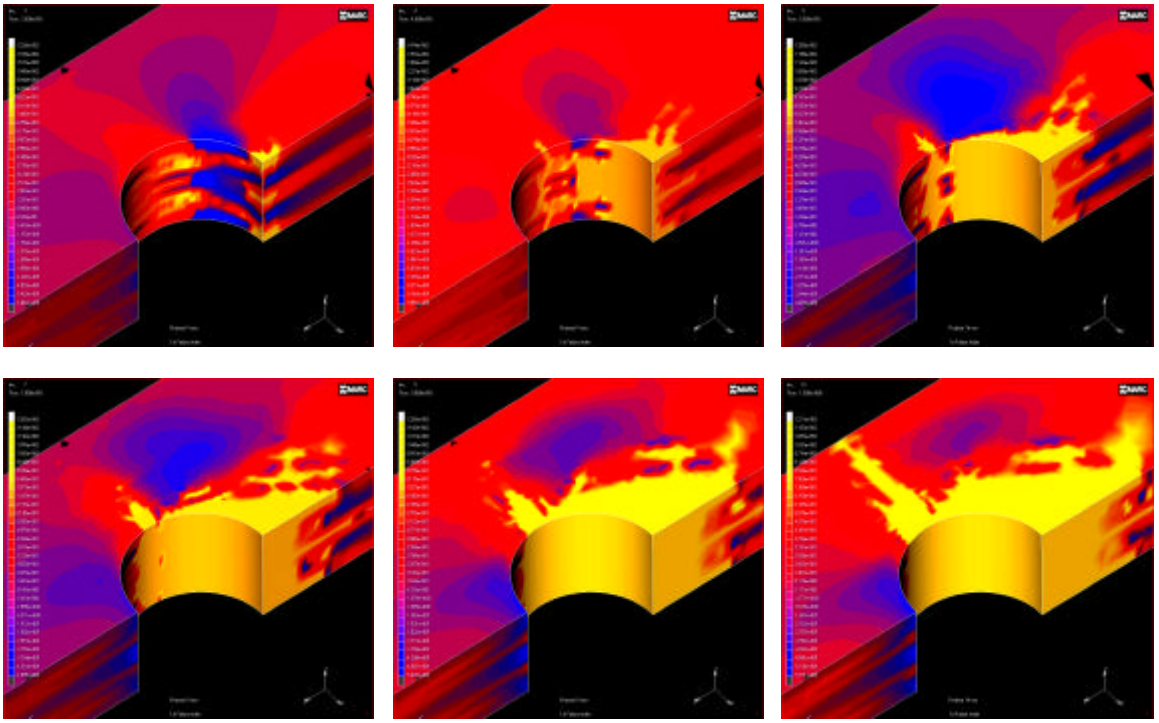


Figure 6. *Finite element modelling of CFRP hole and extent of damage under increasing load from bolt.*

CONCLUSIONS

Tests on carbon fibre laminates were performed and information on strain was obtained. Optical fibre sensors (Bragg gratings) proved to be adequate for measurements when conventional strain gauges were not suitable (no enough room to place them in metal/composite interface). Optical fibre demodulation equipment worked perfectly. Bragg gratings survived high strain levels, both under tension and compression. Measurements demonstrated differences in load bearing in both rows of the bolted joint. Load transfer theories in such a complicated arrangement were checked. As demodulation scheme looks for a single peak in the reflected wavelength spectrum, when local failure (bearing) begins, some kind of strain gradient leads to a double peak, and measurements skip between two values. Permanent deformation remains after load release. Physical check on the size of the hole found some ovality and surface delamination. Further analysis on gradients should be performed, using complete spectrum of gratings instead of just peak reflectivity values.

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