CREEP MEASUREMENTS OF STEEL BOLTED AND PRETENSIONED GFRP COMPOSITE JOINT USING FIBRE OPTIC STRAIN SENSORS

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Abstract
Due to the viscoelastic nature of monolithic composite laminates bolted joints with pretension will lose its initially enforced stress level over time. This stress relaxation can lead to unintended failure of the connection due to loss of friction. For monitoring a relevant bolted joint, an experimental set-up using fibre optic strain sensors for creep measurements has been designed. This set-up made it possible to determine the creep induced strains inside the glass fibre reinforced polymer (GFRP) laminates with a bolt joint, as well as the strain reduction in the steel bolt itself. Two joints with different pretension levels have been instrumented and stored at room temperature for twelve years. One main observation from the study is that almost half of the pretension is lost during the first year, and the main creep contribution occurs initially. Moreover, a retightening of the joint resulted in a significant improvement in the creep behaviour. As a conclusion, a retightening after 24 hours is recommended in order to improve the long-term properties of such bolted joints.

1 Introduction
Due to the viscoelastic nature of monolithic composite laminates bolted joints with pretension will lose its initially enforced stress level over time. This stress reduction can lead to unintended failure of the connection due to loss of friction.

Most of the viscoelastic data available in the literature are measured from glass fibre reinforced polymer (GFRP) laminates loaded in tension, either as constant strain (i.e. stress relaxation) or constant stress (i.e. creep) experiments, see e.g. [2]. Furthermore, the tension loads are typically applied in the fibre directions, or in the directions of the in-plane coordinate directions for the laminate. However, in bolted joints the loading is in compression, and the loading direction is transverse/normal to the fibre/ply directions, which means that most of the experimental data and the theories available are not directly applicable to bolted joints. Another challenge is to determine the correct clamping force. One can back calculate from measurements of the torque. However, in this case one then has to know the torque coefficient, which is dependent of, among other things, different finishes, lubrication, coatings, and wear.

In this paper, we present an experimental set-up where fibre optic (FO) Bragg strain sensors are adhered into both the bolt and the monolithic GFRP composite laminate. The sensors in the GFRP test specimen measure the strain response in the thickness direction, i.e. normal to the in-plane directions of the plies. The two GFRP bolted test specimen/panels included in the experiment are stored at room temperature. They were both initially pretensioned. One of the test specimens (i.e. specimen #2) was then retightened after fourteen months. The measuring of the strains was performed by drilling a small hole through the bolt, and then adhere a FO sensor inside the bolt. In this way, one can rule out the uncertainties connected to the torque coefficient, as described above. The strain data has been recorded over a period of twelve years.

2 Experimental set-up

The produced specimen and the experimental set-up is an idealization of a bolted joint with initial pretension and without external loading. The parts in compression consist of one thick, monolithic GFRP composite plate between two thinner steel plates. The part in tension is represented by the bolt. The configuration of compression and tension parts made it possible to pretension the bolts with stress levels typically used for standard steel joints. For a standard bolted joint it is desired to have a stiff as possible compression parts and a much softer tension part, in order to keep the clamping force as constant as possible. However, due to the viscoelastic behaviour of the monolithic GFRP composite, the initial compressive stress level in the GFRP will start to relax. This time-dependent relaxation results in an undesired decrease in the clamping force of the bolted joint. The experimental set-up described in this paper makes it possible to record the time-dependent strain reduction experienced by the bolts in both specimens, and strain relaxation in the monolithic GFRP composite in specimen #1. Details about the sensors for each of the test specimen and test set-up will be given in the following subsections.

2.1 Manufacturing and sensors

Two monolithic GFRP laminates of thickness 60mm were manufactured using wet lay-up, with a fibre volume fraction equal to 35%. The laminates consist of a polyester resin from Reichhold (Norpol 480-80) with a stacking of balanced bi-axial knitted fabrics plies from Devold AMT (E-glass plies with 800g/m^2 and fibre directions $[0°, 90°,]^n$). Each laminate was square shaped with edges equal to 215mm, and with a 22mm hole at the centre. A standard M20 steel bolt was used together with two steel discs (Ø45mm and thickness 20mm), two standard washers, and a M20 nut. The steel bushings were glued to the GFRP laminate using Scotch Weld DP 100. The GFRP surfaces were initially sanded, and the steel bushings were sanded, cleansed, and wiped off using acetone wetted tissue prior to adhering. A schematic cross section of a test specimen is shown in Figure 1.

In order to be able to measure the strain response inside the bolt, a small through hole (Ø3mm) was drilled through the centre of each bolt. Standard M20 (8:8 quality) bolts where used. To ensure good adhesion between the FO sensor and the steel bolt, a pre-treated procedure was applied to the bolts. First, the bolts were soaked in triethylenechloride for 2 days. Then, the holes where scrubbed using Q-tips, wetted in trichloroethylene and rinsed using clean triethylenechloride, before they were soaked in acetone and methanol. Finally, the bolts were heated to 110°C for 2 hours, and then cool down to room temperature over night.

To be able to attach the sensors at a prescribed location, a cannula (Ø1mm) was put inside a standard FO protection sleeve (Ø3mm), and then the sleeve was bonded a few millimetres down the hole in the bolt. After one day, the FO sensor was then treaded through the cannula and placed at the correct position, that is, 30mm from the outer surface of the GFRP laminate. The FO connection cable was first fixed using Scotch tape. Then, the adhesive (Scotch Weld

DP 100) was slowly injected using a syringe and a hypodermic needle all the way though the bolt. The adhesive was injected from below in order to avoid air bubbles in the adhesive. The adhesive was sealed before it was left to cure.

Four additional through holes were also drilled transverse to the monolithic GFRP laminate of test specimen #1 to be able to measure the compression response. Note that it is important to drill the holes without using any coolant liquid, since the coolant will introduce contaminations that can impair the adhesive bond. The FO sensors were adhered inside the specimen #1 using the same procedure as for the bolts, i.e. the sensors were positioned transverse to the laminate plies, 30mm from the top surface, in order to measure the through thickness strain response. A schematic overview of the sensor locations are shown in Figure 2, together with a photo of test specimen #1. Note that no additional sensors where inserted in the GFRP laminate for specimen #1.

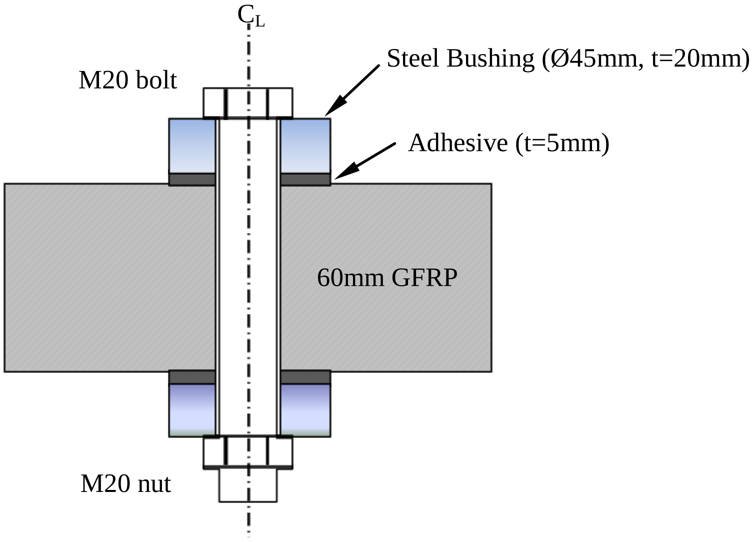


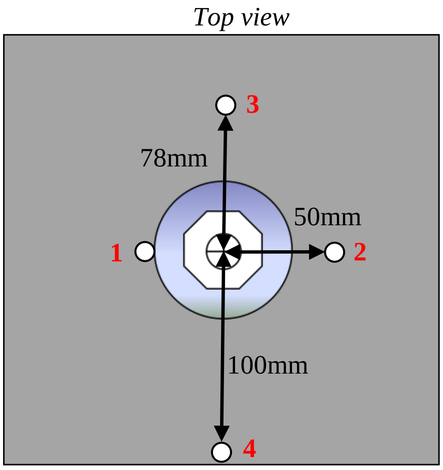
Figure 1. Schematic cross section of a test specimen.

2.2 Fibre optic instrumentation

When illuminated with a broad band light source, a FO Bragg sensor reflects light in a narrow band around a specified centre wavelength. A shift in the temperature, and/or the strain, of the sensor along the fibre grating causes a proportional shift in this wavelength [1]. Since the measurements where done in a varying room temperature environment, a reference FO sensor was used to indirectly measure the change in temperature of the specimens by measuring the change in room temperature. The strain and reference sensors had centre wavelengths between 1538 and 1556 nanometer.

A FAD-180 broad band light source from National Optics Institute was used to illuminate the sensors. A HP 70951 optical spectrum analyzer from Hewlett Packard was used to measure the wavelengths of the light reflected from the FO Bragg sensors. The light source, the spectrum analyzer and the FO Bragg sensors were connected using a fibre optic 2x2 coupler.

The relative contribution of strain to the wavelength shifts of the strain sensors were found by subtracting the measured wavelength shifts from the reference temperature sensor. Furthermore, the strain values, in microstrain, were estimated by dividing the strain induced wavelength shifts, in picometers, by 1.2. The change in temperature, in degrees centigrade, was then estimated by dividing the wavelength shifts of the reference sensor by 10.9 [1].



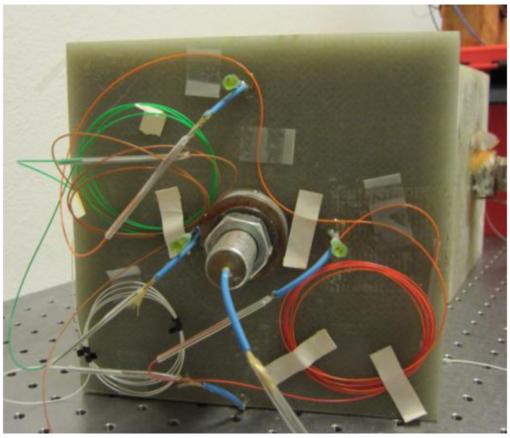


Figure 2. A schematic overview of the sensor positions inside the monolithic GRP (specimen no. 1) measured from the centre axis of the bolt. To the right is a photo of specimen no. 1.

2.3 Initial test parameters

Both specimens were initially tensioned in September 2000. The specimens were stored in air at room temperature (20 ±3°C). The air humidity was not controlled, but was left to follow the seasonal variations inside the building. The initial test parameters are presented in Table 1. The pretension level was tuned to match the initial strain values given in the table below. The corresponding stress levels in the bolts are calculated.

Specimen	Pretension force in bolt	Initial stress/strain level in bolt	
#	kN	MPa	με [10^{-6}]
1	**93,5**	**381**	**1900**
2	**59,1**	**241**	**1200**

Table 1. Initial parameters for pretension force and stress/strain level in the bolts.

2.4 Data logging

The first 24 hours the strains values were recorded every second. Then, the recording intervals were approximately as follows:

- One recording once a day for the next six days
- One recording once a week for the next four weeks
- One recording once a month for the next eleven months

After 14 months specimen #2 was reloaded to its initial pretension level, while specimen #1 was neither reloaded nor loosened during the (entire) test period. The data logging sequence was then repeated for some weeks for both specimens. After that the specimens were, more or less, "forgotten" until March 2012, when a final recording was performed.

3 Results

Figure 3 shows the recorded strains from the four sensors inside GFRP laminate in specimen #1, as well as the recorded strains inside the bolt in specimen #1 and specimen #2. The strain levels in strains sensor #3 and #4 in the GRFP do not respond significantly to the pretension because they are too far away from the clamping zone. The noise floor in the strain signal from the FO system used is $\pm 20 \cdot 10^{-6}$, so the small variation seen is most likely caused by temperature changes and small drifts in the read-out system. Strain sensor #1, which is located closest to the steel bolt, has the most significant response and it is loaded in compression.

However, when the distance from the bolt increases all the other strain sensors in the GFRP are measuring a tensional response. One explanation could be that the local compressive deformation underneath the steel bushing creates a local bending of the plate, and together with the Poisson's effects, a transverse tension stress can be created at the mid surface.

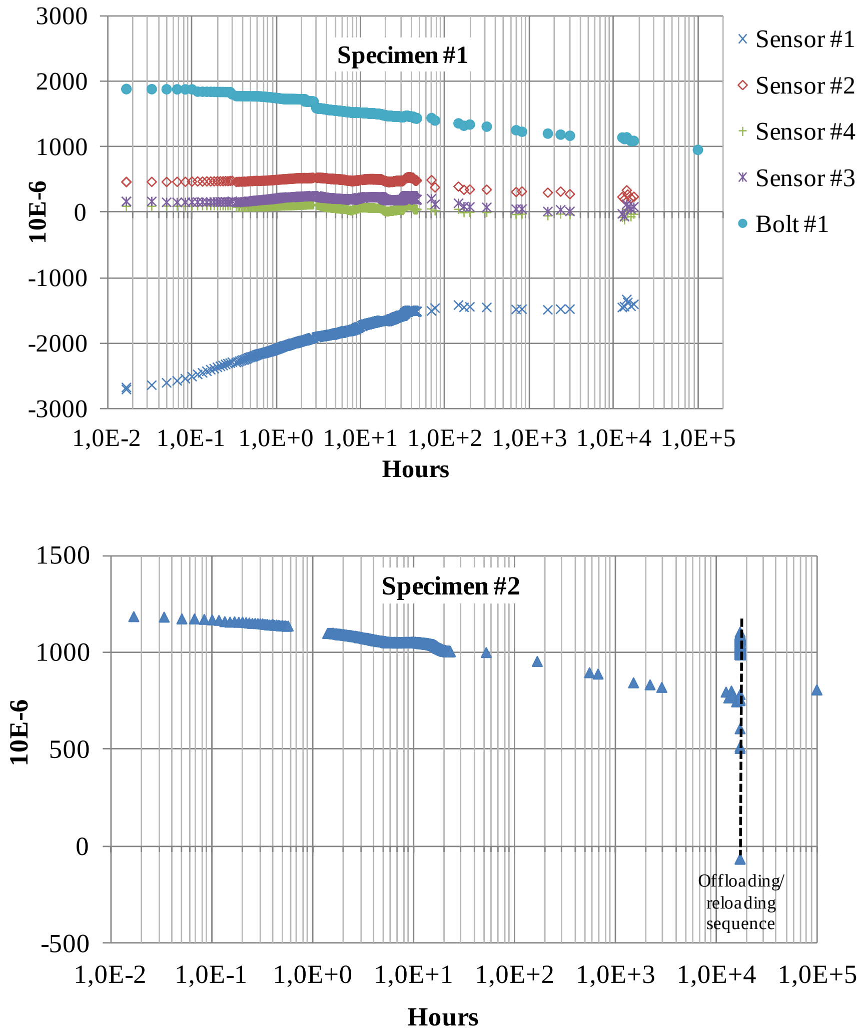


Figure 3 Strain responses in micro strain (10^{-6}) from the FO sensors in specimen #1and specimen #2.

After fourteen months specimen #2 was first fully unloaded. Then the bolted joint was lubricated and pretensioned back to its original level. The reload sequence can be seen as a peak in the strain value. In order to be able to compare the relaxation in strain response after the initial pretension and reloading, respectively, the time at reloading has been set back to t=0 after the reloading of specimen #2. Hence, the time-dependent strain response for specimen #1 and the responses before and after retightening of specimen #2 can be compared in a log-linear diagram.

The recorded strain reduction in the two steel bolts are normalized and presented in Figure 4. The initial values are indicated with markers at the left vertical axis, and a thin dotted line is connecting the initial value to the measured data. The normalization was done by using the measured strain value at a time equal to 24 hours after the initial pre-tensioning. The reason for leaving out data from the first 24 hours was that the remaining data set fitted well with analytical expressions on the form, $\varepsilon(t) = C \cdot (t)^{-k}$, t = [24h , 12years]. The analytical fitted curves are plotted in Figure 5. The curves are extrapolated outside the measured data range, indicated with dotted lines in the figure. If earlier data were included in the data set it would not have been possible to include both the initial values and the values in the tail in the same expression. As can be seen in Figure 4, the strain level in the bolts dropped 20% during the first 24 hours. Then, the next 20% was lost after approximately one year. Thus, the viscoelastic response in bolted GFRP joint can be divided in two stages. The first stage is a transient and relatively rapid stress relaxation stage, see Figure 3. After approximately 24 hours, this period is followed by an exponential decaying curve for the remaining time as seen in Figure 4 and Figure 5.

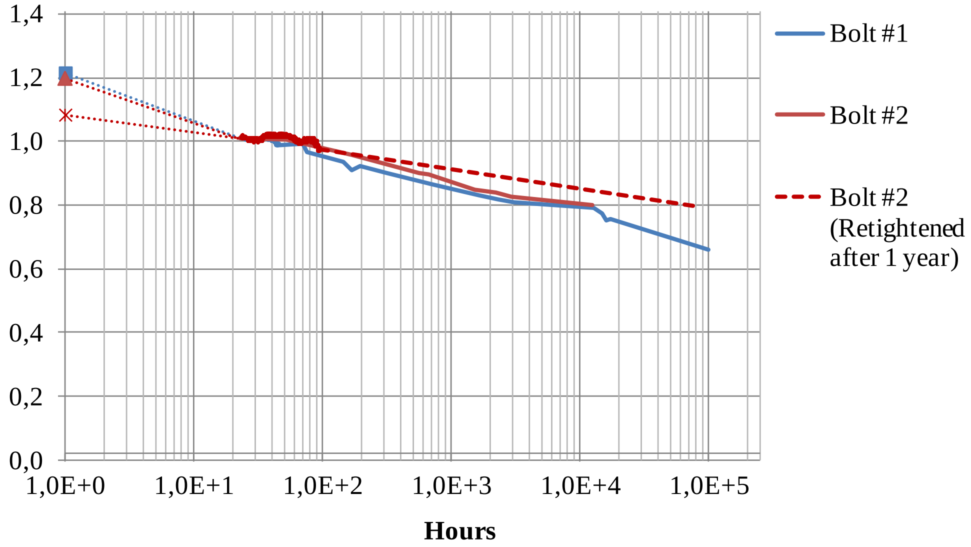


Figure 4. Normalized measured strain response from the two bolts. (After retightening Bolt #2 the time is set to t=0 in order to be able to compare with the initial strain responses in Bolt #1 and Bolt #2). Markers show the initial tension level and are linked by thin dotted lines to their respective data series.

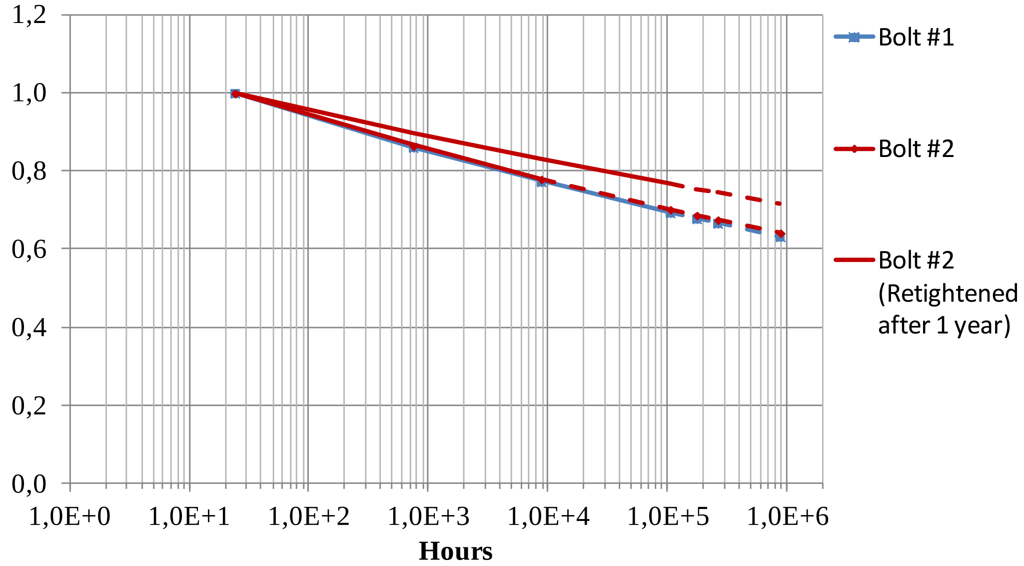


Figure 5. Normalized strain response calculated from fitted curves starting at 24 hours after pretension. (Extrapolations outside recorded data range are marked with dotted lines).

The results after reloading test specimen #2 showed that the strain decay is not dropping with the same rate as it did after the initial pretension. 100 hours after reloading the strain level in the reloaded bolt is 5% higher, compared with the strain level 100 hours after the initial pretension. Furthermore, after the first 24 hours the reloaded bolt had lost only 7% of its initial stress level, and it took another eleven years before the bolt lost the next 20%. This is a substantial improvement in the creep resistance for the bolted joint compared with the initial decay, which first lost 20% after 24 hours, and then 20% during the next fourteen months. These results indicate that the long-term properties of a bolted joint in GFRP can be improved by a reloading sequence carried out within the installation period for a structure.

An analytical expression has been fitted to the strain measurements for sensor #1.(i.e. inside the GFRP), and the calculated values have been normalized with the strain value measured after 24 hours. The result is presented in Figure 6, together with the normalized strain response from the bolt in specimen #1. After 24 hours the strain relaxation in the GFRP and the bolt are following the same decay. However during the first 24hours the initial strain level in the GFRP in between the steel bushings has decreased by 41%, and it took less than 100 hours to lose 50% of the pretension in GFRP at sensor #1.

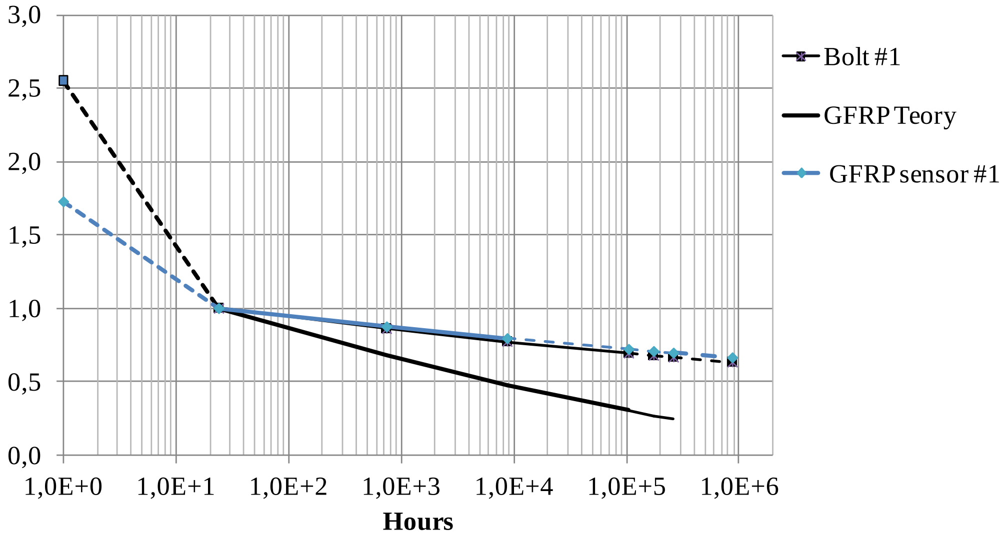


Figure 6. Normalized strain response in senor #1 and bolt #1, together with theoretical strain relaxation in the GFRP calculated from trend curves.(Extrapolations are marked with dotted lines).

As pointed out in Section 1, most of the viscoelastic data available in the literature are measured from GFRP laminates loaded in tension. For this bolted joints case, the laminate is loaded in compression, where the forces are applied in the direction normal to the fibre direction for each ply of the laminate. This means that the experimental data, and the theories based on in-plane tensional loading, are not directly applicable to bolted joints. However, the response of the composite laminate in the bolted joint is dominated by second order effects from surrounding GFRP. The Poisson's ratio and resulting in-plane strain from clamping force creates a 3D stress state. Consequently, one cannot apply creep data for the through thickness direction. This would result in far too high creep response since the fibre reinforcement will increase the in-plane stiffness considerably and prevent the polymer from "floating to the sides".

A more engineering based approach is to use existing creep data from tensional in-plane loading, and use several stress relaxation curves depending on the stress level in the bolted joint. For each time the stress relaxation drops down to another stress level the calculations of the remaining stress valve and creep history is based on a constant stress curve closest to the actual stress level. This iterative process becomes better and better as the number of constant stress curves available increases. This engineering method has been used with input values found in [2] and the calculated strain response has been presented in Figure 6. As one can see from the strain reduction, this approach results in a faster strain reduction, and consequently, the designed bolted joint using this theory will be on the safe side.

The initial stiffness in the through thickness direction was set to 7.5GPa in the theoretical calculations. By increasing this stiffness a better match could be found between the measured data and the theoretical calculations. This indicates that creep data determined by standard experiments in tension have to be adjusted in order to include the increase in in-plane stiffness (i.e. the stiffness normal to the main load path) for bolted joints. This stiffness is absent when the load is applied parallel to the fibres, and the viscoelastic property of the polymer becomes more significant for the total GFRP composite.

4 Summary

A M20 (8:8) steel bolt has successfully been instrumented with an FO Bragg strain sensor adhered inside the centre of a bolt for the purpose of measuring the strain due to pretension. The GFRP composite was clamped transverse to the fibre orientation by a bolted joint, and no additional loading was applied. The specimen configuration made it possible to pretension the bolts to representative levels used in standard bolted joints for steel materials.

The instrumentation made it possible to measure the time-dependent strain reduction inside the bolt due to the viscoelastic behaviour of the GFRP material. A similar through thickness instrumentation was also done for one of the GFRP composite specimen in order to measure the strain relaxation in the mid surface of the GFRP laminate.

The experimental results indicated that the creep behaviour can be divided in two stages. The first initial stage lasts approximately 24 hours. The bolt lost 20% of pretension during this stage. In the second stage the strain reduction followed an exponential function up to the last measurement point, which was measured after twelve years. After fourteen months the stress level was reduced another 20%.

One of the bolts was unloaded, lubricated and retighten to its initial stress level after fourteen months. Now, the initial phase resulted in a 7% reduction in stress level after 24 hours, and it took eleven years before it lost another 20%. Thus, the results indicate that the long-term properties of a bolted joint in GFRP can be significantly improved by a reloading sequence. This has also been reported by Isaicu et al. [2]. Whereas they suggested a reloading after a couple of minutes, we suggest a reloading interval of approximately 24 hours, based upon experimental results. The time required before reloading is most likely dependent of the thickness of the monolithic GFRP laminate.

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