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Study on the Anchor Efficiency and Stress Relaxation of BFRP Bars using Digital Image Correlation and FBG Sensing Technology

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Abstract
The present study experimentally investigates the feasibility of utilising industrial wedge anchors, originally developed for steel pre-stressing strands, as mechanical anchors for basalt fibre reinforced polymer bars. The peak load and rupture strain of the bars were obtained using load cells and strain gauges, respectively. The anchor slips during the stressing of the bar were monitored using digital image correlation and compared with linear potentiometers. A fibre optic sensor was integrated inside the bar to compare its results with conventional strain gauges. The results revealed that industrial wedge anchors can stress the bars up to 67% of its ultimate tensile capacity, which is beyond the initial stress limit of 55% as per ACI guidelines. The results also demonstrate the effectiveness of using digital image correlation technique and fibre optic sensor for measuring anchor slips and strains in the bars, respectively. Relaxation tests showed a strain loss of 13% over a period of 1000 hours and an anchor slip of 0.85 mm. The experimental data could be beneficial for further development of design principles for pre-stressing concrete with basalt bars.

Keywords: Anchor Efficiency, Basalt Fibre Reinforced Polymer, Pre-stressing.

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Introduction

Stress relaxation, which is defined as the decrease in stress under constant strain, is considered as a major concern in the application of fibre reinforced polymer (FRP) as an effective pre-stressing element. This is because excessive relaxation loss can reduce the pre-stressing effect of tendons on pre-stressed concrete (PC) structures [1]. A study [2] reported a relaxation rate of 20% for basalt fibre reinforced polymer (BFRP) bars. However, the details of the test setup and methodology adopted to measure the reported relaxation rate was not provided. Another study [3] reported a much lower relaxation rate of 11% over a period of 50-years for BFRP at an initial pre-stress of $0.50f_{pu}$ (where, f_{pu} is the peak rupture stress of the bar). A recent study [4] reported 1000-hour relaxation rates of 4.2%, 5.3 % and 6.4 % for BFRP bars, under stress levels of $0.4f_{pu}$, $0.5f_{pu}$ and $0.6f_{pu,}$ respectively. Although, some studies have reported relaxation rates for BFRP bars on the basis of experimental investigation, very few studies have considered the contribution of slippage of the bars at the anchors. The studies that have considered slips [4] utilises chemically bonded anchors to hold the bars in the setup (which is not practical). This does not adequately simulate the field conditions where mechanical wedge anchors are used to pre-stress the BFRP bars. Thus, the relaxation results reported in the study may have under or overestimated the actual results since the relaxation of FRP is not only related to the type of fibre and polymer matrix but is also dependent on the gripping mechanism. In the present study, static tensile tests have been conducted on BFRP bars using off the shelf industrial wedge anchors (represented as anchor A). These anchors were originally developed for steel pre-stressing strands. Anchor efficiency tests were performed on these anchors to judge its adequacy for pre-stressing applications using BFRP bars. The peak rupture stress (f_{pu}) from the static tests was used as a reference to perform long term relaxation tests in which the stress retention of BFRP bar was monitored over a period of 1000 hours.

Experimental Program

The test setup used in the present study comprised of two identical anchors installed at each end of a 12 mm BFRP bar of length 1050 mm. The mechanical wedge anchors used in this study are preferred over the adhesively bonded anchors since the wedge anchors can be easily installed at site and do not require any complex mixing or prolonged curing time. Four BFRP bars obtained from a local supplier (represented as C1 in this paper) were subjected to short term and long term loading. The nomenclature used during the testing of the four specimens are shown in Table 1. All the four specimens were instrumented with electronic resistance strain gauge (ERSG) and linear potentiometer (LP). Black and white speckle patterns were painted over the dead end region of specimen 12-C1-A-S2 to monitor the three dimensional movement of the BFRP bar during pre-stressing using digital image correlation (DIC). Test specimen 12-C1-A-S3 was integrated with a single-mode (SM) fibre optic sensor (FOS) installed inside the bar by cutting a longitudinal groove on the specimen (Fig. 1). Previously, the authors observed that the adhesive layer plays a crucial role in the strain transfer mechanism between the host material and the FOS. Hence a uniform

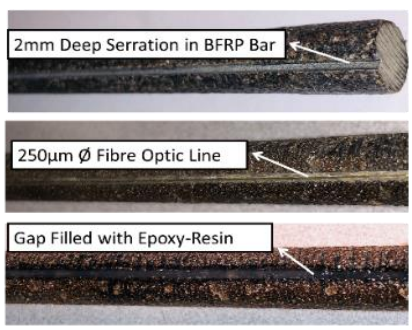

Fig. 1 Preparation of Specimen 12-C1-A-S3

pressure was applied on the sensor after its installation. This has been done to ensure minimal adhesive layer thickness between the FOS and basalt fibres of BFRP bar. The FOS with a single fibre Bragg grating (FBG) sensor was positioned exactly at the same location where an ERSG was installed on the bar surface. Three of the four BFRP bars were subjected to short term static tensile loads until final rupture of the bar. As per ASTM-D7205 [5], the recommended rate of loading for static tensile tests is 0.01 min^{-1}. However due to the manual operation of the hydraulic pump used in the present study, it was difficult to control the loading rate in the individual tests. Nonetheless, in all the cases the test duration was kept greater than 60 seconds (Fig. 2b) to ensure a strain rate of less than 0.01 min^{-1}. A lower strain rate would result in a conservative estimate of the strength as compared to a higher loading rate. Test specimen 12-C1-A-R1 was pre-stressed up to an initial pre-stress of $0.55f_{pu}$ and the elongation of the bar was kept constant to the initial set value. The reduction in tensile forces was monitored over a period of 1000 hours and extrapolated for 1-million hours (116 years). The upper limit of initial pre-stress ($0.55f_{pu}$) was selected as per ACI 440.4R [6] guidelines for pre-stressing FRP tendons. After the application of the initial load, the system was left to stabilize for a duration of 10 minutes before taking any readings.

Results and Discussion

Failure Loads

Table 1 shows the results obtained from the tests performed on BFRP bars using industrial wedge anchors. The peak stress of the specimens that failed due to typical fibre rupture ranged between 597 MPa and 671 MPa. Specimen 12-C1-A-S3 failed at a lower stress level of 385 MPa due to a premature anchorage failure. Previously, the authors conducted tensile tests on BFRP bars using chemically bonded anchors subjected to a controlled loading rate of 0.01 min^{-1}. The average longitudinal strength for the BFRP bars was estimated as 1000 MPa. A higher peak stress was expected in the tension test with bonded anchors due to the use of larger grip length and a higher loading rate of 0.01^{-1}. Considering 1000 MPa as the peak stress, an anchor efficiency of 59-67% has been obtained using the industrial wedge anchors. As per the PTI manual [7], a reliable anchorage for steel pre-stressing strands should be able to carry an ultimate load of 95% of the ultimate strength of the strands. Despite the fact that the industrial anchors could not reach 95% of the ultimate capacity of the bar, it can still be considered as a reliable anchor since it has exceeded the maximum initial pre-stress limit ($0.55f_{pu}$) for FRP tendons as per ACI 440.4R [6]. Furthermore, the 95% clause in PTI manual [7], is majorly intended for post-tensioned applications in which the anchor is expected to hold the strands while the stress in pre-stressed reinforcement reaches the designed nominal strength denoted as f_{ps}. Since the major focus of the present study is on the application of BFRP bars for pre-tensioning applications, a 59-67% anchor efficiency satisfies the objectives of the current study.

Table 1: Experimental Results for Short-term and Long-term Test.

Nomenclature	Test Type	Results from the Experiment				
		F_p [kN]	f_{pu} [MPa]	E_{pu} [GPa]	ε_{pu} [%]	Failure Type

12-C1-A-S1	Short Term	67.5	597	37.1	1.17	Fibre Fracture
12-C1-A-S2		74.2	656	44.1	1.82	Fibre Fracture
12-C1-A-S3		43.2	385	42.5	0.69	Anchor Failure
12-C1-A-R1	Long Term	75.8	671	43.7	1.6	Fibre Fracture

Although, specimen 12-C1-A-S1 failed at a slightly lower load as compared to the specimen 12-C1-A-S2, the final rupture in both specimens occurred over the free length of the BFRP bar away from the anchorage zone. Few cracks in the specimens were observed to extend up to (and may be initiated at) the dead-end anchor. The end slippage in all the test specimens was observed to be less than 5 mm (Fig. 2a) and the stress-strain relationship in all the tests showed a linear elastic relationship until failure (Fig. 2c). Fracture of the bars was sudden with loud sounds of fibre breaking and occurred at a distance of about 20 mm from the live-end anchor. Specimen 12-C1-A-S3 which was instrumented with a FOS, suffered an anchorage failure due to the crushing of the BFRP bar in the anchor region. It is anticipated that in this specimen, the sharp edges of the wedge crushed the epoxy resin layer on the BFRP bar in the anchor region. The specimen failed with a large breaking sound and left a characteristic pattern on the bar.

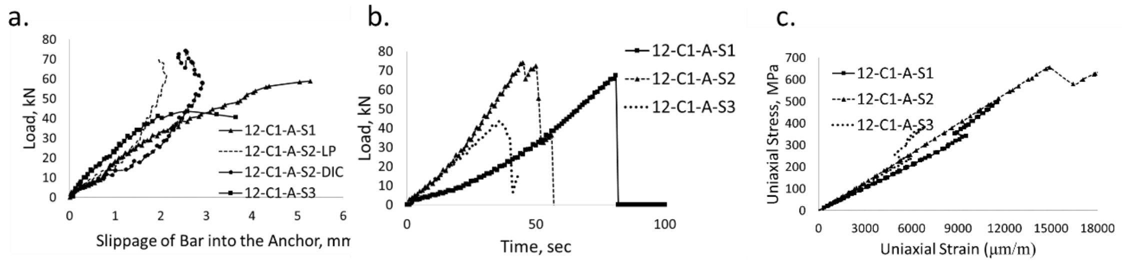

Fig. 2 Static Tensile Test Results.
(a) Load v/s Slip Relationship (b) Load v/s Time Relationship, and (c) Stress v/s Strain Relationship.

Comparison of Strains obtained from ERSG and FOS

During the test it has been observed that the FOS installed on the specimen 12-C1-A-S3 stopped giving results after a strain value of 2000 micro-strain. A plausible reason for the breakage of the FOS at such low strain value could be due to the damage of the FOS line caused by large transverse strains generated due to the wedge clamping. In further studies, the authors aim to establish a suitable approach to achieve higher strains from the FOS by installing a soft silicone layer between the FOS and the epoxy-resin at the clamping area. Nonetheless, ERSG and FOS showed good agreement in the initial strain values (Fig. 3a) indicating that the FOS can

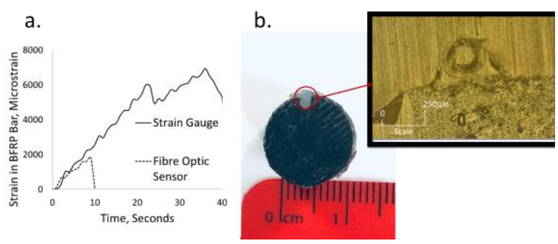

Fig. 3 Test Results for Specimen 12-C1-A-S3.
(a) Comparison of Strains between FOS and ERSG
(b) Microscope Image of the Specimen.

be utilised for monitoring of strains in the BFRP bars. A microscopic image (Fig. 3b) of specimen 12-C1-A-S3 at the FBG location showed that the FOS was appropriately position inside the BFRP bar while maintaining adequate thickness of the adhesive layer. This indicates towards the effectiveness of the installation technique used to integrate the FOS into the BFRP bar.

Comparison of Displacement obtained from DIC and LP

The correlation process for the digital images recorded by the DIC system for specimen 12-C1-A-S2 was carried out using ISTRA-4D commercial code in order to obtain full field displacement of the BFRP bar. A comparison of the load-slip relationships obtained using DIC and LP results for specimen 12-C1-A-S2 has been shown in Fig. 2a. The results showed that for the initial displacement of 1mm, the DIC system and LP reported similar values of axial displacement (along the longitudinal axis of the bar) thereafter the results differ significantly with the peak value reported by DIC being 28% higher than the total displacement reported by LP. The higher values recorded by DIC could be due to the out of plane movement recorded by DIC system, which the conventional instrumentation like LP fails to capture. Despite this, both DIC and LP showed a stiffening effect of the bar as shown in Fig. 2a. In further tests, the authors aim to test more samples to check the reproducibility of the result reported by the DIC technique.

Long Term Tensile Tests

Specimen 12-C1-A-R1 was subjected to a constant displacement corresponding to an initial pre-stress value of $0.55f_{pu}$ over a period of 1000 hours (approx.). The percentage of relaxation loss after one-hour and twenty-four hours were 2.41% and 8.16%, respectively. Thereafter, an additional relaxation loss of 4.93% was observed between 24 hours and 1000 hours, indicating that the major stress loss in BFRP bar occurs within 24 hours of stressing. A rapid decrease of load can be observed during the initial stage from Fig. 4 and the rate of relaxation loss gradually reduces with time. The rapid reduction in load is anticipated due to the alignment of the originally miss-aligned fibres with the viscoelastic deformation of the resin-matrix. After approximately 24 hours, the bar stabilizes and experiences a lower rate of relaxation loss due to the second stage of relaxation which typically occurs due to the fibres itself. A plausible reason for several fluctuations observed in Fig. 4 could be due to the differences in the coefficients of thermal expansion of the testing rig, ERSG and the BFRP bar which might have resulted in different expansion rates due to the change in ambient temperature. Similar observation has been reported in other studies on the relaxation behaviour of FRP's [4] [8]. ACI 440R.04 [6] recommends to eliminate the anchor slippage in order to correctly estimate the relaxation loss in FRP bars. The slippage of the bar at the anchorages has been considered and the axial load on the specimen was modified. The mean stress-relaxation rate after 1000 hours (approx.) with and without elimination of end slips were found to be 13% and 16%, respectively. This indicates that an average loss of stress due to the grip seating was 3% of the initial prestress of $0.55f_{pu}$.

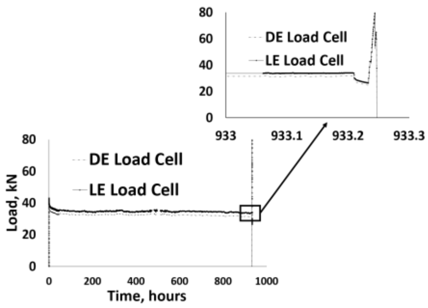

Fig. 4 Long Term Test Results

Conclusions and Scope of Future Work

The relaxation rate for BFRP bars using off the shelf industrial anchor after 1000-hours has been found to be 13% at an initial pre-stress value of $0.55f_{pu.}$ The fibre optic sensors provided a good insight into the possibilities of using FOS in this particular application by overcoming the high transverse strains generated on the FOS line. The outcome from the static tensile tests will later be utilized to develop a finite element model in order to perform parametric studies and propose an optimized design for FRP anchors in order to increase the anchor efficiency.

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