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AN INNOVATIVE EXPERIMENTAL DEVICE TO CHARACTERIZE THE CREEP BEHAVIOR OF CONCRETE /FRP ADHESIVE BOND

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Abstract

During its life-time, a bonded assembly is subjected to various ageing mechanisms which may induce synergistic effects. In the case of civil structures strengthened by bonded fiber reinforced polymer (FRP), the influence of coupled mechanical/environmental factors is still a matter of investigation. In this context, an innovative experimental device has been designed to study the durability of concrete/FRP interfaces subjected to both sustained load and hydrothermal ageing. This test setup is able to load simultaneously several double shear specimens and can then be installed in a climatic chamber in order to superimpose accelerated ageing conditions to the creep load. Besides, the design of the test-bodies is compatible with an existing single shear method that allows to determine the residual capacity of aged specimens. This paper aims at describing the proposed creep test setup and its instrumentation, as well as the validation stages, including a comparison of preliminary experimental data with simple analytical and finite element modeling approaches.

Keywords: Analytic/finite element modelling, Concrete/FRP bonded joints, Creep.

1. Introduction

Rehabilitation/strengthening of civil structures by externally bonded Fiber-Reinforced Polymers (FRP) is now considered as an effective technique [1] which presents major advantages over traditional methods, such as high corrosion resistance or high strength-to-weight ratio. In the framework of flexural strengthening applications, Carbon FRP (CFRP) materials are routinely used to increase the load carrying capacity and the serviceability of repaired structures. Tensile stress is transmitted from the concrete substrate to the CFRP reinforcement through the shear load path provided by the adhesive layer.

If pultruded FRP laminates generally demonstrate satisfactory environmental resistance and limited creep deformation, the durability of the adhesive bond still remains a critical issue which hampers the extensive use of composite strengthening systems in the field. This drawback is mainly due to the environmental sensitivity and the creep response of cold curing epoxy adhesives used in construction. While many studies have investigated the influence of moisture or hydrothermal ageing on the adhesive bond properties [2, 3], only limited research

has been conducted on the long term creep behaviour of concrete-FRP interfaces subjected to sustained load [4]. In most cases, the authors used a double shear test configuration and the creep load was applied to the specimens by means of a sustained dead weight attached to a cantilever steel beam. Unfortunately, this type of cantilever setup is voluminous and is therefore not adapted to the characterization of numerous specimens in a limited space.

In this context, an innovative and compact experimental creep device has been developed, which makes it possible to apply a sustained load on several test bodies stored in a limited space. This setup involves a centralized hydraulic system which actuates flat jacks. Due to its reduced volume, it can be installed in a climatic chamber so that accelerated ageing conditions can be coupled to the mechanical loading. This article presents both the experimental creep test setup and its associated instrumentation, and gives additional details regarding the validation stages: verification of i) the constancy of the applied load, ii) the symmetry of the double shear test-bodies and iii) the relevance of recorded creep strains.

2. The double lap joint shear test: general principle and elastic analysis

The literature reports several test configurations which are suitable for the shear characterization of adhesively bonded joints. The most popular is the single lap joint shear test, but in this case, the adhesive layer is subjected to a combination of shear and bending stresses which may affect the failure mode. In fact, the effectiveness of the load transfer is enhanced if the adhesive joint is designed for pure shear. Consequently, a double-lap shear configuration (Figure 1) was preferred in this study, since the bending moment and stresses are negligible due to the symmetry of the test bodies.

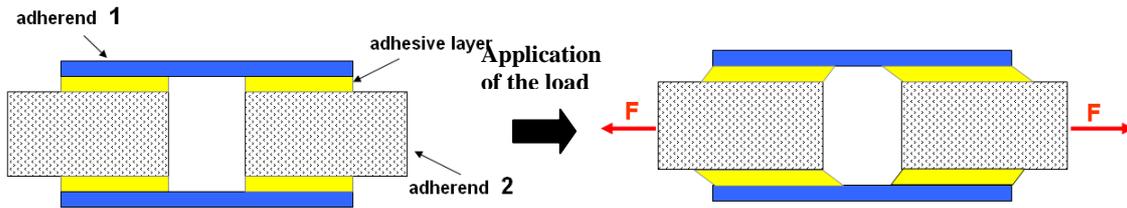


Figure 1. Schematic description of the double lap joint shear test.

Volkersen [5] has proposed an elastic model based on the concept of differential shear, leading to the following expression for the shear stress distribution along a single lap joint:

$$\tau_a(x) = \frac{G_a \sigma_{10}}{e_a \lambda E_1} \left[\left(\frac{E_1 e_1}{E_2 e_2} + \cosh(\lambda L) \right) \frac{\cosh(\lambda x)}{\sinh(\lambda L)} - \sinh(\lambda x) \right] \quad (1)$$

with

$$\lambda = \sqrt{\frac{G_a}{e_c} \left(\frac{1}{e_1 E_1} + \frac{1}{e_2 E_2} \right)} \quad (2)$$

and

$$\sigma_{10} = \frac{P}{b e_1} \quad (3)$$

Where:

- L , b , e_1 , e_2 and e_a are respectively the lap length, width of the joint, the thickness of the adherends and the thickness of the adhesive layer.
- σ_{10} is the axial stress applied to the upper adherend.
- x is the abscissa along the lap joint ($x = 0$ corresponds to the loaded end of the joint).

- E_1 , E_2 and G_a are respectively the tensile modulus of adherends and the shear modulus of the adhesive.

As regards concrete/FRP assemblies where $E_{concrete} * e_{concrete} \gg E_{FRP} * e_{FRP}$, shear stresses are concentrated near the loaded end of the joint and become negligible beyond a certain distance from this end, called anchorage or transfer length [6]. According to [7], this anchorage length can be defined as the portion of the joint carrying at least 97% of the applied load.

3. Innovative double shear creep test setup for concrete/FRP assemblies

In order to study the creep behaviour of concrete-FRP bonded interfaces, an innovative double shear test device was designed. The setup had to meet the following requirements:

- its volume must be limited, so that a large number of specimens (up to 15) can be tested together in a climatic room of surface area 10m^2 ,
- the loading system should be able to apply a constant load in the long term (at least for one year) on all the tested specimens,
- specimen's geometry must be compatible with an existing single shear test that allows to assess the residual shear capacity of the bonded assembly after creep experiments.

3.1 Test bodies and loading conditions

Each test specimen consisted of two concrete blocks of dimensions $205 \times 210 \times 415 \text{ mm}^3$, connected together by two CFRP plates (Sika Carbodur®) symmetrically bonded to the lateral faces using a structural epoxy adhesive (Sikadur® 30), as shown in Figure 2. The commercial strengthening system (FRP and adhesive) was kindly supplied by SIKA France.

Such a double shear test geometry has been used in many studies devoted to the short-term [8] or long-term performances of concrete/FRP bonded joints (see [9] for environmental durability investigations or [4] for creep characterizations). The loading principle was also inspired from previous works ([10], [11], [12]) and involves an hydraulic jack located between the two concrete blocks. The jack pushes away the blocks from each other and imposes a shear stress to the concrete-CFRP interfaces (Figure 2).

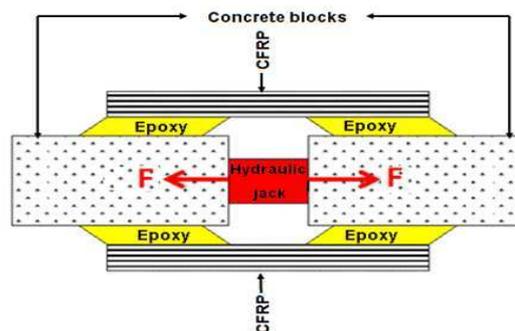


Figure 2. Principle of the double shear test with a schematic description of the loading conditions.

The main innovation of the present device consists in using a flat hydraulic jack (without piston) which makes it possible to lower the distance between the 2 concrete blocks and consequently the overall size of the test body (Figure 3). Such flat jacks are well adapted to impose a constant load in the long-term, compared to traditional jacks operating with pistons, since their design doesn't involve sealing joints that may stick to the piston or the cylinder under sustained pressure. Flat jacks of diameter 150 mm, thickness 25 mm and maximum capacity 150 kN were supplied by Freyssinet.

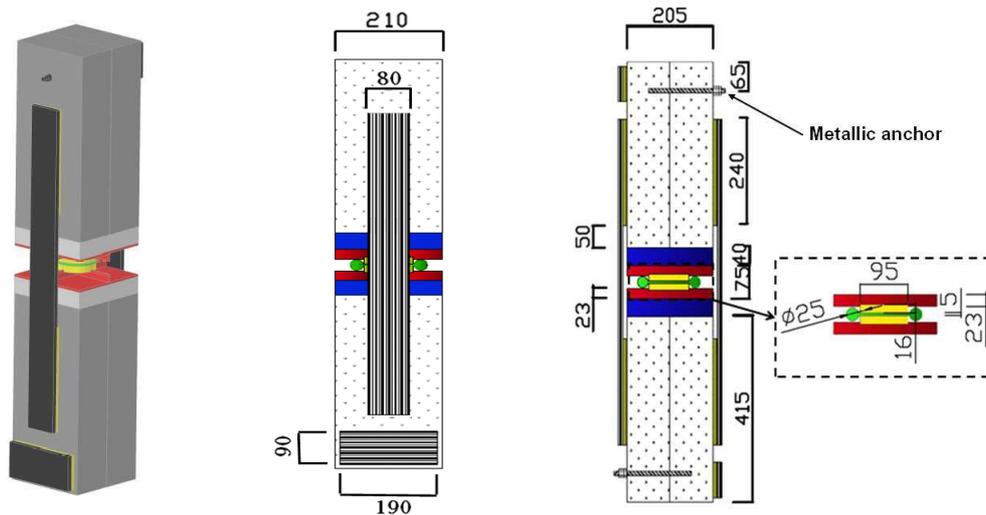


Figure 3. Geometry of the test specimens (dimensions are given in mm).

3.2 Centralized hydraulic system for multi-specimen characterization

Multiple specimens associated to the same number of flat jacks can be connected to a centralized hydraulic system consisting of an accumulator and a hydraulic pump or electronic station. A three-test-bodies prototype was constructed to validate the concept (Figure 4). For each test body, the surface of each of the four bonded joints was $240 \times 80 \text{ mm}^2$. The hydraulic system was pressurized to reach an average shear stress level of 0.6 MPa in the bonded joints, corresponding to 30% of the ultimate shear strength at 25°C . Load was sustained at the chosen constant level thanks to the hydraulic accumulator and was transmitted from the flat jack to the concrete blocks by mean of stainless steel transmission pieces.

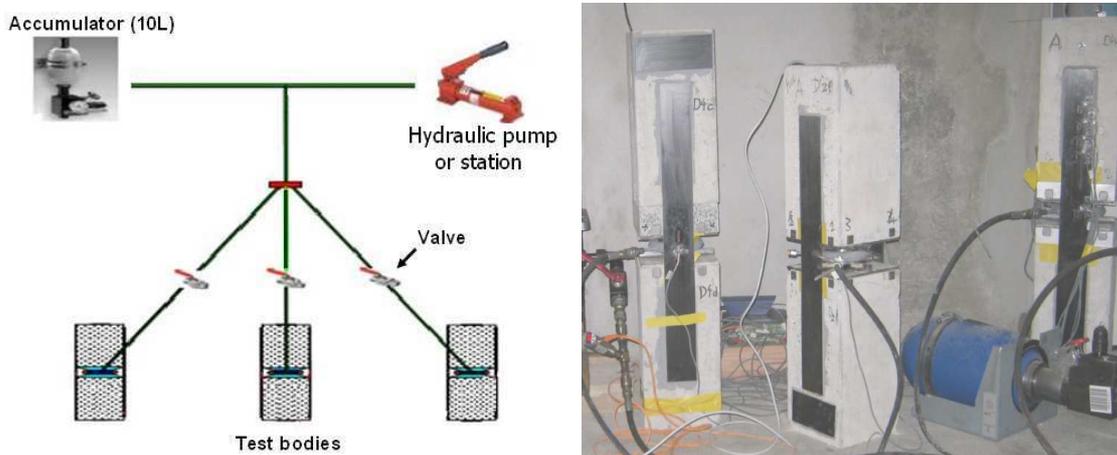


Figure 4. Centralised hydraulic system and prototype setup involving 3 test bodies.

3.3 Gauge instrumentation

A specific strain gauge instrumentation was installed at the top surface of the CFRP plates, in order to monitor the evolution of strain profiles during loading and creep stages. Five strain gauges were disposed along the lap joint and one gauge in the middle part of the CFRP plate (unbonded zone). A symmetrical configuration was respected for CFRP plates bonded on the two opposite sides (A and B) of the test specimens, as shown in Figure 5. The gauge lengths were respectively 5mm for gauges 1 and 2 and 10 mm for gauges 3 to 5.

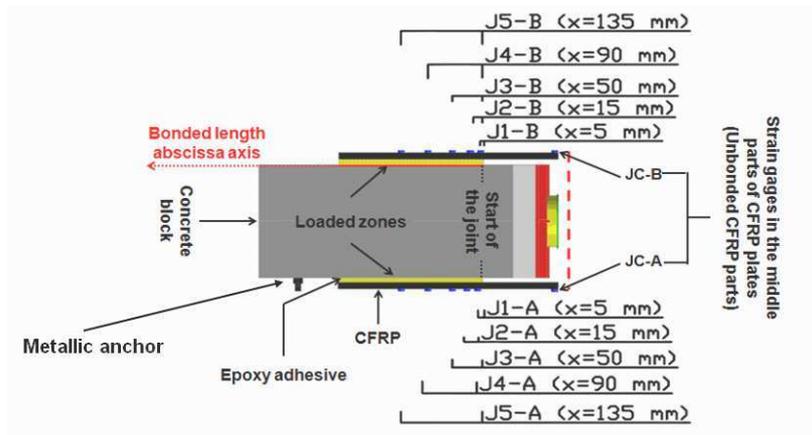


Figure 5. Details of the strain gauge instrumentation on the top surface of CFRP plates.

4. Validation of the proposed creep test setup

4.1 Experimental verifications

The prototype setup was settled in a climatic chamber at a controlled temperature of 25°C and at 50% relative humidity. Creep tests were performed for a period of one month, and both gauge signals, applied pressure and ambient temperature were continuously monitored.

Figure 6 depicts the evolutions of the creep deformations recorded by the various strain gauges, and the variation of hydraulic pressure during the test. It is to note that:

- i) the hydraulic system allows to maintain a constant pressure (32.5 bar),
- ii) strain responses obtained for the 2 opposite sides of the test bodies (A and B) are quasi identical, which demonstrates the symmetrical behaviour of the double shear specimens,
- iii) gauges located in the central part of the CFRP plates do not show any creep deformation of this free portion of the composite (pure elastic behaviour), which was expected.

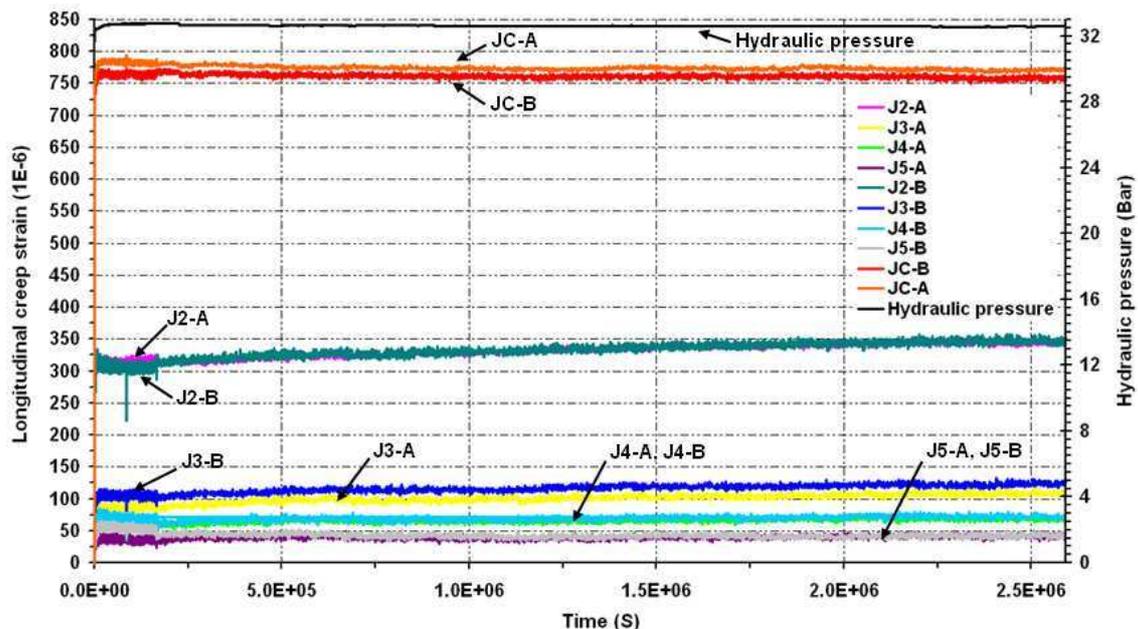


Figure 6. Strain evolutions recorded by gauges bonded on opposite sides (A and B) and evolution of hydraulic pressure during a one month creep period at 25°C.

4.2 Comparison between experimental and modelled elastic responses of concrete/FRP bonded joints

Figure 7 compares the instantaneous shear stress distributions along the lap joint, either determined from experimental strain data, or obtained from two calculation approaches: Volkersen's model and a 2D finite element (FE) analysis.

As regards the experimental determination, the average bond shear stress between two adjacent strain gauges (J_i and J_{i+1}) was calculated by introducing strain measurements into the following equation:

$$\tau_{a(i,i+1)} = E_{CFRP} t_{CFRP} \frac{\varepsilon_i - \varepsilon_{i+1}}{x_{i+1} - x_i} \quad i = 1,2,3,4 \quad (4)$$

where $\tau_{a(i,i+1)}$ is the average adhesive shear stress between gauges J_i and J_{i+1} , ε_i and ε_{i+1} are the longitudinal strains measured by gauges J_i and J_{i+1} , x_i and x_{i+1} is the respective distance of gauges J_i and J_{i+1} from the loaded end of the joint, t_{CFRP} and E_{CFRP} are respectively the thickness and the Young's modulus of the CFRP plate.

In the calculations (Volkersen's model or FE analysis), a linear elastic behaviour was assumed for all the components of the bonded assembly (concrete, CFRP plate, adhesive). Considered mechanical characteristics are listed in Table 1. The instantaneous elastic response of the lap-joint was either calculated from Equation (1) or modelled using CESAR-LCPC FE code [13]. It is to note that the measured shear stress is averaged over the distances between successive gauges; in order to make comparisons, it was thus necessary to calculate Volkersen's and FE shear stresses values averaged over the same distances. Such data are denoted respectively "Volkersen analytical averaged shear stress" and "F.E. averaged shear stress" in Figure 7.

A fair agreement was found between shear stress distributions obtained from experimental data or provided by analytical/FE models. In this context, given that the elastic behaviour of the proposed test setup was consistent with that predicted by conventional models from the literature, the loading device was considered validated.

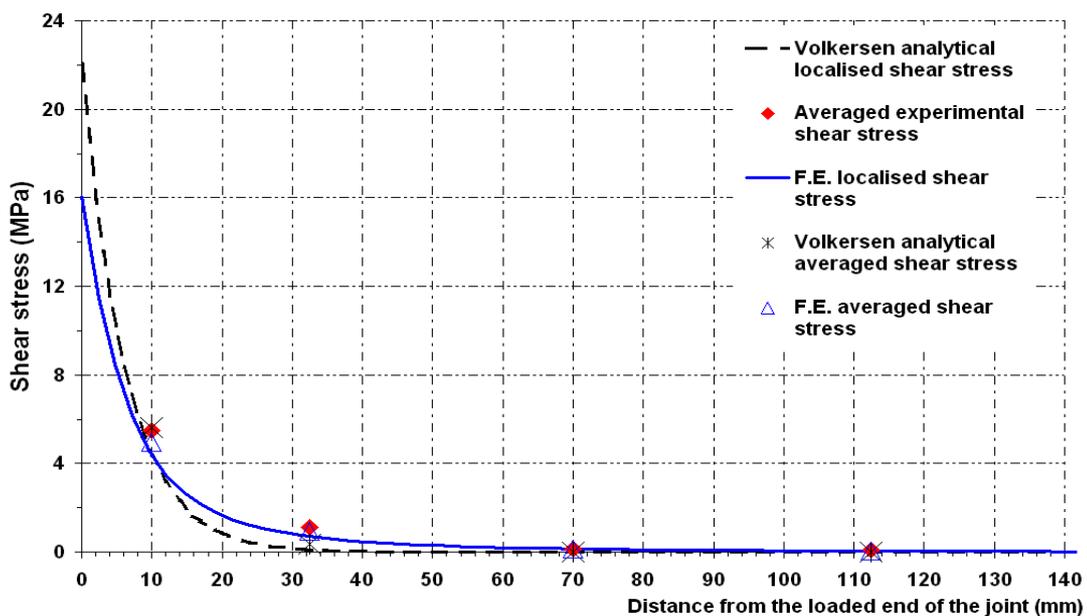


Figure 7. Shear stress distribution along the adhesive layer- Comparison between the FE analysis, Volkersen's analytical model and the experimental profile.

Table 1. Elastic properties of constitutive materials (determined experimentally or given by the supplier).

MATERIAL	YOUNG'S MODULUS (GPa)	POISSON'S RATIO	THICKNESS (mm)
Epoxy adhesive	12.7	0.3	1.0
CFRP plate	165	0.3	1.2
Concrete	35	0.3	102.5

5. Complementary destructive tests

The specific design and the geometry of the concrete blocks (each block are composed of two half-blocs of dimensions 102.5 x 210 x 415 mm³ connected together by a metallic anchor, as shown in Figures 3 and 8) allows at the end of the creep test, to obtain four single shear specimens from each double-shear test body (after cutting the FRP in the central zone). Those specimens make it possible to perform single shear experiments up to failure, using a single shear test machine previously described in other studies ([3], [6], [14]) in order to assess the residual shear capacity of the concrete/FRP interface after creep testing.

In addition, other destructive tests can be performed, such as compression tests on concrete cores drilled from the concrete blocks, or pull-off tests (NF EN 1542 standard) if specific test zones have been initially planned on the specimens (see Figure 8).

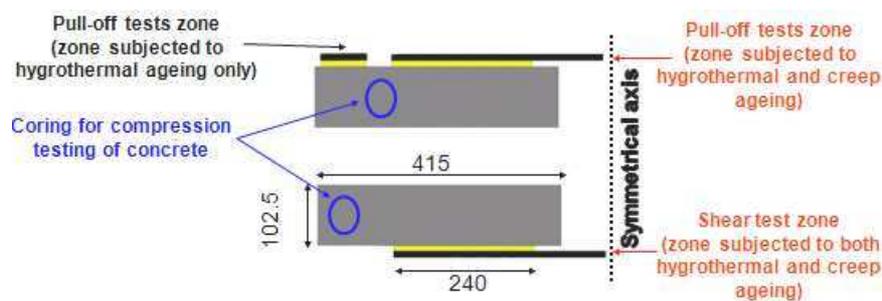


Figure 8. Destructive tests offered by the double-lap shear test bodies in order to assess the residual capacity of the adhesively bonded joints after ageing.

6. Conclusion

The aim of this research was to design and validate an innovative experimental device intended for the creep characterization of bonded concrete/FRP interfaces. An important requirement was to limit the volume of the test setup so that it can be installed in a climatic room in order to study synergistic effects of creep and environmental ageing on the concrete/FRP adhesive bond.

In this context, an original creep setup was designed involving double shear test bodies, with a loading system based on a flat hydraulic jack. A prototype setup with 3 test bodies was constructed to validate the concept. A specific gauge equipment was installed on the test bodies in order to monitor the creep deformation along the bonded joint. Experimental verifications demonstrated the constancy of the hydraulic pressure in the long term (over one month), the effectiveness of the strain gauge instrumentation for monitoring the creep strains, and the symmetry of the double shear test bodies.

In addition, the instantaneous shear stress distribution (elastic behaviour) determined from the strain gauges data was found in fair agreement with prediction provided by classical modelling approaches from the literature (Volkersen's model and FE analysis).

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