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**Durability of concrete/FRP bonded assemblies subjected to coupled hydrothermal and creep ageing mechanisms: Experimental and analytical investigations**

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## Abstract

An innovative experimental device was designed for characterizing the long-term behavior of concrete/composite bonded interfaces subjected to both sustained loading and hydrothermal ageing. This test setup makes it possible to load simultaneously several double shear specimens, by means of flat jacks connected to a hydro-pneumatic accumulator. A prototype involving three double-shear specimens was first designed and built in order to validate the concept. Besides, an analytical model was developed for studying the creep behavior of bonded concrete/FRP interfaces, and validated by comparing the simulations to experimental data.

This paper aims at describing the proposed creep setup and its instrumentation, as well as the validation stages and the proposed creep analytical model. In a final part, we introduce an ongoing large scale experimental program involving fourteen test specimens (with two different commercial FRP systems) installed in a climatic room at 40°C and 95% R.H., in order superimpose a hydrothermal ageing to the creep load.

*Keywords:* concrete/composite bonded joints; creep; durability; analytical modelling; coupled ageing.

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## Résumé

Un dispositif expérimental innovant a été conçu pour étudier la durabilité des interfaces collées béton/composite soumises simultanément à une sollicitation de fluage et à un vieillissement hygrothermique. Plusieurs corps d'épreuve peuvent être mis en charge au moyen d'un système hydraulique centralisé. Pour valider ce concept, un prototype à trois corps d'épreuve à double recouvrement a été construit. Les résultats issus du prototype ont permis de développer et de valider un modèle analytique permettant d'étudier le fluage des interfaces collées béton/composite.

Cet article se propose de décrire le dispositif de fluage, son instrumentation, les différentes phases de validation et le modèle analytique proposé. Dans la dernière partie, nous décrivons également un vaste programme expérimental, actuellement mené sur un banc de fluage comportant quatorze corps d'épreuve à double recouvrement. Ce banc de fluage complet a été installé dans une chambre climatique à 40°C et 95% H.R., afin de coupler le vieillissement hygrothermique à la charge mécanique de fluage.

*Mots-clé:* joints collés béton/composite; fluage; durabilité; modélisation analytique; sollicitations couplées.

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## 1. Introduction

Rehabilitation/strengthening of civil structures by externally bonded Fiber-Reinforced Polymers (FRP) is now considered as an effective technique (Quiertant, 2011) which presents major advantages over other traditional methods. FRP strengthening systems consist of the strengthening composite material and the polymeric resin (usually an epoxy adhesive) used to bond the reinforcement to the concrete substrate. Due to the growing number of field applications of this technique, a major concern is the durability of the repairs and the long-term mechanical behavior of concrete/composite adhesive joints. In order to account for actual in-service conditions, durability studies should investigate the synergistic effects of mechanical and environmental ageing mechanisms on the performances of concrete/composite bonded assemblies. If the individual effects of environmental ageing (temperature, humidity) and mechanical loading on the long-term behavior of concrete/composite interface begin to be understood (Mazzoti & Savoia, 2011; Benzarti *et al.*, 2011), the ageing process of bonded joints under coupled environmental and stress conditions remains largely unexplored. Its analysis requires not only the knowledge of concepts related to physical-chemistry and mechanics, but also the development of specific experimental methods. For this reasons, the French institute of Science and Technology for Transport, Development and Networks (IFSTTAR), is conducting researches on the durability of concrete/composite assemblies subjected to both sustained load and hydrothermal ageing. The main objective of these researches is to establish a consistent and rigorous methodology for studying the long-term behavior of bonded concrete/FRP interfaces, based on the development of an innovative experimental creep device (double shear test configuration) that can be coupled to environmental ageing. This paper aims at giving an overview of this research program.

*First*, a prototype involving three double-shear specimens was designed and built in order to validate the proposed concept. The mechanical behavior of the bonded assemblies involved in the test setup was then compared to numerical and analytical modeling, done either by calculating the instantaneous response using the Völkersen's analytical model (Völkersen, 1938), or by simulating the delayed creep response of the adhesive layer. In this line, analytical models have been developed to describe the creep behavior of the concrete/FRP interface.

*Finally*, a more advanced creep test setup involving fourteen double shear specimens (with two different commercially available FRP systems) was built and installed in a climatic room (40°C, 95% R.H.). After each planned exposure period, two specimens are removed from the climatic room and subjected to destructive tests in order to determine the residual capacity of the FRP/concrete interface. Simultaneously, physico-chemical analyses of the polymer adhesive are also performed on these specimens.

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

In order to study the creep behavior of concrete/FRP bonded interfaces, an innovative double shear test device was designed to meet the following requirements:

- its volume must be limited, so that a large number of specimens (up to 15) can be stored together in a climatic room of surface area 10m<sup>2</sup>,
- the loading system must be able to apply a constant load in the long term (at least for one year) on all the test specimens,
- specimen's geometry must be compatible with an existing single shear test (Chataigner *et al.*, 2009; 2011), in order to evaluate the residual shear capacity of the bonded assembly after creep experiments.

### 2.1. Description of the shear creep test

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. The double-shear test geometry was previously used in many studies devoted to the short-term (Dolan *et al.*, 1998; Ferrier *et al.*, 2010) or long-term performances of concrete/FRP bonded joints focusing on environmental durability (Cromwell *et al.*, 2011) or creep characterization (Meshgin & Choi, 2009; Ferrier *et al.*, 2011; Meaud *et al.*, 2011).



In the proposed setup, load is applied using a thin hydraulic flat jack positioned between the two concrete blocks, pushing away the two blocks from each other and resulting in an imposed shear stress along the concrete/CFRP interfaces. This loading principle was inspired from previous works (Dolan et al., 1998; Serdar & Binici, 2007; Matana et al., 2005). However, in the present setup, a flat hydraulic jack (jack without piston) was used, which makes it possible to reduce the initial distance between the two concrete blocks and consequently the overall dimensions of specimens. Moreover, flat jacks are well adapted for imposing a constant load in the long term, compared to traditional jacks operating with pistons, since their design did not involve sealing joints that may stick either to the piston or the cylinder under long-term sustained hydraulic pressure. Flat jacks of diameter 150 mm, thickness 25 mm and maximum capacity 150 kN were supplied by Freyssinet (Figure 2).

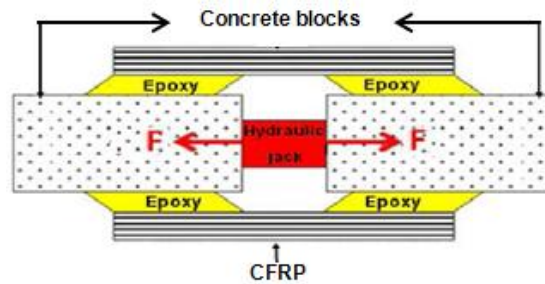


Fig. 1. Principle of the double-shear test with a schematic description of the loading conditions.

## 2.2. Geometry of the double shear creep test specimens

Each specimen is composed of two blocks and each block is constructed with two half-blocks (Figure 2) of dimensions  $102.5 \times 210 \times 415 \text{ mm}^3$  connected together by a metallic anchor. This specific design and the geometry of the concrete blocks allow at the end of the creep period, to obtain four single-shear specimens from each double-shear test body (after cutting the FRP in the central zone, as shown in Figure 3). At the end of each planned exposure period, specimens based on the half-blocks are submitted to single shear experiments up to failure, using a single shear test machine previously described in other studies (Chataigner et al., 2009; Benzarti et al., 2011; Chataigner et al., 2011) in order to assess the residual shear capacity of the concrete/FRP interface.

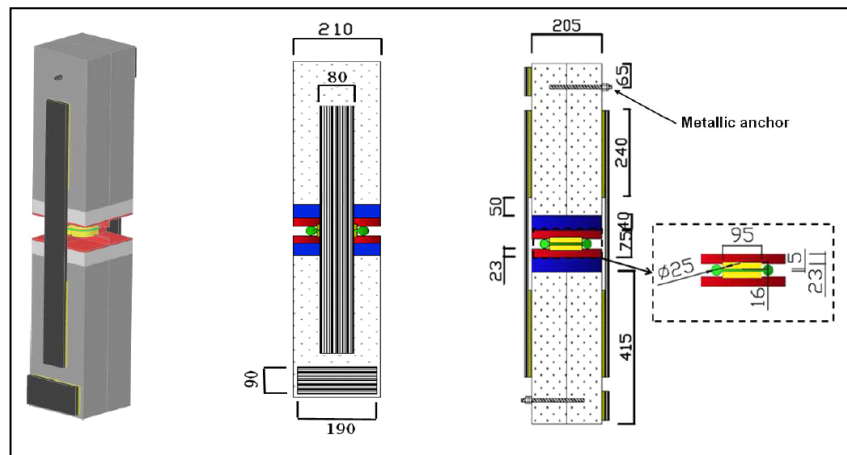


Fig. 2. Geometry of the test specimens (dimensions are in mm).

Concrete blocks are connected together with two Carbon FRP (CFRP) plates commercialized by SIKKA under the trademark “Sika Carbodur®” (Sika®Carbodur® S, 2011). The CFRP plates are symmetrically bonded to the lateral faces of the blocks using the structural epoxy adhesive “Sikadur® 30” (Sikadur® 30, 2011), as shown in Figure 2. The commercial strengthening system (FRP and adhesive) was kindly supplied by SIKKA France. For each test body, the surface of each of the four bonded joints was  $240 \times 80 \text{ mm}^2$  (Figure 2). Each bonded joint began 50 mm away from the front side of the concrete block in order to prevent edge effects.



It is well known that a bonded joint subjected to shear does not exhibit constant shear transfer along the bonded length. There is a concentration phenomenon due to the elastic behavior of the adherends, as first explained by Völkersen in 1938. This concentration effect is related to the existence of an effective transfer length which is an extremely important design criterion in the case of adhesive bonding. Several authors have shown that this length increases when adhesive layer is subjected to hydrothermal ageing (Benzarti et al., 2011) or to creep loading (Diab & Wu, 2007). When coupling both creep and hydrothermal ageing, a substantial increase in the anchorage length is thus predictable. Therefore, to investigate properly the mechanical behavior of the joint after ageing, the joint's bonded length was chosen to be much greater (240 mm) than the effective transfer length of the Sika Carbodur® strengthening system (around 90 mm).

The aforescribed specimens were mainly designed to study the evolution of the concrete/FRP joint's mechanical properties after being subjected to coupled environmental and creep effects. However, in order to understand the single effect of environmental ageing (temperature and humidity), a strip of CFRP plate was also bonded on a non-mechanically stressed region of each specimen (Figure 3). Pull-off tests can be performed in this region after selected periods of ageing, and the results can then be compared with those of pull-off tests carried-out on mechanically-loaded zones. In addition, destructive compression tests can also be performed on concrete cores drilled from the concrete blocks, in order to check any evolution of the mechanical properties of concrete possibly induced by the ageing treatment.

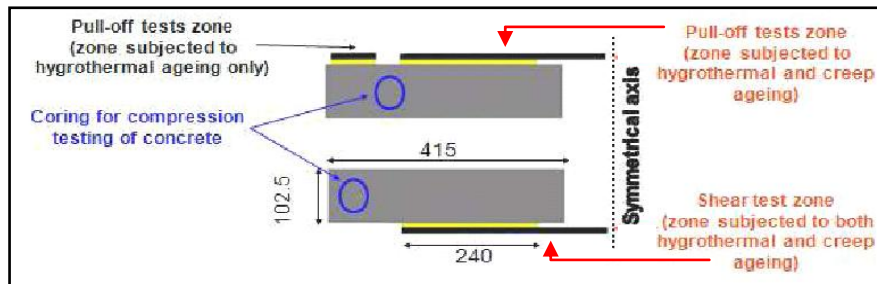


Fig. 3. Destructive tests provided by the double-lap shear test bodies in order to assess the residual capacity of the adhesively bonded joints after ageing.

### 3. Construction of a three-test-bodies prototype

#### 3.1. Description

A three-test-bodies prototype was constructed to validate the setup concept (Figure 4). The hydraulic system was pressurized to reach an average shear stress level of 0.6 MPa in the bonded joints (shear averaged over the bonded surface area), corresponding to 30% of the load-capacity of the bonded joint 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. The overall test setup was installed in a climatic chamber at a controlled temperature of 25 °C and at 50% Relative Humidity (RH). Creep tests were carried out for a period of one month and both the applied pressure and the room temperature were continuously monitored.

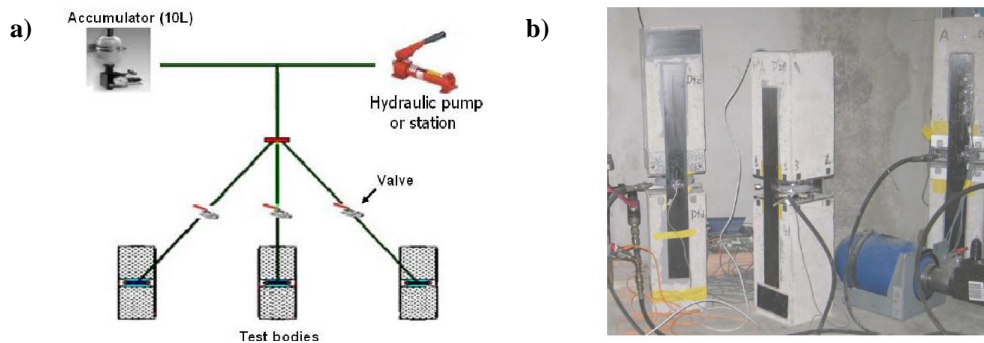


Fig. 4. (a) Centralised hydraulic system; (b) Prototype involving three test-bodies.



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 was glued in the middle part of the CFRP plate (i.e. in the middle of the 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. Values of the longitudinal strains measured on the upper face of the composite were used to determine the shear stress profile along the lap joint and its evolution during the creep test.

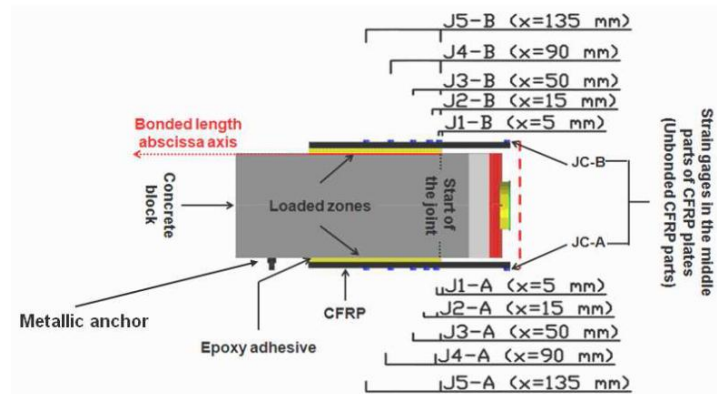


Fig. 5. Details of the strain gauge instrumentation on the top surface of CFRP plates.

### 3.2. Validation of the proposed creep test setup

#### i) Experimental verifications

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:

- the hydraulic system ensures a constant pressure (32.5 bar) throughout the duration of the test,
- the strain responses obtained for the 2 opposite sides of the test bodies (A and B) are similar, which demonstrates the symmetrical behavior of the double-shear specimens,
- 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 behavior), which was expected.

Strain values provided by the gauges installed near the loaded end (J1-A and J1-B) differ significantly for the joints of the two opposite sides. However, the strain gradient is so important in this area (near to the loaded edge) that this observed deviation can be attributed to a possible slight difference in the location of the gauges.

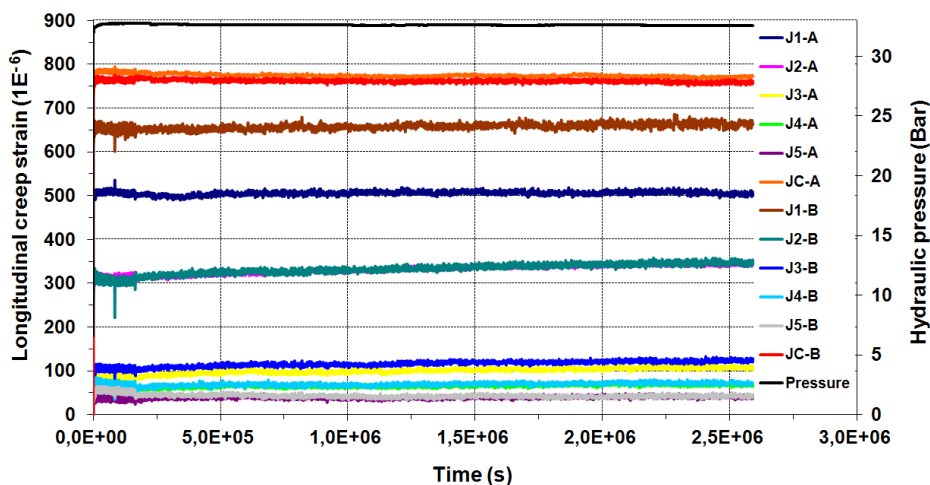


Fig. 6. Evolutions of the strain for various locations at the surface of the CFRP plates (on the two sides A and B of the test body, cf. Figure 5), and evolution of the hydraulic pressure during a one month creep test at 25°C.



**ii) Analytical verifications**

a) Modeling of the instantaneous elastic response

Völkersen (1938) first proposed a simple shear-lag model for load transfer from one adherend to another only by shearing of the adhesive. Respecting the boundary conditions of our concrete/FRP joints, this theory leads to the following expression for the shear stress distribution along the bonded joints:

$$\tau_a(x) = \frac{G_a \sigma_{10}}{\lambda e_a E_{FRP}} \cdot \left( \frac{E_{FRP} e_{FRP}}{E_c e_c} - 1 \right) \cdot \left( \frac{\text{Sinh}(\lambda x)}{\text{Tanh}(\lambda L)} - \frac{\text{Cosh}(\lambda x)}{\text{Tanh}(\lambda L)} \right) \quad (1)$$

With:

$$\lambda^2 = \frac{G_a}{e_a} \cdot \left( \frac{1}{E_{FRP} e_{FRP}} + \frac{1}{E_c e_c} \right) \quad (2)$$

Where:

- $E_{FRP} = 165\text{GPa}$ ,  $E_c = 35\text{GPa}$  and  $G_a = 4.88\text{GPa}$  are respectively the tensile moduli of adherends (FRP: fibre reinforced polymer and c: concrete) and the shear modulus of the adhesive.
- $e_{FRP} = 1.2\text{mm}$ ,  $e_c = 102.5\text{mm}$  and  $e_a = 1\text{mm}$  are respectively the thicknesses of the adherends and the adhesive layer.
- $L = 240\text{mm}$  is the lap length.
- $\sigma_{10}$  is the axial stress applied to the upper adherend.

In the model, a linear elastic behavior was assumed for of all the components of the bonded assembly (concrete, CFRP plate, adhesive). Figure 7 compares the instantaneous shear stress distributions along the lap joint, either determined from experimental strain data, or obtained by Völkersen’s model using the following equation:

$$\tau_{a(i,i+1)} = E_{FRP} e_{FRP} \cdot \frac{\varepsilon_i - \varepsilon_{i+1}}{x_{i+1} - x_i} \quad (3)$$

Where:

- $\varepsilon_i$  and  $\varepsilon_{i+1}$  are the longitudinal strains respectively measured by gauges  $J_i$  and  $J_{i+1}$  immediately after loading’.
- $x_i$  and  $x_{i+1}$  are the respective distances of gauges  $J_i$  and  $J_{i+1}$  from the loaded end of the joint.

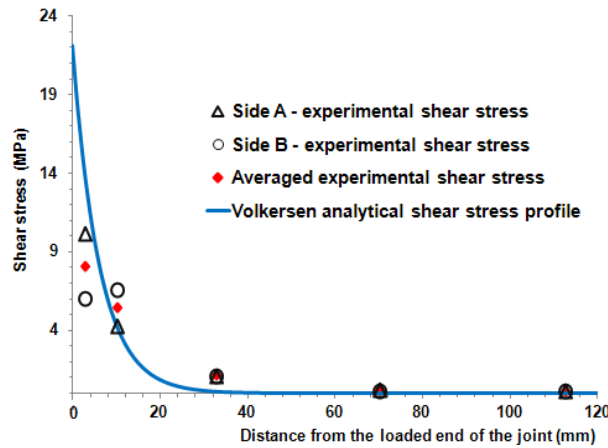


Fig. 7. Shear stress distribution along the adhesive layer- Comparison between Völkersen’s model and experimental data.

In fact, Equation (3) leads to a shear stress value averaged between the two adjacent strain gages ( $J_i$  and  $J_{i+1}$ ). This equation makes it possible to evaluate the experimental instantaneous elastic shear stress profile along the lap length. A fair agreement was found between shear stress distributions obtained either from experimental data or provided by Völkersen’s model (Figure 7). Considering that the experimental behavior of the proposed test setup was consistent with that predicted by Völkersen’s model, the loading device was assumed to be validated.



b) Modeling the creep behavior

First, the visco-elastic response of the epoxy adhesive was characterized by conducting uniaxial tensile creep tests at different temperature. These tests were conducted on parallelipedic bulk samples of the structural epoxy adhesive (Sikadur® 30) using a VA2000 viscoanalyzer from METRAVIB (Limonest, France). Then a predictive approach based on the Time-Temperature Superposition Principle (construction of master curves) and the use of Burger's rheological model (Figure 9 (b)) allowed us to propose a linear creep model for the studied adhesive. In the present study, series of short-term tensile creep/recovery cycles (30 min creep followed by 30 min recovery) were carried out under isothermal conditions, for temperature levels ( $T$ ) ranging from 25 to 57 °C and with variation of 2 °C between two successive cycles. Tests were performed at constant stress level ( $\sigma_0$ ) of 5MPa.

Figure 8 (a) presents the creep compliance vs. time ( $t$ ) curves ( $J(t,T) = \varepsilon(t,T) / \sigma_0$ ) recorded under isothermal conditions. These individual curves were then horizontally shifted along the log-time scale axis according to the Time-Temperature Superposition Principle (Vaidyanathan et al., 2003; Sheng et al., 2010), in order to obtain the creep compliance master curve at the reference temperature of 25 °C and for the considered stress level of 5 MPa (Figure 8 (b)). This master curve provided a prediction of the creep behavior of the bulk epoxy adhesive over a period of  $10^{13}$  s, which may not be very realistic. However, we were mainly interested in a one-month prediction (Figure 9 (a)) which will be used to identify parameters of the Burger's rheological model in the next step.

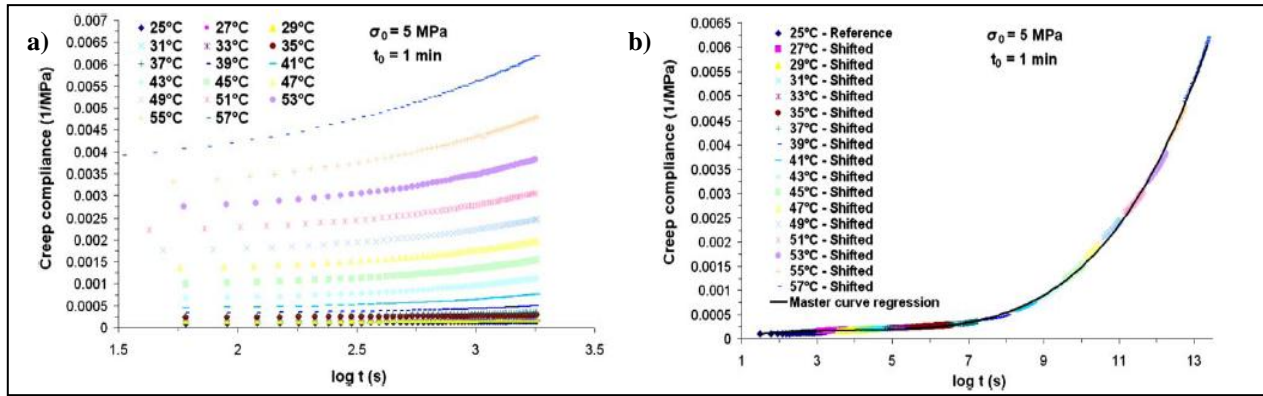


Fig. 8. (a) Creep compliance vs. time curves obtained from short-term creep experiments under various isothermal conditions and for a constant applied stress of 5 MPa; (b) Creep compliance master curve of the bulk epoxy adhesive, for a reference temperature of 25 °C and an applied stress level of 5 MPa.

Constitutive equations for Burger's model can then be derived by considering the strain response under constant stress of a Maxwell unit and a Kelvin unit connected in series (Figure 9 (b)). Then, the total strain at time  $t$ , noted  $\varepsilon(t)$ , is equal to the sum of strains of these two elements:

$$\varepsilon(t) = \sigma_0 \left[ \frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2} \left( 1 - \exp\left( \frac{-E_2}{\eta_2} t \right) \right) \right] \quad (4)$$

Where  $E_1$  and  $E_2$  are the elastic moduli of the springs, and  $\eta_1$  and  $\eta_2$  are viscosities of the dashpots in this model.

The elastic modulus of the adhesive  $E_1 = 12.7$  GPa was determined experimentally by static tensile tests carried out at 25°C. The other parameters ( $\eta_1$ ,  $\eta_2$  and  $E_2$ ) are identified by fitting Burger's model to the experimental (creep strain vs. time) curve, as shown in Figure 9 (a). An extended description of the determination of Burger's model parameters are presented in the reference by Houhou et al. (2012). Identified values are listed in Table 1.

In a second stage, this rheological model of the adhesive layer was implemented in Völkersen's model. This introduction is done by replacing in Equation (1) the constant value of the shear modulus of the adhesive layer ( $G_a$ ) by a time dependent value  $G_a(t)$  deduced from Equation (4), and expressed as:

$$G_a(t) = \frac{1}{2 \cdot (1 + \gamma) \left[ \frac{1}{E_1} + \frac{t}{\eta_1} + \frac{1}{E_2} \left( 1 - \exp\left( \frac{-E_2}{\eta_2} t \right) \right) \right]} \quad (5)$$

Where  $\gamma$  is the Poisson's ratio of the adhesive.



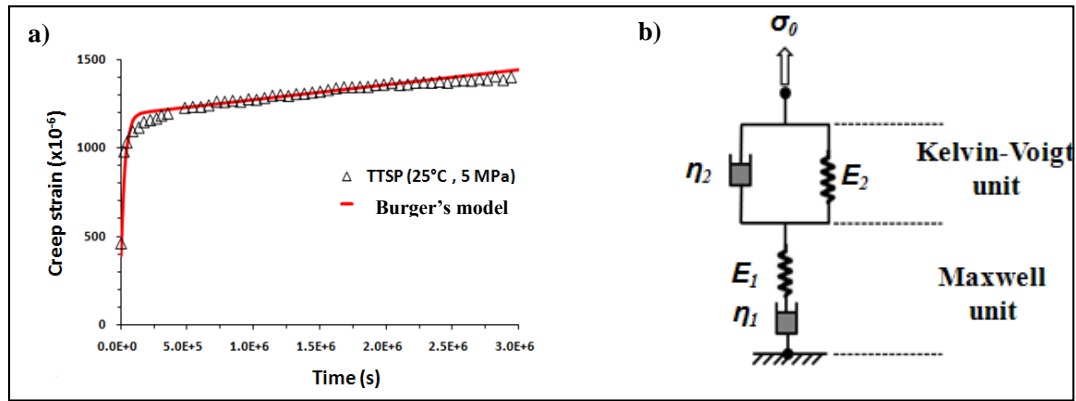


Fig. 9. (a) Creep strain vs. time curve calculated with Burger's model and compared to the curve obtained from the creep compliance master curve; (b) Schematic description of Burger's analytical model.

Table 1. Parameters of Burger's model identified by fitting the experimental (creep strain vs. time) curve.

$\eta_1$ (GPa.s)	$\eta_2$ (GPa.s)	$E_2$ (GPa)
$59.1 \times 10^6$	$19.0 \times 10^4$	6.3

Such an approach was used to calculate the shear stress distribution along the lap joint at different stages of the creep test, and to describe the creep behavior of the concrete/FRP interface over the considered period. The experimental shear stress at creep time  $t$  is determined by replacing  $\varepsilon_i$  and  $\varepsilon_{i+1}$  in Equation (3) by  $\varepsilon_i(t)$  and  $\varepsilon_{i+1}(t)$ .

A comparison between these simulations and the experimental data obtained after one month of creep test is proposed in Figure 10. This result demonstrates the robustness of the proposed model.

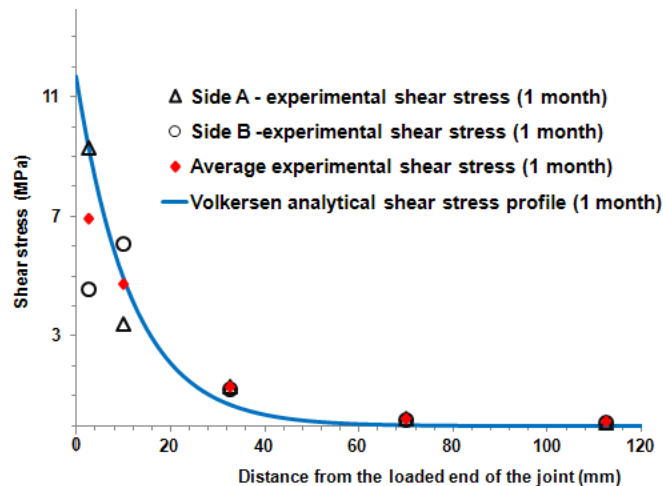


Fig. 10. Shear stress distribution along the adhesive layer after one month creep- Comparison between Volkersen's analytical model and the experimental profile.

#### 4. Full-scale creep setup

After the validation of the prototype creep device, a more advanced creep setup involving fourteen double-lap test specimens was constructed (Figure 11 (a)). Half of the specimens were strengthened with Sika®Carbodur® S and the other half with Compodex® C12 reinforcing composite systems. This creep setup was installed in the climatic room and hydrothermal ageing conditions were set at 40°C and 95% R.H.. Specimens were subjected to



sustained load thanks to flat jacks powered by a hydraulic system similar to the one used in the prototype, but controlled by an electronic station connected to a pressure sensor. Beside these characterizations of the bonded interfaces, tests were also conducted on samples of the bulk adhesive material stored in the climatic room, some of these samples being simultaneously subjected to creep loading (Figure 11 (b)). The first results of this ongoing experimental campaign are presented in Houhou et al. (2012).

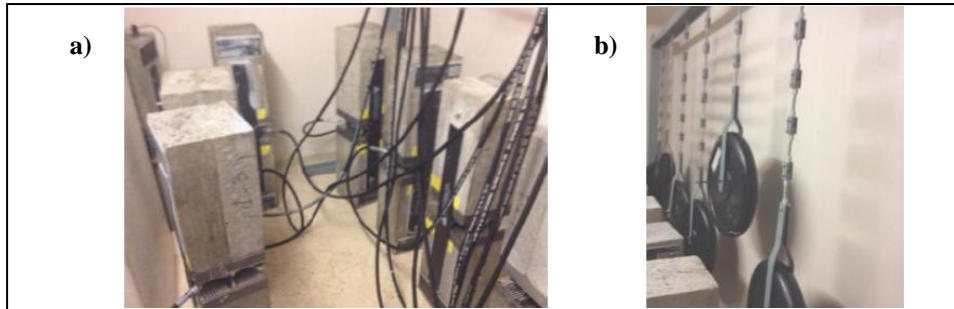


Fig. 11. (a) Full scale creep setup in the climatic room; (b) samples of bulk epoxy adhesive subjected to coupled hydrothermal and creep ageing.

## 5. Conclusions

The aim of this research was to develop an innovative experimental device suited for the creep characterization of bonded concrete/FRP interfaces, and more particularly for studying synergistic effects of creep and environmental ageing.

An original creep setup was designed, based on double-shear test bodies loaded by hydraulic flat jack. A prototype with three test bodies was first constructed and equipped with gauges to monitor the creep deformation along the bonded joint. Experimental verifications demonstrated the constancy of the hydraulic pressure in the long term, the effectiveness of the strain gauge instrumentation for monitoring the creep strains and the adequate symmetry of deformation of the double-shear test bodies.

Besides, an analytical model was developed for simulating the creep behavior of bonded concrete/FRP interfaces, and it was then validated by comparing simulation to experimental evidences:

- the long-term response of the epoxy adhesive was first identified from a predictive approach based on the Time-Temperature Superposition Principle and the use of Burger's model, which made it possible to propose a linear creep model for the bulk epoxy adhesive.
- this calibrated creep model of the adhesive layer was then implemented in Völkersen's model to simulate the creep behavior of concrete/FRP bonded joints. Such an approach was used to calculate at each time step of the creep test, the shear stress distribution along the lap-joint.
- a comparison between calculations and experimental results showed that the proposed model reproduces properly the shear stress profiles measured just after the load application or after one month of creep.

Finally main features of an ongoing full-scale experimental program are described. This setup involves fourteen test specimens, reinforced with two different commercial FRP systems and installed in a climatic room (40°C, 95% R.H.) in order superimpose a hydrothermal ageing to the creep load.

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