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Determination of Creep Behaviour of Adhesively Bonded Assembly – Application to Adhesively Bonded Steel Fasteners

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Abstract. The use of adhesively bonded assembly is clearly justified for the case of all-FRP structures. Yet, there are still some issues related to the appraisal of the durability for such assembly. This article presents some investigations led on adhesively bonded connections in the case of steel fasteners bonded to steel plate. The studied solution was developed by Cold Pad to propose alternative assembly to welding or bolting (Figure 1). This allows avoiding heavy on-site operations and is particularly well adapted to applications requiring cold working. In addition, it prevents from local steel material fragilization, residual stresses creation, or geometrical stress concentration that may decrease the structure’s life expectancy. The understanding of creep behavior may help in a greater appraisal of long-term behavior of bonded solutions in other cases, such as all-FRP structures for instance. To be able to investigate the creep behavior of the developed solution, both experimental and numerical investigations were carried out. The experimental investigations were led on real scale assembly, at different stress levels, and under different load situations. The fastener may indeed be submitted to either predominant tension load, or shear load. These investigations led at different load levels allowed obtaining failure modes, repeatability, time to failure data, but also, local displacements evolution with time. The results revealed a non-linear evolution of those displacements closed to a Burger law. This model was thus chosen, and an analytical determination of creep parameters was realized. This was compared to finite element investigations to verify the adequacy of the proposed methodology. The good suitability of the modelling approach is demonstrated, and the dependency of the parameters with stress level is highlighted. In addition, the finite element investigations allow giving insight of internal stresses evolution during creep.

Keywords: Adhesively bonded connections, creep behaviour, experimental investigations, modelling.

1 Introduction

A European report has been recently published to propose preliminary design guidelines for the realization of structures in composite materials [2]. Those guidelines should help designers to study the possibility of alternative design strategies. One of the key issues in relation with the design of structures is the assembly. In the case of composite materials, the use of structural adhesive bonding appears as an excellent option as it is highly compatible with the polymer matrix of the composite and as it should decrease localized stress concentration effects.

Structural adhesively bonding is however still a recent technology (in civil engineering) and its design encounters some barriers linked especially to the justification of its durability. Durability covers a wide range of topics that should be considered: environmental durability (moisture, temperature, ...), mechanical durability (fatigue, creep, ...), and combined effects.

In this paper, some recent investigations related to the creep behaviour of structural adhesively bonded joints are presented. In the first part, the led experimental investigations (realized on adhesively bonded steel fasteners) are described. Two loadings were studied: tension and shear. Then, a rheological model is used to analyse the obtained results. The identification of the rheological parameters for both loadings are consistent and allow determining which parameter may be considered as constant or stress dependent.

2 Experimental investigations

2.1 Studied bonded samples

The firm Cold Pad developed adhesively bonded fastener solutions (Fig. 1.a), whose aim is to replace welding by structural bonding, to repair tertiary steel structure in offshore area. A specific installation tool was also developed (Fig. 1.b) in order to ensure precise control of the bonding between the two substrates [3]. These bonded fasteners are specific for a type of load: tension and shear (Fig. 2).

Regarding the durability issue raised by such a solution, as there are specific protections against moisture diffusion, creep behaviour appears to be one of the main phenomena that must be studied.

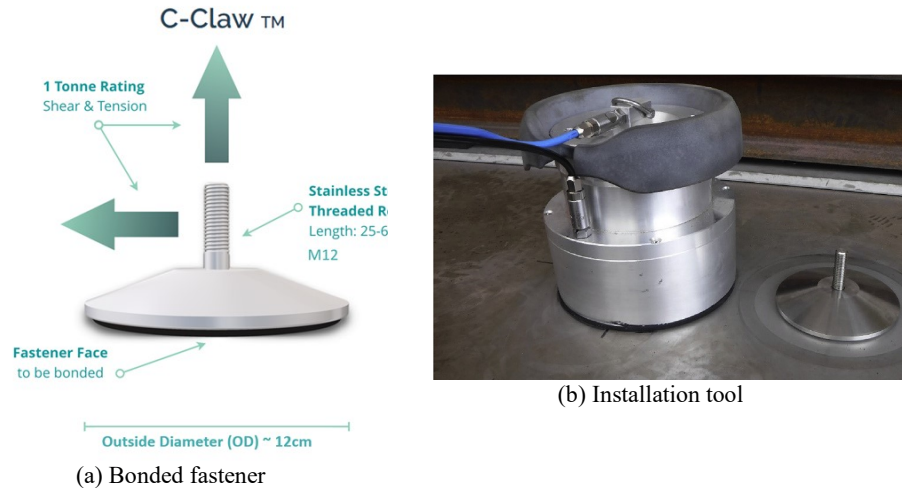


Fig. 1. Bonded fastener solution developed by Cold Pad [3]



Fig. 2. Photo of studied fastener (tension on the left and shearing on the right) [4]

2.2 Tests set up

The analysed tests follow the same procedure than the one used for the study of E. Djeumen and al. [4]. The fasteners were bonded to square 20 mm thick steel plate. The used adhesive is a methacrylate, with approximately 1500 MPa of elasticity modulus. The tests are performed at $20^{\circ}\text{C} \pm 3^{\circ}\text{C}$. Before each bonding, a surface preparation is done to the substrate and the fastener. The fastener is bonded to the substrate with the C-Hawk, the installation tool developed by Cold Pad, at ambient temperature.

The test set up has been developed in order to represent at best the real conditions of use of the fasteners. The tests are equipped with three LVDT sensors. For the tension tests, they are placed perpendicularly to the joint plane at 120° to measure out-of-plane displacements and to assess the symmetry of the test (Fig. 3). Using geometry, it is possible from those three measurements to assess the maximum out-of-plane dis-

placement value. For the shear tests, one sensor measures the displacement in the plane (sensor 1) and three other sensors are placed at 120° to measure the out-of-plane displacement (Fig. 4). The measures are recorded every 20 seconds.

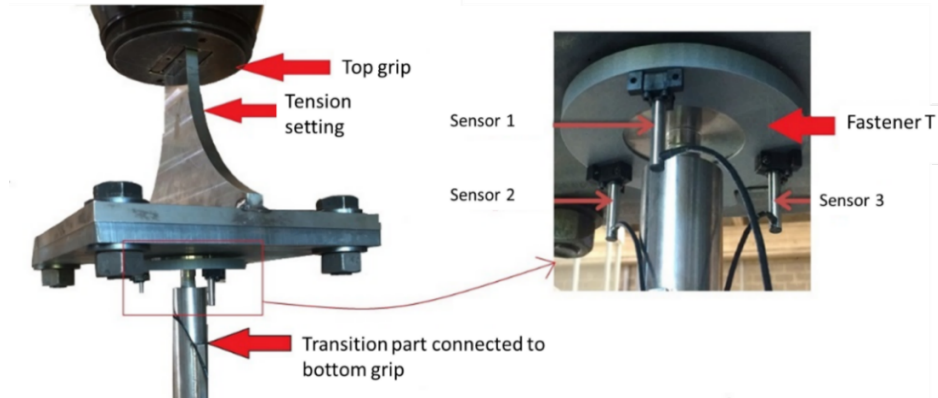


Fig. 3. Set up for the tension test

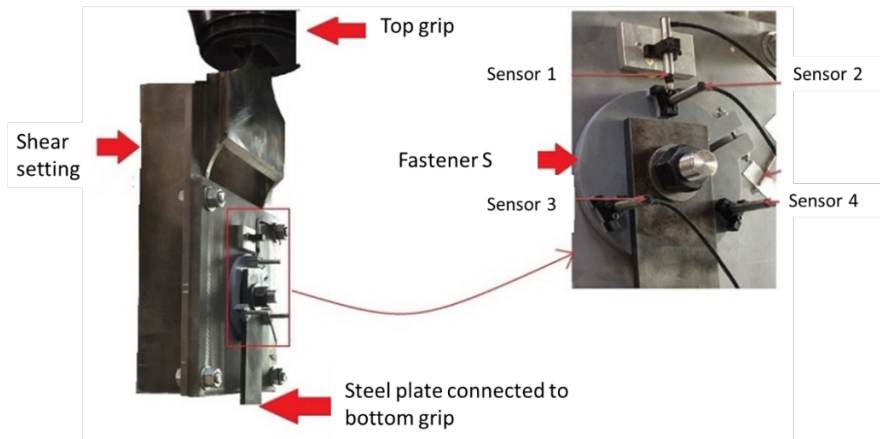


Fig. 4. Set up for the shear test

Preliminary monotonous investigations have been carried out to determine, based on three identical tests, the expected average ultimate capacity for both tensile and shear loadings.

2.3 Realised investigations

The tests are carried out at constant loads between 40% and 80% of the ultimate capacity (defined as S_{ult} for shear and T_{ult} for tension). Each load condition is repeated three times in order to assess the repeatability of the results. **Erreur ! Source du ren-**

voit introuvable. gives the time to failure of each tensile test and Erreur ! Source du renvoi introuvable. of each shear test.

Table 1. Time to failure of the tensile creep tests

Normalised applied tension (%)	Time to failure			Failure mode
	Test 1	Test 2	Test 3	
47%	22 days			Cohesive
50%	38 days	35 days		Cohesive
60%	36 hours	23 hours	26 hours	Cohesive
70%	3h16	5h07	47 minutes	Cohesive
80%	3 minutes	2.9 minutes	2 minutes	Cohesive

Table 2. Time to failure of the shear creep tests

Normalised applied shear (%)	Time to failure			Failure mode
	Test 1	Test 2	Test 3	
40%	> 3 months			Cohesive
50%	4,9 days	3,4 days	4,2 days	Cohesive
60%	1h26	1h50	4h54	Cohesive
65%	20,8 minutes	45,6 minutes	18,7 minutes	Cohesive
70%	25 minutes	15 minutes	6 minutes	Cohesive
80%	3,9 minutes	2 minutes	2,3 minutes	Cohesive

For all the tests in tension and shear the failure mode is cohesive (Fig. 5).



Fig. 5. Photo of the fracture surface of a creep shear test at 65% of S_{ult}

The order of magnitude of the times to failure is very different for all the load levels (from several minutes to several days). To compare all the curves from a type of load

(tension and shear) in the same graph, the creep curves are given as a function of the normalised time, which is defined as with Equation (1).

$$t_{normalised} = \frac{time}{t_{failure}} \quad (1)$$

With $t_{failure}$ the time to failure of the test.

Fig. 6 shows that the logarithm of time to failure evolves linearly with the applied load. As the data are saved every 20 seconds, the results from the tensile tests at 80% of the ultimate tensile load and those from the shear tests at 70% and 80% of the ultimate shear load will not be analysed, because there are too few points. The shear test at 40% of S_{ult} will not be analysed because it was stopped before its failure. Interestingly, the obtained slopes seem to be identical for the two loading modes, yet, the shear loading situation seems to be more susceptible to creep. Such kind of curve could certainly be used during design steps.

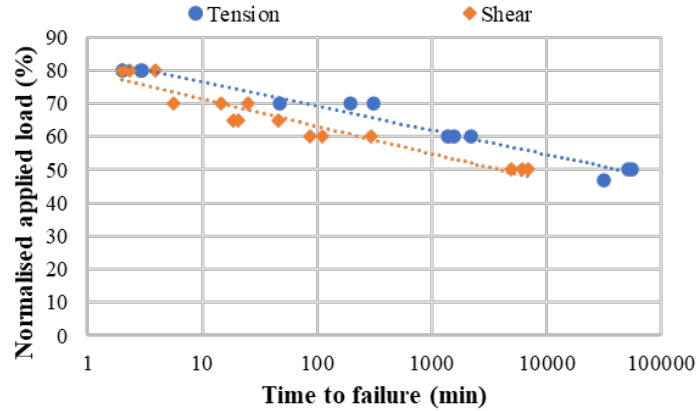


Fig. 6. Normalised applied load as a function of the logarithm of the time to failure

2.4 Study of the displacement results

Fig. 7.a and Fig. 7.c show the maximum axial displacements during one of the creep tensile tests and the in-plane displacement in the case of one of the shear tests for the different studied load levels. Fig. 7.b and Fig. 7.d illustrate those measure displacements of the three tests for one load level in tension and shear. For the tensile tests, we can notice that the displacements increase with the load level. We can also notice the existence of three stages. It is important to note that such investigation suffers from a rather important dispersion especially with a linear time axis.

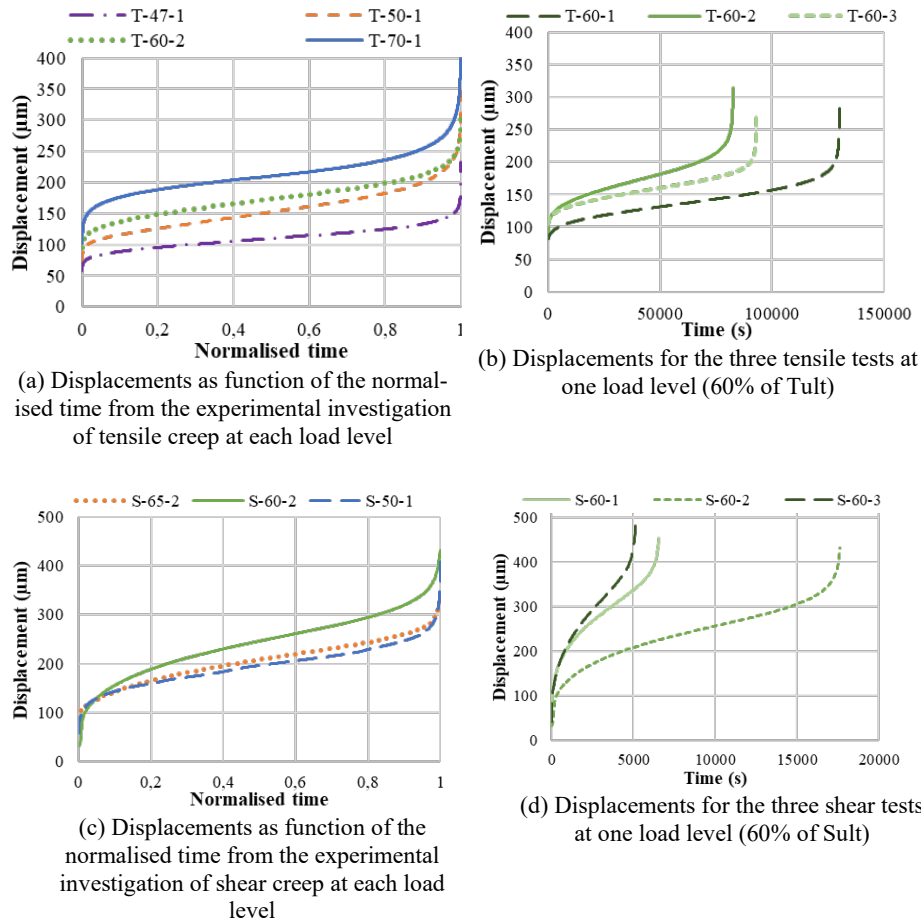


Fig. 7. Experimental data from the experimental investigation of creep

3 Burger model

In order to investigate the possibility to express design criteria in relation with the measured displacement, it was decided to try modelling the assembly. Such a criteria could indeed allow proposing design guidelines adapted for other geometries. The Burger model has been chosen to describe the creep behaviour of the assembly for tensile and shear tests.

3.1 Model presentation

The Burger model is one of the most used creep models. This rheological model associates the Maxwell and the Kelvin-Voigt models (Fig. 8), with springs (E_1 and E_2) for the elasticity and dashpots (η_1 and η_2) for the viscosity. It describes the primary and secondary creep stages [6][5].

This model enables expressing the strain with four parameters (E_1, E_2, η_1, η_2) (Eq. (2)).

$$\varepsilon(\dot{t}) = \sigma \left(\frac{1}{E_1} + \frac{\dot{t}}{\eta_1} + \frac{1}{E_2} \left(1 - \exp \left(-\frac{E_2}{\eta_2} \dot{t} \right) \right) \right) \quad (2)$$

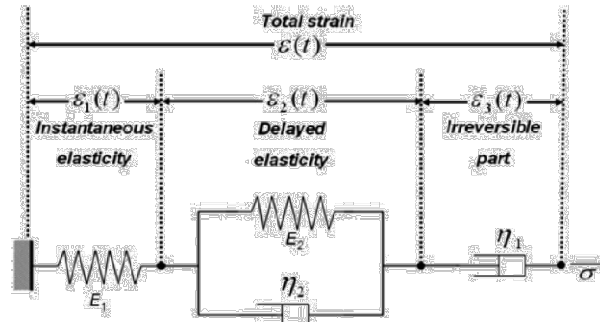


Fig. 8. Burger rheological model [5]

These parameters are identified with a curve from a creep test (Fig. 9): E_1 with the instantaneous strain, η_1 with the slope of the secondary stage, E_2 with the intercept of the same line, and η_2 with the tangent at the origin [6][5].

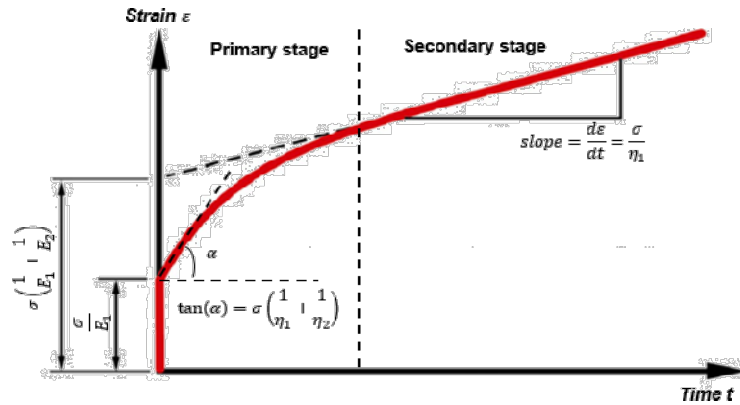


Fig. 9. Parameters identification for Burger model [5]

The Burger model can describe linear and nonlinear material behaviour. If it is linear, the parameters are constant, otherwise they depend on the load level [5].

3.2 Main hypothesis

Several hypotheses are necessary to use the Burger model.

This model defines the strain using the creep stress σ_0 constant during the whole test. In our case, only the applied force to the bonded fastener is known in the experimental investigation. For the modelling, an average creep tensile stress and an average creep shear stress will be used and defined with equations (3) and (4) making the hypothesis that stresses are uniform in both loading modes in the adhesive plane.

$$\sigma_0 = \frac{F}{\pi R^2} \quad (3)$$

$$\tau_0 = \frac{F}{\pi R^2} \quad (4)$$

With F the applied load to the fastener and R the radius of circle which defines the contact surface between the adhesive and the fastener.

The available data from the tests is the maximal axial displacement of the fastener as a function of the time. However, the models use the strain. For the experimental data, the strain is defined with the thickness of adhesive between the two substrates. It is important to note that in our case this thickness is not constant. Thus, Equations (5) and (6) give the definition of strain ϵ and γ used.

$$\epsilon = \frac{\text{displacement}(t)}{l_{a,F}} \quad (5)$$

$$\gamma = \frac{\text{displacement}(t)}{l_{a,S}} \quad (6)$$

With l_0 the value of the average thickness over the surface of the adhesive in the assembly.

3.3 Parameter identification

The Burger model gives the strain with Equation (2). The parameters identification is detailed in Fig. 9. The parameter E_1 is the elastic modulus of the adhesive for the tensile tests, and it is the shear modulus G_1 in the case of the shear tests. The shear modulus is calculated using the hypothesis of an isotropic material (Eq. (7)) and a Poisson's ratio equal to $\nu = 0.4$:

$$G_1 = \frac{E_1}{2(1+\nu)} \quad (7)$$

The parameter η_1 is determined thanks to the slope of the straight line of the secondary stage. E_2 is identified with the intercept of the same line and the parameter E_1 . The parameter η_2 is found with a minimization of an error function for the primary stage.

3.4 Comparison of the model with experimental results

Fig. 10 compares the experimental data with the curve determined with the Burger model, for a creep tensile test at 60% of T_{ult} and a creep shear test at 60% of S_{ult} . **Erreur ! Source du renvoi introuvable.** and **Erreur ! Source du renvoi introuvable.** give the average error for each modelled stage (primary and secondary) between the model and the experimental data. This average error is calculated with Equation (8).

$$\overline{\Delta \varepsilon} = \frac{1}{t_{k_n} - t_{k_0}} \sum_{t_i=t_{k_0}}^{t_{k_n}} (t_{i+1} - t_i) \frac{|\varepsilon_{th_i} - \varepsilon_{exp_i}|}{\varepsilon_{exp_i}} \times 100 \quad (8)$$

With t_{k_0} the time at the beginning of the stage k ; t_{k_n} the time at the end of the stage k ; ε_{th_i} the theoretical strain given by the model at the index number i and ε_{exp_i} the strain given by the experimental data at the index number i .

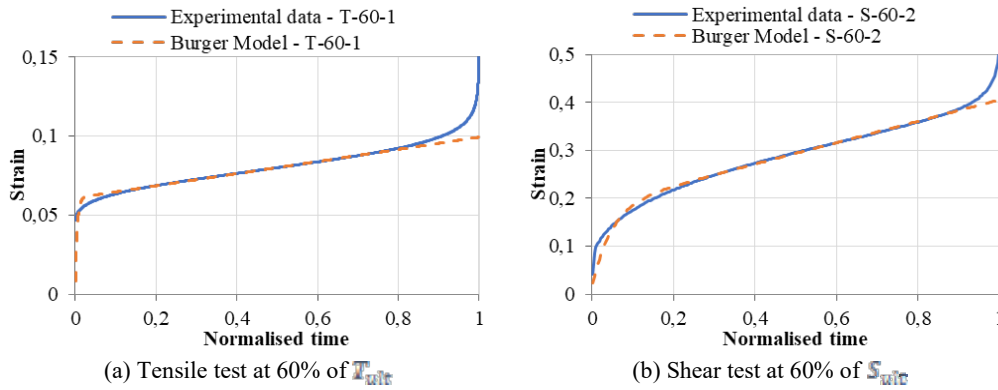


Fig. 10. Comparison between the experimental data and the Burger model of the strain

Table 3. Average relative error of the Burger model compared to the experimental data of the tensile tests

Normalised applied tension (T/Tult) (%)		47%	50%		60%			70%		
		Test 1	Test 1	Test 2	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Average relative error (%)	Stage 1	8,6	7,93	9,93	6,94	6,77	5,27	6,64	3,95	5,65
	Stage 2	0,57	0,59	0,68	0,31	0,4	0,39	0,41	0,42	0,45
	Stage 1 & 2	1,07	0,85	1,67	1,02	1,38	1,06	1,51	0,58	1,08

Table 4. Average relative error of the Burger model compared to the experimental data of the shear tests

Normalised applied shear (S/Sult) (%)		50%			60%			65%		
		Test 1	Test 2	Test 3	Test 1	Test 2	Test 3	Test 1	Test 2	Test 3
Average relative error (%)	Stage 1	8,7	9,89	11,5	8,52	7,62	8,65	8,43	9,06	8,18
	Stage 2	0,64	1,25	0,46	0,51	0,49	0,49	0,46	0,55	0,44
	Stage 1 & 2	1,86	3,18	4,66	2,43	2,39	2,68	2,31	2,56	1,85

We can notice that there is almost no difference between the two curves on the secondary stage, but it is more important on the primary stage. This is probably due to the identification method of the parameter η_2 which has an impact mostly on this creep stage. It is more relevant to describe correctly the secondary than the primary stage of a material, because this is the long-term effect that is useful to characterise the creep behaviour. Moreover, the average error on the primary and secondary stages is very reasonable (lower than 2 % for the tensile tests and 3% for the shear tests). We can also notice that the Burger model describes better the tensile tests than the shear tests. This is mainly caused by the fact that the primary stage is longer for the shear tests than the tensile tests.

3.5 Burger nonlinear model

The Burger model seems to correctly describe the creep behaviour on the primary and secondary stages of the assembly. However, the parameters are different depending on the studied load level. Consequently, the current model does not enable to predict this behaviour. The next phase of this study is to analyse the evolution of the parameters as a function of the load level and type (tension or shear), in order to propose a nonlinear Burger model.

Fig. 11 gives the Burger model parameters identified through the methodology described in the previous paragraph as a function of the normalised average stress in the adhesive for the tensile and shear loads. For both load conditions, the evolution of the parameters with the average stress is the same: the logarithm of the parameters η_1 and η_2 can reasonably be expressed as a linear function of the average stress in the adhesive. The parameter E_2 does not seem to be directly linked to the average stress. This evolution of η_1 and η_2 has already been shown in the work of N. Houhou and al. [5]. For the rest of the model, E_2 will be considered constant for one load condition (tension or shear) and equal to the average value.

We can notice that the parameters values are similar for tensile and shear tests. Consequently, the material could reasonably be considered isotropic.

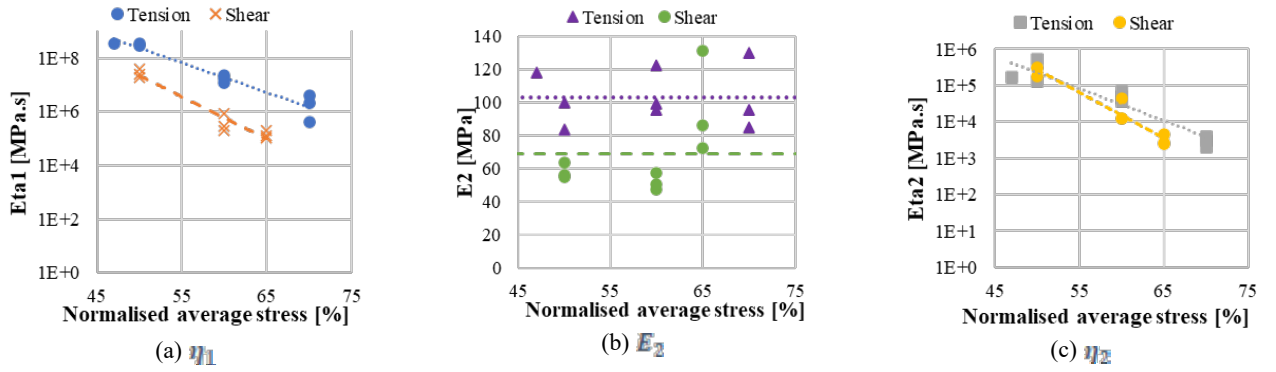


Fig. 11. Burger parameters as a function of the normalised average stress in the adhesive

The nonlinear Burger model enables determining the strain as a function of the time with Equations (9) and (10).

$$\varepsilon(\dot{t}, \sigma_0) = \sigma_0 \times \left(\frac{1}{\varepsilon_1} + \frac{\dot{t}}{\eta_1(\sigma_0)} + \frac{1}{\varepsilon_2} \left(1 - \exp \left(- \frac{\varepsilon_2}{\eta_2(\sigma_0)} \dot{t} \right) \right) \right) \quad (9)$$

$$\gamma(\dot{t}, \tau_0) = \tau_0 \times \left(\frac{1}{\varepsilon_1} + \frac{\dot{t}}{\eta_1(\tau_0)} + \frac{1}{\varepsilon_2} \left(1 - \exp \left(- \frac{\varepsilon_2}{\eta_2(\tau_0)} \dot{t} \right) \right) \right) \quad (10)$$

With: \dot{t} the time; σ_0 the average stress in the adhesive, $(E_1, \eta_1, E_2, \eta_2)$ the Burger parameters with the logarithm of η_1 and η_2 depending linearly with σ_0 , given by Equations (11) and (12) for the tensile tests and (13) and (14) for the shear tests.

$$\eta_{1T}(\sigma_0) = \exp(-2.21 \times \sigma_0 + 31.92) \quad (11)$$

$$\eta_{2T}(\sigma_0) = \exp(-1.76 \times \sigma_0 + 22.39) \quad (12)$$

$$\eta_{15}(\tau_0) = \exp(-2.51 \times \tau_0 + 34.5) \quad (13)$$

$$\eta_{25}(\tau_0) = \exp(-2.01 \times \tau_0 + 26.6) \quad (14)$$

Fig. 12 shows the curve determined with this model for a load level at 60% of T_{ult} for the tensile test and 60% of S_{ult} for the shear test. The graphs compare the model to the experimental data at the same load level. The nonlinear model parameters are calculated using the functions showed in Fig. 11. These graphs also show a spread of the parameters from the fitted function. Consequently, an error of 10% to 20% is noticed at the end of the secondary creep stage between the experimental data and the model. However, the nonlinear Burger model seems to correctly describe the behaviour of the assembly.

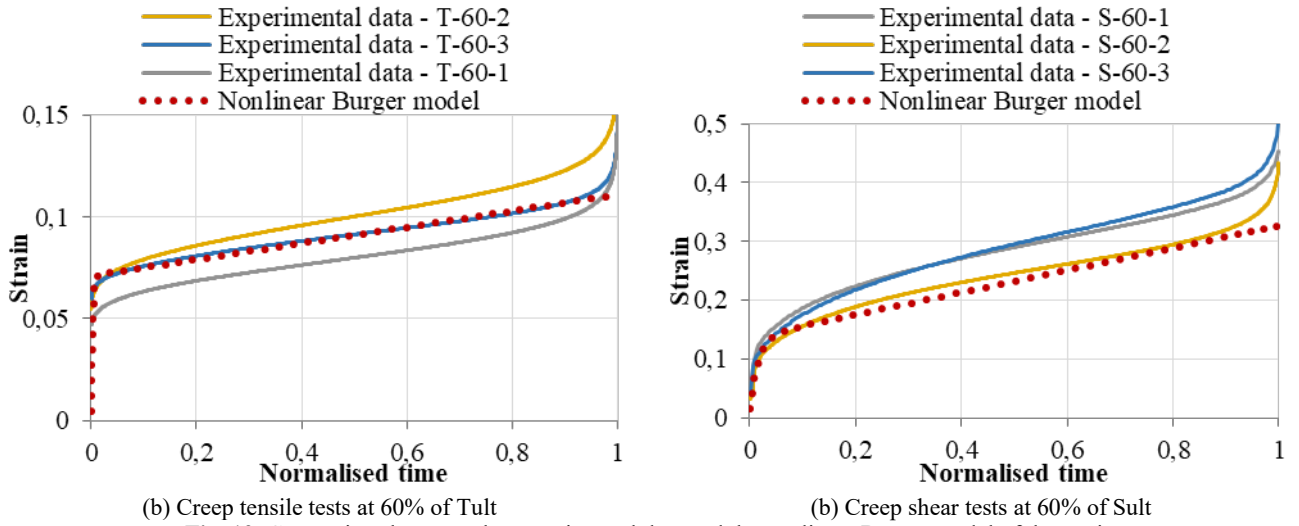


Fig. 12. Comparison between the experimental data and the nonlinear Burger model of the strain

4 Conclusion

Experimental investigations of tensile and shear creep tests of bonding fasteners have enabled analysing their behaviour. A linear link has been noticed between the logarithm of the time to failure and the load level and the time to failure is similar for tensile and shear load. This link could enable to design the lifetime of the assembly, but it would be suitable only for the studied geometry of fasteners.

The Burger model was used to describe the tensile and shear creep behaviour. The Burger model describe very precisely the primary and the secondary creep stages. As the creep tests were carried out at several load levels, a direct link has been observed

between the model parameters and the average stress in the adhesive. This has enabled to build a nonlinear Burger model for the two types of load.

Analyses are in process to propose a criterion for the beginning of the tertiary creep stage.

A numerical model is currently studied to evaluate the impact of the strong hypothesis of homogeneous stress and constant thickness in the adhesive. It will also be used to verify whether the isotropic behaviour of the adhesive by analysing the out-of-plane displacements of the fastener for shear test.

The modelling process could also be improved by taking into consideration the temperature dependency and the possible coupling effects, such as the fatigue creep phenomenon [1].

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