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Fatigue behaviour of adhesive joints

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Abstract

This paper deals with the complexity of mechanical characterization of adhesives and modelling its behaviour in an assembly. Different testing systems have been studied such as tensile tests on bulk specimens, Arcan-Mines tests in different loading conditions, to characterize the mechanical behaviour and failure criteria of an epoxy base adhesive, under static and fatigue loading by taking into account viscoplastic behaviour of the adhesive.

A static failure criterion has been proposed and extended for fatigue loading.

Thick Adherent Shear Tests and single lap shear tests have been performed and compared with previous ones. A Finite Element (FE) simulation has been made in order to validate the proposed models.

Keywords: Adhesive joints; static and fatigue behaviour; modelling

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1. Introduction

The objective of weight reduction for lightweight structures is explained by the motivation of reducing energy consumption in many industrial sectors and particularly transportation. In this context, application of polymer-matrix composites as structural parts is expected to be one of the key-solutions. That explained their increasingly interest in partially substituting steel.

However, there are many technical issues which have to be solved for the implementation of these materials. If many solutions are linked to the choice of materials themselves, a single type material for a given structure is rarely realistic according to the principal stress and the different function of the structure. If metals cannot be excluded as fundamental base material from many applications, plastic materials are used for their low weight (2.7 or 7.8 times lighter than aluminium or steel respectively), high corrosion resistance, excellent formability and greater design flexibility. In this context, economical and technical reasons lead to think that most engineering structures or products will be made of multi-components including several types of materials. Then the main important question is how to join dissimilar materials or structural parts made by them, how to characterize assembly zones and model them. The stability of the joint, its life-time and its durability become structurally sizing for designers.

A previous fatigue study [1] carried out on adhesively bonded joints published few years ago has shown that the creep and fatigue limits of two adhesives (one two-part epoxy paste and one two-part methacrylate), using the TAST specimens, were slightly higher than the "reversibility" limit determined in quasi-static shear .

Fatigue tests were also monitored on single-lap shear specimens (NF-EN 1465) with these two adhesives in the same conditions (frequency, stress ratio, room temperature…) as those used for characterization on TAST specimens. S/N curves and fatigue limits (maximum loads for running 10^7 cycles without any damage of the bonded joint) were obtained.

A good correlation was observed between these experimental fatigue limits and the predicted ones determined by stress distribution computation using the Von-Mises strength criterion and the static "reversibility" limits obtained on thick-adherend shear specimens for both adhesives.

This work is carried out on an adhesive with more complex stress/strain behaviour (elasto-visco-plastic) and using a more complex strength criterion.

2. Materials

In this study, adhesive SikaPower-4588 is characterized in order to propose behaviour model and failure criterion. SikaPower-4588 is a thixotropic single component adhesive with epoxy and polyurethane base. This adhesive cures at high temperature, 180°C during 30 minutes. The mechanical properties of this adhesive are dominated by its viscosity. The viscoplastic behaviour is selected for this kind of material in which time and pressure dependence of plastic strain are taken into account.

3. Experimental testing: specimens and set-up

In order to characterize the mechanical behaviour of adhesive, four different testing systems have been carried out: tensile tests, Arcan-Mines tests in different loading conditions Thick Adherent Shear Test (TAST) and single lap tensile shear test. We used typical bulk specimens (dog bone shape) for tensile tests and adhesive joint specimens for the others (Figure 1). The edge interface beak in Arcan-Mines specimens reduce efficiently the stress concentration and peeling stress close to the free surface of specimen in quasi-pure shear case (90°).

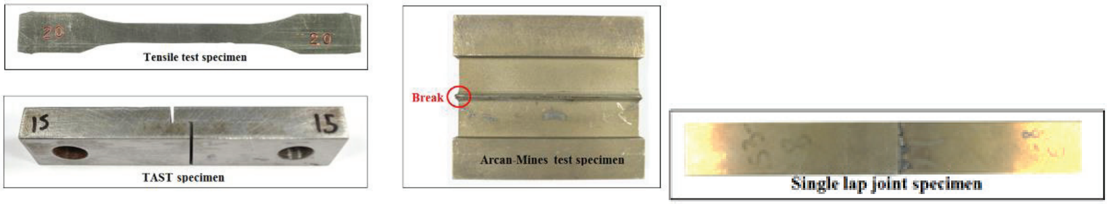
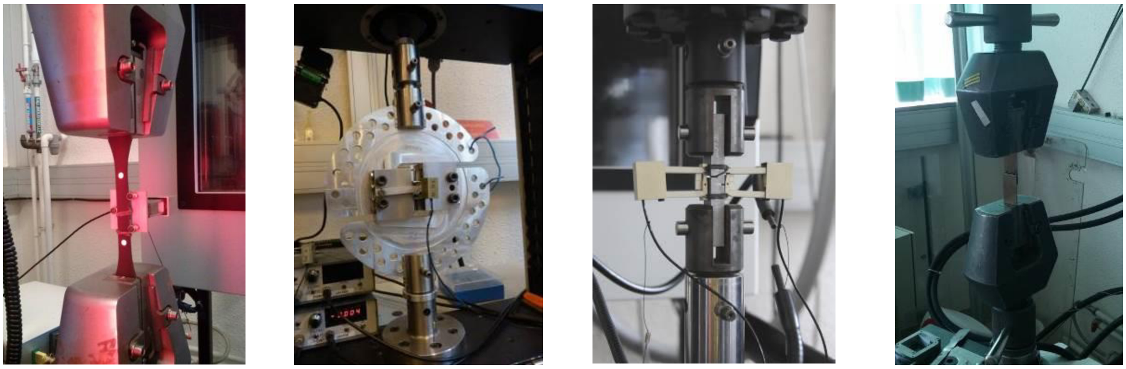


Figure 1 : Different testing specimens

Static tests:

For static loading, we initially performed tensile tests on bulk specimens. Strains of material were measured both in longitudinal and transversal directions (Figure 2a). Then, Arcan-Mines tests have been performed. This specific setup inspired from the previous work of Arcan [2] allows varying the applied loading direction on the bonded joint [3, 4, 5]. While direction 0° and 90° represent the tri-axial and quasi-pure shear state of stress respectively, directions 30° and 60° denote the combination of tensile-shear (Figure 2b). These series of different loading condition demonstrated the pressure dependency in the material, each direction induces the different pressure fields on the adhesive joint. The deformations of adhesive joint were measured by extensometer sensors located on the metallic substrates close to the joint. In order to appreciate the viscosity of material, the Arcan-Mines test in direction 90° have been additionally performed at different loading crosshead speeds (Figure 2 c). Next, TAST tests have been carried out. We note that this test is close to Arcan-Mines test in direction 90[6]. Extensometer sensors are located on both sides of specimens (Figure 2c). Finally, single lap tensile shear tests have been performed, in which the edge of adhesive joint exhibit high peel stresses (Figure 2d).



a) Tensile test b) Arcan-Mines test c) TAST test d) Single lap tensile shear test

Figure 2: Different tests set-up

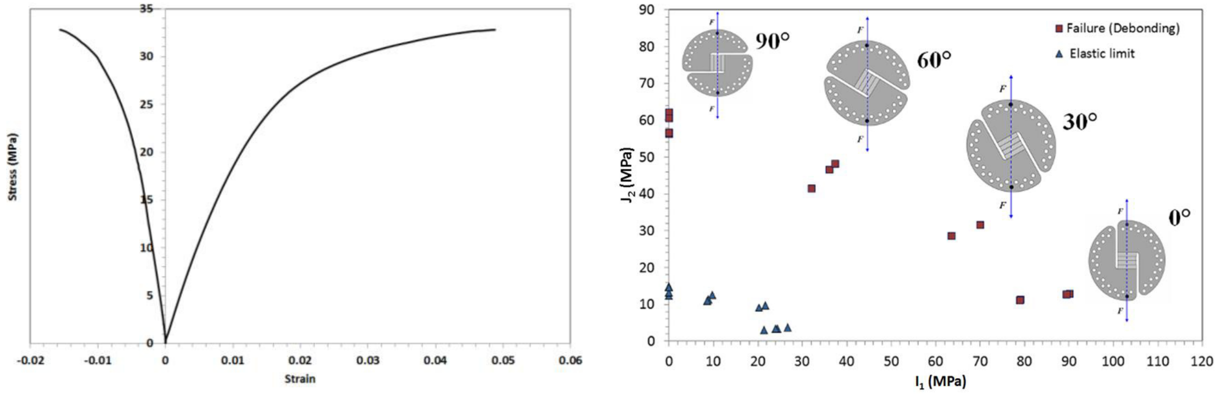
Fatigue tests;

For lifetime study of adhesive joint under fatigue loading, Arcan-Mines, TAST tests and single lap tensile shear tests have been performed on adhesive joint specimens. The frequency was selected to optimize testing time and prevent material from self-heating. Too slow frequency would lead to extremely long time testing; on the other hand too high frequency would introduce the self-heating in the bonded joint. A thermographic camera has been used to investigate the level of self-heating and we found the optimum frequency at 12 Hz. This frequency has been used for all tests with loading ratio (R= 0.1). Finally, for each kind of test, S-N curves (Wöhler curves) have been established.

4. Results

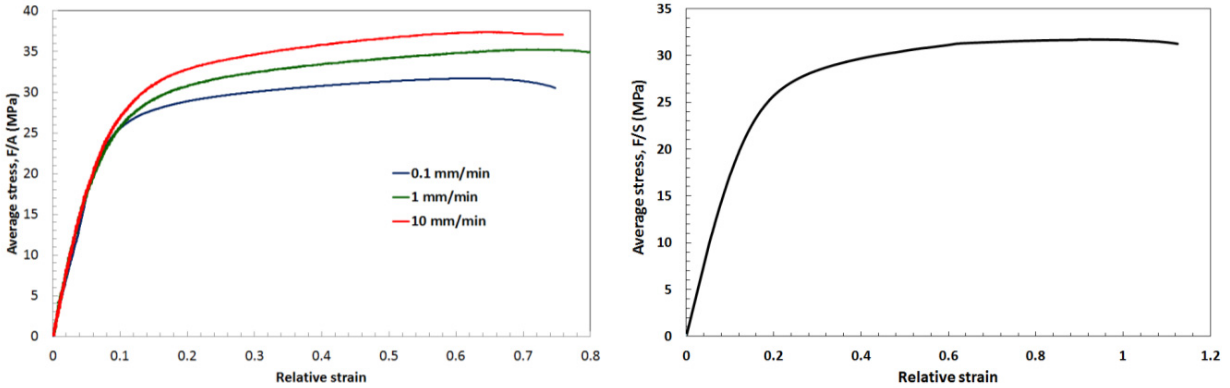
Static tests results and modelling

The results obtained for the different tests described in §3, are shown on Figure 3a to Figure 3d and the corresponding characteristics determined are summarized in Table 1. All the specimens tested failed in a cohesive mode whatever the test used. Each curve exhibit a relatively short linear region followed by a significant non-linear part. We can also notice a strong time dependant behaviour of this adhesive as shown on Figure 3c.



a) Tensile stress/strain curve on bulk specimen

b) « yield » and failure surface limits (ARCAN on bonded joints)



c) stress/strain curves for different strain rates (ARCAN 90°- pure shear)

d) stress/strain curve (TAST-pure shear)

Figure 3: Static results for the different tests

Table 1: Static characteristics determined from the different tests

Testing method	Joint thickness (µm)	Number of specimens	Average Yield stress, F/S (MPa)	Average Failure stress, F/S (MPa)
Tensile	(bulk)	5	8	33.6
Arcan-Mines 0°	300	4	10.3	36.1
Arcan-Mines 30°	300	2	10.4	33
Arcan-Mines 60°	300	3	7.7	30
Arcan-Mines 90°	300	4	5	34
TAST	100	6	10.3	33.1
Single lap joint	200	8	8.6	17.5

- Regarding to these experimental results, we identify the mechanical behaviour as elastic-viscoplastic. We can separate in general for this type of behaviour the elastic domain represented by linear behaviour and plastic domain which is characterized by a non-linear behaviour. Unlike metallic, the volume constant assumption is no longer available in plastic region. The dilatation angle of material is taken into account in the flow rule of plastic hardening. The viscosity effect occurs in plastic region.

First, we identified the elastic properties from tensile tests: Young's modulus and elastic Poisson's ratio. We found by FE simulation that the non-linear behaviour and the failure strength obtained by this elementary test are unable to reproduce the behaviour of the adhesive joint. The reason is the different failure mode of the specimens. In tensile test where the specimen is the material in bulk, the cross-sectional area of specimen reduces during testing leading obviously to an earlier failure. By the way the plastic Poisson's ratio has to be identified· As the adhesive joint specimens are not suitable to identify this parameter, because of constant cross-sectional area during testing, we have to do it with the tensile test on bulk specimen.

In the plastic range we can use the following equation (1)

$$\tan\psi = \frac{3(1-2\nu_p)}{2(1+\nu_p)} \tag{1}$$

Next, a pressure dependent yield criterion has been proposed. We used the second order exponent Drucker-Prager's criterion (2) in which model's parameters can be identified via a series of Arcan-Mines tests (0°, 30°,60° et 90°) [7](Figure 4). The yield surface has a parabola form in meridional plan. The plasticity is identified as an isotropic non-linear hardening with a hyperbolic function (3) in meridional plan. A flow potential takes into account the dilation angle of material. With this model, the flow is always associated in the deviatoric stress plane but non-associated in the meridional plane. The parameter of isotropic hardening in equation (4) has been characterized from Arcan-Mines test at direction 90° with pure shear assumption until failure of specimen as shown on Table 2. The viscosity effect related to the rate-dependent hardening is taken into account by the power law model (5) which modifies the static yield stress with scaling factor. The parameters of power law model are identified via Arcan-Mines test at direction 90° with different crosshead speed (see Table 3). We suppose the plastic strain rate at $0.0001\mathrm{s}^{-1}$ being a static case. For failure of Arcan specimens, the exponent Drucker-Prager's criterion has been employed for the second time. The second parabola curve can be established as a failure criterion of adhesive joint. As a validation of behaviour model and failure criteria, the 3D finite element simulation of TAST test system and of single lap joint has been performed. A good agreement with experimental results had been observed regarding to the experimental scattering (Figure 5 and Figure 6).

$$f = (J_2)^2 - \beta R_0^2 + (\beta - 1)R_0 I_1 = 0 \tag{2}$$

$$F = \sqrt{(\xi\sigma_y \tan\psi)^2 + (J_2)^2} + \frac{I_1}{3}\tan\psi \tag{3}$$

$$\sigma_{eq} = \sigma_y + H\varepsilon_{eq}^p + Q(1 - e^{-b\varepsilon_{eq}^p}) \tag{4}$$

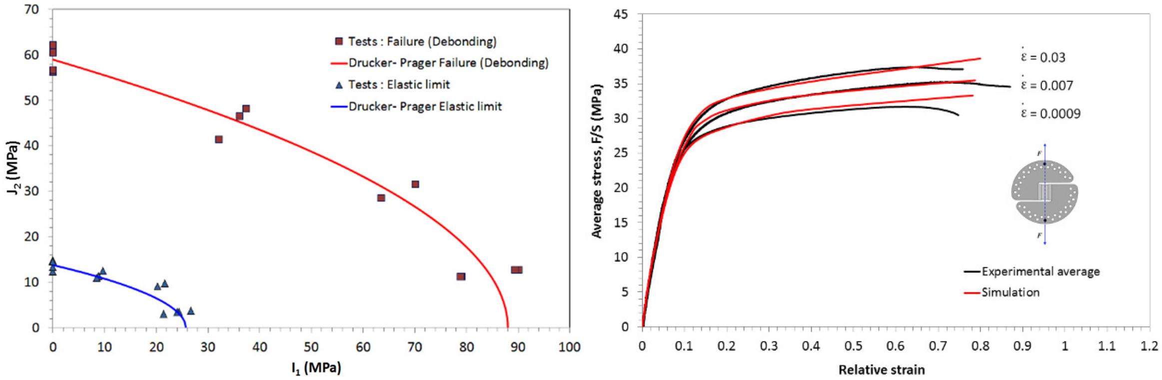
$$\sigma_{eq} = \sigma_{eq}\Big|_{\dot{\varepsilon}_{eq}^p = 0}\left(1 + \left(\frac{\dot{\varepsilon}_{eq}^p}{D}\right)^{\frac{1}{n}}\right) \tag{5}$$

Table 2: Drucker Prager’s parameters for yield and failure surfaces

Yield surface		Failure surface	
βR_0^2	$(\beta-1)R_0$	βR_0^2	$(\beta-1)R_0$
190	7.4	3476	39.5

Table 3: Behaviour model’s parameters

E	N	Ψ	σ_y	q	b	H	ξ	n	D
2272	0.4	16.9	13.8	31.5	110	12.6	8.4	4.7	22.9



a) b)

Figure 4: -a) Drucker-Prager “yield” and failure surfaces, b) stress/strain curves for different strain rates (ARCAN 90°-pure shear)

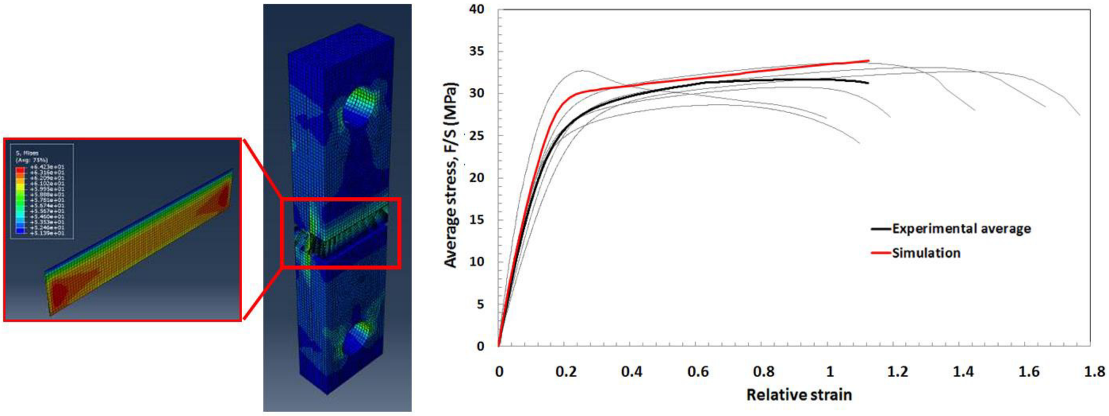


Figure 5: Comparison of FE simulation and experimental results of TAST

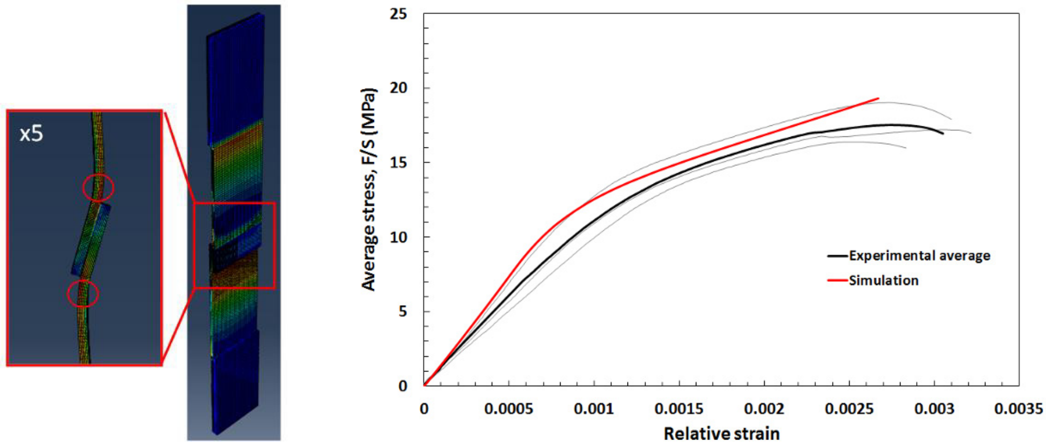
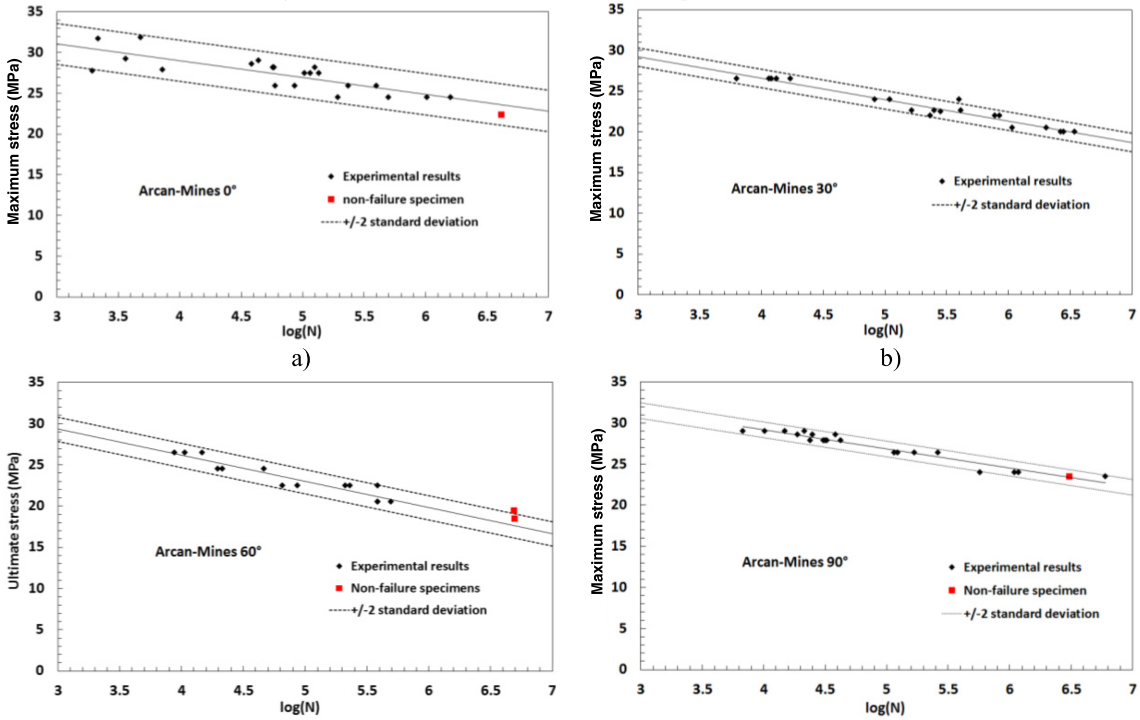


Figure 6: Comparison of FE simulation and experimental results of single lap tensile shear test

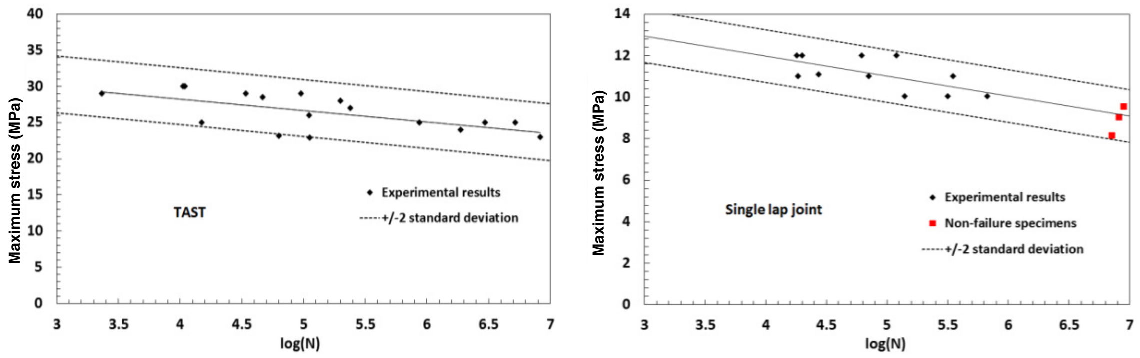
Fatigue tests results and modelling

The results obtained for the different tests described in §3 (with a loading ratio, R= 0.1), are shown on Figure 7 and the characteristics determined are summarized in Table 4. Linear regressions have been implemented on the testing results: maximum stress σ versus the log (Number of cycles) with self-intervals at 96% which means ± 2 standard deviations. In addition, it may be noticed that the Arcan-Mines 90° pure shear tests show the minimum scattering.



a) b)

c) d)



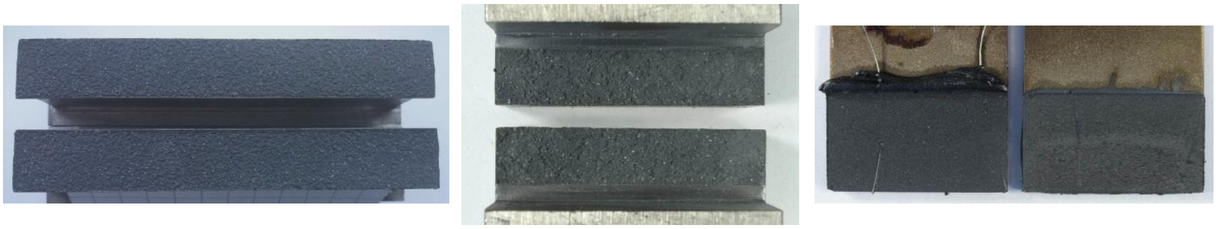
e) f)

Figure 7: Fatigue tests results

Table 4: Comparison of fatigue results using the different tests

Testing method	Joint thickness (µm)	Number of level	Number of specimen	Endurance limit at 10^7 cycles (MPa)			Standard deviation
				σ_D	I_1	J_2	
Arcan-Mines 0°	332	5	22	22.8	51.4	8.5	1.23
Arcan-Mines 30°	398	6	20	18.7	36.4	17.3	0.57
Arcan-Mines 60°	318	5	16	16.6	18.7	25.1	0.74
Arcan-Mines 90°	323	6	24	22.2	0	38.4	0.47
TAST	97	6	13	23.5	0	40.8	1.48
Single lap joint	200	4	14	9.1	0	15.8	0.63

All the specimens tested failed in a cohesive mode whatever the applied stress level (Figure 8).



a) Arcan-Mines b) TAST c) Single lap joint

Figure 8: Cohesive rupture of the fatigue specimen

It may be noticed that the results present a low scattering. Nevertheless this scattering differs from one test to another. We can see also on Figure 9 and Table 4 that in the “shear” mode, similar results are obtained with ARCAN 90° and TAST, but the single lap joint exhibit a lower SN curve, due to high peeling and shear stress concentration close to the edge. This confirms that the single lap joint is not appropriate to characterize the static and fatigue behaviour of adhesives.

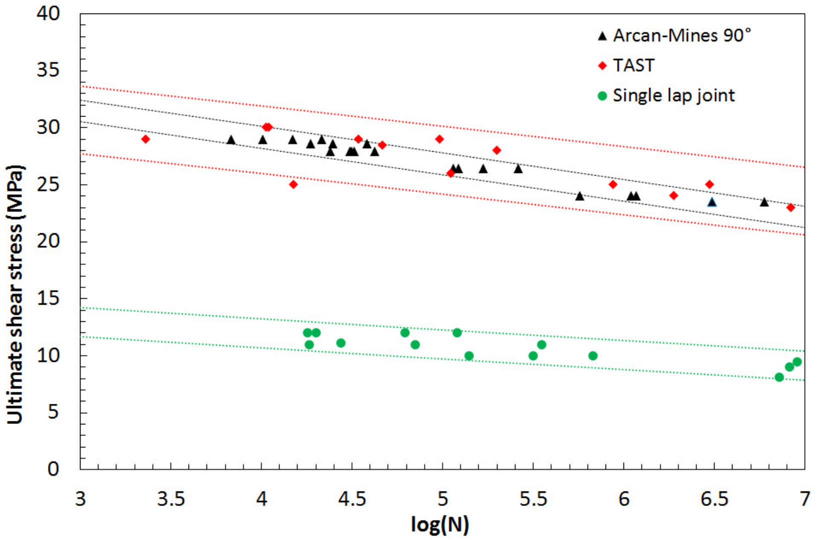
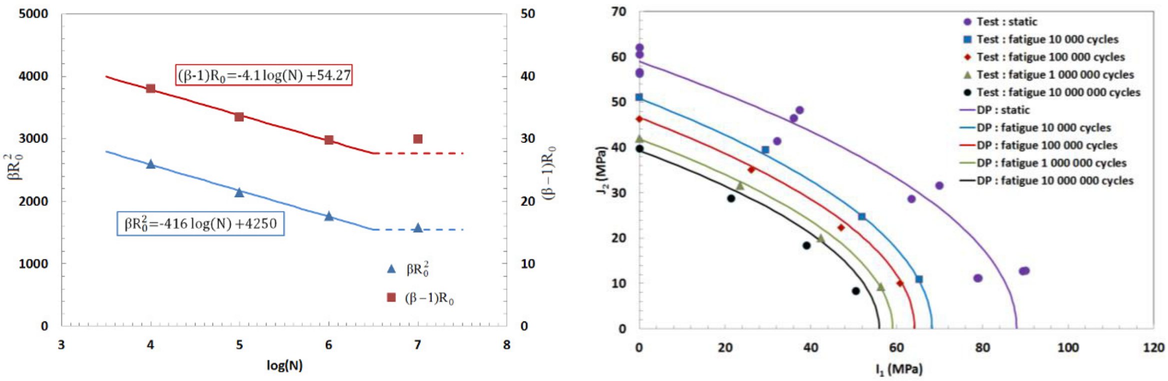


Figure 9: Comparison of fatigue results using the different “shear” tests

In order to extend the former Drucker-Prager criterion to fatigue loading, we implement the fatigue number of cycles N as an additional parameter (Figure 10). A modified failure criterion for fatigue load has been proposed



a) b)

Figure 10: Extended Drucker-Prager for fatigue load: a) variation of model parameters with the number of cycles, b) model failure region for different number of cycles

5. Conclusions and perspectives

The behaviour of adhesive SikaPower-4588 has been characterised by using different testing systems. The validation by FEA simulation has been done and confirmed that the proposed viscoplastic pressure dependency model, is suitable for this type of material. Failure criteria have been proposed, coupling both static and fatigue loadings.

A second structural adhesive (two parts methacrylate) is under testing with the same methods and specimens. After the analysis of the results and comparison with these ones, the objective is to propose a relatively simple methodology in order to characterize the static and fatigue mechanical behaviour of structural adhesives enabling to design safely adhesively-bonded structures subjected to fatigue loading.

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