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Creep investigations on steel fasteners adhesively bonded to steel plates

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Résumé :

L'entreprise Cold Pad a développé une solution innovante de connecteurs collés pour structures métalliques permettant d'éviter les opérations de soudure. Ceci permet de limiter la pénibilité des opérations sur site et est particulièrement bien adapté aux environnements contraignants pour lesquels les travaux à chaud sont proscrits. En outre, ce procédé permet d'éviter une fragilisation locale de la structure métallique et limite les concentrations de contrainte qui tendent à diminuer la durée de vie en fatigue. Des questions se posent cependant concernant la durabilité de la solution proposée. L'étude présentée aborde un aspect particulier de ce sujet : le comportement au fluage.

Les études menées ont porté à la fois sur la réalisation d'investigations expérimentales et de travaux de modélisation. Nous décrivons dans un premier les investigations expérimentales réalisées à échelle réelle, pour différents niveaux et types de sollicitations. Les connecteurs peuvent en effet être soumis à deux sollicitations différentes : de la traction ou du cisaillement. Les investigations ont permis d'obtenir les modes de rupture des assemblages, d'estimer la répétabilité du procédé, d'obtenir les temps à rupture sous fluage mais également de mesurer pendant l'essai l'évolution de déplacements locaux pertinents. Ceux-ci ont révélé un comportement non-linéaire proche du modèle proposé par Burger. Ce modèle a ensuite été choisi pour mener des travaux de modélisation décrits dans la seconde partie. L'implémentation de la loi sera détaillée, puis les résultats des modélisations comparés aux résultats des investigations expérimentales. Enfin, on s'intéressera à l'évolution des profils de contrainte interne pendant les essais de fluage. Des investigations additionnelles sont en cours et devraient permettre d'améliorer la stratégie de modélisation utilisée.

Abstract :

Cold Pad has developed an innovative solution alternative to welding or bolting that relies on the use of adhesive bonding to connect mechanical fasteners to existing steel structures. This allows avoiding heavy on-site operations and is particularly well adapted to applications requiring cold working. In addition, such a process prevents from local steel material embrittlement, residual stresses creation,

or geometrical stress concentration that may decrease the structure's life expectancy. There is however a legitimate concern regarding the durability of structural adhesive bonding that needs to be studied. The presented investigations were carried out on one particular aspect of durability: the creep behavior of such connections. For the considered applications (constant load), it may indeed be one of the main issues that governs the connected fastener mechanical capacity.

In order to be able to investigate the creep behavior of the developed solution, both experimental and numerical investigations were carried out. The experimental investigations will first be described. Those were led on real scale assembly, at different stress levels, and under different load situations. The fastener may indeed be submitted by either predominant tension load, or shear load. The investigations 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 for the numerical modelling that will be presented in the second part. The law implementation will first be described, and the numerical results will be compared to the obtained experimental measurements. In addition, the evolution of the internal stress state inside the adhesive layer will be described and discussed.

The experimental investigations are still ongoing with different parameters that may affect the creep behavior of the adhesive. In addition, the modelling strategy is still under development in order to be able to describe the whole creep process and to better describe the assembly behavior.

Keywords: creep, adhesive bonding, fasteners, Burger model

1 Introduction

Steel structures in service, especially in harsh environments, may be locally affected by fatigue and corrosion and may therefore need reinforcement or repair. In addition, most often there is some need during the structure service life to connect additional equipment, secondary structures or distribution systems. In the case of steel structures, this is carried out using bolted or welded assembly that may be detrimental regarding operation issues (e.g. hot works such as welding in an explosive and flammable environment) and may induce heavy on-site constraints for the structure exploitation. In regards with these issues, adhesive bonding solution may appear as a good solution, provided that the robustness and the durability of the assembly is confirmed. The firm Cold Pad, Paris, France is currently developing an adhesively bonded fastener to provide such a solution for offshore applications [1]. They are also developing an overall solution that includes an application disposal ensuring precise control of the adhesive joint quality during application, and water tightness of the joint to prevent any durability issue linked to wet environment [2] (Figure 1).



Fig. 1: Photo of the solution developed by Cold Pad (application disposal on the left and adhesively bonded fastener on the right)

Durability of adhesively bonded joint covers several damage mechanisms that may be induced by the environment or the applied load [3]. In the case of the studied bonded fasteners, as water tightness is ensured, creep appears to be one of the main durability issues that needs to be addressed [4]. Most often, experimental creep studies of adhesively bonded joints are carried out at the scale of the adhesive alone [5]. Yet, it is well known that stress states at full scale of the bonded assembly are strongly non-uniform [6]. It was thus decided for this study to realize experimental investigations at the scale of the bonded fastener, and to develop in parallel a finite element model. This model takes into account the creep behaviour of the adhesive in order to be able to visualize the internal stress state of the joint during the test and to compare some local measurements with numerical results.

A short literature review on the main available creep models will first be introduced. Then, the developed experimental investigations will be described. Their aim was to investigate the two main loadings that may encounter the developed bonded fasteners: tension loading perpendicular to the bonded surface, and shear loading parallel to the bonded surface. After a presentation of the obtained results, the developed finite model will be introduced and the obtained results analysed. The last part will be dedicated to the comparison of the numerical model with the experimental results.

2 Literature review on creep modelling

Creep is the response of a material to a constant stress [7]. The creep is characterized by three stages as illustrated in Figure 2 delimited by the evolution of the strain rate: primary stage with a decreasing strain rate, secondary stage with a constant strain rate and tertiary stage with an increasing strain rate until the failure. Mathematically, the creep strain $\varepsilon(t)$ should be noted in the form of equation (1) [7].

$$\varepsilon(t) = \sigma^0 J(t, T, \sigma^0) \quad (1)$$

J being creep compliance that depends mainly on time t , temperature T and applied stress σ^0 [8].

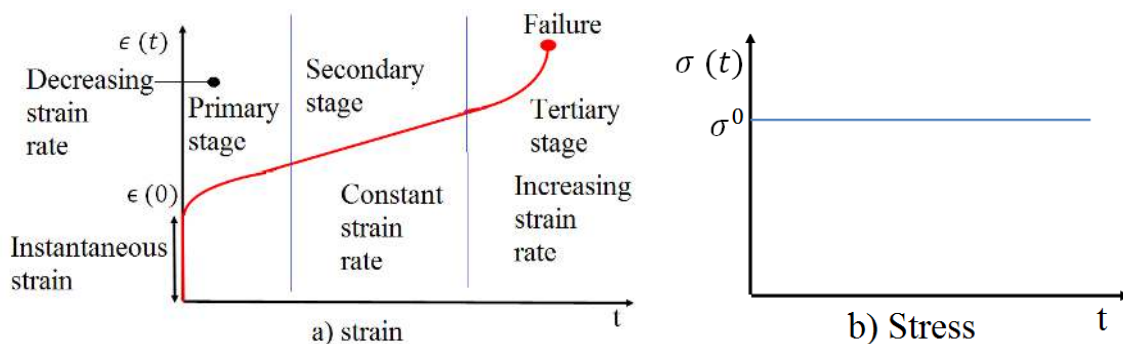


Fig. 2: Creep stages.

Two main categories of modelling strategies exist in the literature: the empirical or semi-empirical approaches and the rheological ones. Main models will be described in the two following parts.

2.1 Semi-empirical models

Various mathematical forms have been empirically proposed to describe the mechanical behaviour under creep loading. The simplest is a linear function of the stress but non-linear (logarithmic for example) when depending on time. The most commonly used expression of creep compliance is a power law given by equation (2) [9-10].

$$J(t) = J_0 + J_1 t^n \quad (2)$$

where $(J_0; J_1; n)$ are material parameters of the model.

Other empirical models exist. An example is that of Bailey Norton which allows to take into account the nonlinear behaviour and the influence of the temperature. The expression of creep compliance is then given by equation (3) [9].

$$J(t, \sigma, T) = C_0 \sigma^{C_1} t^{C_2} \exp(-C_T/T) \tag{3}$$

($C_0; C_1; C_2; C_T$) being the material constants of the model.

Another example of a nonlinear model is given by equations (4) [11]. This empirical model is based on the fact that increasing the stress level has the effect of reducing the relaxation time t_0 .

$$J(t, \sigma) = J_0 \exp(-t/t_0)^m \tag{4}$$

$$t_0 = A \exp(-\alpha \sigma_0^2)^m$$

where ($A; \alpha$) are material parameters of the model.

2.2 Rheological models

The creep behaviour can also be described by a rheological approach with basic mechanical systems. Figure 3.a and Figure 3.b show the rheological formulation and the representation of elasticity by the spring (E) and the viscosity by the dashpot (η), where σ is the stress in the system and ε is the strain. Kelvin-Voigt's model combines spring and dashpot in parallel (Figure 3.c). It is a solid model at infinity [7]. The expression of creep compliance is given by equation (5).

$$J(t) = 1/E [1 - \exp(-E/\eta \cdot t)] \tag{5}$$

η/E being the characteristic time of the model.

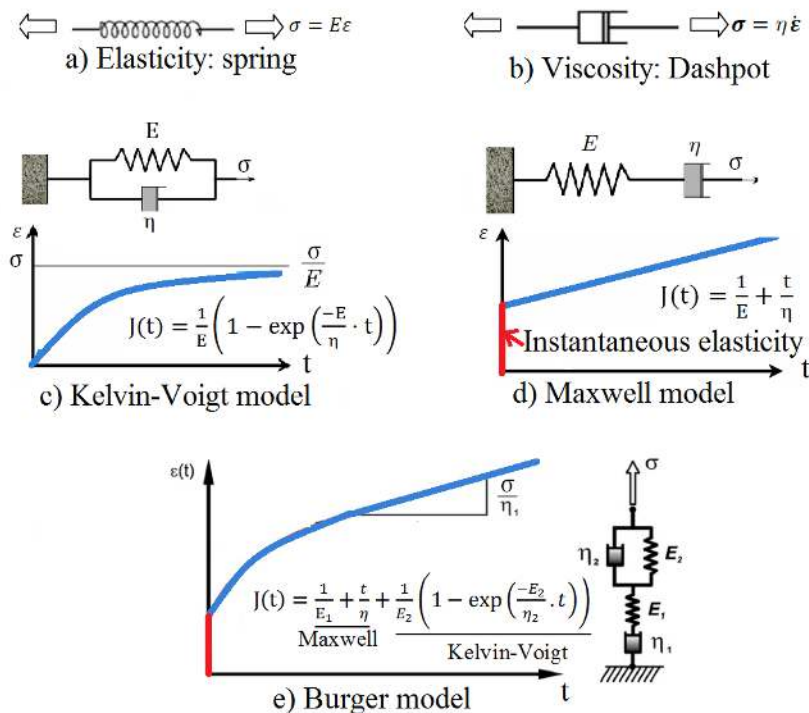


Fig. 3: Rheological creep models.

The creep response of a material for the Kelvin-Voigt model is shown in Figure 3.c. We find that this model does not predict the instantaneous elasticity ($J(0) = 0$). It only illustrates the first stage of creep. The Maxwell model itself consists of a spring and a dashpot mounted in series (Figure 3.d). It is a fluid model at infinity [7]. The expression of creep compliance is given in equation (6).

$$J(t) = 1/E + t/\eta \tag{6}$$

where E is the Young's modulus and η the viscous parameters.

The creep response of a material for the Maxwell model is shown in Figure 3.d below. This model brings out the second stage of creep. The Burger model is obtained by associating in series the Kelvin-Voigt model and the Maxwell model. This model shows the first two stages of creep (Figure 3.e). Creep compliance is obtained by summing up the compliances of the Kelvin-Voigt and Maxwell models (equation 7) [4].

$$J(t) = 1/E_1 + t/\eta_1 + 1/E_2 [1 - \exp(-E_2 / \eta_2 \cdot t)] \quad (7)$$

where $(E_1; E_2)$ are the spring parameters and $(\eta_1; \eta_2)$ the viscous ones.

2.3 3D creep

The concept of creep can be generalized in 3D. The creep compliance \mathbf{J} is in this case a tensor of order 4. The response to 3D creep is of the form of equation (8) [7].

$$\boldsymbol{\varepsilon}(t) = \mathbf{J} : \boldsymbol{\sigma}^0 \quad (8)$$

In the hypothesis of an isotropic linear viscoelastic behaviour, the relation (8) takes the form of equation (9) [7].

$$\boldsymbol{\varepsilon}(t) = (1 + \nu(t)) J(t) \boldsymbol{\sigma}^0 - \nu(t) J(t) \text{tr}(\boldsymbol{\sigma}^0) \mathbf{I} \quad (9)$$

where $J(t)$ and $\nu(t)$ are respectively the uniaxial creep compliance and the Poisson's ratio determined from a simple tensile creep experiment carried out in any direction. In general, the Poisson's ratio doesn't depend on time, $\nu(t) = \nu$ [12].

It was decided to focus in the presented work on the first two stages of creep relying on the use of the presented Burger rheological model and to make a hypothesis of an isotropic behaviour.

3 Experimental investigations on adhesively bonded fasteners

The led investigations have been carried out at full scale of the developed adhesively bonded fasteners. Preliminary quasi-static tests have been realized to determine the ultimate capacities of the assemblies for two solicitations: tension loading (perpendicular to the bonded surface) and shear loading (parallel to the bonded surface). Then, creep investigations have been carried out for the two solicitations.

3.1 Description of the tested specimens

The tested steel fasteners have been developed by Cold Pad, Paris, France and are called C-Claw_{TM} [1]. Two different fasteners were tested: one dedicated to a shear dominant solicitation mode: fastener S, and the other one dedicated to a tension dominant solicitation mode: fastener T. A photo of both studied fasteners T and S is given in Figure 4. Both consist in a circular steel plate with a connected steel stud (i.e. threaded rod). The circular steel plate geometry has been adapted to the applied load.



Fig. 4: Photo of studied C-Claw_{TM} steel fastener T on the left and S on the right.

These fasteners have been bonded to square 20 mm thick steel plates. The studied adhesive is a commercial methacrylate adhesive whose main characteristics are given in table 1 where E are respectively the Young's modulus and RT , the Tensile strength. The surface preparation has been carried out in agreement with the adhesive specifications. Two specific test settings have been developed to be able to apply the selected solicitation using a hydraulic test machine both in quasi-static and creep situations (Figure 5).

Table 1: Characteristics of the tested adhesive provided by the supplier

E (MPa)	RT (MPa)
1200-1700	22-24



Fig. 5: Scheme of the two tested solicitation modes: Tension and Shear loadings.

3.2 Tension test protocol

The tensile test was performed with the tensile fastener bonded to a 20mm thick plate bolted to a tensile frame. The assembly was connected to a hydraulic test machine via the tensile frame for the upper grip and a connection sleeve for the lower grip as shown in Figure 6. Alignment of the frame and the connection sleeve was essential to macroscopically ensure a load in pure tension and limit the cleavage of the assembly. The loading was applied at a speed of 1.2 kN/s. Three LVDT sensors placed at 120° measured out-of-plane displacements during the test as shown in Figure 5. It allowed obtaining indication on the symmetry of the test, but also on the long-term behaviour during creep tests.

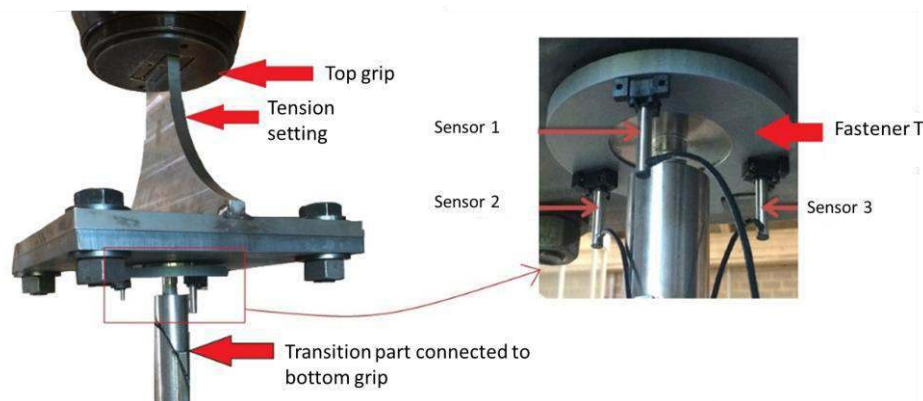


Fig. 6: Protocol of the tensile test.

3.3 Shear test protocol

The shear test in principle was identical to that in tension. The shear fastener was bonded to a 20mm thick plate bolted to the shear frame. Figure 7 presents the assembly used for the realization of shear tests. The assembly was connected to the loading machine via a shear frame for the upper grip and the connection plate for the lower grip. For the same reason as in tension, the alignment of the shear frame and the connection plate had to be achieved to limit cleavage of the assembly. Loading was done at the same speed of 1.2kN/s. A sensor makes it possible to measure the displacement in the plane (sensor 1) and three sensors placed at 120° made it possible to measure the out-of-plane displacement (sensors 2, 3, 4) during the test as illustrated in Figure 7.

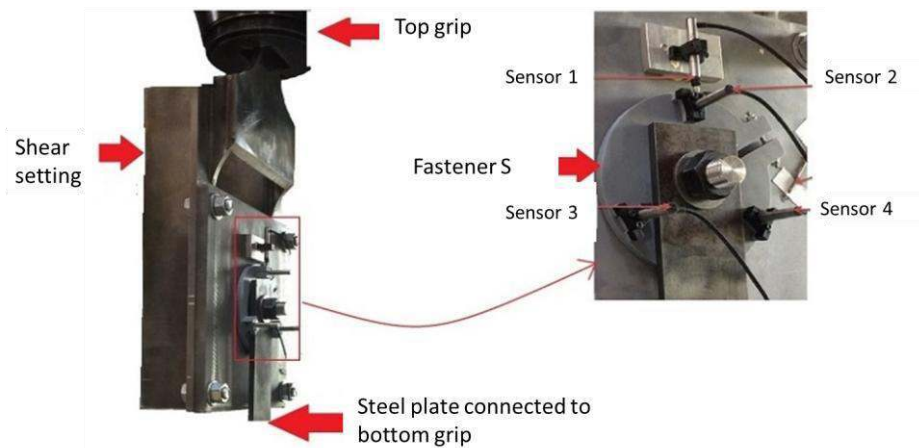


Fig. 7: Protocol of shear test.

3.4 Preliminary quasi static investigations

For both solicitations, preliminary quasi static investigations up to failure were carried out to determine the ultimate capacities of the bonded assemblies. Three tests for each configuration were realized at 25 °C. Similar capacities were obtained for both configurations.

3.5 Results of tensile creep tests

It was decided to carry out two creep tests in tension at an applied load corresponding respectively to 59 % and 69 % of the ultimate quasi static load capacity. Figure 8.a and Figure 8.b shows the evolution of the experimentally measured out-of-plane displacements for the tensile creep tests for these two respective loads. The test at 59% of the ultimate load capacity lasted 10 hours 36 minutes before being interrupted. Only the first two creep stages are visible in Figure 8. The test at 69% of the ultimate load capacity lasted 3 hours 16 minutes before failure occurred. The displacement measured by the sensor 3 made it possible to distinguish the three creep stages. The first stage lasted about 30 minutes and the second stage 2.5 hours before the final stage started (stage 3). Interestingly, in both cases, it can be noticed that measured displacements are highly asymmetric. There seems to be a localisation of the phenomenon. Obviously, creep phenomenon was more pronounced when the applied load is higher.

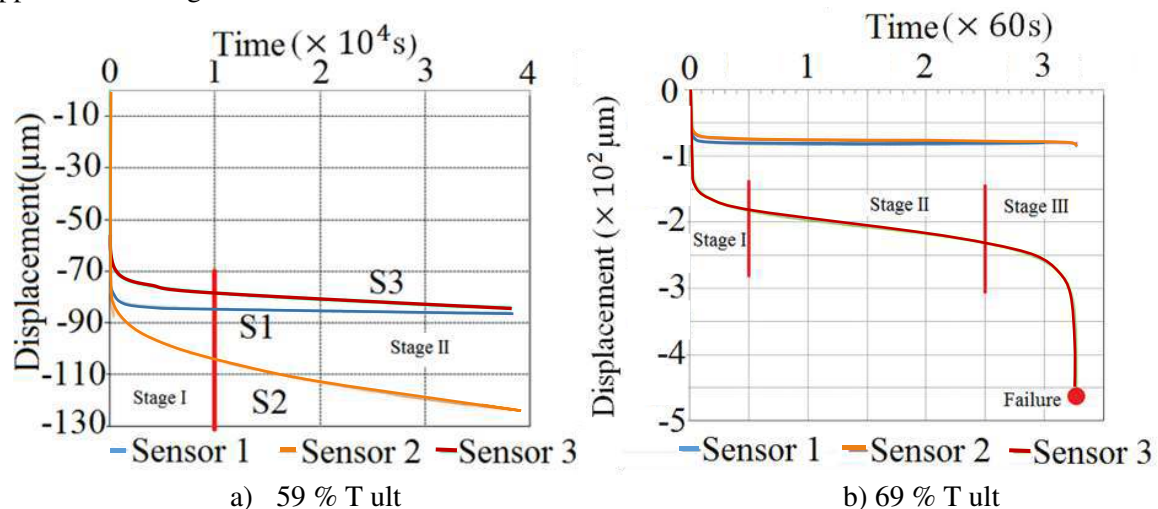


Fig. 8: Measured displacements during tensile creep investigations at T = 25°C

3.6 Results of shear creep tests

The shear creep tests were carried out for closed values of the percentage of the applied load in comparison with the quasi static ultimate load capacity: 59 and 67 % of the ultimate load capacity in shear. Figure 9.a and Figure 9.b shows the results of the measured displacements for these two shear creep tests. Only two displacements are presented: sensor 1 represents the displacement in the direction parallel to the bonded surface, sensor 3 represents the peel displacement in the extremity of the assembly. The sensors 2 and 4 measured very low displacements and are therefore not plotted here.

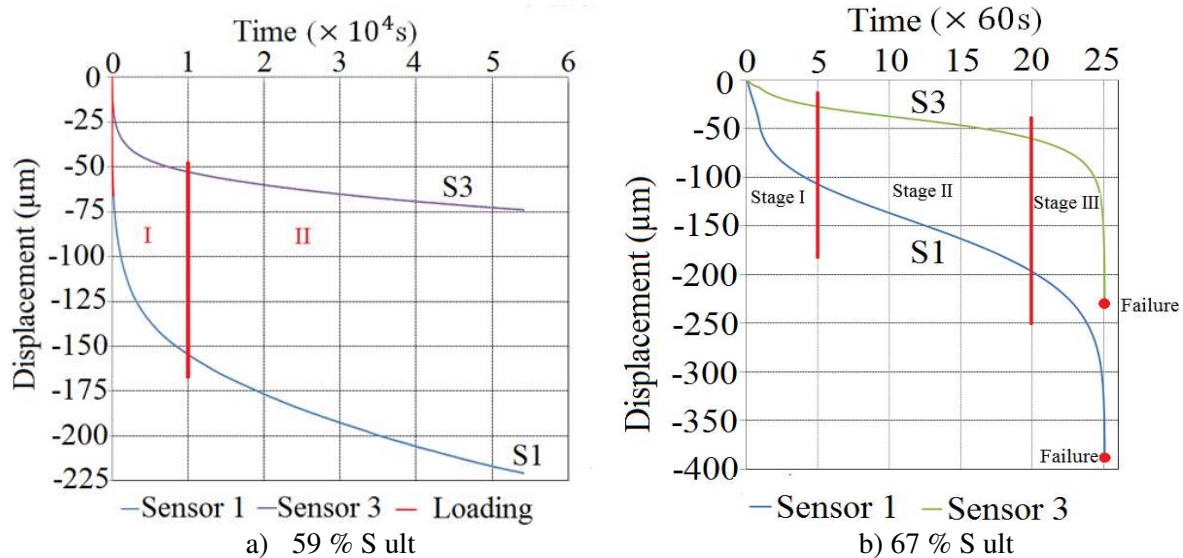


Fig. 9: Creep shear at $T = 25^{\circ}\text{C}$.

The test at 59 % of the ultimate load capacity in shear S lasted 15 hours before being interrupted. Only the first two creep stages were measured. The in-plane displacement of the shear fastener measured by the sensor 1 was 221 μm (5 times the static displacement during the loading). The out-of-plane displacement of the fastener measured by the sensor 3 has reached 74 μm (6 times the static displacement). Only the first two stages were measured. The test at 67 % of the ultimate load capacity S lasted 25 minutes before failure of the assembly for an in-plane displacement measured by sensor 1 equal to 380 μm and an out-of-plane displacement (sensor 3) of 230 μm . The three creep stages were measured in this case.

4 Modelling of the tests

4.1 Development of models

For both solicitations, finite element analyses were carried out using the commercial Software Abaqus, Paris, France. To model the tensile test, it was possible to use a 2D axisymmetric model (Figure 10) by making the assumption that the bolted zones were sufficiently far from the adhesive layer. To further simplify, the assumption was made that the support parts (tensile frame, sleeve) were dimensionally stable and did not need to be taken into account in the model. The behaviours of the adhesive, the plate and the tensile fastener were assumed to be isotropic linear elastic. In a bonded assembly, the accuracy of the stress state is dependent on the number of elements in the thickness of the adhesive [13]. A convergence study of the mesh allowed obtaining the necessary mesh refinement: 12 linear rectangular elements were used in the thickness of the adhesive to obtain representative results.

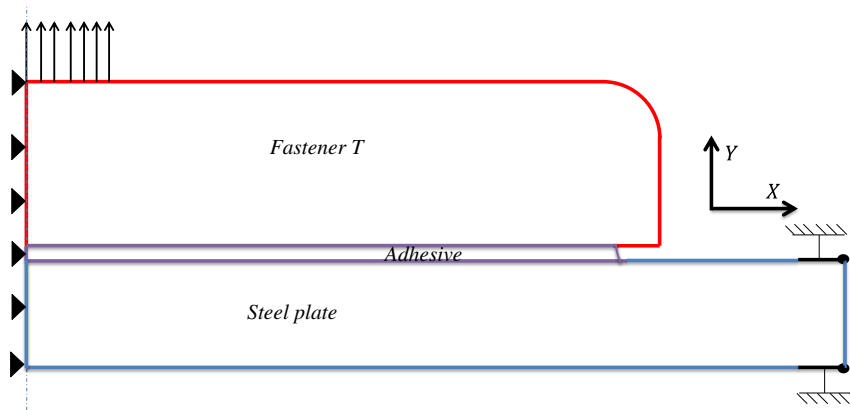


Fig. 10: Scheme of the studied 2D axisymmetric model.

On the whole, the assumptions made for the shear calculation were the same as in tension. Only the plate, the adhesive and the non-cylindrical part of the fastener were modelled. It was necessary to use a 3D model as the loading was not axisymmetric. The 3D shear model had a plane of symmetry shown in Figure 12 below. This plane of symmetry made it possible to model only half of the total geometry. The boundary conditions used for the shear calculation were shown in Figure 11.

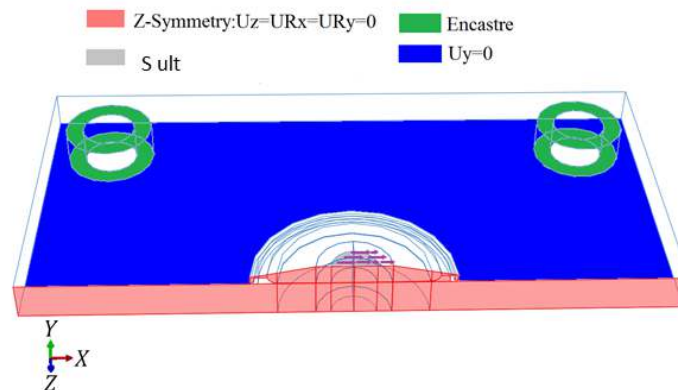


Fig. 11: Boundary conditions for the shear model.

4.2 Study of stress distribution and 2D/3D comparison

As preliminary investigations, the modelling was realized in elastic situation taking into account the obtained average quasi static ultimate capacities for both sollicitations. For both cases, several stresses are studied: shear (SXY) and peel stresses (SYY), von Mises equivalent stress (SVM) and hydrostatic pressure (p).

For the case of tension load, Figure 12 presents the normalised stress states (in comparison with the ultimate von Mises stress) along the normalised bonded length (on one radius, as the assembly is axisymmetric). For each studied stress component, three positions in the adhesive layer were studied: top of the adhesive closed to the fastener, middle of the adhesive and bottom of the adhesive closed to the steel plate.

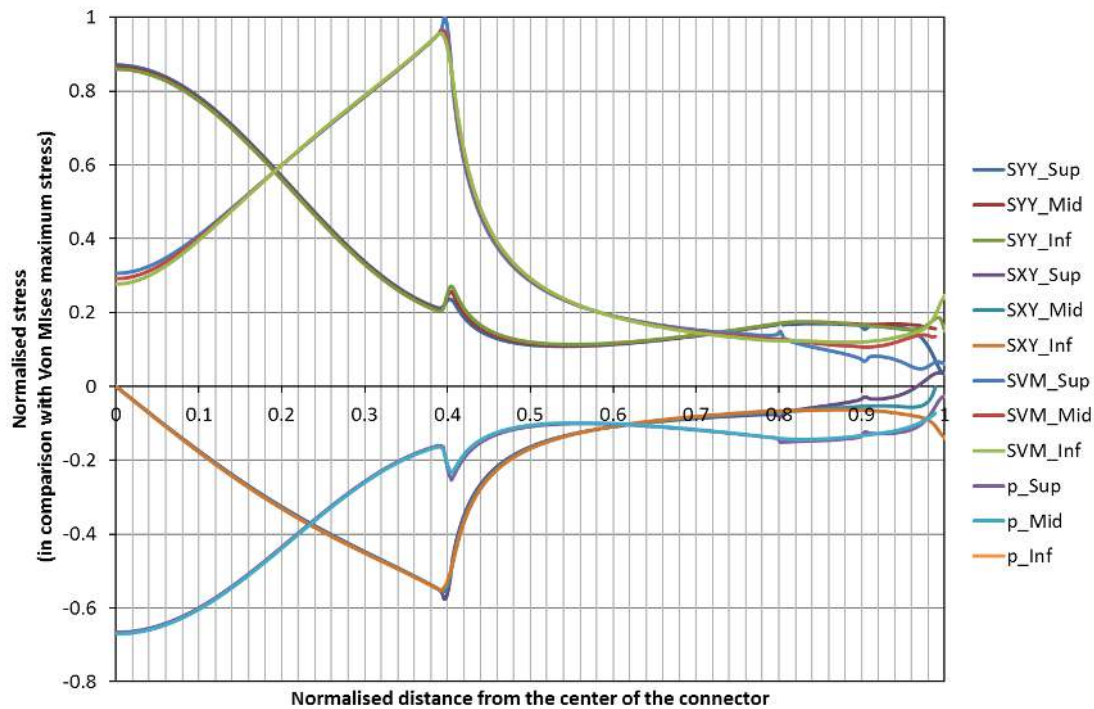


Fig. 12: Stress state for 2D axisymmetric model.

It can be observed that the position in the adhesive thickness does not seem to have a great influence on the studied results. In addition, it can be highlighted that although the macroscopically applied load is a tensile stress, the stress state in the adhesive is not simple. The multiaxial stress state in the adhesive is explained by the non-regular geometry of the tensile fastener. In the middle of the adhesive layer, there seems to be mostly tensile stresses in the adhesive, whereas, far from the centre, shear stress seems to be predominant. Interestingly, the geometry of C-ClawTM seems to avoid obtaining stress concentrations at the free edges of the assembly in tension.

For the case of the shear load, the results in terms of normalised stresses (relatively with the maximum von Mises stress) along the main diameter (oriented along the load axis) are given in Figure 13. Again, there is no large difference between the different studied adhesive thickness locations. The obtained stress state is also multiaxial with a non-uniform shear stress and an equilibrated peel stress profiles (due to the applied moment). Interestingly, it can also be checked that the geometry of C-ClawTM seems to avoid obtaining stress concentrations at the free edges of the assembly in shear.

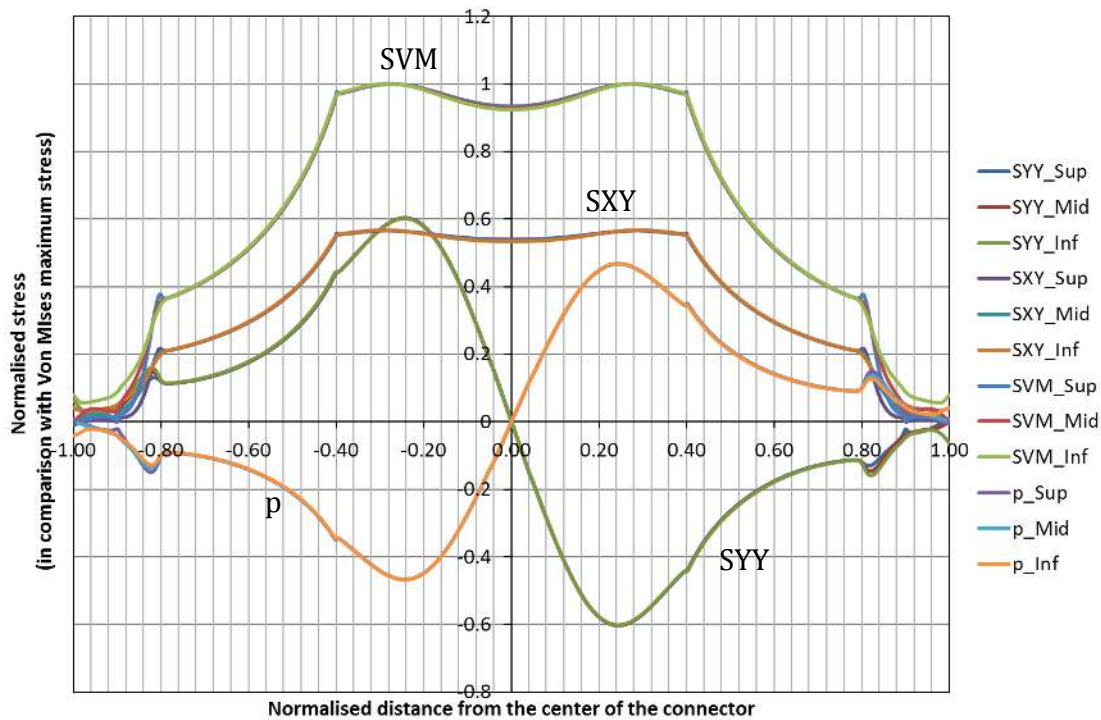


Fig. 13: Stress state along the adhesive for the shear model.

4.3 Determination of creep parameters from the measured displacements

The creep law used to model the creep behaviour of the adhesive is Burger's law. This is the most used law for polymeric materials. Moreover, the observation of the evolution of displacements measured during creep tests seems to be rather close to the Burger model.

The identification of Burger's law parameters is done by hand for both assemblies assuming a uniaxial tensile stress for tensile creep test and uniaxial shear stress for shear creep test. The used stress for identification is the average tensile and shear stress along the adhesive respectively for tensile and shear creep test. The obtained parameters are given in the table 3. The model is applied to the adhesive material in Abaqus software using a subroutine especially developed for the application.

Table 3: Burger's law parameters

Applied load	E_1 (MPa)	η_1 (MPa.h)	E_2 (MPa)	η_2 (MPa.h)
Tension (59%)	1200	5000	400	300
Tension (69%)	1200	750	220	30
Shear (59%)	1200	1700	40	35
Shear (67%)	1200	19.83	100	2.083

4.4 Study of the Von Mises stress distribution during creep

Figure 14 illustrates the phenomenon of stress redistribution for the tensile model that occurs due to the initial non-uniform distribution of stresses along the adhesive. Figure 14 b represents the von Mises stress state along the radius of the bonded surface during creep. Figure 14 c shows the average tensile displacement during creep and the localization of the three studied time moments. Interestingly, the stress redistribution with time allows decreasing stress concentration effect, and more particularly the ultimate von Mises stress by 23 %.

Figure 15 illustrates the phenomenon of stress redistribution in the case of the shear test. This redistribution was less pronounced in shear than in tension because, initially, the distribution is more uniform in shear than in tension. The maximum von Mises stress after creep was reduced by 14%.

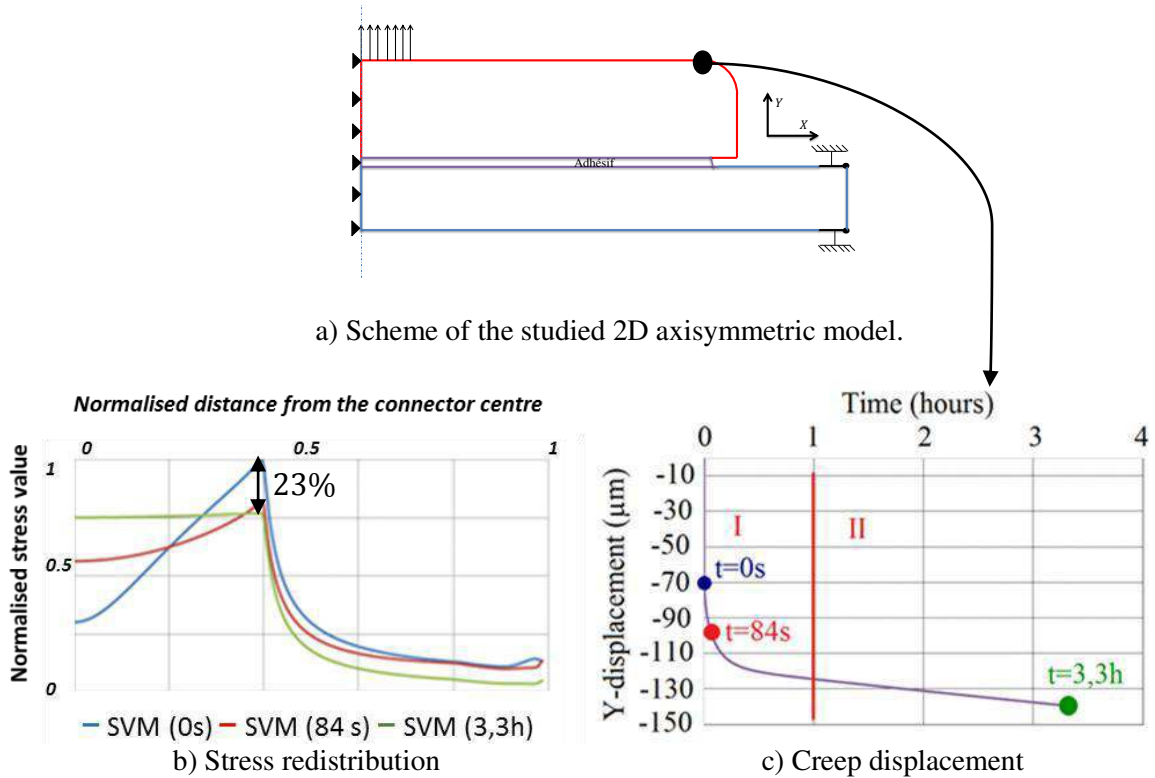


Fig. 14: Redistribution of von Mises stress for tensile model.

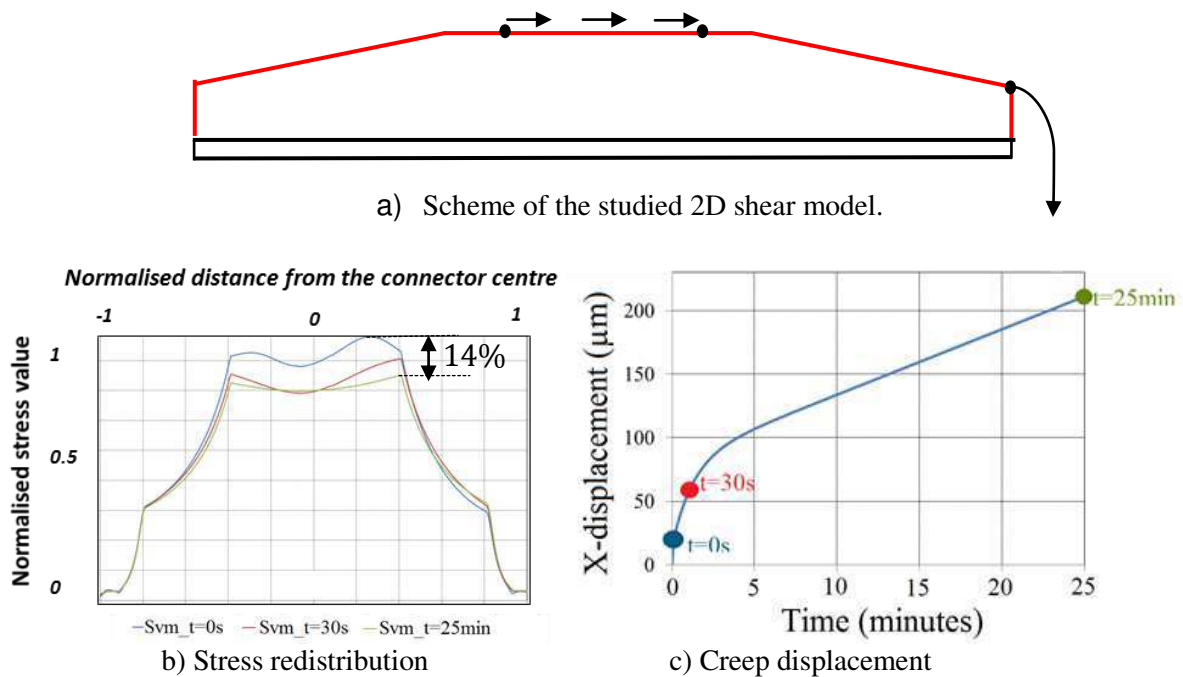


Fig. 15: Redistribution of von Mises stress for the shear model.

5 Comparison of measured displacements /model displacement

5.1 Tension load

Figure 16 shows the comparison between the mean creep displacement measured during the tests (mean displacement of the three sensors placed at 120°) and the creep displacement determined numerically for the two tested loads. The differences between experimental and numerical curves were negligible. It was possible to model with good accuracy the creep displacements for the first two stages at different levels of loads. Yet, it must be highlighted that it was necessary to modify Burger's parameters and that they seem consequently to be dependent on the load level.

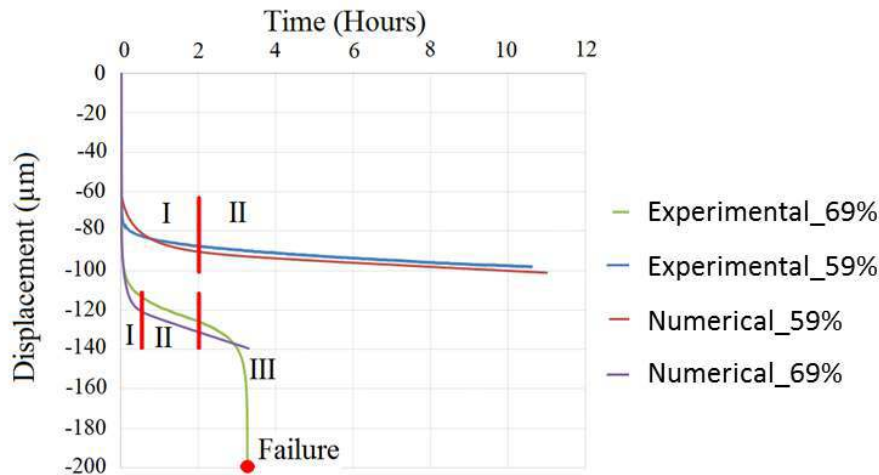


Fig. 16: Experimental and numerical comparison of out-of-plane displacement for tensile creep test at 25°C.

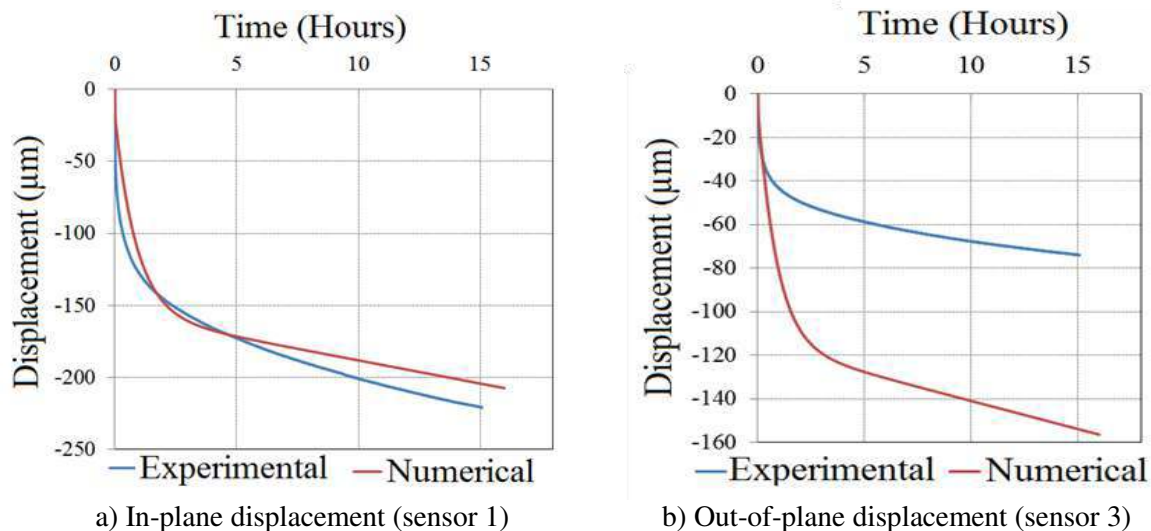


Fig. 17: Experimental and numerical comparison of creep displacements (in-plane and out-of-plane) for shear test at 59 % and 25°C.

5.2 Shear load

Figures 17 and 18 represent the comparison of experimental and numerical results of out-of-plane (sensor 3, Figure 17.b and Figure 18.b) and in-plane (sensor 1, Figure 17.a and Figure 18.a) displacements for shear creep tests with the two studied load levels. The difference between the experimental curve and the numerical one for the creep displacement in the plane was negligible

(Figure 17.a and Figure 18.a). Again, the used modelling approach seems to be well suited to the modelling of the creep of the assembly. Similarly, to the tension case, the Burger parameters had to be modified indicating a dependency of these parameters to the applied load. As far as out-of-plane displacements were concerned, there seemed to be large differences between the experimental measures and the model (Figure 17.b and Figure 18.b). There was therefore a need to improve the use model especially regarding isotropy hypothesis.

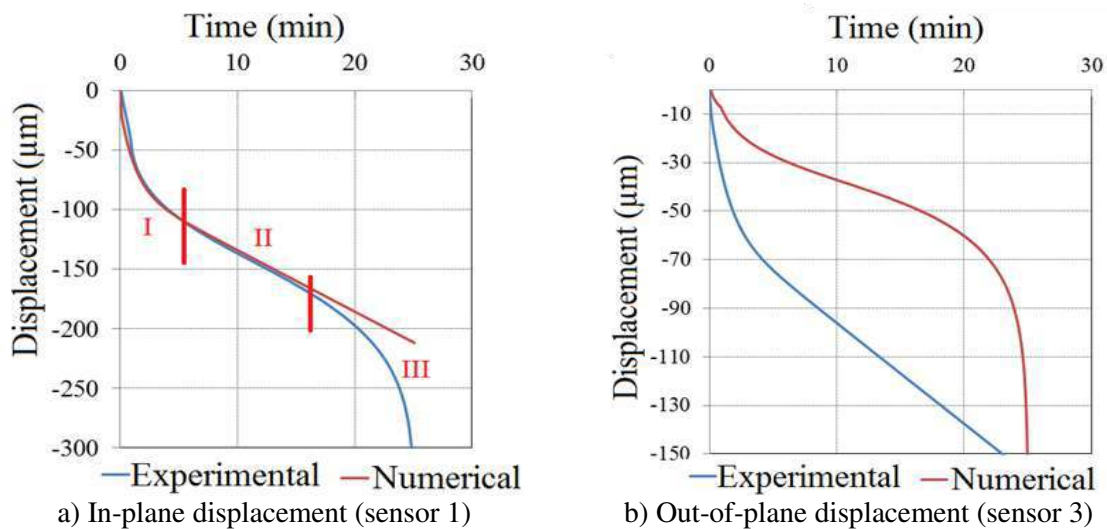


Fig. 18: Experimental and numerical comparison of creep displacements (in plan and out-of-plane) for shear test at 67 % and 25°C.

6 Conclusions

If the interest in using adhesively bonded fasteners exists for steel structures, there have been few studies presenting experimental investigations led at the scale of the fastener. The presented study is one of those and aimed at initiating investigations on the creep behaviour of such fastener.

The presented work investigated C-ClawTM solution developed by Cold Pad, Paris, France with a methacrylate adhesive system [1]. After a specific development on the test protocol, two main load situations that may be encountered on site were studied: tension and shear. Preliminary investigations allowed determining the ultimate capacities and the repeatability of the assembly process.

A modelling work was then carried out using commercial finite element software Abaqus, Paris, France with specific development dedicated to the integration of Burger's isotropic creep model. This work aimed at first in analysing the initial stress state in both load situations (tension and shear). It was proved that for both cases, stress is not uniform and is actually composed of peel and shear components (or pressure and von Mises stresses) depending on the fastener's geometry and the applied load.

Creep modelling was then carried out with an initial determination of Burger's parameters from the obtained experimental results. A good agreement was obtained between the measured average main displacements (out of plane in the case of tension and in plane in the case of shear), and the numerically obtained ones provided that Burger's parameters were dependent on the applied load. The stress redistribution during creep was also highlighted for both load situations during stages 1 and 2. This in agreement with other studies led on different applications [14-17]. In the case of shear load, a closer study of the measured displacements allowed determining large differences for the out-of-plane displacement. This seems to indicate that there may be an anisotropic behaviour of the adhesive that is not currently taken into account in the modelling. Additional investigations are under progress to

improve Burgers parameters identification, and study the possible implementation of anisotropic creep behaviour for stages 1 and 2. There is also a strong need for a model that would consider stage 3 to be able to model entirely creep process of such a bonded assembly [18].

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