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### Development of a mechanical frame adapted to Arcan tests to identify the creep behaviour of adhesive joints

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### **Résumé :**

Le collage structural est une méthode d'assemblage de plus en plus utilisée. En effet, cette solution présente plusieurs avantages par rapport à d'autres techniques comme le rivetage et le soudage : distribution uniforme de contraintes, assemblage de matériaux de nature différente, pas de production de chaleur. Le fluage est un phénomène important à prendre en compte en termes de durabilité lors de la conception d'un assemblage collé. Pour étudier ce phénomène, une analyse à l'échelle du joint mince est nécessaire. L'essai Arcan dispose de plusieurs avantages par rapport à d'autres méthodes expérimentales à l'échelle du joint de colle (plusieurs types de chargement possibles, effets de bord limités). Par conséquent, cet essai a été choisi dans le cadre d'un projet s'intéressant au fluage de connecteurs collés. Pour utiliser cette géométrie, un bâti de fluage spécifique a été conçu. Pour analyser la déformation locale au niveau de la couche d'adhésif, deux capteurs LVDT mesurent le déplacement selon deux directions (normale et tangente à la surface collée). L'ensemble de ce dispositif expérimental permet d'étudier le comportement en fluage selon plusieurs paramètres : niveau de chargement, type de chargement, température, réversibilité du fluage. L'analyse des résultats de ces investigations expérimentales permet d'appréhender au mieux le comportement l'utilisation de l'assemblage collé vis-à-vis de son utilisation.

### Abstract:

The use of structural adhesive bonding is increasing in the structural assembly field. It has indeed several advantages compared to other assembly techniques such as welding and riveting: uniform stress distribution, assembly of materials with different natures, no heat production. Creep is an important long-term phenomenon that needs to be considered for adhesive joints. To investigate this aspect, a study at the scale of the adhesive joint is required. At this scale, Arcan test presents several advantages compared to other existing tests (analysis of different loads, limited edge effects). Consequently, Arcan test was chosen for an ongoing creep study aimed at studying bonded fasteners. A mechanically operated creep testing machine for adhesive joints and adapted to this test was

developed. To study the local strain of the adhesive, two LVDT sensors measure the displacements according to two directions: normal and tangential to the bonded surface. These sensors are placed in a support, which is fixed at the beaks of the sample. This mechanically welded frame enables investigating the creep behaviour of adhesive joints according to a lot of parameters (load levels, type of load, temperature, adhesive thickness). The analysis of the behaviour allowed suggesting some design tools adapted for the use of the bonded fasteners under creep loads.

## Keywords: creep behaviour, Arcan test, experimental investigations, adhesive bonding

### **1** Introduction

Structural adhesive bonding is being increasingly used in civil engineering applications. This joining technique has in fact several advantages: weight reduction, facility to joint different materials, uniform stress distribution, no heat production. This last feature is particularly interesting for offshore activities, where there may be some need to connect new elements to existing structures without constraining their service properties [1]–[3]. However, there are still some issues preventing a wider development of this technique such as the durability of structural adhesive bonding. The firm Cold Pad developed adhesively bonded fastener solutions (Figure 1) whose aim is to replace welding by structural bonding, for repair or reinforcement of steel structures in offshore area. A specific installation tool (Figure 2) was also developed to ensure precise control of the bonding operation between the two substrates [4].



Figure 1. C-Claw<sup>TM</sup>, bonded fastener [4]



Figure 2. C-Hawk, installation tool [4]

Regarding the durability issue raised by such a solution, as specific protections against humidity diffusion have been provided, creep appears to be one of the main phenomena that must be studied for the considered case. To do so, experimental investigations were carried out at real scale on the assembly in creep for two geometries of a bonded fastener, at different stress levels and under different load situations (tension and shear) using a methacrylate adhesive [5]. However, these investigations remain specific to the studied fastener geometry, preventing their use for creep prediction of alternative geometries. Most of existing literature focused on the creep characterisation on bulk samples of the adhesive. Yet, as interphase may influence this behaviour, studies at the scale of the adhesive joint are required.

The present study will focus on the analysis of the creep behaviour of bonded assemblies using the Adekit A310-1 methacrylate adhesive. Creep is defined as the time-dependent strain of a material or

an assembly under a constant load. It is characterised by a slow flow of the material, which behaves viscously. If it is subjected to a constant load, the decrease in cross-sectional area generates an increase in stress. When the stress reaches an ultimate value, failure occurs. Temperature and stress are the main parameters affecting creep (strain increases with temperature and stress level) [6].

First, a short literature review of mechanical tests for adhesive joints will be introduced. Then, the development of testing resources (creep mechanical frame and sensors support) adapted to Arcan test will be described. The last part will be dedicated to some results of creep tests studying several parameters in order to characterise the creep behaviour of an adhesive joint.

## 2 Literature review of mechanical tests used to characterize adhesive joints

An adhesive joint is characterised by its dimensions: a small thickness (a few hundred micrometres), a width and a depth [7]. This geometry and the nature of the adhesive (sometimes inhomogeneous) [7], [8] complexifies the measurements of the mechanical properties of a bonded assembly. Moreover, the lower the film thickness, the more important is the influence of the interphase on the global behaviour of the assembly [7], [9]. Thus, to investigate the mechanical behaviour of a bonded assembly, it is necessary to carry out experimental investigations with samples having the same adhesive thickness than the one used for the industrial application [9], [10].

Several experimental methods have been developed to study the mechanical behaviour of adhesive joints, such as the single lap shear test (SLJ) (Figure 3-a), the thick adherent shear test (TAST) (Figure 3-b), and the Arcan test (Figure 4). These methods rely on a specific geometry of sample and on dedicated testing equipment.



Figure 3. (a) Single lap shear test (b)Thick adherent shear test [11]

Figure 4. Arcan test [12]

The most used test is the single lap shear test [7], [10]. The sample consists in two rectangular plates bonded on a part of their section. The validity of the results relies mainly on the alignment of the substrates and the control of the adhesive thickness. However, this method has some disadvantages: the geometry of the assembly induces a moment in the loading which causes a bending of the substrates [10] and therefore a normal stress in the adhesive layer (peel stress at edges) [12]; the stress field in the adhesive layer is inhomogeneous [9], [10], [13]; only a shear load can be applied [14].

In order to reduce the bending of the substrate in the single lap shear test, the thick adherent shear test was developed with thicker substrates and a short overlap. Nevertheless, numerical studies have shown that the edge effects are very significant and the inhomogeneous stress field induced in the adhesive layer has still major effects on the measured mechanical properties [13].

For these reasons, Arcan test has been selected for this study. It shows several advantages. First of all, various types of load can be applied to the assembly using the holes of the sample (Figure 4) [11]:

tension  $(0^\circ)$ , shear  $(90^\circ)$ , tension-shear  $(45^\circ)$ , compression-shear  $(135^\circ)$ . Furthermore, the samples have a specific design of beaks, closed to the bonded surface, to homogenise the stress in the adhesive layer compared to other tests for adhesive joints [11] (Figure 5).



Figure 5. Beak on a sample for an Arcan test [11]

# 3 Development of a testing protocol adapted to Arcan test3.1 Creep mechanical frame

To investigate the creep behaviour using the Arcan test, an adapted creep testing machine was developed (Figure 6). The load applied to the specimen is created thanks to gravity. It is amplified with two level arms. To control the loading speed, the upper arm is supported by a threaded rod. The rod is removed progressively to apply the load on the sample. In order to carry out several creep tests at the same times, four similar mechanical frames were used at the same time. The adhesive joints have the following geometry: a bonded surface of  $9.54 \times 25.4$  mm<sup>2</sup>, and an adhesive thickness of 200  $\mu$ m.



Figure 6. Creep mechanical frame

### 3.2 Support adapted to LVDT sensors

A Digital Image Correlation (DIC) technic is often used to extract displacements data with Arcan tests [15]–[18]. However, for this study, Linear Variable Differential Transformer (LVDT) sensors were chosen to measure the displacements of the bonded assembly. Table 1 gives the properties of the used sensors. The relevant displacements to record were in the normal and orthogonal directions of the bonded surfaces.

| Туре                | D6/01000A/L10/RA/3M |
|---------------------|---------------------|
| Range               | ± 1 mm              |
| Accuracy            | 1 µm                |
| Linearity           | ± 0.1 %             |
| Maximum temperature | 125°C               |

Table 1. Sensor properties

A specific system was designed to fix the sensors on the sample (Figure 7). This system must be adapted to all the load situations (tension, shear, tension-shear). Moreover, it has to be close enough to the bonded surfaces to measure only the displacement due to the deformation of the adhesive. To comply with these specifications, the support was designed to be fixed on the beaks of the sample. Figure 8 highlights that the support can be used for all the load situations. For tensile tests, the relevant displacement is the one that is normal to the bonded surface, and for shear tests, it corresponds to the displacement that is tangent to the bonded surface.





Figure 7. Photos of the support for the LVDT sensors adapted to the sample



(a) Tension





(c) Tension-shear

Figure 8. Sensors support adapted to three load situations

### 4 Creep test investigations

For loads in tension and shear, preliminary quasi-static investigations up to failure were carried out to determine the monotonic ultimate capacities of the adhesive joints. For each load situation, the test was repeated at least three times. The temperature of the test was  $20^{\circ}$ C. Table 2 gives the average stress measured for each load situation. The average ultimate capacity in tension is noted  $T_{ult}$ , and  $S_{ult}$  in shear. It can be noted that  $T_{ult}$  and  $S_{ult}$  are close.

| Load situation | Average stress | Standard deviation |
|----------------|----------------|--------------------|
| Tension (0°)   | 17,9 MPa       | 10 %               |
| Shear (90°)    | 18,5 MPa       | 9 %                |

Table 2. Average ultimate capacities in tension and shear at 20°C

### 4.1 Influence of the stress level

The developed mechanical frame allows investigating the creep behaviour of the adhesive joint at several load levels. The weight used to create these loads levels are between 0.100 kg and 2 kg. In tension, the studied load levels are between 50% and 80% of  $T_{ult}$ . In shear, the studied load levels are between 80% and 90% of  $S_{ult}$ . The tensile and shear tests are respectively noted T-N-i and S-N-i,

with N the percentage of the load level and i the number of the tests. Figure 9 details the creep stress as function of the time to failure of tensile and shear creep tests

performed at 20°C. It highlights that the logarithm of the time to failure of tensile and shear creep tests performed at 20°C. It highlights that the logarithm of the time to failure  $(t_f)$  is linearly linked to the stress applied to the adhesive joint. Moreover, the creep strength is better for the shear loading: shear creep tests were performed until 90% of S<sub>ult</sub> and last over 1 day, whereas at 70% of T<sub>ult</sub>, tensile creep tests last around one hour.



Figure 9. Stress as a function of the time to failure for tensile and shear creep tests

Figure 10 shows the displacements normal to the bonded surface during tensile creep tests at  $20^{\circ}$ C as a function of the normalised time. This time is defined as the ratio of the time and the t<sub>f</sub>. This definition of normalised time has already been used for previous creep studies, such as in [19], [20]. It can be noticed that all the tests present the three creep stages. The load level does not seem to have a major impact on the creep displacement.

The three repetitions of the tensile creep test at 70% of  $T_{ult}$  are presented in Figure 11. This graph points out the spread of the results, especially in terms of time to failure.

The same observations were made for the shear creep tests.



*Figure 10.* Normal displacement depending on time during tensile creep tests at 50%, 60% and 70% of  $T_{ult}$ 



*Figure 11.* Normal displacement depending on time during the three tensile creep tests at 70% of  $T_{ult}$ 

### 4.2 Influence of temperature

To investigate the influence of temperature on the creep behaviour of the adhesive bonding, one of the frames was placed in a thermal chamber. To carry out this kind of test, the heating of the chamber is first carried out, then the load is applied to the sample and the creep test starts. The heating of the chamber is considered to be complete when all the components of the frame and the specimen are at the desired temperature. To verify this, a PT100 sensor is bonded on the structure of the frame. When the temperature and the displacements stabilize, the heating of the system is considered finished. For a temperature of  $50^{\circ}$ C, it takes approximately one hour and a half. The creep tests at high temperature were performed at  $35^{\circ}$ C and  $50^{\circ}$ C, at 50% of T<sub>ult</sub> for the tensile tests, and 70% of S<sub>ult</sub> for the shear tests.

As expected, the time to failure declines sharply when the temperature increases (Figure 12): for a load level at 50% of  $T_{ult}$ , at 20°C, the time to failure is approximately of one month, at 50°C, it is about one hour. Moreover, the impact of temperature is more significative when the adhesive joints is loaded in shear. Figure 12 also shows that the logarithm of the time to failure seems to be linearly linked to temperature. Figure 13 highlights that the displacement during shear creep tests increases with temperature. The same conclusion was made for tensile creep tests.



**Figure 12.** Time to failure as a function of the temperature for tensile creep tests at 50% of  $T_{ult}$  and shear creep tests at 70% of  $S_{ult}$ 



Figure 13. Tangent displacement depending on normalised time during shear creep tests at 70% of S<sub>ult</sub> at 35°C and 50°C

### 4.3 Creep recovery

Creep recovery tests were also carried out. They allow assessing the reversibility of the phenomenon due to the applied load. These tests were performed for tensile loading at 60% and 70% of  $T_{ult}$  and for shear loading at 80% and 90% of  $S_{ult}$ .

The first studied issue was the impact of unloading of the sample during a creep test on the lifespan of the bonded assembly. To do so, the time to failure of the creep recovery tests is evaluated by removing the parts of unloading during the tests. These times were then compared with the time to failure of creep tests in Figure 14. This graph highlights that the unloading during creep does not seem to have an impact on the time to failure.

The second analysed aspect was strain evolution when the load is removed during a creep test. Figure 15 shows an example of the displacement curves obtained during a tensile and a shear creep recovery test. This graph points out that the measured displacement decreases more significantly during tensile test than shear test. However, it appears that most of the creep displacement is not recovered at unloading.





Figure 14. Stress as a function of time to failure for creep and creep recovery tests in tension and shear

Figure 15. Displacement during a creep recovery tests in tension at 70% of Tult and in shear at 90% of Sult

### 5 Conclusion

This study focused on the development of testing resources adapted to Arcan creep test. A creep testing machine was conceived, on which the load applied to the specimen is created thanks to gravity and amplified with two level arms. LVDT sensors are used to measure local displacements of the assembly. These sensors are fixed on the specimen with a specific support.

The mechanical frame has allowed investigating the creep behaviour of the bonded assembly according to several parameters: stress level, type of load, temperature, and creep recovery.

For the studied adhesive, the ultimate capacities in shear and tension are similar. However, the creep strength is significantly more important in shear than in tension. Experimental investigations at several load levels and temperatures showed that the logarithm of the time to failure is linearly linked to the creep stress and the temperature. Moreover, the creep displacement increases with the temperature, and the impact of temperature is more important in the case of shear tests than tensile tests. Creep recovery tests showed that most of the creep displacement is not recoverable when the load is removed.

The possibility to study the creep behaviour according to these parameters could enable the development of complex creep model of bonded assemblies at the scale of adhesive joints.

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