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# USE OF A CURVED ADHESIVELY BONDED ANCHORAGE FOR A PULTRUDED COMPOSITE CABLE

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**ABSTRACT:** In order to join a plane composite cable to the main structure of a composite footbridge designed within (Caron, 2009), it was decided to investigate structural adhesive bonding. This technique is indeed particularly adapted to composite materials. However structural adhesive bonding induces stress concentrations at the edges of the adhesive joint, which have been studied by a large number of researchers in order to reduce these phenomena and increase the capacity and service life of the bonded joint (Kinloch, 1987). These studies are all concerned with optimizing shear stress transfer in adhesively bonded joints. This paper investigates the role of hydrostatic pressure on the ultimate capacities of common civil engineering adhesives. The conclusions led us to study a new joint geometry, the "curved" bonded joint that naturally creates compressive stresses on the edge of the bonded joint. Several experimental investigations are presented within this paper to illustrate the optimization. These are quasi-static tests that compare classical shear lap joints to curved joints. Additional testing is currently in progress, but the curved bonded joint seems to hold good prospects and a patent has been filed.

## 1. Introduction

Adhesive bonding is not a new assembly technique, but its use in structural applications is comparatively recent. The structural bonding concept was developed in the middle of the 20th century with the advent of synthetic resins and the technique is currently applied in a number of areas, such as aeronautical, nautical and construction. In civil engineering, structural bonding is mainly used to repair or strengthen structures with adhesively bonded steel plates or composite materials (Hamelin, 2002). However, a large number of studies are currently attempting to use it as an assembly technique in its own right in new structures. This study sets out to obtain a better understanding of the problems relating to the design of adhesively bonded joints and presents some preliminary ideas about the optimization of adhesive bonding.

The starting point for this study is the anchorage of a flat cable on a full-composite footbridge designed at the Navier Research Unit (Caron, 2009). The stay in question is a composite carbon fibre epoxy matrix strip that is adhesively anchored in the structure. The strength of an adhesive bond depends on the strength of the constitutive materials (adhesives and adherents (Pan, 2007)) as well as the magnitude of the interfacial stresses that are imparted to the assembly during surface preparation. Surface preparation has an influence not only on bonding stresses but also on the way these change over time (Matana, 2005). This aspect shall not be considered in this paper, which will focus on an investigation of the materials present in the bonded joint and the optimization of stress transfer within the assembly.

With regard to this point, some researchers have examined the influence of the edge conditions, for example the shape of the adhesive fillet or the use of profiled adherents (Da Silva, 2007). Other researchers have considered the use of materials whose Young's modulus or thickness varies along the joint (Hadj-Ahmed, 2001). It should be noted that this variation can involve the adherent and/or the adhesive and that, in some cases, it simply comes down to the use of two different materials, for example two different adhesives. It was decided in this study to concentrate on the mechanical characterization of the adhesives in order to highlight an interesting aspect of their behaviour which may increase their capacity.

The first part of the paper describes the investigations we performed to characterize bulk specimens of various adhesives. Three adhesives that are used in civil engineering and industrial applications were studied. The results showed that an increase in the hydrostatic pressure led to an increase in capacity in the case of the elastic brittle adhesives, or an increase in the elastic limits in the case of the elastoplastic adhesives. The remainder of the study deals with experimental investigations into a geometry that naturally creates out of plane compressive stress in the bonded joint. The first experimental results are promising, revealing a considerable increase in the capacity of the bonded joint. Other tests are in progress, but this study has already resulted in the development of a new anchorage system concept, for which a patent has been filed (Caron, 2008).

## 2. The role of hydrostatic pressure

The term hydrostatic pressure does not have wide application in connection with civil engineering structures, being more used in soil mechanics. To clarify its meaning, some general remarks will be given. After this, a description of the tests we have performed to investigate how the hydrostatic pressure affects the behaviour of adhesives will be given. Two types of adhesives will be studied: a brittle elastic adhesive that is often used in civil engineering and an elastoplastic industrial adhesive. Last, the results of these tests will be described and exploited in order to come to a conclusion about the influence of hydrostatic pressure.

### 2.1. General remarks on hydrostatic pressure

The stress field acting on a member is frequently broken down into two separate parts: the deviatoric stress which is associated with the shear field, and the hydrostatic stress, which is not associated with shear stresses. In most cases, the deviatoric stress corresponds to the von Mises stress, which means it is possible to use this parameter, frequently used in mechanics. The hydrostatic stress is the mean of the normal stresses. This is summarized by Eqs. (1) and (2) where rij is the component of the stress tensor with indices (1, 2, 3), i and j vary between 1 and 3, p is the hydrostatic pressure, and q is the deviatoric stress.

$$p = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3} \quad (1)$$

$$q = \sqrt{\frac{1}{2}\left((\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2\right) + 3\sigma_{12}{}^2 + 3\sigma_{13}{}^2 + 3\sigma_{23}{}^2} \quad (2)$$

To give some idea, and perhaps also to explain the reasons for breaking a stress field down into these two components, many studies lead to the von Mises stress being taken as the yield criterion or the plasticity criterion for certain materials such as metals (Eq. (3), σlim being a characteristic value of the material). For other materials, for example many soils, it is necessary to use a linear criterion that takes account of both components: this type of criterion is known as the Drucker–Prager yield criterion (Eq. (4), φ being the friction angle, and d being the cohesion when no pressure is applied). Both parameters φ and d are characteristic values of the material. The behaviour of a material that obeys the von Mises criterion is therefore independent of the hydrostatic pressure.The behaviour of a material that obeys a linear criterion of the Drucker– Prager type is linearly linked to the hydrostatic component.

$$q = \sigma_{\lim} \quad (3)$$

$$q = p \cdot \tan(\phi) + d \quad (4)$$

## 2.2. Tests for the characterization

With reference to the case which is considered, in order to determine whether or not the capacities of the studied civil engineering adhesives depend on the hydrostatic pressure, the results from several destructive tests that provide values for a number of hydrostatic pressure and deviatoric stress pairs are needed. In theory, just two tests may be enough. It was decided to use three tests, as was done in previous research on ceramic materials (Wang, 2007). The three tests were performed on bulk adhesives, so they characterized the capacities of the materials and not that of the interfaces in an adhesive bond. These tests were the uniaxial tensile test on dog-bone specimens, the compressive test on cylindrical specimens, and the diametral compression test, also on cylindrical specimens. It should be noted that there is some debate about whether tests on bulk materials are appropriate to characterize materials that are used in thin joints. In the present case, the study is interested in adhesive bonded assemblies used in civil engineering. For these applications, the adhesive joint is thick enough (more than 0.25 mm, the minimum thickness value given in the technical data sheet and controlled by the insertion of nylon wires) and simple modelling tools must be proposed to designers. Though additional testing is necessary to validate the hypothesis, it was decided to correlate the properties of the bulk materials with those of the adhesive joints as a first approach. Based on the fracture or elastic limit results from these tests, three points on the fracture envelope or within the elastic domain of the tested adhesive material can be determined.

## 2.3. Test results and conclusion

Two adhesives (Etancol 492 provided by Bostik company, and Sikadur 330 commercialized by SIKA France) that are used in civil engineering for strengthening with composite materials were studied in particular detail. They both exhibit brittle elastic behaviour prior to ageing and are both two component epoxy adhesives. One industrial adhesive (DP460 commercialized by 3 M) was also studied. This exhibits elastoplastic behaviour and the given results correspond to the elasticity limit. The cylinders and dog-bone specimens were manufactured in silicone moulds. The tests were performed 48 h after the beginning of polymerization. The test results are depicted in two different ways in Fig. 1. The graph on the left side shows the three tests, and the graph on the right side shows the three fracture or elasticity envelopes.

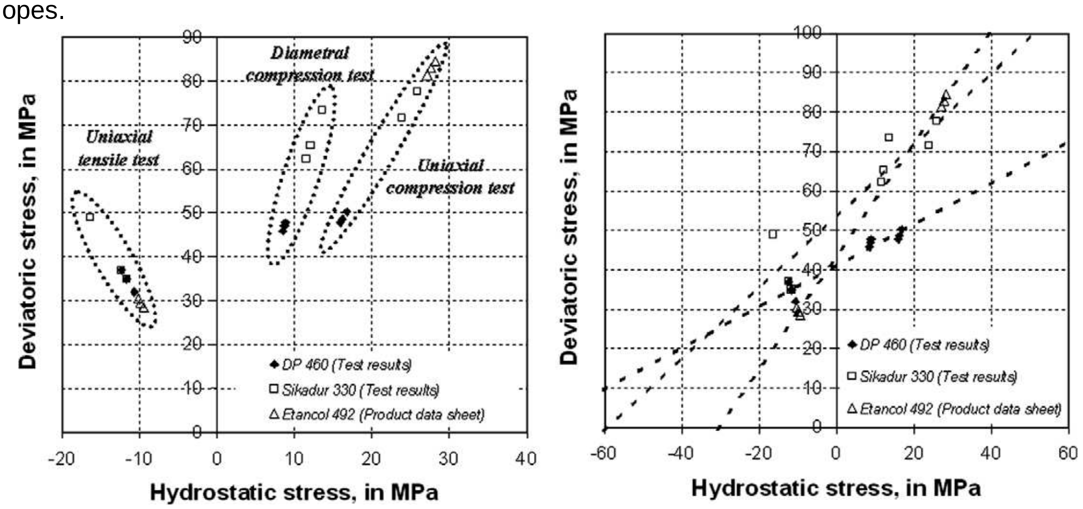

**Fig. 1 - Test results: von Mises stress versus hydrostatic pressure with the results of the three tests on the left side and the fracture or elasticity limit envelopes on the right side.**

It can be seen that the fracture envelopes and the plasticity envelope are far from horizontal, so the capacity of the adhesives in question is highly dependent on the hydrostatic pressure. The yield criterion or the plasticity criterion of the adhesives is, therefore, closer to a Drucker–Prager type criterion. This means that peeling (negative hydrostatic pressure) is deleterious to the bonded joint as it tends to reduce the shear capacity of the adhesive. In contrast, compression is beneficial as it tends to increase the shear capacity of the adhesive in question. This persuaded us to work on a joint whose geometry would naturally create compressive stresses at the joint edge, i.e. a ”curved” joint. There are, of course, other ways of applying compressive stress to an adhesively bonded joint, for example by using bracing. The difference between bracing and a curved joint is that in the former, the compressive stress is determined by the initial tightening. In a curved joint, however, the compressive stress increases with the applied load.

## 3. Experimental investigations

In order to check that the observed adhesive material behavior may indeed increase the bonded joint capacity in the case of a curved geometry, experimental investigations were carried out. They are still in progress, but the first findings are promising.

Specimens with three different geometries were manufactured, each with the same bonded length and therefore based on the same quantity of materials. These were a lap joint, a curved joint and a curved joint with a friction surface. The friction surface reduced the load to be transmitted by the adhesively bonded joint. In each case the adherent substrate was a steel cylinder whose surface had been abraded and degreased with acetone prior to adhesive bonding, and the bonded length Lc was identical.

A variety of adherents and adhesives were tested in this first series of tests. For the adherents, two composite systems were used: a unidirectional carbon fibre system having a longitudinal Young's modulus of 120 GPa (Eight 0.167 mm-thick layers of unidirectional carbon fibres), and a carbon fabric system that is frequently used for strengthening civil engineering structures (the realized composite has an equivalent longitudinal Young's modulus of 70 GPa and an equivalent thickness of 1 mm).

The two studied resins were a brittle elastic resin, Sikadur 330 (SIKA France) that was used with both composite systems, and an industrial elastoplastic, DP460 (3M) which was used exclusively for the unidirectional carbon fibre strip.

A specific test apparatus, shown in Fig. 2, was designed. This can be used to test both the lap and curved assemblies while ensuring that the composite adherent remains aligned with the axis of the testing machine. A 100 kN tensile testing machine operating with a constant rate of displacement of 2 mm/min was used.

**Fig. 2 - From left to right: diagram of the test device for curved joints, picture of the experimental set-up, and photograph of a specimen after fracture showing the marking of the steel by the friction zone.**

Two different types of fracture were observed, cohesive fracture within the adhesive joint and tensile fracture of the strip. It is to note that after the test the steel surfaces were highly marked in the friction zone, so it is important to take this into account from the theoretical standpoint. The results of the investigations for each specimen with regard to fracture mode and capacity are reported in Table 1.

It can be observed that in all cases the use of a curved joint increased the capacity of the assembly. In the case of the carbon strip which was bonded with ductile adhesive this increase was considerable, showing the benefit of a friction zone at the joint entrance. However, in further work, it will be interesting to check that the friction phenomena are not excessively reduced by cyclical stresses in the case of fatigue loading. As regards the strip that was bonded with a brittle elastic adhesive, the increase in capacity was very great, leading the fracture mode to change from cohesive fracture in the resin to tensile fracture in the adherent. This change in the fracture mode is shown by the brackets in the ”increase compared with a lap joint” column in Table 1 because this increase leads to an underestimation of the actual capacity of the bonded joint. New tests need to be performed with a different geometry with which fracture occurs in the adhesive joint rather than in the strip. In the case of the fabric bonded with a brittle elastic resin, the fracture mode was also modified, changing from cohesive fracture in the resin to tensile fracture in the composite adherent. A slight increase in the capacity of the assembly was observed which, once again, constitutes the lower bound of the increase in the capacity of the adhesive joint.

**Table 1 – Experimental results on adhesive joints**

| Composite | Adhesive | Configuration | Fracture location | Capacity (MPa) | Standard deviation (%) | Increase compared with lap joint (%) |
|---|---|---|---|---|---|---|
| Carbon fabric | DP460 | Plane | Adhesive | 641 | 13 | - |
| - | - | Curved | Adhesive | 785 | 23 | 22 |
| - | - | Curved with friction | Adhesive | 1167 | 4 | 82 |
| Carbon fabric | Sikadur 330 | Plane | Adhesive | 656 | 13 | - |
| - | - | Curved | Composite | 2242 | 5 | (242) |
| - | - | Curved with friction | Composite | 1935 | 8 | (195) |
| Carbon sheet | Sikadur 330 | Plane | Adhesive | 283 | 25 | - |
| - | - | Curved | Composite | 349 | 6 | (23) |
| - | - | Curved with friction | Composite | 374 | 6 | (32) |

## 4. Results analysis

In the case of the strip which was bonded with an elastoplastic resin, the increase in capacity was due to an increase in the plasticity limit brought about by the hydrostatic pressure present in the curved joint. In the case of the joint that is bonded with DP460 elastoplastic resin and which has a friction surface, the additional increase in capacity is the result of friction phenomena. Based on the friction length and considering the phenomena to be uniform, we can calculate a mean friction coefficient for the steel surface that is in contact with the composite strip. In the present case study, the resulting friction coefficient is approximately 0.45. This coefficient of friction is a commonly used criterion, and it was verified that it is able to explain the observed increase in the joint capacity. The issue of how the value of the coefficient changes over time needs further examination in order to be able to consider the long-term behaviour of the bonded joint. However, it should be noted that this is a potentially interesting way of increasing anchorage capacity.

For the fabric and the strip bonded with a brittle elastic resin, an increase in the capacity of the bonded joint was checked, but also, and above all, a change in the failure mode. In the lap joints, cohesive fractures in the adhesive were obtained, whereas tensile fractures of the strip were observed in the curved joints. The experimental values obtained for the capacity of the joints are therefore minimum values which should be taken as lower bounds. However, in the case of the strip bonded with the brittle elastic resin, the capacity of the joint was increased by a factor of three, showing the considerable potential of the curved geometry. This topic is currently under further investigation, but it is clear that the dependency of the behaviour of the adhesive on the hydrostatic pressure cannot, on its own, explain the observed increase in capacity. The answer no doubt lies more in the fact that the curved geometry controls crack propagation, and perhaps also in the fact that a friction surface is created during the test after the onset of cracking in the bonded joint.

## 5. Conclusions and outlook

Investigations were carried out on a new anchorage geometry that involves adhesive bonding of flat cables. Such assemblies can be used for structural bonding applications, either for reinforcing or repairing existing civil engineering structures or in new construction.

The first stage of the study was to characterize a variety of adhesives in order to observe their dependency on hydrostatic pressure. An elastoplastic adhesive and two brittle elastic adhesives were studied and, by applying three different test configurations on bulk adhesive, we partially identified the plasticity envelope or the fracture domain for each system. It was found that the hydrostatic pressure has a major influence on the properties of the adhesives and that we should therefore adopt a criterion that takes into account this parameter. The linear Drucker–Prager criterion was presently adopted for subsequent investigations of different bonded joint geometries.

The second stage was to verify some theoretical expectations by conducting experimental investigations of the curved bonded joint. This allowed to check the increase in capacity that occurs with the elastoplastic adhesive (Chataigner, 2010) and showed the considerable impact of friction phenomena for the capacity of the assembly. Additional investigations are required for the brittle elastic adhesive, but a very significant increase in the bearing capacity of the assembly has been demonstrated (this was increased by a maximum factor of three with fracture of the composite strip and not of the adhesive joint). In this case, the dependency of the capacity of the adhesive on the hydrostatic pressure cannot explain the observed increase on its own. Future investigations will need to consider cracking phenomena.

A patent has been filed for the curved geometry which seems to hold interesting prospects. Although the application considered here was the anchorage of a cable on a footbridge other possibilities may be envisaged. Additional studies into the fatigue behaviour of the assembly are in progress and should enable some of the issues raised by this study to be resolved. The most important of these issues relate identifying the domains of strength or plasticity of the adhesives and how they change over time, the control of cracking in the case of the curved geometry, issues concerning the tribology of the surfaces, and the influence of possible surface treatments. Besides, investigations of the ageing of epoxy resins are currently in progress (Benzarti, 2009). This will provide more information about the long-term behaviour of adhesively bonded structures and the service life of such assemblies.

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