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# Analysis of the behaviour of a bonded joint between laminated wood and ultra high performance fibre reinforced concrete using push-out test

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Bonded composite constructions using timber and ultra-high performance fibre reinforced concrete (UHPFRC) are investigated as highly innovative structural elements technically and economically efficient, and having better environmental performances. Such technique could indeed offer new structures typologies for bridges for instance associating timber for main beams with UHPFRC slabs. In timber-concrete-composite structures, connection is traditionally achieved with mechanical means. The research presented herein describes the timber-concrete assembly by adhesive bonding and specially the behaviour of bonded joint between Laminated Wood (LW) and UHPFRC. This type of assembly has to be investigated concerning mainly the durability of the bonded assembly and its ability to transmit the forces concentrated on edges. The present study describes the development of a test called "Push-Out" used to characterize the behaviour of the timber-concrete bonded after or prior to environmental ageing. Following the development of the used test protocol, investigations are realized on four different commercial resins to study the influence of the adhesive stiffness on the force transfer focusing in particular on the failure mode, on the ultimate capacities and some local deformations. The mechanical behaviour of the bonded joint is investigated in particular from a theoretical point of view and from the determination of deformation field obtained by Digital Image Correlation (DIC).

## 1. Influence of the stiffness of the resin

### 1.1. Context of the research

Timber-concrete composite structures have been used in many countries. These structures are becoming important because they bring many advantages when compared with traditional timber structures. Structurally, wood is a lightweight material, it is renewable and, when properly treated, it is durable.

Concrete increases the stiffness of the structure and protects the wood from environmental effects [1]. There have been few investigations [2–6] on the use of adhesives for the connection of timber beams with standard concrete slabs. Within all these cases, the transfer of shear forces through the bond was limited by the low tensile strength of the concrete material. In this context, the use of steel fibre reinforced high-, or ultra-high-performance fibre reinforced concretes seem promising, because it exhibits high tensile strength of the concrete material [7]. A further advantage that results from the steel fibre reinforcement is that the concrete slabs can be very thin because there is no need for conventional steel-bar reinforcement. Thereby, the weight of the composite construction can be reduced further.

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IFSTTAR Institute (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux) has worked from many years on the development of composite timber-concrete structures to obtain new typologies of structures, technically and economically efficient, and having a better environmental performance [8]. Up to date, the connection between the timber and the concrete has been achieved with mechanical means such as screws, bolts or with a concrete indentation into the wood [9–13]. Since a few years, the technique of structural adhesive bonding has been used and developed and is the subject of a patent. This technique, unlike the conventional assembly techniques (local or discontinuous connectors), can ensure an almost-perfect connection between the two materials [14,15], and thus optimize the quantity of material to be used in structures as each part may contribute to the structure according to its own mechanical performance.

Although the assembly by structural bonding has been used for several years for other civil engineering applications (for example, in the case of adhesively bonded composite reinforcement or composite steel-concrete structures [16–22]), its possible use for this type of application has to be investigated in particular to verify its ability to transmit the forces concentrated on edges or to resist to environmental loading. First studies conducted at Navier Laboratory have investigated on large scale the process for composite wood-concrete beams. Static and fatigue validations of the process have been realized [14], and there is now an interest in the environmental durability of such structures [23].

In order to conduct a more consistent number of investigations with a more limited quantity of material, it was decided to investigate the use of the “Push-Out” test that consists in loading the two symmetrical joints in shear using a compression tool in order to study in particular the influence of the properties of the resin on the shear capacity of the bonded joint. In the following section (Section 1.2), as a preliminary work, a numerical study is undertaken to confirm the importance of the choice of the resin on the mechanical behaviour of a bonded composite construction. The experimental program will then be described (Section 1.3).

### 1.2. Properties of bonded composite construction, preliminary work

In composite structures, strength and deformation characteristics of interface connections are very important in order to evaluate the mechanical behaviour of the structure. The degree of composite action depends on the type of connector, timber and concrete properties.

The major influence on the effectiveness of timber-concrete composite structures can be assigned to the stiffness of the connection between timber and concrete. Flexible connections like dowel-type fasteners, which were mostly used up to now, lead to decreasing bending stiffness of the members. Using the adhesive bonding technology is a way to realize a rigid compound. Especially if fibre-reinforced concretes are applied, this technology is reasonable because of the high tensile strength of the concrete material. Until now, few investigations were made on this type of application.

Many studies got interested in the influence of the stiffness of the connector on the stiffness of the obtained composite structure studying different existing connector systems. These studies allowed [14,24,25] to realize a pseudo-classification of the used connectors: Local connectors (tips, screws, studs, long bolts, etc.) that provide a limited stiffness to the structure, half-continuous connectors (set of long bolts, expanded metal, etc.) whose properties of stiffness are highly dependent of the distribution and geometry of the elements, and structural adhesive bonding, that allow to ensure an optimal mixed functioning of the structure (Fig. 1). It is

important to note that structural adhesive bonding reduces stress concentration phenomena compared with more conventional methods of assembly and that the stiffness of the connection depends in that case on the stiffness of the used adhesive and the thickness of the adhesive layer.

The connecting system exhibits a non-linear shear force-relative slip relationship even for low load values [26,27]. Indeed, the use of an adhesive allows distributing the shear forces uniformly over the entire surface and thus limits the local force concentrations which are unavoidable when mechanical connections are used. The adhesive connection is also quite slip-free, which helps to reduce the deflections.

In order to assess the influence of the stiffness of the adhesive on the elastic behaviour of a composite beam, numerical modelling using finite elements FE was carried out [28]. A 10 m long, and 240 mm wide timber-concrete beam has been modelled and subjected to 4 points bending. Distance between the loading points is 2.2 m and the value of each applied load is 500 kN (Fig. 2b). A rectangular section is included to simplify the analysis and realize a 2D calculation supposing plane strain conditions. The concrete element has a thickness of 170 mm, the element in wood has a thickness of 600 mm and the adhesive layer has a thickness of 2 mm (Fig. 2a). The three materials are supposed to be isotropic and elastic, and perfect adhesion between the three materials is considered. The study focused on the evolution of the mid-span displacement as a function of the elastic modulus of the adhesive (Fig. 3).

The numerical modelling shows that mid-span displacement of the composite structure is very little affected by the elastic modulus of the used adhesive when its stiffness varies between 200 and 10 000 MPa (Fig. 3). Most so-called structural adhesives have an elastic modulus greater than 200 MPa and are thus within this range of stiffness. This result is consistent with Fig. 1.

It exists therefore an important range for the designer on the choice of the adhesive. It must be emphasized that the stiffness of the used adhesive will also impact on the behaviour of the structure in response to hygro-thermal stress. This is in particular the subject of this work.

### 1.3. Aim of the research

If in the short term, structural adhesive bonding seems adequate [14,15], it is momentous to get interested in the ageing of such an assembly solution. More particularly, the influence of the stiffness of the used connection in the case of thermo-hygroscopic loading (ageing conditions) may be an important topic to investigate. Initial investigations on constrained shrinkage phenomenon

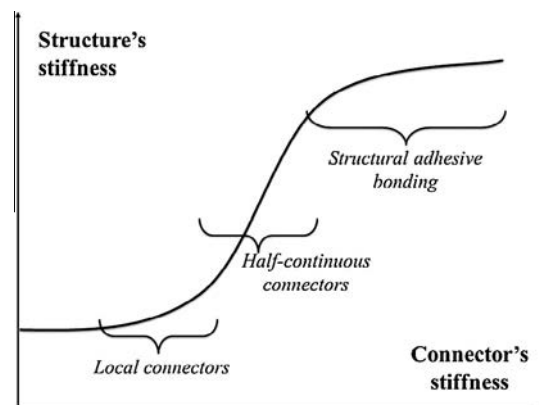


Fig. 1. Stiffness of a composite structure against the stiffness of the used connector.

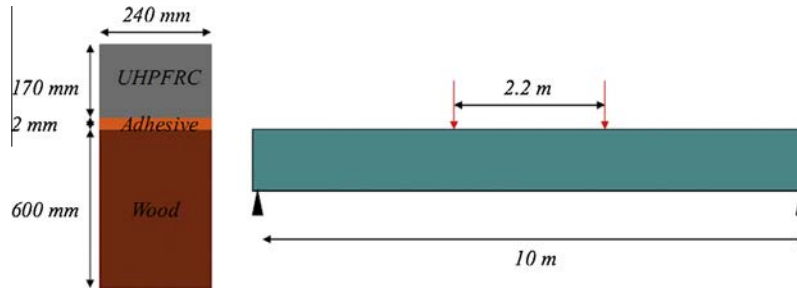


Fig. 2. Cross-section of the studied composite beam (left). Load configuration (right).

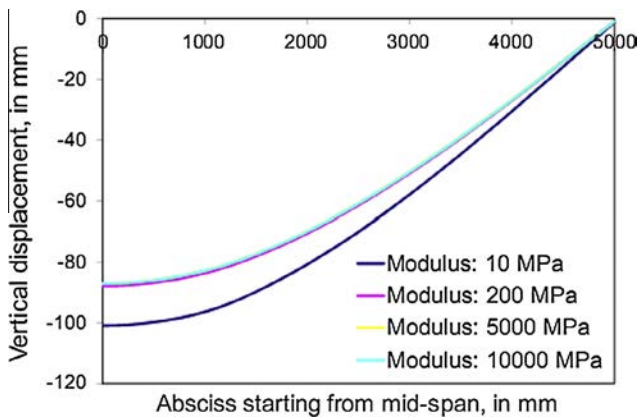


Fig. 3. Vertical displacement along half of the composite beam for different adhesive's Young modulus.

for this type of composite structures were realized in [29]. The study here is complementary and is designed to determine the influence of the stiffness of the adhesive on a composite structure connected by bonding with no ageing in a first step. Consecutive studies are underway on the subject of hygro-thermal loading with the same adhesive materials [30]. Four adhesive materials with various elastic stiffnesses are here studied using push-out tests. Moreover, the stiffness of the used organic materials also depends on the thermo-hygroscopic conditions and may change with time [31]. Thermo-hydro-mechanical characterization methods (using a dynamic mechanical analysis for example for the thermo-mechanical issue) are therefore necessary to help choosing the adhesive.

The stiffness of a connection system is determined using its slip modulus that quantifies the resistance offered against displacement in the contact surface between concrete and timber when a load is applied to the structure. In addition to stiffness, ductility of the connection is also an important safety characteristic of the composite structure. Strength, stiffness and ductility of interface connection are usually evaluated through shear tests. Few researchers have worked on shear tests for adhesively bonded joints in the case of timber-concrete composite structures. In general, researchers use national standards such as EN 26891 [32] and ASTM D 5652 [33], both for timber joints, or EUROCODE 4 [34] for steel-concrete composite structures. Steel-concrete composite structures already have a standard shear test for joints (push-out) [35]. As far as timber-concrete composite structures with mechanical connectors are concerned, there exists in the literature a shear tests for joints (push-out) [36]. One of the aims of this paper reports on the development of a shear test for timber-concrete composite structures using a static test (push-out) without mechanical connectors.

The presented study describes in the first part the development of this test: choice of the assembly materials, choice of sample dimensions, realization of samples, and realization of the mechanical tests. The second part of the study focuses on the results of this test: failure mode, interpretation of the results from a theoretical point of view (theory of Volkersen) and using Digital Image Correlation (DIC). The theory of Volkersen allows to determine the stress concentrations along the joint which may be correlated to the strain mapping obtained by the DIC method. Digital images are recorded during mechanical test and processed using an image correlation algorithm to obtain the displacement field from the reference image and the deformed images [37,38]. The DIC procedure consists in finding the mechanical transformation between the reference and deformed images, by optimizing a correlation coefficient which measures the similarity of the grey level distribution in the two considered images. From the obtained displacement field, local strains are then determined.

## 2. Materials and testing

### 2.1. Materials

In order to realize tests to choose the most efficient resin and to study the influence of hygroscopic thermal cycles on the resistance of the assembly, four adhesive materials of various elastic characteristics (stiffness, strength, etc.) were used to make push-out investigations. The four adhesive materials, chosen in order to cover a large range of glue properties, are given in Table 1. The four materials are two-component and cold-curing.

The pot life is the time for the application of the material without risk of rheology losses. The mechanical behaviour of the resins was determined by tensile tests realized at a rate of 1 mm/min (Fig. 4). Strain was measured either by strain gauge in the case of the two stiffer adhesives or by laser optical strain sensor in the case of the two softer adhesives. To determine the kind of mechanical behaviour, load-unload cycles were performed. Glass transition temperature was determined using DSC analysis (differential scanning calorimetry) according to EN 12 614. It must be highlighted that the glass transition temperature is close to the maximum service temperature of structural adhesives.

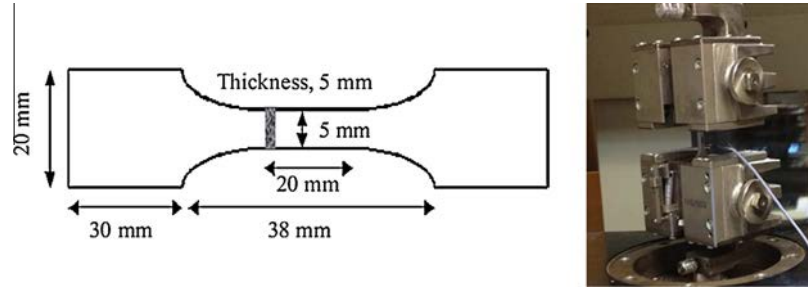
The adhesive material samples were realized at the same time than the push-out samples (three specimen for each resin), and stored under the same conditions. Tests were performed for all samples (resin samples and push-out samples) four months after the beginning of the polymerization of the resins. Two series of tests have been considered (without and with ageing). The first one was related to tests without RH (Relative Humidity) and  $T$  (temperature) variations (room conditions, the moisture content MC in the wood is about 13%). Another series of tests was made to test assemblies similar to those previously studied after one year of ageing in various conditions (constant temperature:  $T = 20^\circ\text{C}$  but variable Relative Humidity:  $50\% < \text{RH} < 95\%$  or  $\text{RH} > 95\%$ , the moisture content in wood varies between 13% and 22%).

The four studied resins, provided by SIKA company are:

- Resin Sikadur<sup>®</sup> 30: bi-component epoxy resin used in the field of civil engineering for bonding of pultruded carbon plates on concrete civil engineering structures (Sample named E1).
- Resin<sup>®</sup> Sikadur 330: two-component, solvent-free, moisture-tolerant, high strength, high modulus structural epoxy adhesive used in Structural Strengthening Systems (Sample named E2).
- Resin<sup>®</sup> SikaForce 7550L15: two-component polyurethane sealant used in the industrial field (Sample named PU).

**Table 1**  
Main properties of the four used adhesives.

Adhesive	Epoxy 1	Epoxy 2	Modified Acrylic	Polyurethane
Pot life at 20 °C	1h10	30 min	5 min	15 min
Short term mechanical behavior	Elastic and brittle	Elastic and brittle	Elasto-plastic (important viscosity)	Hyperelastic
Tensile Young's modulus (MPa)	12,000	5200	200	10
Ultimate tensile stress (MPa)	32	32	3 (Yielding) <.....<10	...<4.5
Glass transition temperature (°C)	51	63	70	...<-50



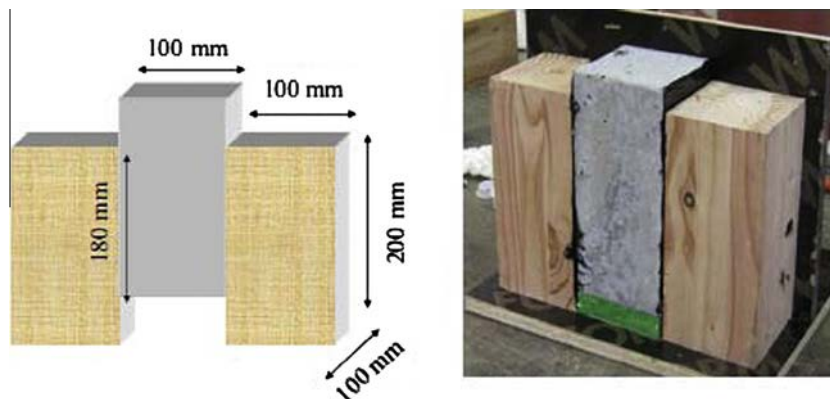
**Fig. 4.** Geometry and dimensions of samples and Specimen under tensile test in the Zwick machine.

– Resin SikaFast® 5215: two-component modified acrylic used for structural bonding in the industrial field (Sample named MA).

As far as concrete and wood are concerned, no characterization tests were carried out. Mechanical data necessary for these materials were taken from the literature.

## 2.2. Dimensions of the samples

The protocol presented below was developed following the realization of several series of push out tests (see Fig. 5 for the dimensions of the samples). It allows working on small samples easy to manipulate with [39] similarly to the work carried out in [40]. In the case of the push-out test, two failure modes can occur: (i) failure at the interface by shearing or tearing (which may occur in one of the adherents, one of the interfaces or in the adhesive), (ii) or failure in one of the adherents by compression. The size of specimen should allow obtaining a shear failure mode of the assembly, and it is therefore necessary to work with samples having sufficient compressive ultimate capacities (and then sufficient cross-section). It is also important to limit cleavage forces at the end of the bonded joint with a constraint at the edges of the sample for example to prevent from peeling failure of the assembly. The two adherent materials are laminated Douglas wood GLULAM GL24 with a characteristic bending strength of 24 MPa, and UHPFRC (“Ultra High Performance Fibre Reinforced Concrete” interim recommendations, AFGC, France, French/English) with an average compressive strength of 150 MPa. One notes therefore that among the two adherents, the wood material is less strong in compression and it was consequently chosen that within the push out samples, wood would have the largest cross-section. The elastic tensile modulus of the wood is about 10 GPa. The elastic modulus of UHPFRC is approximately 60 GPa.



**Fig. 5.** Dimensions of the push-out samples.

It is possible from these data and the stiffness of the adhesive to determine the value of the characteristic elastic anchorage length of the realized bonded joint  $L_c$  according to the theory of Volkersen [41] and the development given in [42,43]. The bonded joint length  $L_c$  is then given by:

$$L_c = \frac{1}{\lambda} \times \left( \frac{1}{1-\xi} \times \left( \xi M + \sqrt{1 + \xi^2 (M^2 - 1)} \right) \right) \quad (1)$$

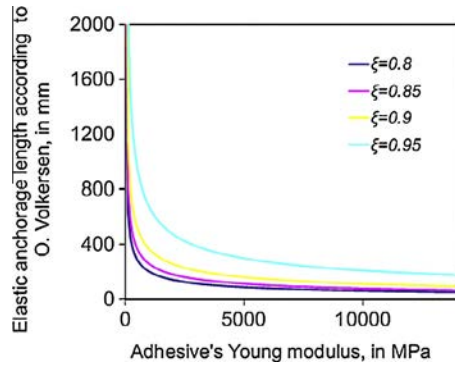
with  $\lambda$  the exponential term of elastic shear stress distribution  $M$  the joint balance factor defined as:

$$\lambda = \sqrt{\frac{G_c}{e_c} \left( \frac{1}{E_1 e_1} + \frac{1}{E_2 e_2} \right)} \quad (2)$$

$$M = \text{Min} \left( \frac{E_2 e_2}{E_1 e_1}, \frac{E_1 e_1}{E_2 e_2} \right)$$

where  $E_1, E_2$ : respectively, the axial elastic moduli of the first and second adherent;  $e_1, e_2$ : respectively, the thickness of the first and second adherent;  $G_c$ : the elastic shear modulus of the adhesive;  $e_c$ : the thickness of the adhesive layer;  $\xi$ : An efficiency factor representing the quantity of stress transmitted on the  $L_c$  length.

Considering 100 mm-thick elements (to obtain three strips of wood in GLULAM element), and an adhesive thickness of 1 mm, the evolution of the anchorage length was plotted against the elastic stiffness of the resin and the efficiency factor  $\xi$  (Fig. 6). Assuming that 90% of the ultimate capacity ( $\xi = 0.9$ ) should be transferred during the realized push-out test, for common structural adhesives (elastic modulus of about 5000 MPa), it is necessary to have a bonded length of 180 mm (Fig. 5). It was thus decided to adopt this value for the bonded length of the studied samples. It is noteworthy that this value varies with the modulus of the used adhesive. In the case of more flexible resins, the bonding length should be greater. However, for practical reasons (size of the test sample and prevention from buckling), the same bonding length is considered for all tests.



**Fig. 6.** Elastic anchorage length according to Volkersen [41] as a function of the stiffness of the adhesive and the efficiency factor  $\xi$ .

### 2.3. Samples realization

In general, there are three arrangements of test specimens used for shear tests in timber-concrete composite structures: push-out type with concrete in the centre and timber on both sides [44–48], push-out type with timber in the centre and concrete on both sides [49–52] and pure shear type [53,54].

Carvalho and Carrasco [36] compared results obtained from shear tests conducted with different specimen arrangements using a mechanical connector (push-out type with concrete in the centre and timber on both sides and push-out type with timber in the centre and concrete on both sides) and assessed the influence of this arrangement on test results. He concluded that slip modulus of type-A specimens (Wood–Concrete–Wood) was greater than type-B (Concrete–Wood–Concrete) for all connector diameters. Since stiffness of a connection system is estimated using slip modulus, adopting the results of type-A specimens could lead to overestimation of composite structure stiffness and a decrease in safety of the design. Moreover, type-B specimens better represent the conditions of the composite beam and are closer to standard tests for steel-concrete composite structures. Among the different presented test samples geometries, wood-concrete-wood had lower strength and higher slip modulus. As in our case, the concrete has good compressive strength; the weak element in compression is wood. This is the reason why we chose in this study to adopt push-out samples with concrete in the centre and timber on both sides.

The push-out samples are made of two elements of laminated timber with a section of 100 mm × 100 mm, bonded to an UHPFRC element having a cross section of 100 mm × 100 mm. The bonded lap length is 180 mm and 20 mm were left on both sides of the sample (Fig. 5). In reason of the importance of the symmetry of the specimen on the result, the samples realization should be done with great care. After 28 days of curing of UHPFRC elements (endogenous treatment), concrete surfaces are sanded with a diamond disk. The surfaces of the laminated timber elements are prepared using sandpaper (the wood fibres being aligned with the axis of loading). The resin is then applied after dusting and degreasing surfaces as recommended by the technical data sheet (double bonding in most cases, respect of pot life). A specific wooden frame was realized to ensure correct geometry of the whole assembly. A clamp is then put in place to maintain the item and to transport it more easily. All is left in place during the polymerization in laboratory conditions (which is conformed to the polymerization conditions recommended in the data sheet). Then, samples bases are polished in order to get a horizontal and symmetrical support. For each kind of adhesives, three samples have been tested.



**Fig. 7.** (a) Sample position under the compressive tool with wedges to block horizontal displacement. (b) Push-out instrumented sample and (c) Optical set-up for DIC measurements during mechanical tests.

### 2.4. Mechanical tests and ageing procedure

Tests were realized using a compressive test machine with a capacity of 1000 kN. An initial load of the sample is done up to 20 kN. Then, a loading ramp is applied until 30kN (at a rate of 100 N/s). After maintaining this load for 60 s, a second loading ramp is applied until failure at a rate of 500 N/s. The horizontal displacement of the specimen at the bottom is blocked in order to limit peel stresses (Fig. 7a).

Samples are instrumented in order to (i) follow some local displacements and (ii) measure the local stiffness of the assembly and check the distribution of shear stresses which is not constant along the bonded lap length. The instrumentation is performed using displacement sensors that measure local slips as defined in [24]. To realize the measure of these slips, rigid metal supports are used and bonded on the surface of the sample (Fig. 7b). It must be noted that it is a measure of pseudo-local stiffness. Four slips are recorded during the test and the results can be compared to numerical calculations results using finite element for example. The positions of the rigid metal supports are precisely measured for each specimen before each test. The used sensors are LVDT type sensors having a range of ±1 mm. Measurements are recorded at a frequency of 10 Hz.

Among the methods of optical measurement, Digital Image Correlation (DIC) can measure the deformation fields on the surface of a sample. This measurement technique has already been used for different assemblies or materials (e.g.: for glued wood joints [55,23], wood fracture mechanisms [56–58] or for reinforced concrete [59–61]). The measuring device is presented in Fig. 7c. Samples have been marked with black speckle painting. This surface is observed with a high resolution camera (2048 × 2048 pixels), and a rather standard optical setup is used to record images of the whole sample (field: 320 × 320 mm<sup>2</sup>, pixel size: 150 μm). Important additional lighting was necessary to ensure good quality of observed images. The analysis of displacement and strain fields by the in-house CMV software [62] provided information about strain fields on the surface of the sample, in particular at the wood/concrete interface. The used CMV software gives local strain values at each centre of a cross of the considered grid where the strain field is calculated. The local strain values are characterized by a specific color and averaged on a domain surrounding the considered point.

Few investigations have been realized concerning ageing of such assembly [63]. It was thus decided to store additional samples under ageing conditions closed to the one defined in [64] (relative humidity RH superior to 60% and constant temperature  $T = 20$  °C). For each kind of adhesives, two samples have been tested.

## 3. Results and discussion

### 3.1. Introduction

The push-out test allows focusing on three results:

- The failure mode that can occur in one of the adherents, in the resin or at one of the interfaces. One can also have a mixed failure mode. Note that in the case of bonded assembly, an interfacial failure is called «adhesive» and highlights the inadequacy of adhesion forces. This may be due to an insufficient or inadequate surface preparation. In the particular case of push-out tests with glued laminated timber adherents, the orientation of the annual rings has an influence on the observed failure mode (Fig. 8a). To increase the capacity of the realized assembly, annual rings





**Fig. 8.** Failure mode within wood ring (left) (a) and Failure mode disturbance due to a knot (right) (b).

**Table 2**

Main results of push-out tests for the four studied adhesives without ageing.

Adhesive	Epoxy 1 Sikadur 30	Epoxy 2 Sikadur 330	Modified Acrylic	Polyurethane
Failure mode	30% concrete, 70% timber	25% concrete, 75% timber	50% timber, 50% interface adhesive/timber	50% interface concrete/adhesive, 50% interface timber/adhesive
Average ultimate capacity (kN)	242	237	177	41.1
Average ultimate shear stress (MPa)	6.7	6.6	4.9	1.1
Dispersion of the ultimate capacity (%)	43	20	13.8	42

**Table 3**

Main results of push-out tests for the four studied adhesives with ageing.

Sample	Ultimate capacity (kN)	Failure mode	Average ultimate capacity (kN)	Dispersion of the ultimate capacity (%)	Average shear stress (MPa)
Epoxy 1: Sikadur 30	E1-1 181.9	–25% Concrete, 75% timber	167.8	24.8	4.7
	E1-2 114 (asymmetric failure)	50% Concrete, 50% timber			
Epoxy 2: Sikadur 330	E2-1 183.4	95% Concrete, 5% timber	122.4	7.7	3.4
	E2-2 191.7	0% Concrete, 100% timber			
Modified Acrylic	MA-1 115.7 (asymmetric failure)	10% timber, 90% interface adhesive/timber	14.8	–	0.41
	MA-2 129	50% Timber, 50% interface adhesive/timber			
Polyu-rethane	PU-1 0	100% Interface timber/adhesive (failure during the initial load)			

should be positioned as possible perpendicular to the bonded surface. Similarly, presence of knots can also affect the observed failure mode (Fig. 8b).

- The ultimate capacity of the assembly that is essential for the design of a composite structure. The ultimate capacity of the assembly may be mostly related to the ultimate capacity of the “weakest” element in which the failure occurred. All the materials, however, influence stress distributions, and it is therefore necessary to take them into account during the results analysis.
- The stiffness (local or global stiffness of assembly) that is linked to the used adhesive. Measurement of local stiffnesses can allow studying stress profiles along the glued joint and this measurement also at the same height on each of the two bonded laps using displacement sensors or DIC can help to check the symmetry of the test too. It is then possible using simple analytical methods [43] to determine the global stiffness of the specimen. These methods suppose that all the materials behave elastically and neglects shear effects within the adherents and bending moment effect due to load eccentricity.

### 3.2. Failure mode and ultimate capacity

The results of the push-out tests for the four studied adhesives are given in Table 2 for sample without ageing and in Table 3 for samples with ageing. Concerning the failure mode, four different cases were observed:

- Cohesive failure in the concrete very close to the interface.
- Cohesive failure in the wood (for these investigations, the annual rings were oriented as much as possible perpendicularly to the bonded surface).
- Failure at the interface between the adhesive and the wood.
- Failure at the interface between the concrete and the adhesive.

For each sample, two failure modes may be observed. A percentage is given for each observation based on the photos realized after testing. Though the method may not be precise, it gives good information on the weak link of the assembly.

It is difficult in the last two cases to differentiate a cohesive failure mode that would be in the adhesive material from an adhesive failure mode that would indicate insufficient adhesion forces and consequently inadequate surface preparation or unadapted adhesive. In the case of the two stiffest resins (epoxy resins) which are also the strongest ones, weak elements are clearly the two adherents. In the case of the modified acrylic adhesive, it seems that the weak element of the assembly is the wood material or the interface between the adhesive and the wood. In the case of polyurethane, the weak element is clearly the adhesive (the material itself, or the adhesion forces). After one year of ageing, we find that the fracture surface is not affected by ageing (Fig. 9).

Concerning the results in terms of the ultimate capacity, several conclusions can be drawn. It is important to note that the calculated dispersion consisting in the ratio of the standard deviation with the average ultimate capacity was only determined using

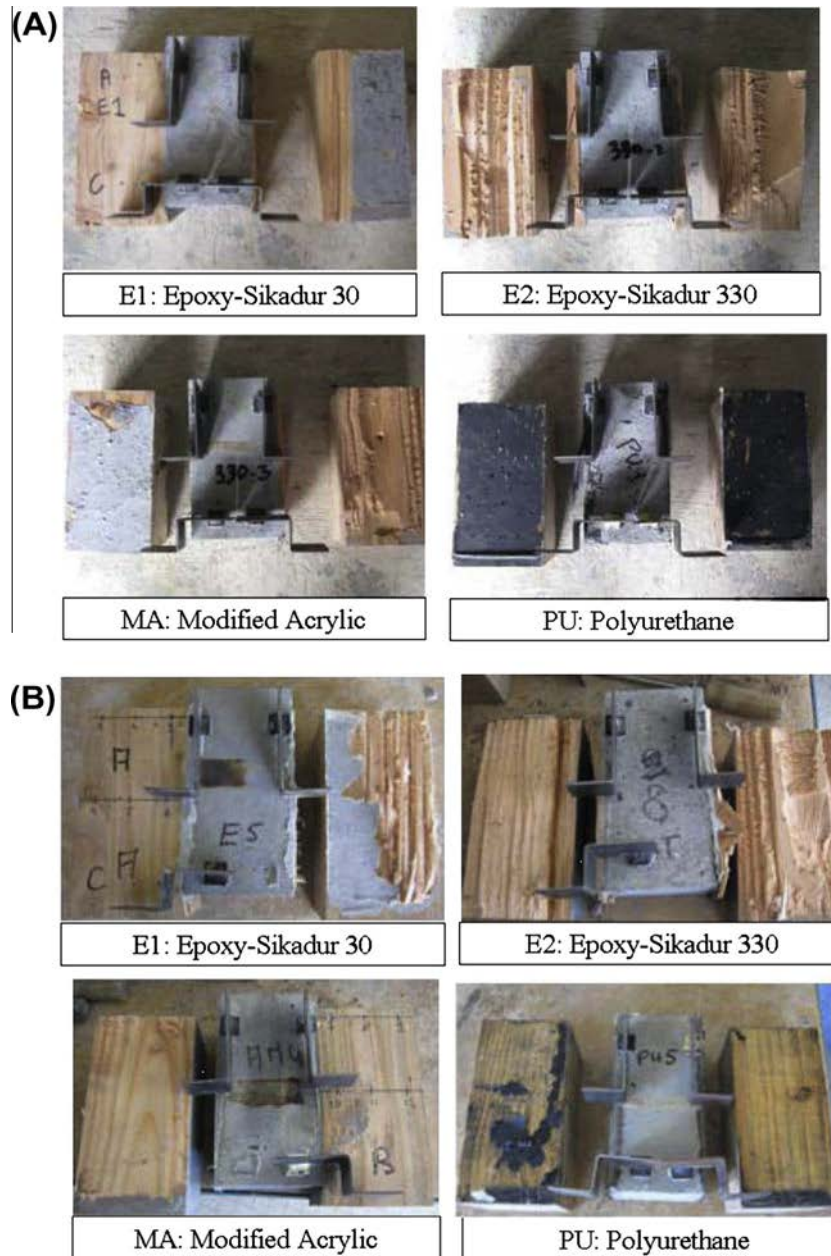


Fig. 9. Photos of fracture surfaces of samples using different adhesives: (A) before ageing and (B) after ageing.

two values. This is thus clearly insufficient from a statistical point of view but it can help in the qualitative examination of the obtained results:

- The most flexible adhesive material (polyurethane) does not provide sufficient capacity for the bonded assembly as no remaining capacity has been found after one year ageing. It is therefore not possible to use it for the realization of composite beams. Actually, at room temperature, this adhesive is under its rubbery state (its glass transition temperature being below 20 °C). This is not a structural adhesive at normal service temperatures.
- Fig. 10 justifies the mismatch between data of the adhesive and data of the assembly (due to Volkersen's theory [41], and failure modes).
- There is no linear correlation of the ultimate capacity of the bonded assembly with the stiffness of the used adhesive; the dispersion of the test in terms of maximum capacity seems to increase with the stiffness of the used adhesive.

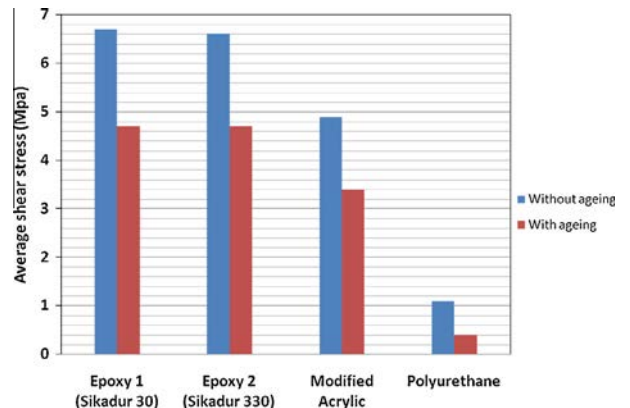


Fig. 10. Average shear stress for the four studied adhesives without and with ageing.



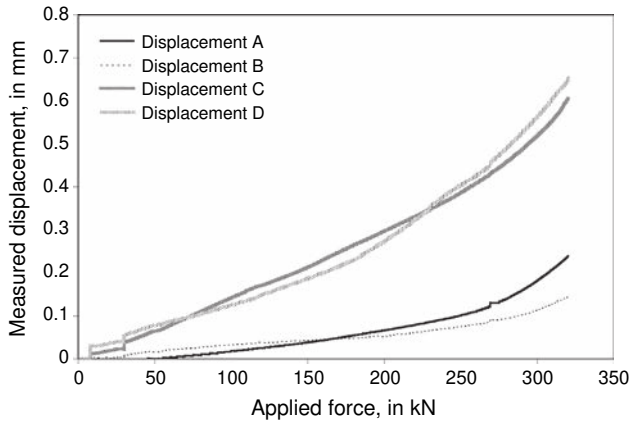


Fig. 11. Displacement at the bond joint of the assembly for the sample E2 (Sikadur 330).

- For the four adhesives, it should be noted, however, a drop of adhesion properties of about 30% due to ageing compared to the case without ageing.
- In the case of cohesive failure, it is expected to achieve the maximum possible capacity (we cannot optimize capacity when we work on surface preparation, for example).

While in the case of a failure in the interface, the capacity tends to decrease.

### 3.3. Displacement measurements and deformation maps

The displacement data (A, B, C and D) are presented in Fig. 11. These measurements allow to check the symmetry of the realized testing and the balanced factor (ratio between slip at the points C and A and at the points D and B). The experimentally measured balanced factor is found to be close to the theoretical factor given by Volkersen [41]. It can be noticed that the possible asymmetric is confirmed using DIC measurement. Despite this possible asymmetric, behaviour of the bonded joint may be characterized to choose

the most efficient resin as shown in particular for three cases (samples E2, PU and MA):

- Resin epoxy, Sikadur 330 (sample E2-1): in the case of the epoxy resin for the tested sample (Fig. 11b and c), more than half of the left block of wood is solicited during the test. It undergoes compression, with negative deformations ( $\epsilon_{yy} = -0.3\%$ ) and shear ( $\epsilon_{xy} = 0.3\%$ ). This phenomenon is explained by a high stiffness of the adhesive and good properties of adhesion to both wood and concrete materials. Strains in the right block are practically nil because the test is asymmetric and rupture, cohesive here, took place as a side in the woods. There was no significant shear concentrated at the both interfaces. Furthermore, contraction on the top and extension at the bottom are observed for the strain  $\epsilon_{xx}$  because of peel stresses. In this case the horizontal displacement of the specimen at the bottom is not completely blocked (see Fig. 7a).
- Resin modified acrylic, Sikafast (Sample MA-1): In the case of modified acrylic, axial strain can clearly be observed in the wood, but in a less important order of magnitude than in the case of epoxy resin ( $\epsilon_{yy}$  is about  $-0.1\%$ ) (Fig. 12b) due to the good rigidity of the adhesive. In contrast, the adhesion of the glue on the wood and concrete materials is insufficient and we observe shear strains concentrated at the interfaces (Fig. 12c), more important at the left interface than the right. This test is not symmetric, and the failure occurred on the left, at the interface wood / glue mainly. As for the sample E2, peel stresses are observed.
- Resin polyurethane, Sikaforce (Sample PU-1): For the case of the polyurethane adhesive, no strain can be observed on the timber adherent; only shear strains are visible at the two interfaces (Fig. 13b and c).

### 3.4. Discussion on the choice of the resin and the effect of ageing

To detail the study of these phenomena and explain the mentioned observations, it is interesting to examine shear stress profiles along the bonded assembly. These can be assessed in a first approach using the formula given by Volkersen [41] (Fig. 14).

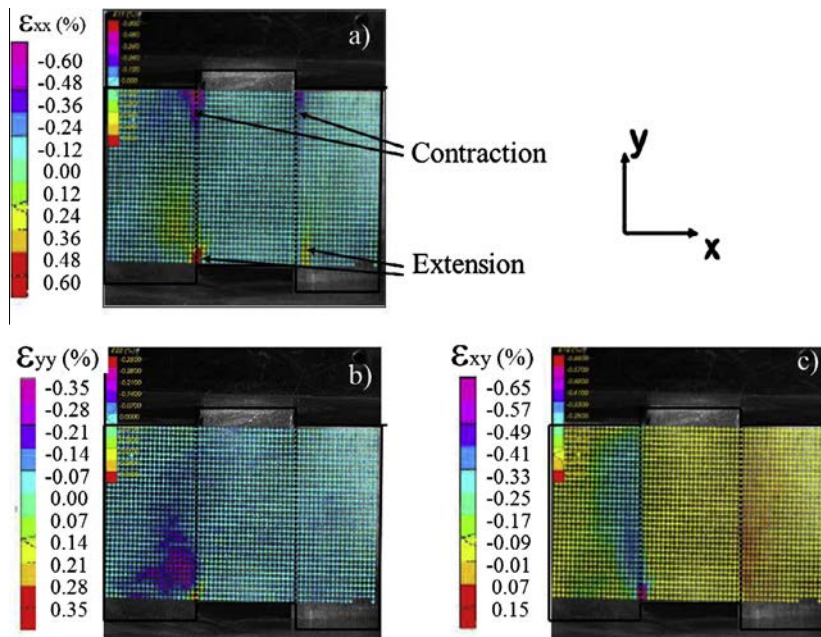


Fig. 12. Local strains for the sample «E2» just before the failure using DIC measurements (a)  $\epsilon_{xx}$ , (b)  $\epsilon_{yy}$  and (c)  $\epsilon_{xy}$ .

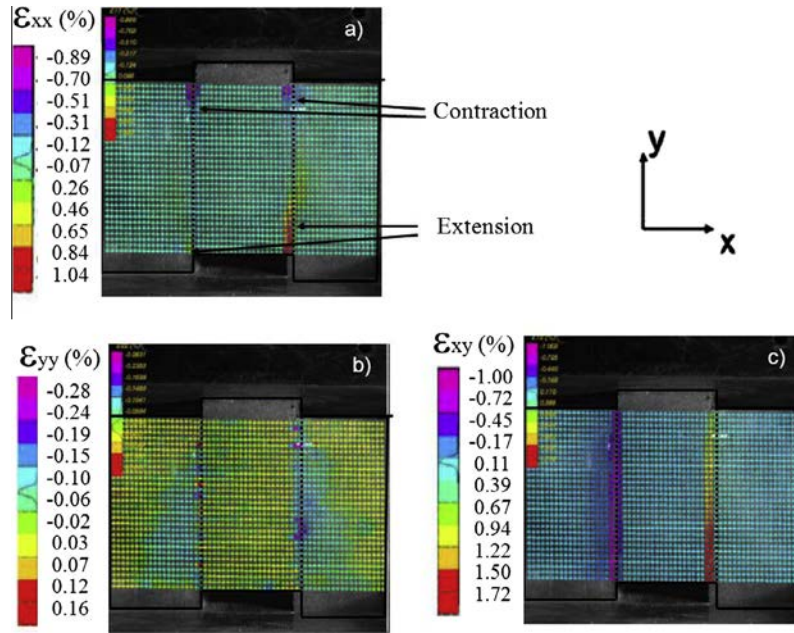


Fig. 13. Local strains for the sample «MA4» just before the failure using DIC measurements (a)  $\epsilon_{xx}$ , (b)  $\epsilon_{yy}$  and (c)  $\epsilon_{xy}$ .

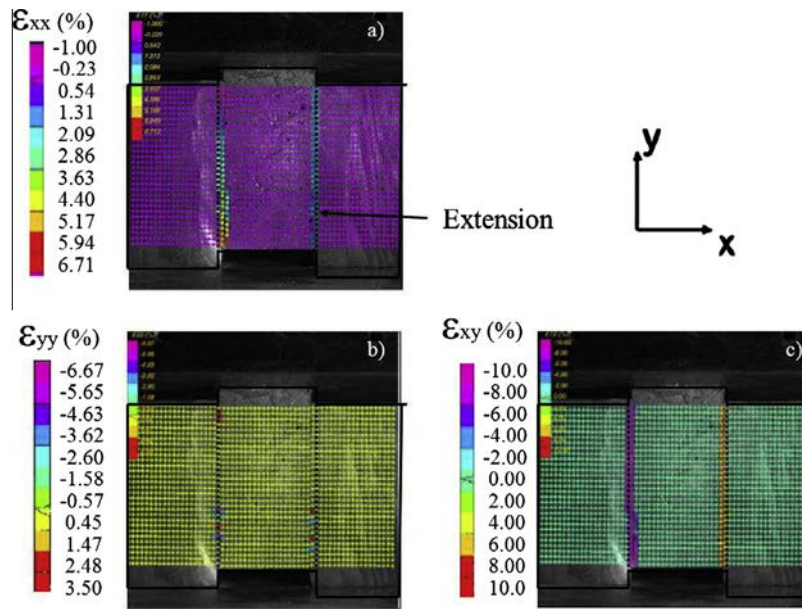


Fig. 14. Local strains for the sample «PU4» just before the failure using DIC measurements (a)  $\epsilon_{xx}$ , (b)  $\epsilon_{yy}$  and (c)  $\epsilon_{xy}$ .

The adhesive's stiffness tends to increase stress concentrations. The increase in these stress concentrations tends to increase the dispersion of the test since the results become more sensitive to material heterogeneities and singularities (see Fig. 15).

In addition, it helps in understanding that the notion of average shear stress (capacity divided by bonded surface) is not consistent with the observed physical phenomena in the case of stiff resins. In the case of the two softer adhesives on the contrary, the calculated average shear stress may be meaningful and may help in predicting the ultimate bonded joint capacity when the adhesive is the weak link of the assembly.

The main results of this study are:

- The epoxy resin presents the most interesting adhesion properties after ageing in terms of ultimate capacity with an average of 4.7 and cohesive fractures (Fig. 9A and B). Given the cohesive

failure mode, this adhesion drop may be partly explained by the decrease of the mechanical properties of wood which is a function of its moisture content.

- Acrylic resin always gives good results in terms of shear stress of 3.4 MPa, and the fracture surfaces are similar to the case before ageing (Fig. 9). As for epoxy resin, we note a drop resistance of about 30% which may be mainly explained by a decrease in adhesion properties of the adhesive given the failure modes essentially adhesives.
- The polyurethane resin has insufficient adhesion properties with a failure during the initial load.

#### 4. Conclusion and Prospects

In this study, a test protocol using the push-out geometry was developed in order to study and characterize the assembly by

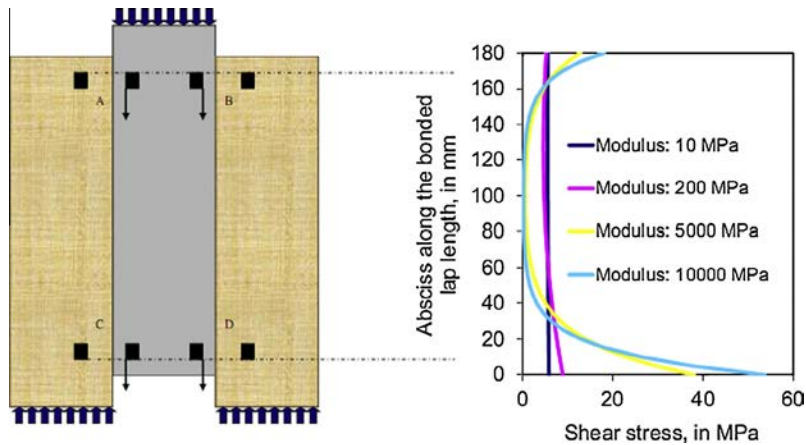


Fig. 15. Push-out sample and shear stress profiles along the bonded joint according to the elastic theory of Volkerksen [37] for four adhesives having different elastic moduli.

adhesive bonding between wood and concrete with and without ageing. It allowed to get interested in the sustainability of the assembly subjected to variable relative humidity for four different types of resins: a soft resin (polyurethane), an elastoplastic resin (modified acrylic) and two elastic and stiff resins (epoxy).

In the first part, a focus was made on the problems linked to on site implementation (type of glue, pot life, surface preparation, etc.) and the ultimate capacity of the assembly and some local stiffnesses were commented. The second part of the paper presents the realized investigations using this type of test on the influence of the stiffness of the adhesive on the realized composite structures. It is shown that the designer of such structures has a wide range of choices in terms of adhesive's stiffness that does not seem to affect much the stiffness of the composite structure. Then, the presented push-out tests allow to illustrate the use of the proposed test protocol with four resins having different stiffnesses. Note that the use of a less rigid resin allows decreasing stress concentrations and thus reducing the sensitivities of the test to local heterogeneities and singularities which may be predicted the theory of Volkerksen [41].

The presented tests are the first investigations of a wider study aiming at studying the consequences of hygroscopic cycles on the resistance of the assembly. It confirms that we obtained four different cases of failure mode for samples without and with ageing: Cohesive failure in the concrete very close to the interface, cohesive failure in the wood, failure at the interface between the adhesive and the wood, failure at the interface between the concrete and the adhesive. After one year of ageing, we find that the fracture surface is not affected by ageing. The epoxy resin presents the most interesting adhesion properties after ageing in terms of ultimate capacity with an average of 4.7 and cohesive fractures.

It is therefore not possible to use the polyurethane for the realization of composite beams. This material does not provide sufficient capacity for the glued and especially after one year aging.

There is no linear correlation of the ultimate capacity of the bonded assembly with the stiffness of the used adhesive; the dispersion of the test in terms of maximum capacity seems to increase with the stiffness of the used adhesive. A reduction about 30% is obtained for adhesion properties after ageing.

Theoretical approaches are also being developed to assess the level of stress suffered by the assembly under these conditions. This should help to further inform the designer on the importance of the choice of the adhesive. A method for measuring strains by image correlation was also tested. The made attempts for recording image and applying image correlation proved to be quite satisfactory. Additional work must be done to compare the obtained strain fields with finite element modelling. This could be a promising

technique to investigate new series of tests on the durability of these assemblies in the longer term.

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