Behaviour characterization of bonded joints in timber structures – thermal influence study

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Abstract

The use of structural adhesives in the rehabilitation of timber structures is a relatively new method, which has been regularly applied for the last 25 years. Its economical and social impact is growing every day due to the process quickness and simpleness, allowing the maintenance of in-service structures with very few alterations to their original form. This paper discusses the tests carried out in order to understand the performance of the adhesives used in the on-site rehabilitation of timber elements. The experimental work was developed in three stages. Firstly, tensile tests were performed on structural adhesives in order to analyse their response to temperature, and also to establish a basis of comparison to the performance of bonded joints. The second stage consisted of the evaluation of the adhesion and mechanical properties of wood joints, involving three species of wood and four structural adhesives, through shear and tensile tests. Finally, the temperature reached at the glue line, with the bonded elements being exposed to high service temperatures, was measured through the use of thermocouples. The adhesives revealed different performances according to the temperature used, mostly depending on their chemical composition. The strength of the bonded joints suggests that the glue line exposure to high temperatures influences the performance of the joint, depending on the wood species and adhesive used. This influence is, however, lower than that found for the glue itself. Globally, the results show that the immediate effects of the temperature can be decisive on the structural stability of timber bonded elements.

Key-words: Bonded joints; Temperature; Adhesion; Rehabilitation, Mechanical Properties

Introduction

There has been an attempt in the last few years to contribute to the development of a healthier and more sustainable construction industry through the use of materials such as timber and engineered timber products. One of the main changes that occurred in the timber construction industry was the use of structural adhesives technology regarding structural engineering, namely for the repair and strengthening of timber structures in service. (Clemente, 1999). However, there has been some mistrust from the scientific community and construction industry about this rehabilitation method because of the lack of knowledge about its structural behaviour, unknown durability and inability to respect maintenance recommendations. Adhesives are able to distribute stress with some degree of efficiency, hence reinforcing the structural element. Efficiency of load distribution applied from one element to another depends on the bonded joint resistance, being its performance closely connected to the complexity of factors associated to wood, adhesive and interface region, which in the end determine the connection strength (Vick, 1999).

While repairing damaged buildings, the consolidation of their timber elements assumes a vital importance and specificity. When these elements, which have structural functions, lose their resistance, they are frequentely replaced for similar elements. This replacement action involves the setting and replacement of large areas of construction which are still important to maintain, thus preserving its integrity and identity. In some cases, the rehabilitation of these partially degradated timber elements is possible with no need to move them out of their original location, keeping the plain use of their structural purpose. The behaviour of adhesive and timber joints in the rehabilitation field was analysed in the work reported in this paper. The most important resistance properties of wood joints are tensile, shear and flexural strength. The association of these stresses with the variation of temperature can lead to a a wide range of different observations. It is common knowledge that temperature is one of the main factors which can affect the final resistance of bonded joints. The temperature reached in the interior of wood elements is also an important issue to be taken into consideration in this kind of applications, since the conductibility of different woods and adhesives may influence the glued line performance. Experimental and modelling work developed in previous studies (Custódio, 2006;2008) clearly showed that the service temperature to which the timber structures are exposed dictates the temperature reached at the glue lines placed inside the bonded elements, despite the insulation provided by the timber cover. The aim of the work reported here was to understand and possibly clarify to what point service temperature affects the wood bonded joint resistance in a similar way it was found to affect the behaviour of the adhesive itself.

Experimental work

In order to understand the performance and safety of epoxy and polyurethane adhesive joints in timber on wood structures, a series of tests were performed on both cured structural adhesives and bonded joints submitted to different temperature levels. An analysis was then made of the decrease of strength and stiffness with the increase of the test temperature. The experimental work undertaken included three different types of tests. Firstly, tensile tests on three previously selected adhesives were performed in order to analyse their behaviour at different temperatures and also to allow a basis of comparison before and after their application on wood. Then, wood bonded joints were subjected to shear and tensile tests in order to evaluate to what extent glued joints react to service temperature in a similar way of the adhesive itself and how it influences the final performance of bonded joints.

Tested Adhesives and Wood

In applications requiring thick bondlines and no pressure application for curing, both polyurethane and epoxy adhesives exhibit excellent joint strength when tested in standard climate conditions. However, their use is often still restrained by the lack of knowledge about the way high service temperature affects their performance and the performance of bonds they form, namely to wood. These adhesives may present different and variable performances to temperature due to their low glass transition temperatures. Table 1 presents the type and some characteristics of the adhesives used in all the tests performed in this research work, including four epoxy adhesives and one polyurethane.

Name	Type of adhesive	Working life	Cure Schedule	Glass Transition Temperature	Description
C	Epoxy	12 hrs - 10ºC 6 hrs - 20ºC 6 hrs - 30ºC	3 days - 10ºC 2 days - 20ºC 1 day - 30ºC	45ºC	Gap filling adhesive (0.2-12 mm). Bonds stainless steel rods, FRP and CFRP rods/plates to timber. Also used for laminating timber.
L	Epoxy	90 min - 5-10ºC 60 min - 20ºC	18 hrs - 20ºC	60ºC	Bonds fresh to existing concrete or mortar, concrete, stone, wood and most metals.
M	Epoxy	60 min - 10ºC 40 min - 23ºC 20 min - 30ºC	7 days – 20ºC	62ºC	Bonds new timber parts to existing timber structures. Fills holes both in the existing timber structural element and in the new wood element to anchor connecting reinforcing rods and/or plates.
D	Epoxy	100 min – 10ºC 30 min – 20ºC 20 min – 30ºC	10hrs – 10ºC 6 hrs – 20ºC 3hrs – 30ºC	59ºC	Gap filling adhesive (0.25-12 mm). Bonds metallic and non-metallic fixings into timber. High strength adhesive with low surface tension.
S	Polyurethane	22 min – 20ºC	-	89ºC	-

Table 1 - Type, specifications and description of the adhesives tested (product data sheets).

The selected wood species for these tests were spruce (Picea abies), maritime pine (Pinus pinaster) and oak (Quercus rubra). Spruce was selected because it is one of the most currently used timbers in construction (specially in glued laminated timber structures), and also because it invariably tends to be used as a research reference due to the fact of being commonly used in laboratory tests. Pine is the most used timber in the Portuguese construction industry, while oak presents recognised bonding difficulties due to its sourness, density and high retraction, hence being used as a comparative element to the performance of other wood species.

Adhesive Tensile Tests

Method

In these tests two epoxy adhesives (C and L) and one polyurethane (S) were used. The specimens were prepared and tested according to the European Standard EN ISO 527-2:1996, while the tests were performed in an universal test machine “Shimadzu Autograph AG-250KNIS” together with a thermal chamber. A total of 75 specimens were made, 25 for each adhesive, 5 of which were intended to be tested at each temperature. Specimens were cured and conditioned in a controlled environment (20ºC/65% RH) for approximately one month, and then tested in tension at different temperatures (20ºC, 30ºC, 40ºC, 50ºC and 60ºC). The stabilization time for each specimen when tested at 30ºC and higher temperatures was about 10 minutes. In addition to the ambient cured specimens, a post-cure procedure (78ºC during one week) was conducted to some specimens of each adhesive in order to subsequently test them at ambient temperature. The adopted test speed in the universal machine was 1 mm/min.

Results and discussion

The thermal behaviour associated to the tensile tests performed are shown in the next three figures with the respective standard deviation. Regarding the ultimate tensile strength (UTS), we can observe that this generally decreases as the temperature raises (Fig.1). Epoxy adhesives demonstrate some decrease on their UTS between the ambient temperature and 30ºC, with an average reduction of 7%. Their UTS noticeably decreases between 30ºC and 40ºC with an average decrease of 34%. Between 40ºC and 50ºC there is a significant break of the epoxy strength values with an average decrease of about 87%. As for the polyurethane adhesive, it presented an inferior performance at lower temperatures compared to the epoxy, with virtually no changes in its UTS values between 20ºC and 30ºC. The main difference between the polyurethane and epoxy adhesives concerns their behaviour between 40ºC and 50ºC, as the polyurethane merely shows a decrease of 13%. Only adhesive S presented reasonable strength at 60ºC, that is even higher than those reached by epoxy at 50ºC. Adhesive C showed the best overall results of UTS, for temperature below 50ºC. The post-cure procedure had a better influence on adhesives C and S, with an increase of 19% and 33% respectively, while no improvements were noticed on adhesive L.

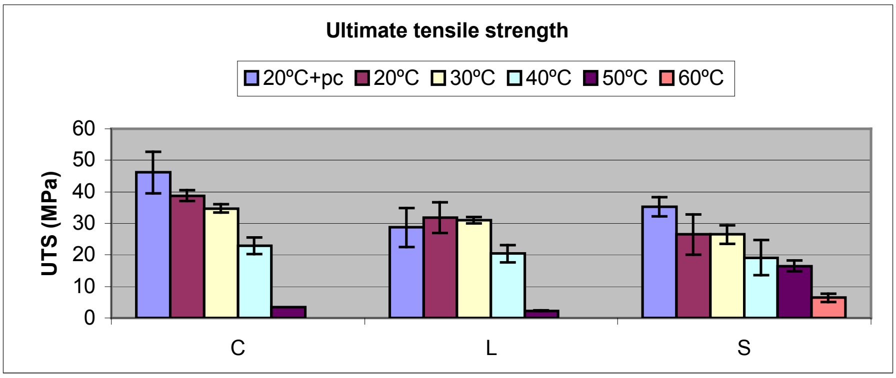

Fig. 1 – Ultimate tensile strength of tested adhesives

The adhesive strain reached at UTS tends to increase with temperature in adhesive L, while the others showed an unstable behaviour, specially the results of adhesive C (Fig.2). Strain values at ambient temperature were very similar in all adhesives, with adhesive C showing a slightly better performance. As temperature raises, adhesive C shows a tendency to slightly decrease strain, while adhesive L increases and adhesive S keeps very much the same level of strain. At higher temperatures, it is visible that the epoxic show extremely high values, while the polyurethane demonstrates a more consistent behaviour, however, with a disrupt at 60ºC. The post-cure procedure had some influence on adhesives C and S strain results with an average increase of 30%.

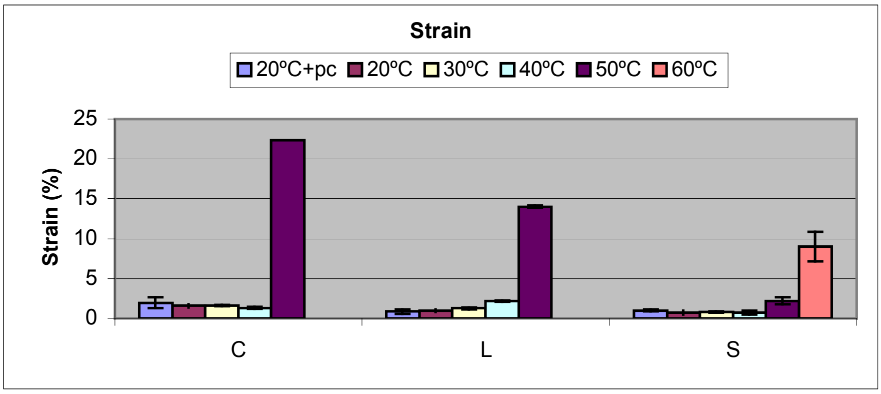

Fig. 2 – Strain of tested adhesives

Results show that the modulus of elasticity (MoE) generally decreases with temperature (increase) and that adhesive S has the most consistent behaviour through all temperatures (Fig.3). All adhesives show a similar behaviour between ambient temperature and 30ºC, while at 40ºC it is patent that adhesive L has an abrupt 40% decrease, as adhesives C and S only decrease 20% and 10%, respectively. At 50ºC, the MoE is practically zero in the epoxy, however, in the polyurethane there is just a 50% decrease from 40ºC to 50ºC. Adhesive S displays the best results in all tested temperatures. The post-cure procedure has not significantly influenced the MoE of any of the adhesives.

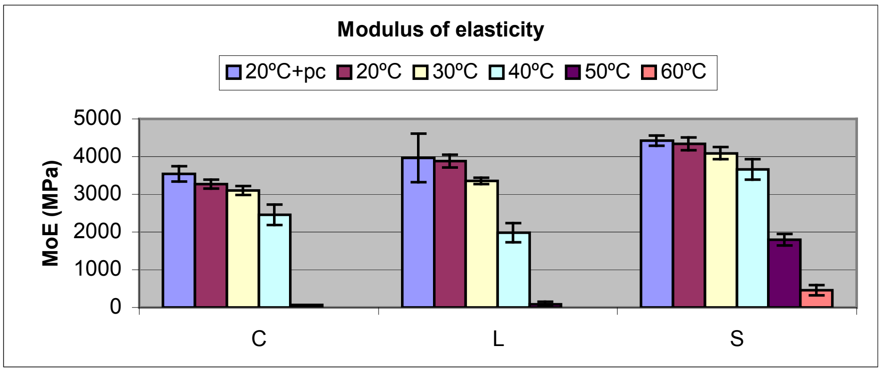

Fig. 3 – Modulus of elasticity (MoE) of tested adhesives

Bonded Joints Shear Tests

Method

Taking into account the high sensitivity shown by most adhesives to temperature, bonded joints were submitted to shear tests at a range of service temperatures in order to determine to what extent the thermal sensitivity of adhesives reflects upon their immediate behaviour. Wood was conditioned (20ºC/65% RH) and planned immediately before bonding. Pairs of matched wood planks 20mm thick, were bonded together, using spacers to guarantee a 2mm thick bondline. Specimens were cured for one month and then cut off to produce compressive shear specimens (50mm x 50mm of bonded area) which were tested according to the European Standard EN392:2002, although at different temperatures (20ºC, 30ºC and 40ºC). The test programme involved the combination of 4 adhesives (L, M, D and S) with 3 species of wood (spruce, pine and oak), tested at 3 different temperatures. Considering 9 specimens tested at each temperature for each combination, a total of 324 compressive shear specimens were made. The specimens were tested again in the universal test machine "Shimadzu Autograph AG-250KNIS" with the thermal chamber.

Specimens to be tested at 30ºC and 40ºC stayed in the test chamber for about 2 hours imediately before the application of load, for the bond line to equilibrate with the chamber temperature (except for the L and M adhesives, which stayed inside for about 10 minutes). In order to compensate for a possible post-curing effect of the 2 hours permanence in the chamber, joint specimens intended for lower temperature tests were post-cured 4 days before shear testing. This post-curing consisted of 2 hours at 40ºC for the specimens to be tested at 20ºC, and 1 hour at 40ºC for the specimens to be tested at 30ºC. After post-curing, specimens returned to their original environment conditioning (20ºC/65% RH) for moisture content equilibrium. For adhesive S, it was decided to skip the 30ºC test and have instead a 40ºC with post-curing one, to establish a comparison between the performance of specimens with and without post-curing at 40ºC. The adopted test speed in the universal machine was of 0,75 mm/min for all tests.

Results and discussion

The thermal behaviour of the compressive shear specimens is represented in the following three figures with the respective standard deviation. Globally, the ultimate shear strength (USS) reached in the specimens is not highly influenced by the increase of temperature (Fig.4). Spruce does not show a significant performance change at all temperatures, only with a 7% slight decrease at 40ºC when adhesive D is used. Pine offers the best results among the timbers tested, with a higher strength of 47%, 60% and 8% over spruce when applied to adhesives L, M and S respectively. Oak presents a worse performance comparatively to pine, but a better one compared to spruce, except with adhesive L, as its USS decreases 14% at 20ºC. The biggest decrease at 40ºC happen in pine/M, pine/D and oak/D with 20%, 13% and 12%, respectively. Generally, at 30ºC the performance changes are very small, in many cases even achieving better strength values than those at 20ºC, as it can be seen in pine/D and oak/L and D. The post-curing procedure at 40ºC doesn´t produce higher resistance values relatively to those tested at 40ºC without it, however in oak it has an 13% increase to 20ºC tested specimens. The adhesives with better overall strength values are M and D, which also present the biggest decreases at 40ºC.

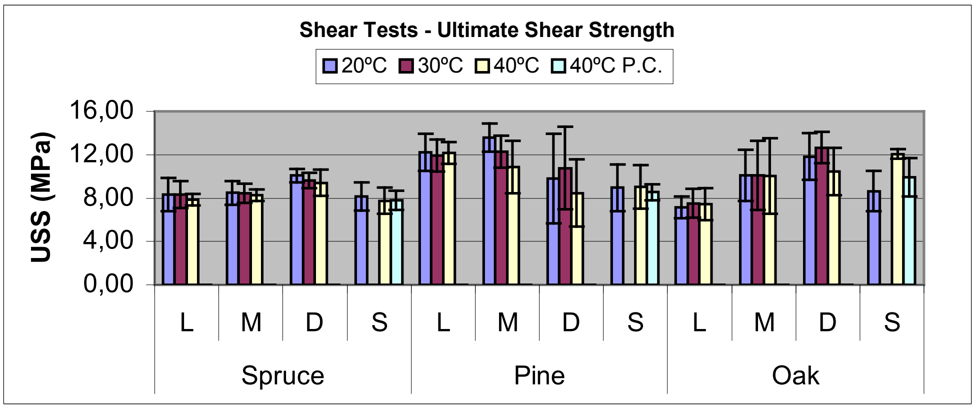

Fig. 4 – Ultimate shear strength of bonded joints shear specimens

Regarding the strain reached by shear specimens at USS, oak reveals the most consistent results through temperature (Fig.5). Its results show that, when bonded with adhesives L and D at 30ºC, and S at 40ºC it reaches superior values than at 20ºC with a 2%, 7% and 12% increase, respectively. Globally, at 30ºC there is a high deviation compared to the others results, as pine/D increases 404% from 20ºC. At 40ºC it is visible another strong deviation behaviour in spruce/D with an increase of 162% to 20ºC. At higher temperatures, adhesive D presents the highest strain values. The adhesive with higher strain at 20ºC was adhesive S, exhibiting for spruce and pine an increase of 120% and 68% in relation to spruce/D and pine/M, the equivalents of wood with higher and closer results. In all other results there aren´t significant response to temperature, probably due to the post-cure effect on adhesives. The post-curing procedure at 40ºC doesn´t influence the specimens behaviour much, only establishing a decrease of 29% in oak.

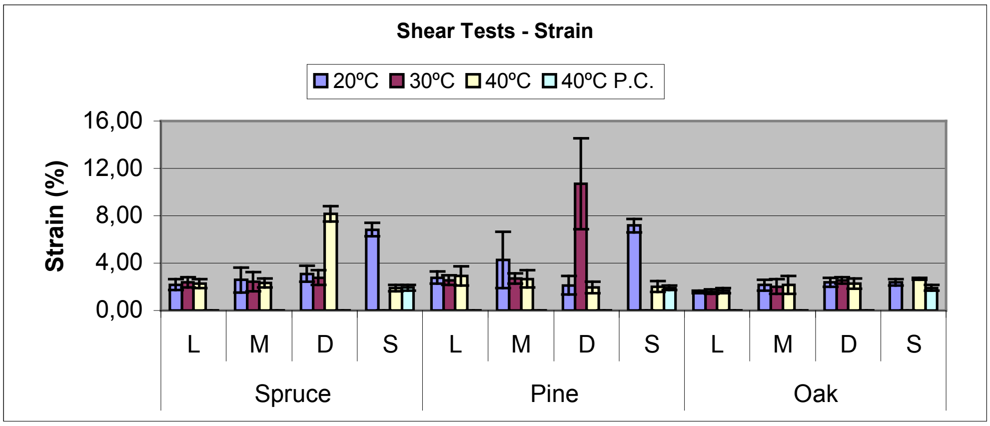

Fig. 5 – Strain reached at ultimate strength of bonded joints shear specimens

Considering the results of wood failure percentage (W.F.P.), it is easily visible that the higher values are present in spruce with an average of 88% at 20ºC, much higher than the 31% and 47% of pine and oak (Fig.6). Spruce is the least affected wood with temperature, while oak has an almost linear behaviour with adhesives L, M and D. Globally, with temperature increase a decrease of W.F.P occurs, except in the case of pine/L, pine/S and oak/S with increases at 40ºC of 33%, 58% and 64%, respectively. Decrease at 40ºC tends to be negligible in spruce, reaching higher values in pine/M and oak/L with 80% and 39% respectively. Increase of temperature up to 30ºC resulted in varied behaviour within all species, specially on pine with decreases of 16% and 47% for adhesives L and M, and an increase of 82% for adhesive D. The biggest decrease from 30ºC to 40ºC occurs on pine/M and pine/D with 63% and 43% decreases, despite the last one occured after the earlier mentioned increase at 30ºC. Within the adhesives, adhesive L always presents an increase from 30ºC to 40ºC, whilst the opposite is noticeable in all others. The post-curing procedure propitiates a significant 24% decrease of W.F.P. on oak, but still a higher value than the 20ºC test. Besides, a small increase on pine and decrease on spruce is observed.

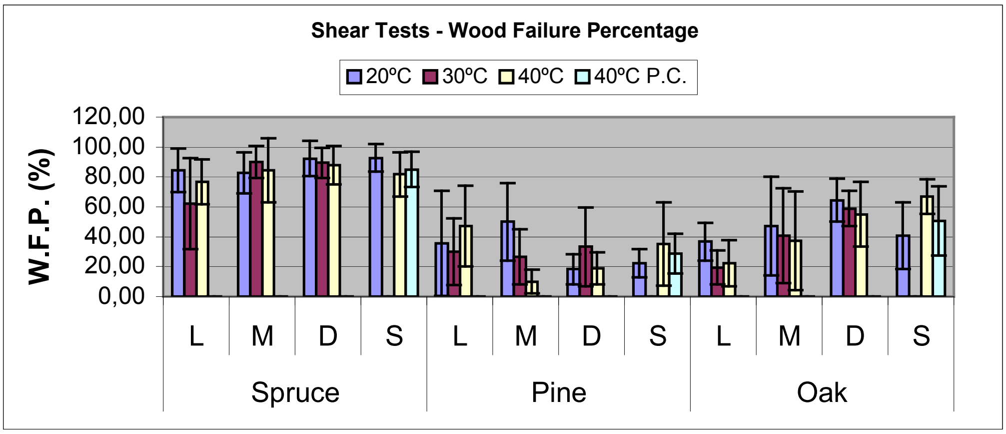

Fig. 6 – Wood failure percentage (W.F.P.) of bonded joints shear specimens

Bonded Joints Tensile Tests

Method

The test programme covered the combination of 2 adhesives (M and S) with 2 species of wood (Pine and Oak), tested at 2 different temperatures (20ºC and 40ºC). Considering 10 specimens tested at each temperature for each combination, a total of 75 specimens were made. Only 15 specimens of the oak/S combination were tested due to the reduced quantity of adhesive available, of which 10 specimens were tested at 20ºC and 5 specimens at 40ºC. Specimens were prepared having in mind to the European Standard EN 326-1, considering a bonded area of 25x25mm, with a 2mm thick glue line. Test method was based on the Portuguese Standard NP EN 319:2002, in the universal test machine "Shimadzu Autograph AG-250KNIS" with the respective thermal chamber. The adopted test speed was of 0,5 mm/min. Specimens tested at 40ºC stayed inside the chamber for about 4 hours before the application of load; therefore, to compensate for possible post-curing effects, specimens tested at 20ºC were submitted to a post-cure procedure during 4 hours at 40ºC. After post-cure, the specimens returned to their original cure conditions (20ºC/65% RH) for moisture content equilibrium before testing.

Results and discussion

On the following three figures the results of the bonded joints tensile tests are represented, particularly the ultimate tensile strength (UTS) and wood failure percentage (W.F.P.), as well as their respective standard deviation. As for the UTS, a decrease in all combinations is visible as temperature increases (Fig.7). Decrease was 20%, 30%, 32%, and 32% for pine/M, pine/S, oak/M and oak/S respectively, as compared to 20ºC. Adhesive M presented the best results in each wood species for both temperatures, while adhesive S had a similar UTS for both temperatures and woods. The combination pine/M achieved the higher UTS at both temperatures. Oak joints had the same 32% decrease with temperature for both adhesives. As for pine, it slightly improved the performances with both adhesives at both temperatures.

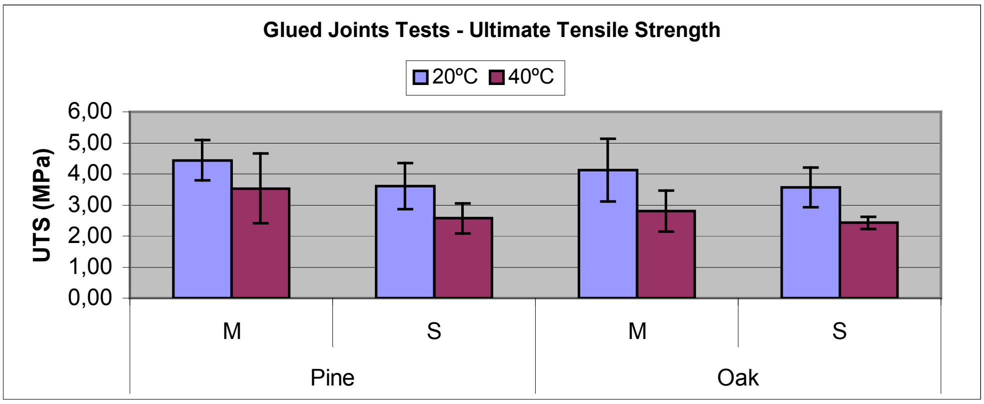

Fig. 7 – Ultimate tensile strength of bonded joints tensile specimens

Regarding the wood failure percentage (W.F.P.) there is also a tendency of decrease as temperature increases (Fig.8). The W.F.P. decrease was of 65%, 53%, 40% and 22% for pine/M, pine/S, oak/M and oak/S respectively. Adhesives show approximately the same W.F.P. reduction from pine to oak with an average decrease of 28%, with the adhesive M decreasing from 65% to 40%, while the adhesive S drops from 53% to 22%. Pine produces higher values at 20ºC, while oak performs better at 40ºC and has a smaller W.F.P. reduction with temperature. Adhesive S has a better performance than M at all temperatures, although there is a higher standard deviation to be found in pine/M. Joints with adhesive M and both wood species suffer higher influence of the temperature as compared to the adhesive S.

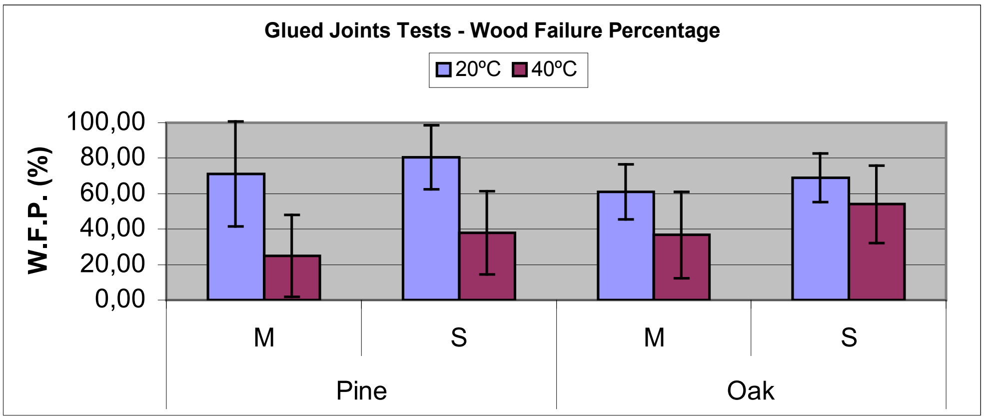

Fig. 8 – Wood failure percentage (W.F.P.) of bonded joints tensile specimens

Comparative Analysis Of The Various Tests Results

The next four figures represent the comparative analysis of ultimate strength (US) reached in all tests (adhesive tensile tests, bonded joints compressive shear and tensile tests) performed for each adhesive at 20ºC and 40ºC. For adhesive L, the decrease of US with temperature was only relevant in the adhesive tensile test with a 36% reduction, whilst on the bonded joints shear test there was not any reduction when bondind pine, and increased when bonding oak (Fig.9). This situation has been adressed before, so we can say that the temperature influence is stronger on the performance of the adhesive itself than on the performance of bonded joints subjected to shear.

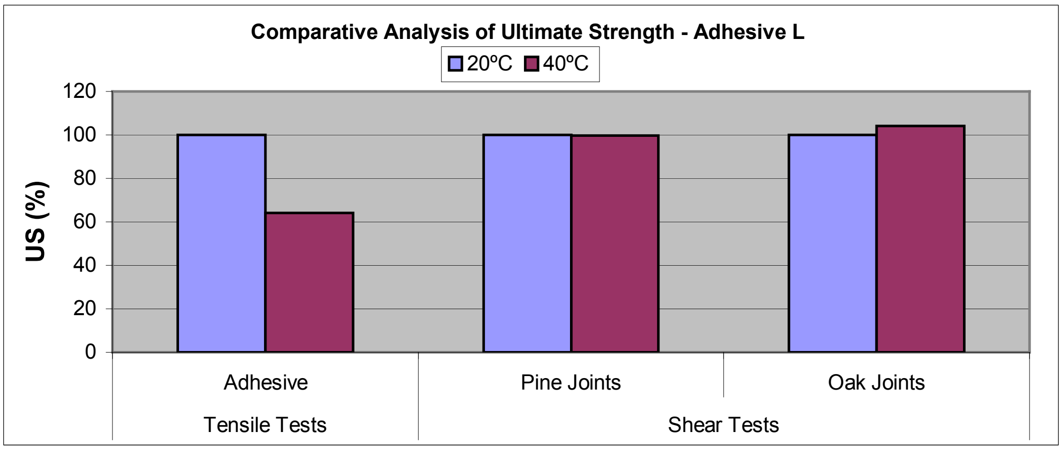

Fig. 9 – Comparative analysis of the ultimate strength (US) achieved by adhesive L in all tests performed

Unlike the analysis made in adhesive L, the adhesive M presents a consistent tendency for reduction of US for all performed tests as temperature increases (Fig.10). That reduction is clearer in the bonded joint tensile test with oak, resulting in a 32% diminution, while the same bonded joint wood has no reduction when shear tested. Adhesive M tensile test demonstrates a lower decrease with temperature than the registered in the oak bonded joint tensile test, merely accomplishing a 28% reduction. Tests performed with pine revealed the same 20% decrease for adhesive and bonded joints.

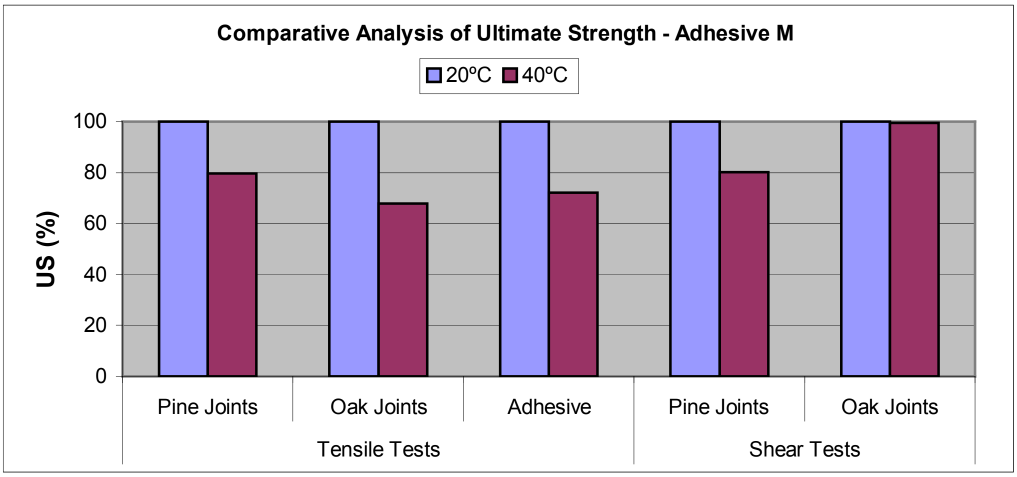

Fig. 10 – Comparative analysis of the ultimate strength (US) achieved by adhesive M in all tests performed

As seen in the adhesive M, a consistent tendency of US decrease with temperature is visible in all performed tests of the adhesive D. Its US reduction is, as registred in the adhesive L, more prominent in the adhesive tensile test with a 49% decrease (Fig.11). The decrease occured in the bonded joint shear tests was substancially lower, with a 13% and 12% reduction, for pine and oak alike what was observed for the adhesive M.

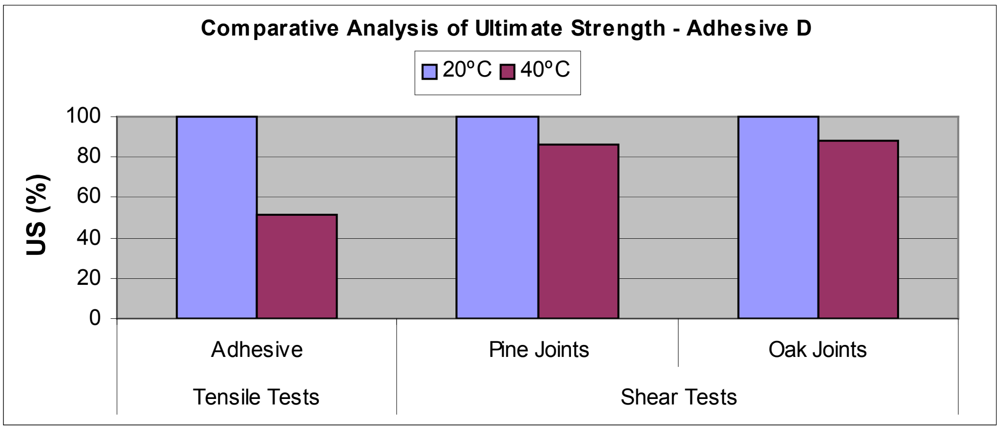

Fig. 11 – Comparative analysis of the ultimate strength (US) achieved by adhesive D in all tests performed

Adhesive S joints shear tests present a different behaviour than those verified on the other performed tests, as they display a crescent tendency of the US with temperature (Fig.12). This fact is similar to the adhesive L behaviour, while the biggest reduction of the US occurs in the oak bonded joint tensile test with a 32% decrease. The remaining tests (adhesive tensile test and pine bonded joint shear test) reveal the same 29% reduction with temperature.

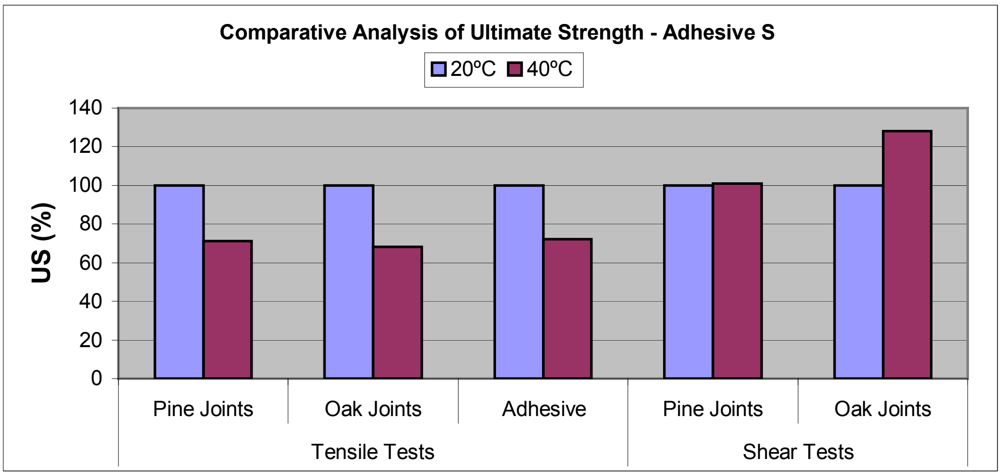

Fig. 12 – Comparative analysis of the ultimate strength (US) achieved by adhesive S in all tests performed

Conclusions

Considering that the in-service temperature is a decisive factor on the efficiency of timber structures rehabilitation with bonding techniques, this paper acknowledges that a deep understanding of the adhesives characteristics is necessary in order to obtain safe and effective bonded joints. Some conclusions about the mechanical tests performed follow:

- The adhesive tensile tests reveal that the cured adhesives are highly influenced by temperature, and that behaviour varies according to the adhesive. The polyurethane adhesive displays a more consistent performance and better results at higher temperatures, while epoxy adhesives have a superior performance at lower temperatures but higher sensitiviy to higher temperatures.

- In the bonded joints tensile tests the influence of temperature is very clear, much associated to the fact that these tests results (as the adhesive tensile tests) are more dependent of the internal adhesive cohesion. Adhesive M presented the best results for all temperatures tested, specially when associated to pine.
- In shear tests there occurs a complex interaction between the materials and the interface of the bonded elements, where the strength and stiffness of the adhesives perform a decisive role. The reduction of the ultimate shear strength of bonded joints with temperature is smaller (or null) than the one occurred in the other tests, as the wood characteristics associated to the reduced resistance effect of the adhesives used seem to decisively influence the mechanical properties of the bonded joint. Spruce is the wood species in which joints vary the least with temperature. Pine and oak joints display essencially adhesive cohesive failure, with the first being more affected with temperature although forming with adhesives L and M the most resistant joints for all temperatures. Adhesive S has a good reaction to temperature increase. All adhesives, excepting S, present a consistent decreasing tendency with temperature, with adhesive M revealing very good results when associated to pine. The wood failure percentage depends mostly on wood species and no consistent influence of adhesives was found.
- Consequently, in bonded joints shear tests there is no consistent tendency for all woods and adhesives with temperature increase, once the joints failure is highly dependent of the internal cohesion of wood, with the pre-heating programme having little influence on the final results.
- Although the sensitivity of the cured adhesives to temperature is reflected in the sensitivity of bonded joints loaded in tension, the effect of temperature is not so high in joints loaded in shear.

References

Clemente, (1995) - Clemente, J. S. – "Consolidação de estruturas degradadas de madeira em edifícios". 1º Simpósio Nacional sobre Materiais e Tecnologias na Construção de Edifícios. IST, Lisboa, 1995.

Custódio, (2006) – Custódio, J.; Cruz, H. – "Acção da temperatura no comportamento de colas epoxídicas – Usadas em reforço/reparação de estruturas de madeira" - Ciência & Tecnologia dos Materiais, 2006

Custódio, (2008) - Custódio, J.; Rodrigues, D.; Rosa, A.; Ferreira, J.; Cruz, H.; Broughton, J. - "Thermal behaviour of epoxy and polyurethane adhesives and bonded timber joints – preliminary results". Cost E34 – Sopron, 2008.

EN ISO 527-2:1996 "Plastics – Determination of tensile properties – Part 2: Test conditions for moulding and extrusion plastics".

NP EN 392:2002 "Madeira lamelada-colada – Ensaio de corte pelos planos de colagem".

NP EN 319:2002 "Particle and fibreboard – Determination of tensile strength perpendicular to the plain of the board"

Vick, (1999) – Vick, Charles B. - "Adhesive bonding of wood materials" - Wood handbook : Wood as an engineering material. Madison, WI : USDA Forest Service, Forest Products Laboratory, 1999.