Feasibility of Creosote Treatment for Glued-Laminated Pine-Timber Railway Sleepers

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Abstract: This article studies the possibility of using market available glued-laminated timber (GLT) based on melamine-urea-formaldehyde (MUF) adhesives as an alternative to traditional solid timber sleepers. The study comprised an examination of the effect of creosote treatment on the short-term and durability after accelerated aging of the glue lines (delamination and shear strength) and the potential for full sapwood penetration by the creosote. Creosote treatment showed a negative effect on shear strength and delamination, more severe in the nonstructural than the structural GLT specimens tested. Full penetration of creosote into the sapwood was not achieved. GLT elements based on MUF adhesives can be considered an alternative to solid wood sleepers if specific grading of lamellas, proper treatment schedule, and highly controlled factory production are implemented. **DOI: 10.1061/(ASCE)MT.1943-5533.0001073.** *© 2014 American Society of Civil Engineers.*

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Introduction

Wood is a natural renewable material that has been used for centuries for different end uses and service conditions (interior or exterior). During the last few decades, the following four main factors explain the observed market shift from solid wood products to so-called engineered wood products (EWP): (1) a decrease in quality and availability of large cross section solid timber elements; (2) long-length solid timber elements can only be obtained at a premium cost and are often unavailable; (3) the higher dimensional stability shown by EWP; and (4) the lower variability of mechanical properties shown by EWP.

In Portugal, large cross section timber elements are usually required both for the rehabilitation of old timber structures and for use as railway sleepers. The main wood species resource available in Portugal for both applications is maritime pine timber (*Pinus pinaster* Ait.). In terms of structural applications, the shortage of large cross section material has already led to a significant replacement of solid timber by GLT pieces, mostly imported from Nordic countries. In contrast, solid maritime pine timber elements are still used as sleepers. During the last few decades, the decrease in the competiveness of solid timber sleepers is partially due to an increase in the cost of maintenance of large air-drying yards, which are needed in order to ensure the availability of a large stock of timber sleepers, as well as a decrease in the overall quality of the available wood material. This low quality is responsible for severe checking and warping during natural drying (Fig. 1), corresponding to a loss of 15 to 20% wood volume at the drying yard. Kiln drying, though reducing the drying time from 3 to 36 month, depending on wood species, to a couple of weeks, is not an alternative to air drying given the large investment in a dry-kiln equipment and the excessive energy costs involved (Webb 1998).

However, this lack of quality is also closely linked to both industrial demand for the available wood resources and the need of forest owners for medium-term revenue. These two factors explain why maritime pine trees, usually cut at the age of 80 in the middle of the past century, are now cut at around 30 years of age. Compared with older trees, the large cross sections obtained from younger trees exhibit a greater percentage of juvenile wood, with the pith often located at or very close to one of the lateral surfaces. Juvenile wood thus presents lower quality in terms of mechanical properties and is more prone to fissures and warping (Machado and Cruz 2005; Tsoumis 1991). These problems are responsible for some of the early damage commonly observed in timber sleepers, one of the main reasons for the latter's replacement by concrete/fiber composites (Manalo et al. 2010) or composite reinforced wood (Qiao et al. 1998).

Despite their replacement by concrete sleepers in high-speed rail tracks, timber sleepers remain competitive for use on conventional tracks (Sadeghi and Barati 2012), with the advantages of workability, damping/shock absorbing capability, as well as their easy and inexpensive installation and replacement (Manolo et al. 2010). The use of dowel and GLT sleepers has been tested in the past, with the study conducted by Carrasco et al. (2012) showing that the latter can achieve a high level of mechanical performance. However, this last study did not cover the sleeper's long-term behavior in terms of biological and glue line durability.

Despite the potential for strong short-term mechanical performance of GLT sleepers, the success of these composite elements will strongly depend upon glue line durability after accelerated aging (the ability of the material to maintain internal cohesion) and timber durability against biological agents under exterior conditions (in this case, use class 4 is defined as exterior and in contact with the groundwater and/or freshwater). Gallery et al. (1999) provide a good example of the long-term behavior of GLT sleepers

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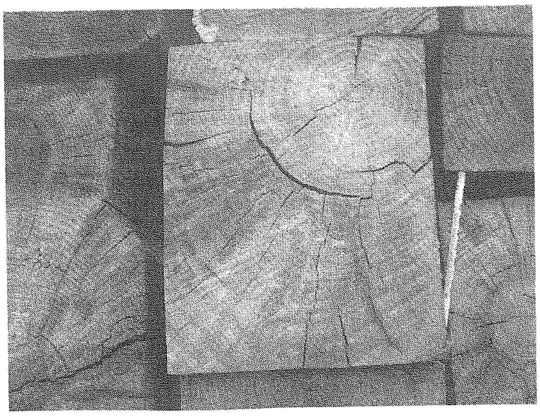


Fig. 1. Defects associated with air drying at timber yards

removed from service after 40 years. These sleepers (visually) showed only minor surface checks, as well as minimum delamination of upper laminations, which are those most exposed to the weather.

GLT material typically available in Europe is composed of lamellae of softwood species, which generally show insufficient natural durability when exposed to exterior conditions. European standard EN 13145 (CEN 2001c) specifies the retention of product conformity for use class 4 (exterior in contact with the groundwater and/or freshwater) and penetration class P8 (full impregnation of sapwood). A posterior revision of EN 351-1 (CEN 2007) modified the designation of this last class to NP 5 (full penetration of sapwood).

Despite all the preservative products currently available on the market, creosote remains one of the most efficient for the protection of wood sleepers. The need to ensure a longer service life (around 100 years) is the major reason for the use of creosote-treated timber members in outdoor applications, such as sleepers and bridges (Abrahamsen 2008). The classification of creosote as an active substance in Annex I of Directive 2011/71/EU (European Commission 2011) currently limits its use. These limitations include the interior of buildings and all locals where a frequent risk of skin contact exists. However, despite these restrictions, creosote-treated wood can still be used as sleepers and fencing, as well as in harbors and waterways.

Creosote is a distillate of coal tar that contains different organic substances, with the majority being polycyclic aromatic hydrocarbons (PAH) compounds. PAH are known or suspected to be responsible for carcinogenicity, mutagenicity, and toxicity (Ikarashi et al. 2005). Due to these compounds, environmental regulation on the use of creosote and creosote-treated wooden sleepers was enforced in the European Union.

Creosote has been used in accordance to industry guidelines, the so-called WEI specifications. These specifications were afterwards included in the European standard EN 13991 (CEN 2003) that comprises two grades (B and C). Grade C shows a low content (below 0.005% volume) of benzo(a)pyrene and of light creosote components (less emission). The characteristics of grade C mean that creosote has a minor role in the definition of the ecological profile of wooden sleepers (Werner 2008). Comparing with concrete, steel, plastic composites, and wooden sleepers, the life-cycle assessment (LCA) studies (Bolin and Smith 2013; Werner 2008) showed that creosote-treated wooden sleepers cause lower impacts in all categories except for that of eutrophication where plastic composite sleepers showed a better behavior.

The disposal of wooden sleepers is subject to restrictions in some cases since the concentration of PAH compounds are above regulation limits, which could affect human health safety (Ikarashi et al. 2005; Thierfelder and Sandström 2008). LCA studies indicate as best end-of-life destiny incineration facilities with cogeneration of electricity and thermal energy (Bolin and Smith 2013; Werner et al. 2007).

Creosote Treatment of GLT

The treatment of GLT beams with creosote can be carried out either on each individual lamella (prior to the gluing stage) or on whole GLT members (after gluing). Kilmer et al. (1998) studied the effect of creosote treatment on the bonding quality of hardwood lamellae, finding that efficient bonding can be accomplished at the environment temperature when a proper adhesive is used. The authors also indicated that elevated room temperature cure phenol-resorcinol adhesives are suitable for bonding creosote-treated hardwood to be used in structural applications. Adhesive based on an emulsion polymer isocyanate was found to be unsuitable for the same purpose.

Manbeck et al. (1995) examined the effect of posttreatment, considering different hardwood wood species and using resorcinol formaldehyde adhesive. The study found that posttreatment did not affect glue line quality for any of the selected species and adhesive.

Tascioglu et al. (2003) applied the ASTM D2559 (ASTM 1999) accelerated aging test in order to check wood to wood and wood to FRP (fiber-reinforcement polymers) pultruded sheet adhesion. Posttreatment with creosote was conducted at a temperature of 65–68°C. Although a significant effect on bond quality between wood/FRP adhesion was observed (increase of 45.7% for pretreatment and 11.9% for posttreatment), the wood-to-wood bond quality was not significantly affected in both cases [below the 5% threshold defined in ASTM D2559 (ASTM 1999)]. This study did not include any examination of the possible long-term effect of creosote treatment on glue line shear strength.

Gong et al. (2013) tested CCA-treated (chromate copper arsenate) and creosote-treated GLT sleepers produced using a mixture of low-grade hardwood species (sugar maple and yellow birch), with bending tests and visual examination employed to assess sleeper quality. The results of creosote treatment (posttreatment) revealed no delamination or warp, in contrast to that observed in GLT sleepers posttreated with CCA. No accelerated aging tests were conducted to assess long-term glue line behavior.

No results were possible to be obtained from literature regarding the effect of creosote treatment of GLT elements produced with melamine-urea-formaldehyde (MUF) adhesives.

Objective

The aim of the present paper is to evaluate the potential of currently available GLT solutions as an alternative to solid timber sleepers. Such GLT beams include those made from softwood lamellae and joined together by MUF adhesives. This adhesive in the European market is replacing the resorcinol and phenol resorcinol formaldehyde adhesives (RF and PRF, respectively) traditionally used in the production of GLT (Simon and Legrand 2010; Gomez-Bueso and Haupt 2010). The principal reason lies in the capacity of modern machinery to allow faster line speeds, which implies the use of quick-curing resins (Gomez-Bueso and Haupt 2010). The change has also some aesthetical concerns. MUF adhesives lead to light glue lines (less visible), whereas PRF adhesives lead to dark red-brown glue lines (more visible). MUF adhesives are typically considered weaker than RF and PRF adhesives, being classified as boil resistant (good initial weather resistance but fail under prolonged exposure), whereas RF and PRF adhesives are both weather-proof and boil-proof (highly weather resistant).

In the present paper, GLT elements commonly available on the Portuguese market were subjected to creosote treatment at an industrial facility. This study included an assessment of (1) any possible reduction in glue line quality due to the creosote treatment, both in terms of delamination and a decrease in glue line shear strength; and (2) possible barriers to the diffusion of creosote inside GLT elements that could jeopardize the objective to reach a full sapwood penetration.

Experimental Study

Wood Material

GLT beams were produced using lamellae from two different wood species (maritime pine, *Pinus pinaster* Ait., and European redwood, *Pinus silvestris* L.), as shown in Table 1. The classifications *structural* and *nonstructural* are based on the requirements of the European market. A GLT member can only be considered as structural (load-bearing application) if it shows the Conformité Européenne (CE) marking. This CE marking is obtain by fulfilling the requirements included in EN 14080 (CEN 2013), namely a system of assessment and verification of constancy of performance is applied. This system implies that a notified product certification body shall issue a certificate of constancy of performance of the product based on initial inspection of the manufacturing plant and of factory production control, and continuous surveillance, assessment, and evaluation of factory production control. European redwood GLT beams are under this control and are commonly imported from central and northern European countries for use in structural applications.

Maritime pine GLT pieces were included based on the fact that maritime pine timber is the major home-grown raw material available in Portugal. Although the GLT elements did not show the CE marking, and are thus not able at the moment to be used for structural applications, the manufacturer claims that it satisfies all requirements of the European standard EN 14080 (CEN 2013). Moreover, the inclusion of GLT specimens with or without CE markings was considered since it allows a comparison between two different factory production control systems (with or without the control of an independent entity).

Considering the aim of the study, all GLT elements had a cross section of 140 × 260 mm, similar to that of the majority of timber sleepers used in Portugal. Generally, no direct strength requirements are indicated for wooden sleepers. Wooden material is selected according to visual grading based mostly on empirical knowledge owned by railway companies. At the European level, the standard EN 13145 (CEN 2001c) provides a list of suitable wood species that includes maritime pine and European redwood, species studied herein. The standard presents the minimum quality (acceptable visual-grade features) of wooden sleepers. No strength requirements are presented, but for softwoods a minimum of 5 annual rings per 25 mm is specified in order to ensure a minimum density. GLT lamellas used in the present study satisfy this requirement (European redwood showed 4.4 mm and maritime pine 4.7 mm maximum growth ring width). GLT sleepers used were in accordance with the visual requirements of EN 13145; therefore, its mechanical performance is equal or superior to solid timber sleepers from the same species.

All maritime pine GLT specimens comprised short beams (350 mm length). This short length was chosen in order to enhance the effect of treatments (greater glue line exposure). Ten beams were thus produced using a PRF adhesive (traditionally used for exterior conditions) and another 10 using a MUF adhesive (currently a common replacement for RF due to production reasons). These different beams enable to compare for the same production conditions a traditional solution (PRF) with the alternative solution available in the market (MUF).

The analyzed European redwood GLT beams included both short (1000 mm length) and long (2400 mm) specimens. Short beams were used to assess glue line quality and for comparison with the maritime pine results, while longer beams were used to assess the penetration of sapwood by creosote.

According to European standard EN 350-2 (CEN 1994), the impregnability of the two wood species is very similar; thus, the sapwood of both species is classified as easily treated. In contrast, the treatment of maritime pine heartwood is extremely difficult, with that of European redwood heartwood difficult to extremely difficult. Hence, both species are typically considered to show the same creosote-absorption ability during vacuum-pressure treatment.

Creosote

A WEI (West European Institute for Wood Impregnation) type C creosote was used in the present study. This type of creosote is now accepted thanks to the amendment made to Biocides Directive 2011/71/EU (European Commission 2011), and presents a low-volatile compound content, reduced smell, and reduced tendency to bleed. This product is currently used in Portugal for the treatment of wooden sleepers.

Methods

Creosote Treatment

The treatment was carried out at an industrial creosote treatment facility that supplies sleepers to a Portuguese railway company. The test pieces were treated alongside maritime pine sleepers (solid timber). A Rüping treatment schedule was applied in which treatment was performed based on a target retention value of 53 kg/m^3,

Table 1. Summary of the Characteristics of the Tested GLT Beams

	GLT characteristics					
	Lamellae					
Identification of GLT beams	Wood species	Thickness	Number	Type of adhesive[a]	Dimensions (mm)[b]	Origin/end-use
MPRF	Maritime pine	Two outer lamellae 24 mm	5	PRF	140 × 260 × 350	Portuguese producer. Nonstructural uses
MPMUF		Three inner lamellae 31 mm	5	MUF		
ER10	European	Two outer lamellae 30 mm	7	MUF	140 × 260 × 1,000	German producer. Structural
ER24	redwood	Five inner lamellae 40 mm	7	MUF	140 × 260 × 2,400	uses—GL24 strength class (EN 1194)

[a]MUF = Melamine urea formaldehyde; PRF = Phenol resorcinol formaldehyde.

[b]Width × height × length.

which is the figure defined by the company. After the timber was introduced into the cylinder, an initial pressure with air was applied (2 bar for 5 min) before the cylinder was filled with creosote, at which point the temperature had reached 60°C. A pressure of 6.5 bar was then applied for 10 min, with the temperature reaching 83°C. A final vacuum of 0.75 bar was applied for 20 min followed by a 10-min stage at atmospheric pressure; the temperature at this final stage of the pressure treatment was 70°C. After treatment, the test pieces were left exposed to outdoor shelter conditions for approximately two weeks in order to lower the temperature and evaporation of volatile creosote compounds.

Bonding Quality Tests

Glue line quality was evaluated in different steps, as shown in Fig. 2. In each step and from each type of maritime pine GLTs (MPRF and MPMUF), four glue lines were tested (five lamellas). Thus, for delamination the sample size (number of test result) in each step was 40. For the shear test, two specimens were cut from the delamination specimen; thus, the sample size was equal to 80. European redwood elements showed more glue lines (six) and test specimens were obtained from both ends, making the samples size equal to 120 and 240 for delamination and shear testing, respectively. The mean value was taken into consideration for the global evaluation of each GLT element at each step, corresponding in each step to a total of 10 maritime pine and 20 European redwood values. Test pieces were cut from the ends of the GLT specimens following the cutting scheme indicated in Figs. 3 and 4.

The quality of the glue line at each step was evaluated by measuring specimen delamination (the opening between two lamellae, recorded at end-grain surfaces) and determining the shear strength. Delamination was assessed visually as follows: during steps 2 and 4, after testing carried out based on the recommendations outlined in European standard EN 386 (CEN 2001a) (structures of service class 3—exterior); and during step 3, after the creosote treatment (conditions that can be considered a glue line *torture* test).

In accordance with EN 386 (CEN 2001a), the A test was applied for adhesives of type I as described in EN 391 (CEN 2001b). This procedure comprises a first step involving impregnation with water after an initial vacuum, followed by a final pressure stage. After applying this stage twice, the test pieces were subjected to a drying stage. The impregnation/drying cycle was repeated three times. The applied accelerated aging conditions are indicated in Table 2. With the exception of step 1 (Fig. 2), at all stages both shear strength and

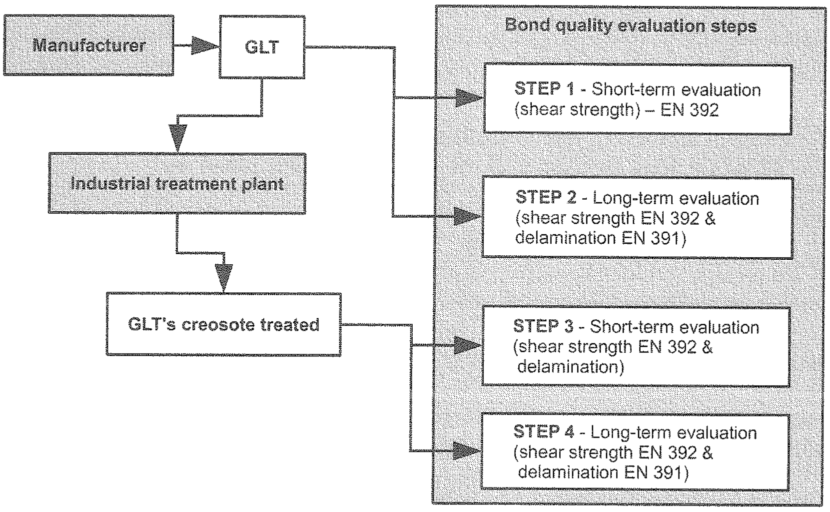


Fig. 2. Glue line testing steps

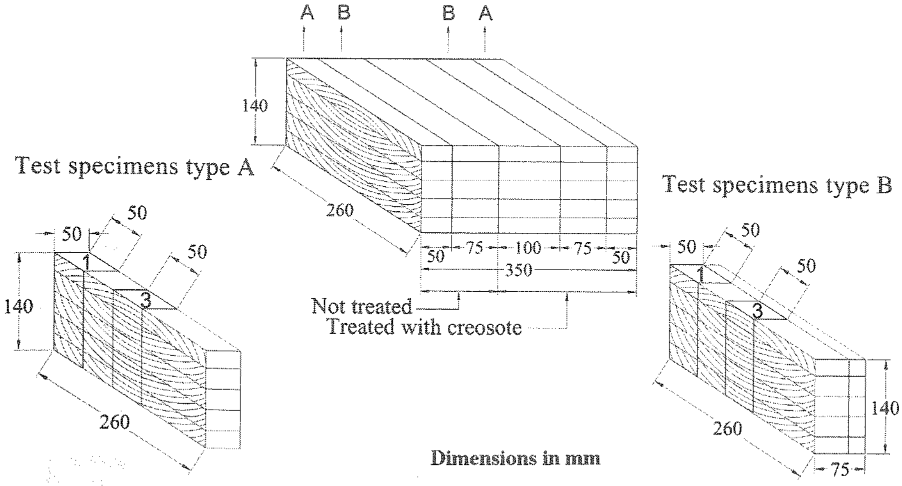


Fig. 3. Test piece cutting plan for MPRF and MPMUF GLTs; A: specimens for shear tests; B: specimens for delamination and shear tests; numbers 1 and 3 indicate the test pieces extracted for shear tests, from both specimens A and B

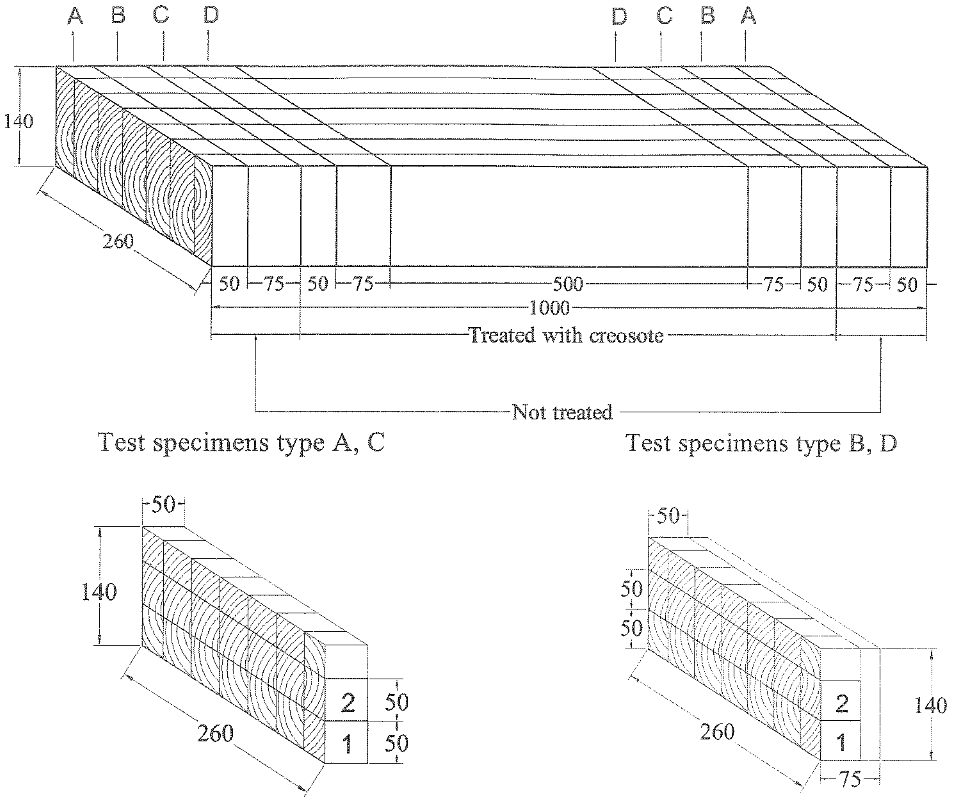


Fig. 4. Test piece cutting plan for ER10 GLT; A and C: specimens for shear tests; B and D: specimens for delamination and subsequent shear tests; numbers 1 and 2 indicate the test pieces extracted for shear tests, from both specimens A and B

Table 2. Applied Accelerated Aging Conditions [Data from EN 391 (CEN 2001b)]

Stages	Parameters	Test conditions
1	Water impregnation in a pilot treatment autoclave	Water temperature between 10 and 20°C 75 to 85 kPa vacuum for 5 min Final pressure (500 to 600 kPa) for 60 min
2	Drying	Drying of the test pieces for 21 to 22 h; drying was carried out in a drying chamber at a temperature between 50 and 70°C, relative humidity below 15% and an air ventilation speed of 2 to 3 m/s

delamination were evaluated, with the shear test pieces obtained from the delamination test pieces after the latter's evaluation.

Delamination was measured at both end-grain surfaces (Fig. 5), with the following parameters measured for each test piece: maximum (total amount) delamination observed in a single glue line ($l_{\text{max,delam}}$); length of a single glue line (l_{glueline}); total amount (length) of delamination in all glue lines ($l_{\text{tot,delam}}$); and the total length of glue lines ($l_{\text{tot,glueline}}$).

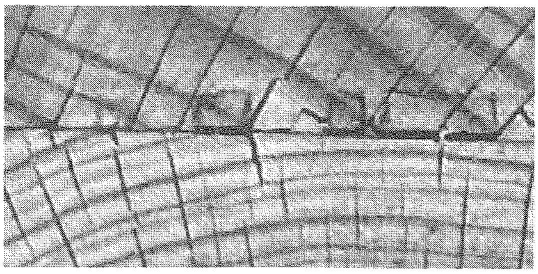


Fig. 5. Glue line delamination showing the measurements taken at the end-grain surface

Total (D_{total}) and maximum (D_{max}) delamination was determined in accordance with EN 391 (CEN 2001b) using Eqs. (1) and (2)

$$D_{\text{total}} = \left(\frac{l_{\text{tot,delam}}}{l_{\text{tot,glueline}}}\right)100 \qquad (1)$$

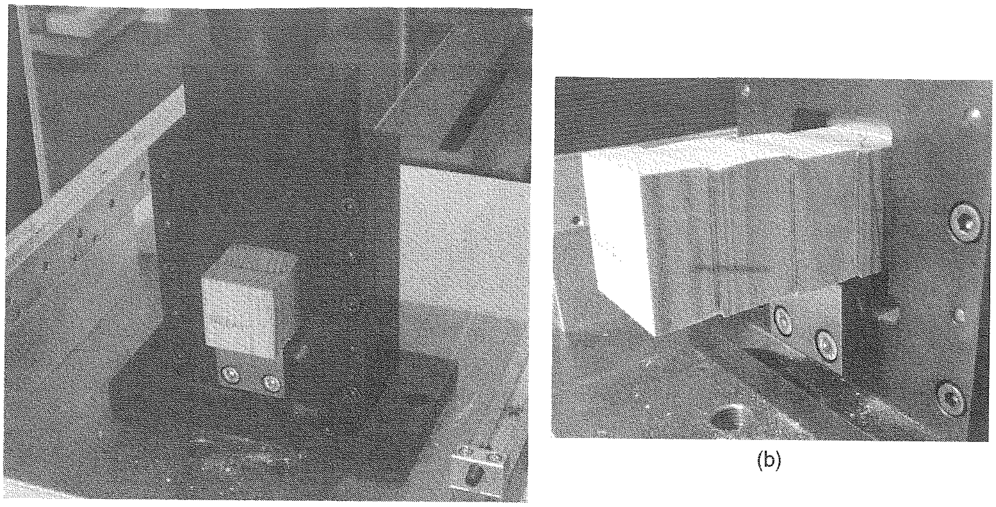
$$D_{\text{max}} = \left(\frac{l_{\text{max,delam}}}{2l_{\text{glueline}}}\right)100 \qquad (2)$$

EN 386 (CEN 2001a) requires that $D_{\text{total}} \leq 10\%$ and $D_{\text{max}} \leq 40\%$ should be obtained for each test piece. According to EN 386, glue line strength is a function of shear strength and wood failure percentage (percentage of failure in or between wood fibers). Glue line shear strength (f_v) at each of the different steps was assessed in accordance with EN 392 (CEN 1995), as shown in Fig. 6.

All glue lines were tested at each step and for each GLT specimen. For this purpose, two specimens were cut (Figs. 3 and 4) in order to determine the shear strength near the lateral surface and in the middle of the GLT specimen for each glue line. The shear area (A) and ultimate load (F_u) were also obtained for each test piece, with the k factor applied when necessary. Shear strength was determined using Eq. (3)

$$f_v = k\frac{F_u}{A} \qquad (3)$$

$k = 0.78 + 0.0044t$: applied when or if the thickness (t) of the shear area in the grain direction is less than 50 mm.



(a)

(b)

Fig. 6. (a) Glue line shear test apparatus; (b) testing of the different glue lines in a specimen of type A

Shear tests were performed in a Shimadzu mechanical testing machine equipped with a 250-kN load cell. The selected machine is able to measure the load applied with an accuracy of 1%. Shear tests were carried out under deformation control at a rate of 2 mm/min, with the test pieces undergoing pretest conditioning inside a climatic chamber (20 ± 2°C temperature; 65 ± 5% relative humidity) until a constant mass was attained.

Data Analysis

The software program R (R Development Core Team 2011) was used for all data analysis and box-plot graphs. The effect of the creosote treatment was evaluated via the application of a one-way analysis of variance (ANOVA). The validity of the ANOVA's assumptions was verified by applying the Shapiro-Wilks (normality test) and the modified robust Brown-Forsy for the Levene-type test based on the absolute deviations from the median (homogeneity of variance test). To compare the significance of different samples inside the same ANOVA, the post hoc Tukey honest significant difference (HSD) test was applied. All tests were applied at a significance level of 5%.

Results and Discussion

Delamination

Table 3 presents a summary of delamination test results obtained for treatment steps 2, 3, and 4. MPMUF pieces exhibited the highest levels of delamination, an expected result given the purpose behind the material's production (nonstructural applications) and the adhesive type employed (MUF). In contrast, the use of the same type of adhesive (MUF) on ER10 timber produced for a more demanding end-use (structural) resulted in the lowest level of delamination. These results demonstrate that creosote treatment has a minor effect on delamination if highly controlled factory production is implemented.

Table 3. Summary of Delamination Results

		Treatment step		
Parameter	Test pieces	2	3	4
D_{total} (%)	MPRF	2.1 (1.8)	4.0 (4.1)	5.8 (2.8)
	MPMUF	5.3 (1.9)	6.7 (3.4)	9.8 (4.3)
	ER10	1.7 (1.9)	0.6 (1.1)	5.8 (3.6)
$D_{\max}$ (%)	MPRF	7.0 (5.9)	12.1 (10.9)	13.5 (7.0)
	MPMUF	11.1 (3.9)	15.3 (8.6)	16.5 (6.8)
	ER10	4.8 (5.2)	4.5 (5.5)	14.9 (6.8)

Note: Standard deviation is showed between parentheses.

Figs. 7 and 8 display box plots illustrating the distribution (average and dispersion) of delamination data obtained for each type of GLT tested. Regarding $D_{\max}$ values for MPRF and MPMUF specimens, the ANOVA/HDS test revealed no significant difference between the results obtained for the three treatment steps. However, a significant difference was found for redwood GLT test pieces (ER10) between step 2 and step 4 and step 3 and step 4, implying that creosote treatment has an effect on glue line quality. Although this effect is not apparent between steps 2 and 3 (i.e., in the short-term), glue line deterioration is demonstrated by the difference in the respective results for steps 3 and 4 (i.e., a long-term effect). Nevertheless, all of these results are well below the threshold limit imposed by EN 386 (Fig. 7); thus despite the effect of creosote treatment on glue line strength, the requirements established in the European standard were fulfilled.

Regarding D_{total} values, a significant difference was found between step 2 and step 4 for the three types of GLT specimen tested. Moreover, a significant difference was also identified between step 3 and step 4 for the ER10 specimens. These results demonstrate a clear creosote treatment effect on glue line durability, resulting in an appreciable increase in total delamination (Fig. 8). In all cases, a slight increase in the median value was observed for step 2→step 3→step 4, with the threshold limit exceeded in the case of MPMUF GLT type. The requirement outlined in EN 386 was not clearly met by the MPMUF specimens. In the case of ER10, although creosote treatment did affect glue line quality, the $D_{\mathrm{total}} \leq 10\%$ requirement was fulfilled.

Fig. 9 presents the results for each individual specimen piece considering the simultaneous fulfilment of the two requirements established in EN 386 ($D_{\mathrm{total}} \leq 10\%$; $D_{\max} \leq 40\%$). Regarding the maritime pine GLT type MPRF (Fig. 9), only one test piece did not comply with the maximum total delamination requirement. In the case of MPMUF, 3 of the 10 test pieces did not comply with D_{total} after being subjected to the creosote treatment (and before undergoing accelerated aging). In the case of ER10, only a single piece failed to comply with the D_{total} requirement; this piece was also identified as an outlier.

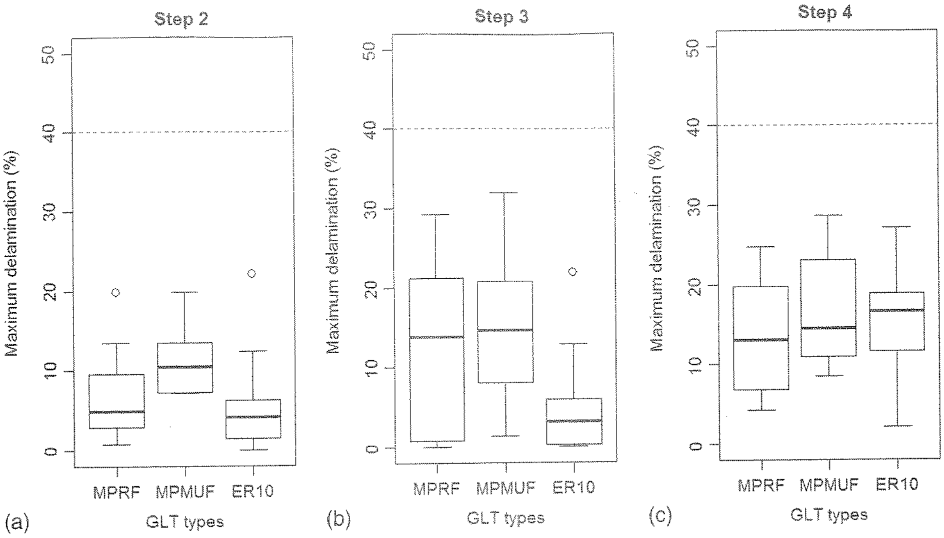


Fig. 7. Maximum delamination results for the different GLT test pieces and creosote treatment steps (Fig. 2) (box plots: central line represents the median value and box length the range of percentile variation; single values represented as circles are outliers)

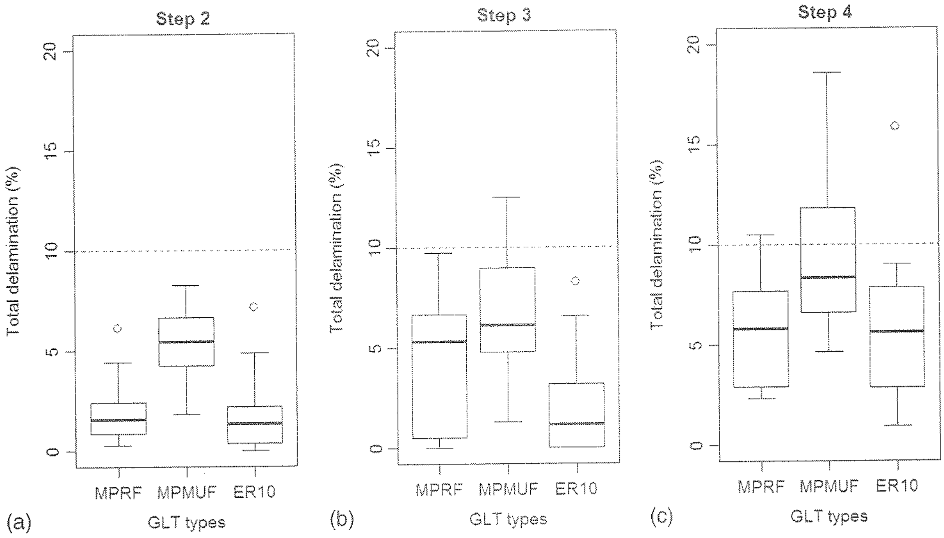


Fig. 8. Total delamination for the different GLT test pieces and creosote treatment steps (Fig. 2) (box plots: central line represents the median value and box length the range of percentile variation; single values represented as circles are outliers)

Analysis of Fig. 9 also reveals that while a clear linear distribution pattern exists for MPRF and ER10, no such pattern is visible for MPMUF specimens. This discrepancy could be indicative of problems at the production level that have not yet been detected by factory production control.

Shear Strength

Table 4 displays a summary of the glue line shear strength results obtained at the different creosote treatment steps for each of the tested GLT element types. Untreated specimens (step 1) were found to fulfil the strength requirements (strength equal or greater than 6 N/mm^2), with the same result obtained for their longer-term behavior (step 2), although an outlier value below the minimum strength requirement was observed for MPMUF.

ANOVA/HSD analysis resulted in the same conclusion for all types of GLT tested. Creosote treatment did not result in any short-term (step 3) decrease in shear strength compared with that of untreated pieces (step 1). However, a slight decrease in glue line shear strength can be seen in Fig. 10, while a significant difference was also found between step 4 and step 2 (i.e., a long-term reduction in durability).

Fig. 11 displays the results for each individual test piece considering their simultaneous fulfilment of the requirements established in EN 386 (shear strength and percentage of wood delamination). Considering both criteria, all three types of material failed to comply with the requirements. However, due to the subjectivity and difficulty in assessing the percentage of wood failure, especially in the range of 30–80% (Scott et al. 2005), the MPRF and ER10 results are considered uncertain (since different observers can obtain different results). The uncertainty of this assessment means that for MPRF and ER10 material, any conclusions can be based only on the obtained shear strength values.

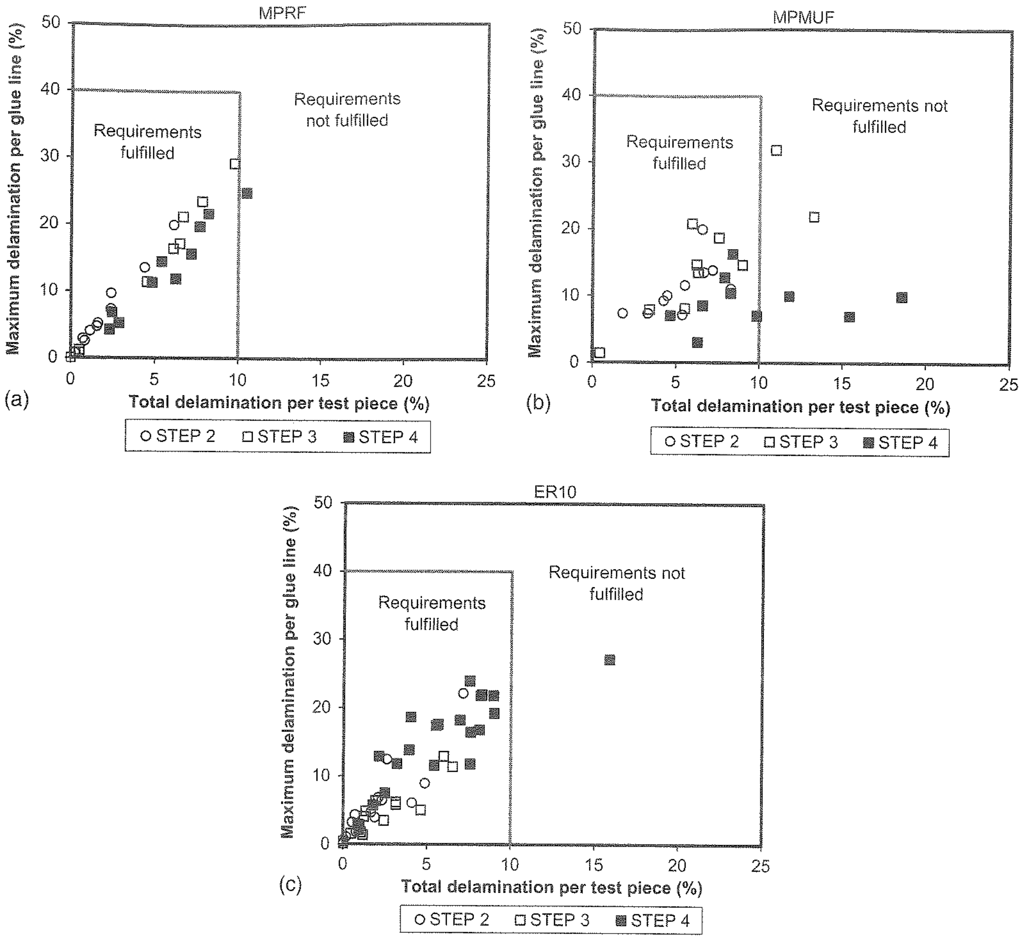


Fig. 9. Total and maximum delamination observed for GLTs test pieces at the different steps; the solid line represents the requirements outlined in EN 386 (threshold limits)

Table 4. Global Shear Strength Results (N/mm^2)

	Treatment steps			
Test pieces	1	2	3	4
MPRF	12.05 (0.80)	10.06 (1.00)	12.80 (1.02)	8.38 (0.60)
MPMUF	12.55 (0.91)	8.80 (1.51)	13.10 (0.87)	6.68 (0.69)
ER10	10.22 (0.84)	8.93 (0.59)	9.75 (0.87)	8.16 (0.85)

Note: Standard deviation is shown between parentheses.

Quality of Creosote Treatment

As well as the maintenance of internal glue line cohesion after creosote treatment, it is also important to ensure full creosote penetration into GLT beams (i.e., full sapwood penetration). Compared with solid timber, the composition of GLT elements introduces additional barriers to the diffusion of creosote inside each element, including glue lines between lamellae and the possibility of sapwood areas surrounded by heartwood. Possible barriers are recognized by EN 351-1 (CEN 2007). This standard provides a safeguard for glued members allowing untreated zones to go until 10% of the total sapwood cross section expected to be treated in each lamella. For the assessment of such diffusion problems associated with GLT composition, in the present study European redwood beams of length 2400 mm were used (ER24).

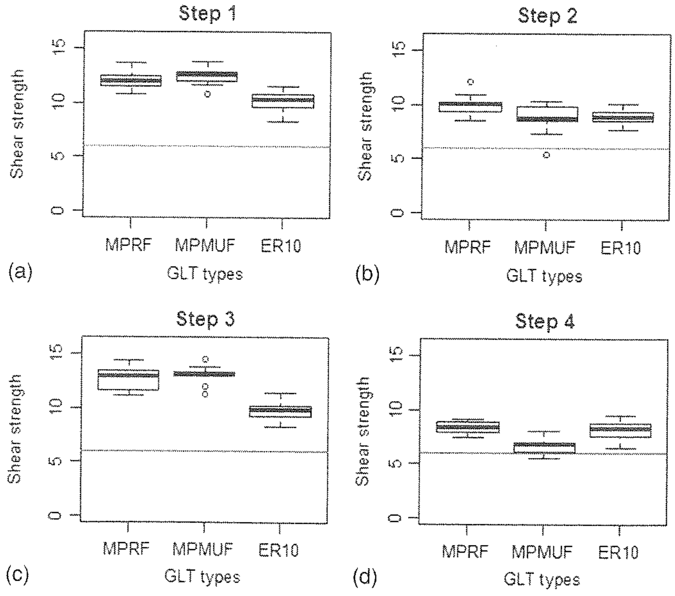


Fig. 10. Glue line shear strength results (N/mm^2) for the different specimens tested and creosote treatment steps (Fig. 2); the solid line represents the requirements outlined in EN 386 (threshold limit) (box plots: central line represents the median value and box length the range of percentile variation; single values represented as circles are outliers)

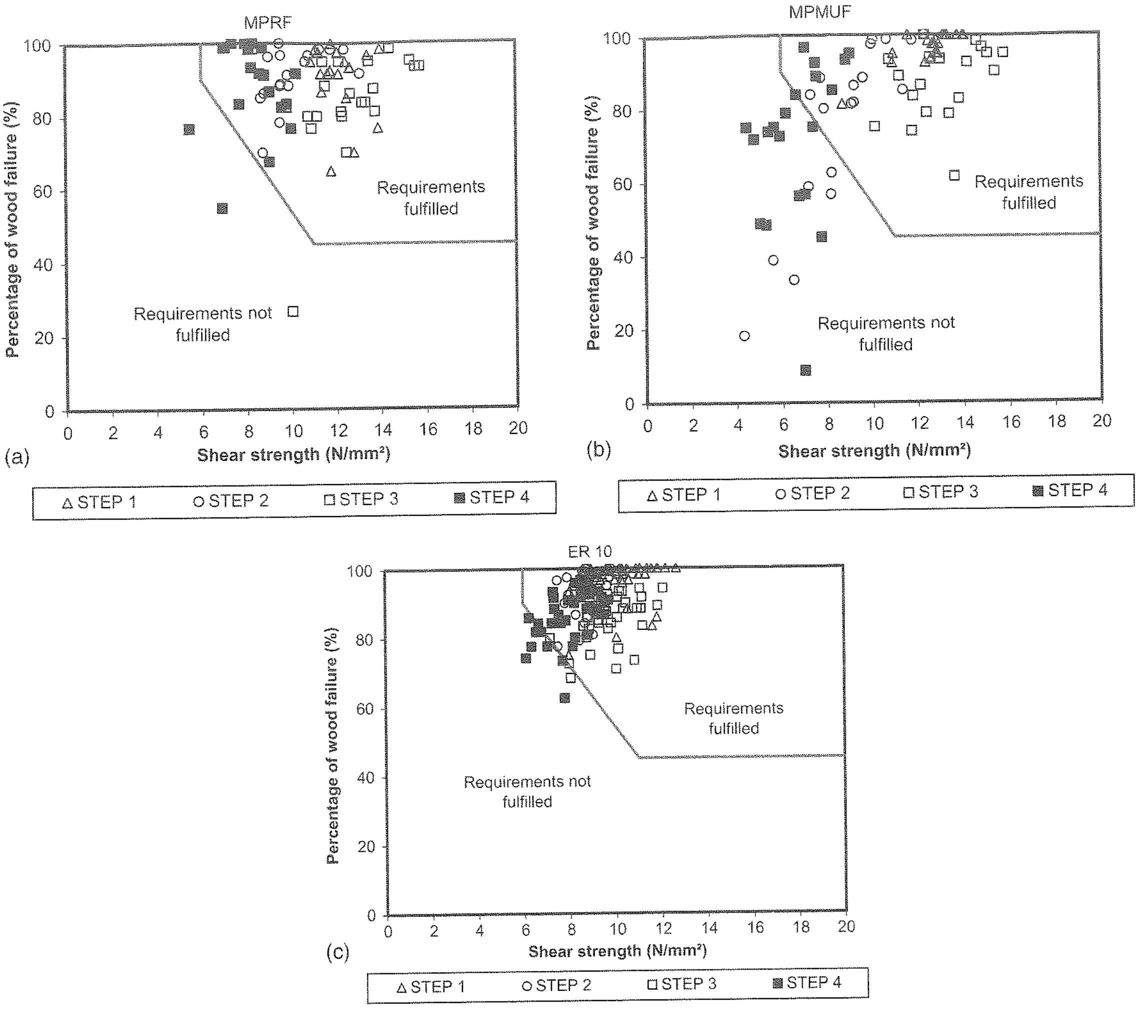


Fig. 11. Shear strength and percentage of wood failure observed for GLTs test pieces at each of the different treatment steps; the solid line represents the requirements outlined in EN 386 (threshold limits)

An initial visual evaluation of the GLT beam ends revealed an average sapwood/heartwood ratio of 0.87 (standard deviation = 0.46). Since heartwood is considered almost impenetrable, the evaluation of product retention used only the estimated sapwood volume. In this case, the estimated average creosote retention rate was 139 kg/m^3 (standard deviation = 58 kg/m^3). This value fulfils the requirement outlined in Portuguese standard NP 2080 (Instituto Português da Qualidade 1985), which prescribes a product's retention equal or superior to 100 kg/m^3.

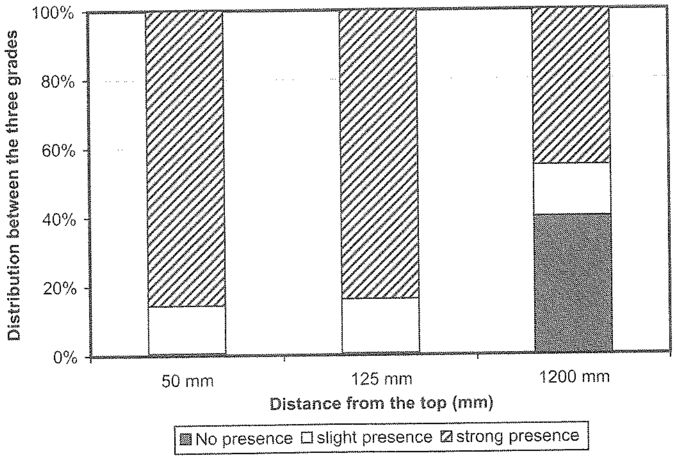


Fig. 12. Creosote diffusion inside ER24 specimens; average value taking into consideration the three visual grades established (no presence, slight presence, and strong presence of creosote)

The diffusion of creosote inside the GLT specimens was visually evaluated by analyzing cross sections cut at 50, 125, and 1200 mm from both ends. The following three visual classes were established: sapwood areas showing strong color alteration (strong presence); sapwood areas showing slight color alteration (slight presence of creosote); and sapwood areas not showing any color alteration (no presence of creosote). The results obtained are shown in Fig. 12. Analysis of this figure reveals that full penetration of sapwood is reached up to 125 mm from the specimen ends. However, in the middle of the pieces (1200 mm from the ends) around 40% of sapwood did not show any sign of creosote (Fig. 12), not achieving the requirement of a full penetration (EN 13145) with a maximum tolerance of 10% untreated zones in each lamella. An example of typical penetration is given for test piece number 7 in Fig. 13.

The average penetration length obtained for the different GLT types tested was around 20–25 mm, which can at most be classified as a penetration level of NP 3 (minimum lateral penetration of 6 mm into the sapwood). Such a result would compromise the long-term biological durability of GLT sleepers, since the natural

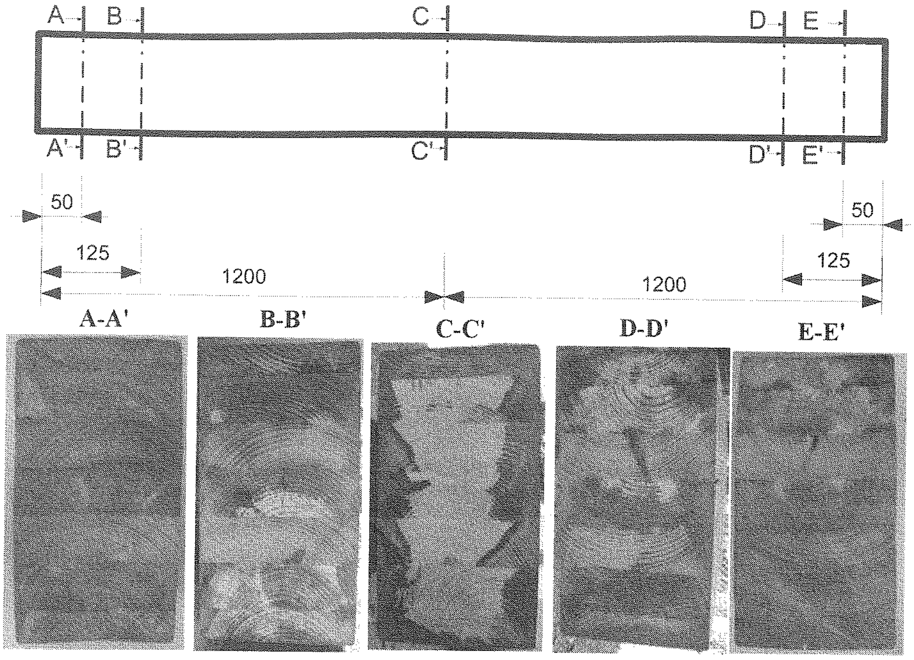


Fig. 13. Creosote diffusion inside test piece number 7

occurrence of superficial fissures and checks (due to swelling/shrinkage cycles) would expose untreated sapwood areas inside elements.

Conclusions

The effect of GLT element creosote treatment on the short-term and durability after accelerated aging of the glue lines (delamination and shear strength) as well as material treatability (penetration) was studied considering three types of GLT elements currently available on the Portuguese market.

The results indicate that creosote treatment has a minor effect on delamination if highly controlled factory production is implemented. The minimum shear strength value of $6\ \mathrm{N/mm^2}$ was reached by all test pieces with the exception of one nonstructural element. The quality of the creosote treatment was found to be insufficient for all GLT elements tested, not ensuring a full sapwood penetration of the lamellas.

The results show that GLT products based on MUF adhesives available on the market for structural uses are a viable alternative to solid wood sleepers. However, matters regarding grading of lamellas and factory production control should be taken into account. Specific grading rules for GLT for sleepers should include minimum use of heartwood and/or avoiding the use of sapwood areas surrounded by heartwood. Treatability can also be improved through incising and/or a retention target superior to that followed in the present paper. A demanding factory production control should be implemented following the current specifications implemented for structural use for application in exterior conditions.

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