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The effects of timber species and adhesive type on the behavior of finger joints in tension under fire conditions

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ABSTRACT

In this work the bonding behaviour of finger joints made of three timber species (chestnut, beech and spruce) and glued with two different structural adhesives (melamine (MUF) and phenolic and amino-plastic (PRF) adhesives) was investigated using small-scale fire tests. An experimental campaign was carried on by testing the specimens under the cone heater at a constant heat flux and tensile load. The time to failure (TTF) as well the residual cross-section and the charring depth were measured. Overall, the specimens bonded with MUF experienced slightly higher time-to-failure (TTFs) than those bonded with PRF. Beech experienced high time-to-failure and failures on timber sided rather than on the bonded joint. A characteristic behaviour was evidenced for chestnut specimens that reached lower TTFs compared to beech and even to spruce, with the same charring rates. The singular outcomes from chestnut tests were explained as the combination of different factors: its low tensile strength even at ambient temperature, the development of overpressures in gas linked to the heat conditions during the tests and the presence of abundant extractives that char over 700°C.

1. Introduction

In the last decades, the use of timber as construction material has been strongly encouraged due to its high sustainability and effort in reducing the carbon footprint in building [1,2]. The application of adhesives for manufacturing the engineered timber products (EWPs) allows going beyond several limitations of sawn solid wood in timber construction field, leading to a more efficient exploitation of the raw material. In the most widespread EWP elements, such as glue laminated timber (glulam) beams and cross laminated timber (CLT) panels, the dimensional limits of sawn logs are overcome through the: *i)* face-to-face bonding of stacking boards (or laminations) and *ii)* end-to-end finger jointing.

The suitability of finger joints for structural applications has been deeply investigated and confirmed by different studies since the 60's [3–8]. Finger joints are considered to be an important link in the glued structural timber in general and can be the dominating factor for the members' load capacities [9,10].

Overall, the estimation of the bonding quality is a fundamental step toward the efficient and safe use of any glued wood-based structural product. Poor inefficient or manufacturing defects could lead to a severe reduction of the mechanical performance of the product due to delamination failures [11,12].

It has been highlighted, mainly for softwood species, that the effectiveness of finger joints on laminated timber beam, is primarily influenced by specific parameters such as: *i)* the finger's profile shape and dimensions [13–16], *ii)* the bonding properties of wood [16–18] and its cell components [19], *iii)* the adhesive features [20–24], *iv)* the bonding method [25], and *v)* the use conditions to which the bonded element will be exposed [19,26–28].

In the last years, the increased interest in the hardwoods structural performances [29–35] led to pointing out their excellent mechanical properties, but also their marked variability, since their performance can vary considerably depending on the combination of species and adhesives. Thus, the technical procedures and the bonding properties cannot be simply transferred from a well-known species to others, especially if the wood species have different characteristics [36–39]. This condition, led the researchers to deeply investigate the behavior of finger joints made of different type of wood species [26,40–42], especially beech [43–45], coming to assess that the wood density and the vessel distribution is an important parameter for the bonding [46]. In particular, the

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Nomenclature

Abbreviation

A_r	Residual cross section
β	Charring rate
CLT	Cross Laminated Timber
EWPs	Engineered timber products
EPI	Emulsion polymer isocyanate
Glulam	Glued Laminate Timber
MUF	Melamine-urea-formaldehyde
PRF	Phenol-resorcinol-formaldehyde
PUR	Polyurethane
TTF	Time to Failure

lower the density, the higher the permeability of a wood structure [47] and probably the stronger the interfacial bonding between adhesive and wood (greater specific and mechanical adhesion) [19].

Concerning the adhesive's role, its stiffness and thickness are highly relevant for finger strength [48–50]. As Groom and Leichti [51] stated, a stiff adhesive is recommended to reduce longitudinal and radial stress concentration at the finger base, while significantly decreasing shear stress within the adhesive layer. While, Obucina et al. [52] showed through their studies that an excessive increase in the thickness of the adhesive layer, results in reduction of the cohesion and strength of the bonded joint.

Basically, the most widespread adhesives employed in the softwood bonding and suitable for structural applications are: *i)* phenolic and amino-plastic adhesives (PRF, MUF, etc.) [53], which exhibit very brittle behavior, *ii)* moisture curing one-component polyurethane (PUR) [54] which are instead ductile, *iii)* emulsion polymer isocyanate (EPI) [55, 56].

Melamine-urea–formaldehyde (MUF) adhesives due to lower costs and shorter hardening times, and one-component polyurethane (PUR) adhesives, which are fast curing at ambient temperature, offer a broad range of application possibilities (no mixing) and are formaldehyde-free. PUR adhesives cure by reaction with water contained in the wood [57]. For hardwood applications, PUR resins exhibit weak performance both on shear and delamination tests, so they often do not meet the delamination requirements [37]. However, some advantages of PUR resins make it worth trying to improve their performance by using primers [30].

If the adhesives play an important role to assure the EWPs load bearing capacity and to address their structural performances, their role becomes essential under fire conditions. In fact, although the reduced cross-section analysis is well suited for solid wood, EWPs have nonhomogeneous properties, and the residual strength depends upon the properties of both the wood and the adhesive at elevated temperatures [58–60].

For many years, the fire performance of engineered wood composites was not a concern as phenolic-based adhesives were widely used and known to break down at temperatures higher than the charring temperature of wood [61], but this cannot be stated for the other adhesives. Currently, the European standards dealing with the performance requirements of the aforementioned adhesives (the EN 301 [53] for phenolic and amino-plastic adhesives and the EN 15425 [54] respectively), don't provide any information on classification methods for adhesives at high temperatures appropriate for fire design. In Northern America, the current regulations require the user to perform large-scale tests to estimate the performance of adhesive bonds; in particular, the cross-laminated timber members are investigated by burning a full-scale compartment [62]. However, the proposed large test requires significant costs and resources. To this end, different research projects such as the FIRENWOOD [63] were brought to life to address the lack of a convenient and small-scale test method to assess the fire resistance of European adhesive bonds. In this framework, some small-scale fire testing methods for adhesive bonds were evaluated for finger joints made of softwood. Eleven adhesive systems were adopted, supplied by four leading European adhesive manufacturers. The proposed method requires to carry out tensile tests on finger joints both at ambient temperature (as reference) and under the heater cone. With the first set of tests, the relationship between density and tensile strength is also studied.

This paper wants to provide an additional contribution to the development of the small testing method aiming to define the finger joints behaviour in fire condition. The outcomes achieved by using this method could be compared with those coming from the large-scale tests, leading to the possibility to standardizing the small-scale test method in Europe. To this aim, tensile tests were carried out by setting the same load level and heat flux condition for all the 28 specimens which were manufactured by varying both the adhesive systems and the timber species. The heat flux was provided by a cone heater preliminary calibrated. Two of the most widespread adhesive types for timber structural applications, MUF and PRF, were used. Both hardwood (beech and chestnut) and softwood (spruce) species were tested by adopting the above proposed method.

2. State of the art

In the last years, many attempts were made to introduce small-scale or bench-scale tests to investigate the performance of adhesives in finger joints and face bonds at elevated temperatures and in fire conditions.

Craft et al. [64] reviewed some of the small-scale test methods available to test finger-jointed specimens at elevated temperatures and proposed a new method to improve the shortcomings of the previous tests. The aforementioned authors proposed to apply a tensile load, since it might be more appropriate than lap-shear tests for applications where finger joints are loaded under pure tension such as the glulam beams. In this instance, the beam depth could be much deeper than the thickness of the single laminations, so the bottom or top outer finger-jointed lamination is subjected to almost pure tension.

The finger joints were tested in a tensile creep test at 220°C, by fixing a target stress of 10.3 MPa.

The time to failure was measured, and the effect of loading as well as the effect of heating under load was investigated. As a result, it was discovered that the temperature was sufficient to highlight the failures of the different adhesives but, on the other hand, the procedure did not carefully represent the temperature evolution in fire situations.

Sviták et al. [65] tested the heat resistance of spruce joints glued with PUR and MUF. The different heat loadings were realized by increasing the temperature at 60, 80 and 110 °C, respectively and comparing the results with wood at 20 °C. The four-point bending tests highlighted that both the elevated temperatures and adhesive type, strongly influenced the bending strength. However, the other hand, the adhesive type had a significant influence on the modulus of elasticity, but elevated temperature had no substantial influence.

Frangi et al. [57] performed tensile and bending tests to evaluate the performance of finger joints bonded with different adhesives at elevated temperatures. They concluded that the bending tests did not seem to be appropriate for the analysis of the behavior of finger joints at elevated temperature, while the tensile ones showed a significant temperature-dependent reduction in strength. Moreover, the different adhesives led to a different reduction of strength and failures, thus, the behavior of the adhesive at elevated temperature influences the performances of finger joints.

Klippel et al. [66] conducted extensive tests on small-scale finger joints at elevated temperatures using 12 different adhesives. In contrast to Frangi et al. [57], taking into account the different failure modes, reported no significant effect of the adhesives on the load-bearing capacity of finger-jointed timber boards at elevated temperatures.

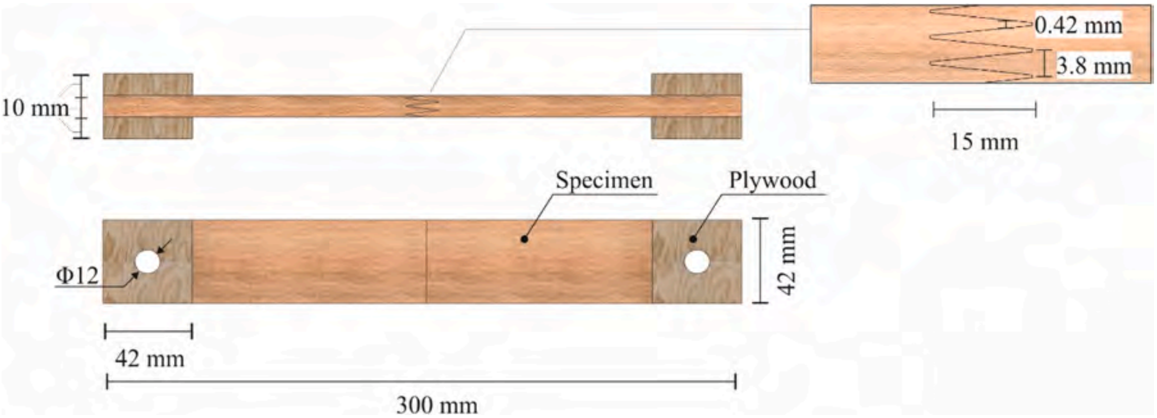

Fig. 1. Geometrical characteristics of the specimens employed in the fire test program (with plywood sides) and in the tensile test program (without plywood sides).

In Ong et al. [67], tensile testing was used to reproduce the behavior of the finger joints at the outermost tension lamella of a glulam beam which experiences the highest stress in a bending test in a standard fire test.

Furthermore, no study was found in the literature dealing with the effect of the adhesive type on finger joints made of hardwood species.

3. Materials and methods

3.1. Adhesives

Two different two-component adhesives, a melamine urea–formaldehyde adhesive (MUF) and a phenolic amino-plastic (PFR) adhesive were studied. Both of the adhesives fulfil current approval criteria for the use in load-bearing timber components according to EN 301–1:2018 [68]. All specimens with finger joints were prepared in accordance with the technical data sheet provided by the manufacturer of the adhesives. The possible use of PUR was deeply discussed and at the end was not addressed since from tests carried out by Dugmore et al. [39], PUR was definitely discouraged to be used as pure and the addition of a primer would be required. Nevertheless, Boger et al. [69] stated that without the use of a primer, commercial 1c-PUR adhesives in combination with some wood species (those with high extractive content such chestnut, larch, yellow-cedar or the species with high strength properties, especially hardwoods, e.g., beech, ash and birch) risk to not reliably fulfilling the complete set of building and safety standards defined for structural wood bonding, e.g., EN 15425 (2017), CSA O112.9-10 (2014) and ASTM D 2559 (2004). The choice of a primer that would be suitable for both the hardwood species resulted hard to achieve and poorly documented so, the PUR was excluded from the current research. However, deepen discussion and studies are ongoing in order to consider the use of PUR for further experimental campaign in the future.

3.2. Timber and manufacturing of finger joints

Two different hardwood species as beech (*Fagus sylvatica L.*) and chestnut (*Castanea sativa* Mill.) and a softwood specie as spruce (*Picea abies*) from Molise a central region of Italy, were adopted to manufacture the specimens. The lamellae have been preliminary visual graded in accordance with [70–73] to reduce the number of possible knots and defects that could led to a premature and unwanted wood failure. The densities were respectively: 720 kg/m^3 for beech, 530 kg/m^3 for chestnut and 465 kg/m^3 for spruce. The production of the finger joints was carried out by a timber industry company in Italy. The lamellas were preconditioned in a climate chamber (T=20°C and M.C.=65 %). The samples were obtained by cutting 130 × 25 mm (width × thickness) lamellas. Finger profiles with length and pitch of 15 and 3.8 mm respectively, were cut from these pieces using the finger joint machine available in the timber company. The length and pitch of the finger joints satisfied the requirements of Annex I, Table I of the standard EN 14080 [74].

The choice of the finger profile is one the most awkward aspects since it heavily affects the lamellae tensile/bending strength both in ambient and hot conditions [57,58,66,75], while their contributions in cold conditions is still unknown. The most commonly used length of the finger joint is 20 mm. However, some previous researches demonstrated that it might not be the optimal one in terms of strength for softwoods [9] and hardwoods [43,76] although, in the case of softwoods, it still delivers the sufficient strength levels needed for the structural members. Other studies on finger joints from high density hardwoods like beech and oak, suggested that the highest bending strength (MOR) was obtained for the highest finger lengths. Fortuna et al. [10] demonstrated for beech that highest strengths values were obtained with longer and thinner fingers, highlighted also that the influence of the adhesive seemed to decrease with the length of finger joints. In the light of above and coherently with the aim of this work to compare the adhesives performances with softwood and hardwood species, the finger joint

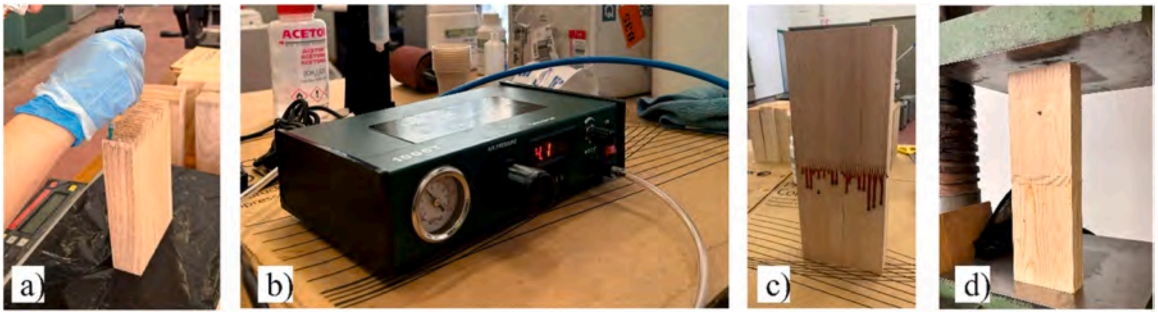

Fig. 2. Specimens manufacturing: a) Specimens gluing; b) Digital manual dispensing machine; c) Specimens bonding; d) Specimen pressing.

Table 1
The adhesive bonding process characteristics as imposed by the manufacturers of the various types of adhesives.

Adhesive Type	Spread Rate [g/m^2]	Pressing Duration [s]	Applied Pressure [N/mm^2]	Mixing Ratio
MUF	250	2	10	100:20
PRF	250	2	10	100:15

Table 2
Test conditions.

Test conditions	Species	Adhesive Type/ Chemical base	Number of Specimens [-]
Tensile test in fire	Beech	PRF	3
		MUF	3
	Chestnut	PRF	3
		MUF	3
	Spruce	PRF	3
		MUF	5
Tensile test at ambient temperature	Beech	PRF	9
		MUF	9
	Chestnut	PRF	9
		MUF	9
	Spruce	PRF	9
		MUF	9
Specimens with thermocouples	Beech	PRF	1
		MUF	2
	Chestnut	PRF	1
		MUF	2
	Spruce	PRF	1
		MUF	-
TOT			**82**

profile was set equal for all the specimens. To maximize the influence of the adhesive, fingers were realized according to the minimum geometrical values (Fig. 1).

Regarding the bonding process, the adhesives were manually applied in accordance with the requirements of EN 14080:2013 [74]. Based on these latter: *i)* the adhesive was applied to only one of the timber ends (Fig. 2a), *ii)* it was visually checked that the adhesive was applied to all finger flanks, and *iii)* the adhesion was considerate satisfied, when the adhesive was squeezed out of all four surfaces of the joint once the pressure was applied (Figs. 2c, 2d).

The adhesives were applied by using an electrical pneumatic dispensing system (DA 1000 T) from DAVtech S.r.l. in order to guarantee a high spread precision and repeatability (Fig. 2b). The dispenser syringe was equipped with a finger switch on its handle for the actuation of the control unit and with a ϕ=0.43 mm tapered polypropylene nozzle. The adhesive spread rate as well as parameters related to the polymerization conditions of the adhesives were adopted from the manufacturers' guidelines and are presented in Table 1. It should be mentioned that the quantity, in terms of weight, of the adhesive agent was applied meticulously while each of the specimens' weight was measured before and after the deposition of the adhesives.

Depending on the finger length, the recommended value of cramping pressure was applied on the finger joints in accordance with the 14080:2013 [74] by using an hydraulic Metrocom press.

By using the previous setting (Table 1), an amount of 82 specimens were made whose main features are summarized in Table 2.

3.3. *Tensile tests at ambient temperature*

The tensile tests were performed using a universal testing machine, LFM-600 (walter+bai AG). The specimens were clamped between hydraulic parallel closing and dual-side grips at each end. The grip force was adjusted in such a way as to reduce the damage of the specimen under the grips to minimum. Reducing the specimen width in the fracture region was unnecessary – the failure occurred predominantly in the area between the grips. Displacement-controlled loading with a speed of 1,2 mm/min was applied, the failure occurred within 5 minutes, in accordance with the time rate of EN 408. The tensile strength, f_t was calculated based on the ration of the maximum load $F_{max}$to the cross-sectional area A of a specimen as:

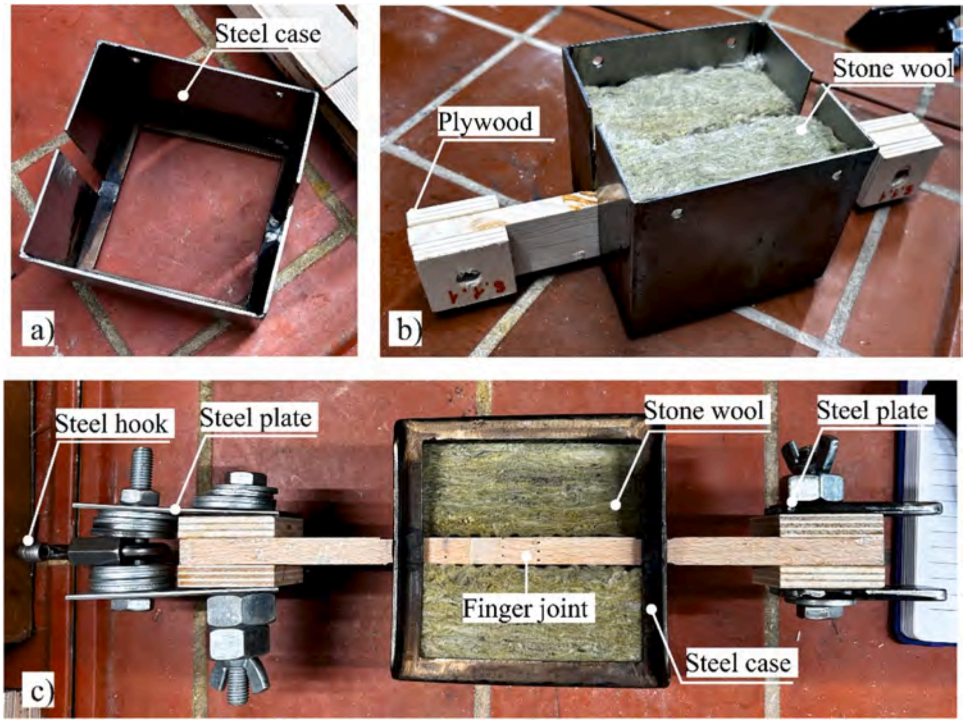

Fig. 3. Equipment for fire tests: a) Steel case; b) Isolation with stone wool sides and plywood reinforcement plates; c) The equipment completed with steel hook and plate.

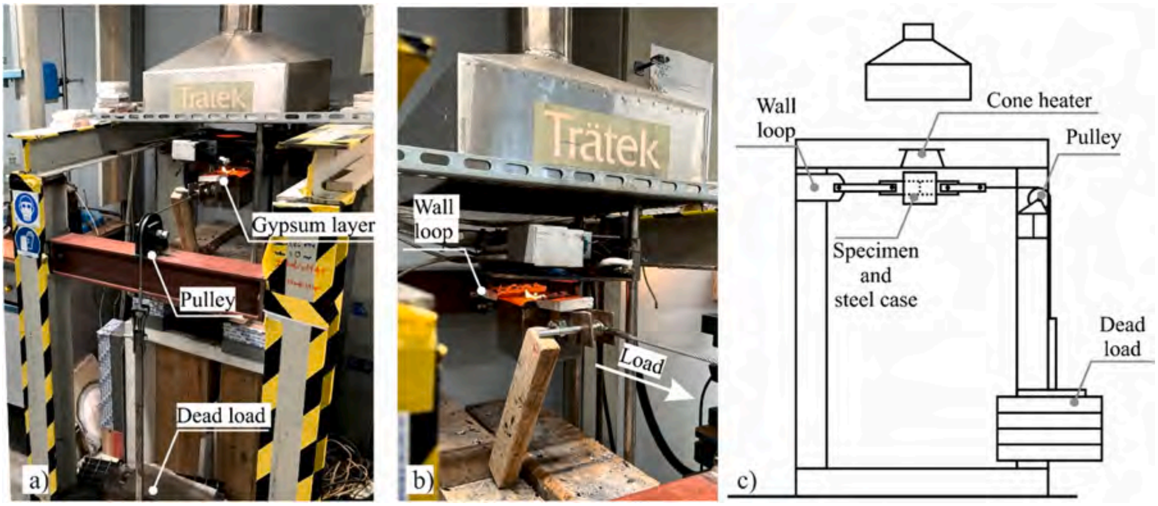

Fig. 4. Fire test setup: a) Cone heater and load system; b) Close up detail; c) General view with load applied.

$$f_t = \frac{F_{max}}{A} \qquad (1)$$

After completing the tensile tests, wood samples were taken from an area without damage to determine the moisture content by performing an oven-dry method and the density by measuring the specimen dimensions and weight.

3.4. Small-scale fire tests

The specimen's ends were drilled (ϕ 12) and reinforced with plywood sides for anchoring purposes to prevent failures at the gripping position (Fig. 1). The specimens were put in a notched steel case (Fig. 3a) and protected against heat exposure of both the lateral faces with stone wool (Fig. 3b). As a result, the specimen was exposed to only the top edge (Fig. 3c).

An amount of tensile dead load equal to 93 kg (corresponding to a stress amount of 1.8 MPa) was applied to one side of the specimen at the start of the test and kept constant for all the duration of the test and for all the species and adhesive types. The load level was set for all the specimens and was defined based on the outcomes from the previous FIRENWOOD test program [63]. The load level was assumed in relation to the specimen width rather than on a percentage of their ultimate tensile load. The cone heater was preliminary calibrated and, then, a constant heat flux of 50 kW/m^2 was introduced at the start of each test. This latter value was also found to correspond well with the ISO 834 and EN 1363–1 standard time temperature curve for the first 30–40 minutes of the fire resistance tests [77–79].

The pierced and reinforced ends of the specimen were bolted to two steel plates (Fig. 3c). One side was anchored to the wall loop by a steel hook and the other end was connected to a dead load using a pulley system (Fig. 4a-b).

The surface below the cone heater was protected with a calcium silicate panel. This latter condition allowed us to put on stage and load the specimen safely. As the protective panel was removed, the test began with time recording. The surfaces of the specimen outside the steel case which were exposed to the heat, were additionally protected with small gypsum layers.

The time recording was immediately interrupted after the failure of the specimen; then, it was quickly removed and soaked in water to retrieve the instrumentation and to stop the charring. The charred area was brushed off and the residual depth was measured with a caliper from both sides to obtain the average value. At last, the residual cross-section and the residual tensile strength were calculated and the time to failure (TTF) was recorded.

In addition, seven specimens of different timber and adhesives (Table 2) were equipped with seven thermocouples placed on their top and side (6 mm spaced). The thermocouples were fixed by clips and spaced 6 mm apart (Fig. 5a). The position was studied to obtain a temperature profile at the finger joint, so the thermocouples were placed in parallel along the same isotherm. The thermocouples were Type K glass fiber insulated, ϕ1.5 mm, and were connected to a data acquisition system (Fig. 5b).

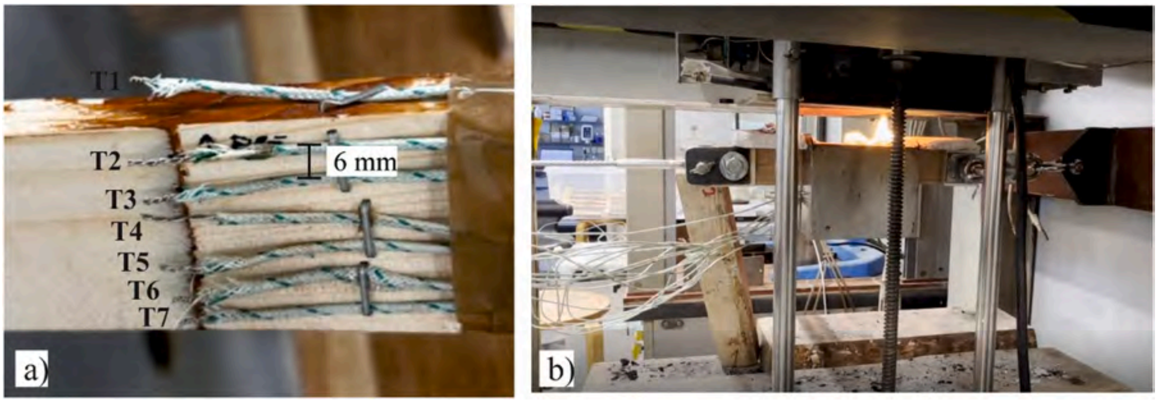

Fig. 5. Thermocouples: a) Position and spacing; b) Test arrangement.

Table 3
Test results (average values).

Specimen [#]	Temperature measurement [-]	TTF [min]	Failure mode	A_r [mm^2]	β [mm/min]
B.1.2	no	15,05	wood	96,06	2,3
B.1.3	no	15,30	wood/adhesive	114,72	2,1
B.1.4	no	14,87	wood	117,6	2,2
B.1.5	yes	12,80	wood	149,46	2,3
Average		**14,50**		**119,5**	**2,2**
St. dev.		1,15			0,09
CoV		8 %			3,9 %
B.2.1	no	12,95	wood/adhesive	138,96	2,3
B.2.2	no	10,93	adhesive/wood	133,26	2,8
B.2.3	no	16,48	wood	102,84	2,0
B.2.4	yes	9,97	wood	187,62	2,6
B.2.5	no	16,82	adhesive/wood	87,96	2,1
B.2.6	yes 2/7	15,50	wood	81,36	2,3
Average		**13,78**		**122,0**	**2,4**
St. dev.		2,93			0,3
CoV		21 %			13,4 %
C.1.1	no	6,25	adhesive/wood	273,6	3,0
C.1.2	no	5,83	wood	281,2	3,2
C.1.3	no	5,08	adhesive/wood	305,5	3,2
C.1.4	yes	6,60	adhesive	258,6	3,1
Average		**5,94**		**279,7**	**3,2**
St. dev.		0,65			0,08
CoV		11 %			2,6 %
C.2.2	no	7,00	wood	274,3	2,7
C.2.3	no	10,83	wood	203,9	2,3
C.2.4	no	7,93	wood	279,5	2,4
C.2.5	yes	7,45	adhesive/wood	197,2	3,4
C.2.6	yes 2/7	7,93	adhesive/wood	225,2	2,9
Average		**8,23**		**236,0**	**2,8**
St. dev.		1,51			0,5
CoV		18 %			16,7 %
S.1.1	no	8,77	adhesive	203,3	2,9
S.1.2	no	7,47	adhesive	219,5	3,2
S.1.3	no	7,35	adhesive/wood	224,6	3,2
S.1.4	yes	7,48	wood/adhesive	170,2	3,7
Average		**7,77**		**204,4**	**3,2**
St. dev.		0,67			0,4
CoV		9 %			11,1 %
S.2.1	no	8,87	adhesive	204,9	2,8
S.2.2	no	10,95	adhesive/wood	163,7	2,6
S.2.3	no	11,55	adhesive	170,8	2,4
S.2.4	no	10,58	adhesive/wood	191,2	2,5
S.2.5	no	10,37	adhesive/wood	137,9	2,9
Average		**10,46**		**173,7**	**2,6**
St. dev.		1,00			0,2
CoV		10 %			8,7 %

4. Results and discussion

4.1. Small-scale fire tests

The major test outcomes, such as the average time to failure (TTF), the residual cross-section (A_r) and the charring rate (β), are shown in Table 3. Further information such as temperature measurement and failure mode are also listed. A letter and two numbers compose the nomenclature of the specimen. The capital letter represents the species, so, it is "B" for beech, "C" for chestnut and "S" for spruce. The first number represents the type of adhesive and it is "1" for PRF and "2" for MUF, and the last number represents the number of the specimens tested. The first repetition concerning the series B.2 and C. 2 were not listed due to a disruption of the load system that was then fixed.

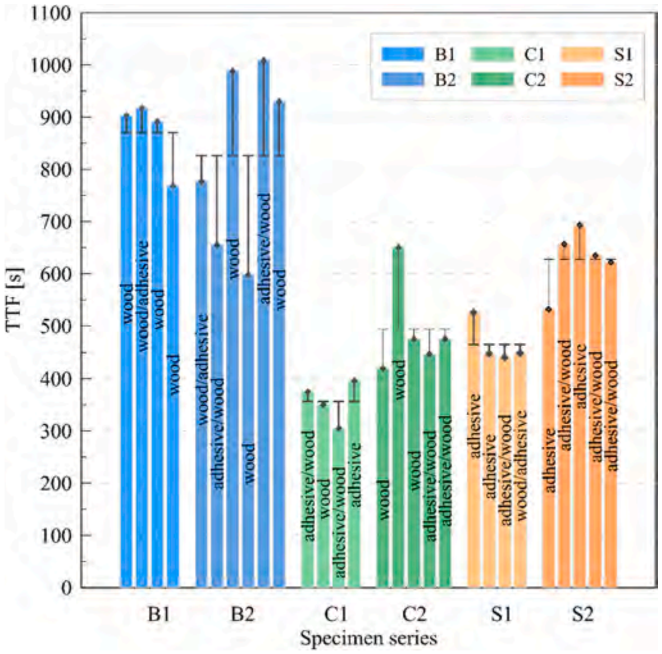

Fig. 6. Plot of TTF and failure modes B1 – beech with PRF, B2 – beech with MUF, C1 – chestnut with PRF, C2 – chestnut with MUF, S1 – spruce with PRF, S2 – spruce with MUF.

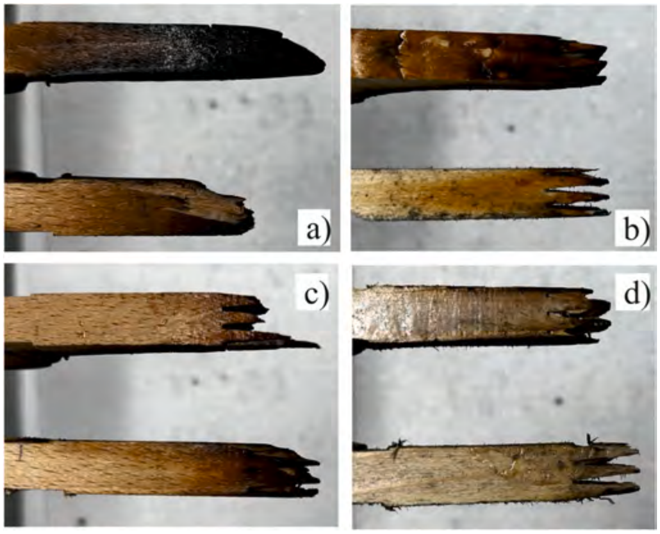

Fig. 7. Photos of failure modes: a) wood failure of specimen B1.4; b) adhesive failure of specimen S.1; c) wood-adhesive failure of specimen B1.3; c) adhesive-wood failure of specimen S2.2.

4.1.1. Fire resistance and failure type

In general, it is possible to clearly distinguish the failure behavior of hardwood specimens from the softwood ones. The latter are mostly characterized by adhesive or adhesive-controlled failure, while for hardwoods, they are due to wood failures or mixed failures involving primary wood and adhesive (Fig. 6). The typical failures of the specimens in the small-scale fire test are shown in Fig. 7.

The specimens made of beech highlighted a high fire resistance

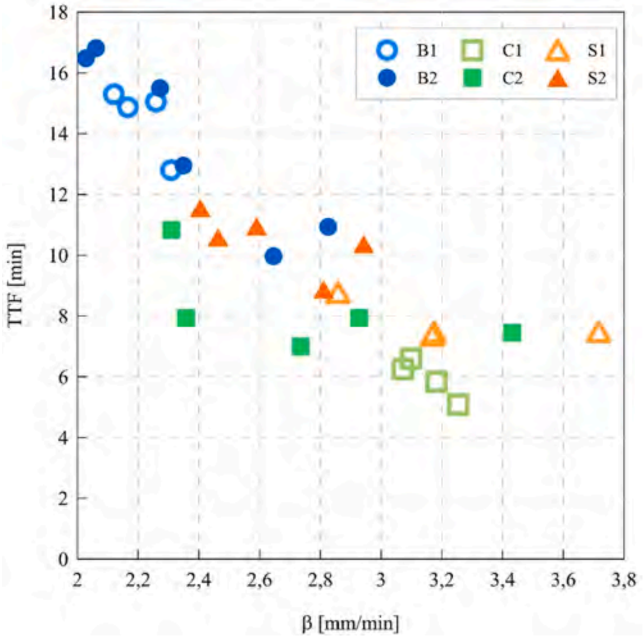

Fig. 8. Plot of failure times vs charring rates B1 – beech with PRF, B2 – beech with MUF, C1 – chestnut with PRF, C2 – chestnut with MUF, S1 – spruce with PRF, S2 – spruce with MUF.

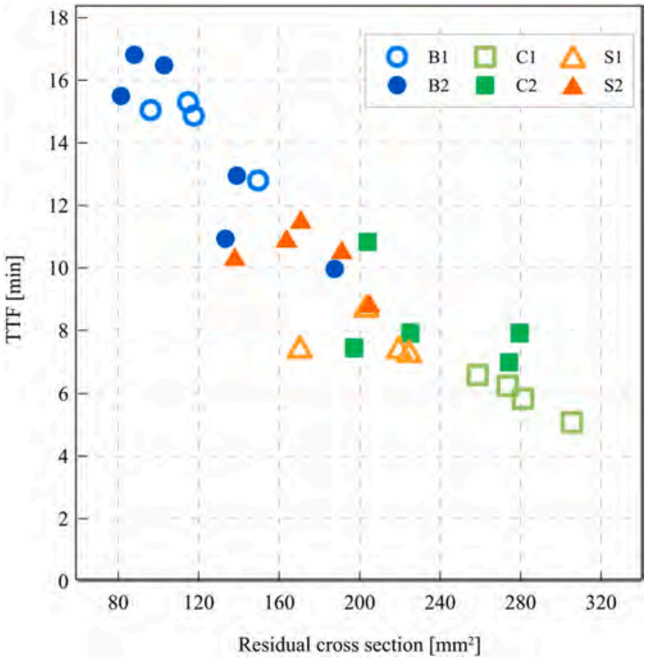

Fig. 9. Plot of failure times vs residual cross section B1 – beech with PRF, B2 – beech with MUF, C1 – chestnut with PRF, C2 – chestnut with MUF, S1 – spruce with PRF, S2 – spruce with MUF.

compared to the chestnut and spruce ones, with an average TTF of 14.5 and 13.78 min respectively for PRF and MUF adhesives. The chestnut specimens demonstrated the lowest TTFs, especially the C1 series, while the TTFs of C2 series are almost comparable with those of S1. On the other hand, the test series have different failure modes, the C2 is mainly governed by wood failures while the S1 is more prone to fail due to adhesion issue.

The failure modes and the TTFs of spruce series S1 are comparable with the evidence coming from the previous experimental program performed within FIRENWOOD [63] and Ong et al. [70] involving spruce timber and PRF glues. In these cases, the TTFs were of 11,6 min and 7.60 min respectively.

In the case of a mixed-type failure, it was not possible to determine the cause of the failure during the fire tests. The specimen assembly was chosen to investigate failure in the finger joint, which occurred in most of the tests.

4.1.2. *Influence of adhesive*

The slightly higher TTFs of specimens bonded with MUF could be due to the adhesive’s chemical composition. In fact, melamine has generally a high nitrogen content leading to sublimation or decomposition of the molecule when heated above a determined value [80], cooling the substrate. This latter process absorbs considerable amount of heat energy and thus serves as a heat sink and as an inert gas source in fire situations [81].

It was also highlighted in [82] that the use of MUF tends to lead to the highest bonding strength and wood failure percentage, which may be explained by its high stiffness (less ductility). Moreover, Ammann and Niemz [83] investigated the rupture energy of beech glued specimens and discovered that MUF and PRF glue joints both fail in the adherend (wood), but MUF glue joints behaves like the solid wood while PRF glue joints could be weaker than the solid wood.

4.1.3. *Charring rates and temperature profiles*

Overall, the average values of charring rates were much higher compared to the dimensional design charring rate, β_0 and notional charring rate, β_n (which includes the effect of corner roundings and fissures) published in EN 1995–1–2 [84]. The design values were $\beta_0 =$ 0.65 mm/min and $\beta_n = 0.8$ mm/min for solid softwood and beech timber; $\beta_0 = 0.50$ mm/min and $\beta_n = 0.55$ mm/min for solid hardwood timber respectively. The most plausible explanation is due to the scale of the tested specimens, which are small compared to the structural elements (such as glulam beams) which have larger outer sections of charcoal protecting the inner sections from increasing in temperature when tested in standard full-size fire tests [84]. Charring rates having the same order of magniture were observed by Ong et al. [70] and in the framework of FIRENWOOD [63] by testing finger-joints under the cone heater to simulate the fire condition. Ong et al. [70] obtained charring rates equal to 2,03 and 1,99 mm/min for Spruce bonded with PFR and PUR respectively and 1,61 and 1,50 mm/min for Dark Red Meranti Spruce bonded with PFR and PUR respectively. From some FIRENWOOD tests [63] which were carried out by using adhesives originate from four different chemical backgrounds from just as many european producers and a dead load of 255 kg (almost 2.5 times higher than the current one), the average value of charring rate was 1,32 mm/min, with a maximum of 1,94 mm/min and a minimum of 0,99 mm/min.

Beech finger joints reached high TTF values (14.50 min and 13.78 min) with PRF and MUF adhesives, these values are associated to close values of charring rate (2.2 mm/min and 2.4 mm/min respectively). Chestnut joints reached relatively low TTF values (5.94 min and 8.23 min) with PRF and MUF adhesives, these values are associated to close values of charring rate (3.2 mm/min and 2.8 mm/min respectively). Spruce joints reached medium TTF values (7.77 min and 10.46 min) with PRF and MUF adhesives, these values are associated to close values of charring rate (3.2 mm/min and 2.6 mm/min respectively) (Fig. 8).

These findings highlighted that the different adhesives used to bond the finger joints do not influence the charring rate in this small-scale fire test. This can be explained by the fact that the bonding area of the finger joints was small in comparison to the overall cross-section of the specimen.

The reduction of the timber section is quite different for the three timber species (Fig. 8), in particular it is possible to observe from Fig. 10a that the most evident reduction (an average of 77 %) occurred for both the first and the second series. The average reduction of section
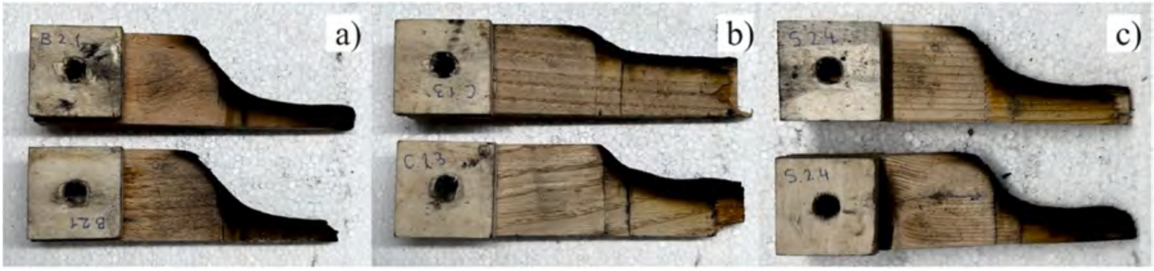
Fig. 10. Residual cross sections: a) Beech series B.2; b) Chestnut series C.1; c) Spruce series S.2.

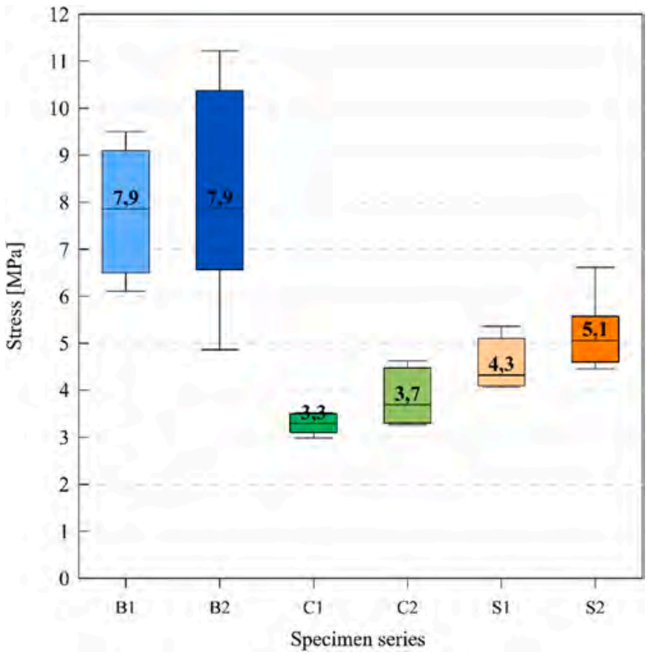

Fig. 11. Plot of stress for the different specimen series B1 – beech with PRF, B2 – beech with MUF, C1 – chestnut with PRF, C2 – chestnut with MUF, S1 – spruce with PRF, S2 – spruce with MUF.

of chestnut is the lowest one (see Fig. 10b) and it is 45 % and 53 % for the first and the second series respectively. The spruce section reduction is equal to 59 % and 66 % respectively for the first and second series and is intermediate between the two aforementioned hardwoods (see Fig. 10c). By the evaluation of the residual cross section at failure, it is possible to define also the stress level in the specimen. It is summarized in Fig. 11. This figure clarifies that, despite the tension level in the chestnut specimens did not reach high values compared with those on beech, it is common to have wood failure. This specific behavior of chestnut cannot be explained by only considering the mechanical resistance of the material, but requires a more detailed explanation of the behavior of the chestnut under fire conditions, which is provided in the next section.

The outcomes from the thermocouples attached to seven specimens along their depth and loaded with a constant dead load (Table 2) were evaluated. The aim of the thermocouples would be to measure the temperature increment along the glue lines throughout the time of fire exposure without affect their mechanical performance. It should be remarked that the thermocouples were fixed on the outer surface of specimens and surrounded by stone wool, this allowed to have an approximate estimation of temperatures due to the presence/influence of pyrolysis gases. The measured temperatures could result lower than the true ones [85] also if the front of charring correlate with 300° charring temperature measured with thermocouples. The issue of the correct temperature measurements in fire exposed wood remains open and worth of investigation since the type, design, form, position method, and location of thermocouples hardly influence the quality and the right temperatures' measurement [85]. The optimal solution to achieve in-depth measurements would be to locate the thermocouples into the finger joint while gluing another solution would be to inlaid them [85] or embedding very thin (0.1 mm diameter) wire thermocouples inside the samples [86].

In particular, three specimens bonded with PRF adhesive and four bonded with MUF glue were compared.

By comparing the behavior of Series 1 specimens which were bonded with PRF (Fig. 12); it is possible to highlight two main outcomes: i) all the thermocouples put on the chestnut specimen recorded a peak of temperature followed by a sudden collapse around 700°C, differently from the profiles of both spruce and beech. *ii)* the outer thermocouple (T1) of chestnut and the thermocouple T2 placed at 6 mm from the exposed surface, recorded a different temperature (around 900°C), highlighting that the heat propagation inside the specimen was slower compared to the other investigated timber species.

Two specimens made of beech and two made of chestnut glued with MUF adhesive were equipped with thermocouples and tested. The full thermocouples configuration was provided for two of each, while the other two were equipped just with the T2 and T7 devices.

In Fig. 13, a large scatter in the TTFs was recorded for the beech specimens, but it is worth noticing that the peak temperature was kept constant and close to 900°C on the exposed surface. The longer TTF of B.2.6 specimen affected the heat transmission too. That effect can be observed by comparing the T7 temperature profile that reached a peak at 600°C instead of 250°C as in specimen B.2.4. Both tests led to a wood collapse.

At last, in Fig. 14 the thermocouple #T2 (at 6 mm depth) 'temperature profiles were compared for the different specimens. For both Series 1 and 2, chestnut specimens reach quite close peak temperatures (773 °C and an average of 777°C respectively), the TTF was also constant and equal to 500 s. The same TTF was recorded for spruce, which reached a peak temperature of 900°C. Beech specimens reached the same peak temperature for higher TTFs. The high temperature achieved by spruce in short TTF is due to the low density and the high presence of extractives of softwood timber species.

4.1.4. *Influence of timber*

In this paragraph the role of the timber was discussed; some aspects concerning its chemical composition and the thermal reactions of its constituents were out of the specific scope of this work, so they were not investigated with additional tests by the authors. Nevertheless, an extended licterature research was carried out to examine these aspects which constitute an interesting evidence to complete the overview of timber's characteristics and to formulate some hypothesis concerning its peculiar behaviour in fire conditions.

The influence of the density on the fire behavior of timber members is well known: by decreasing the density, an increase of the void volume occurs. This leads to a reduction of the conductivity and thus to produce localized heating and heat accumulation, resulting in increased flame

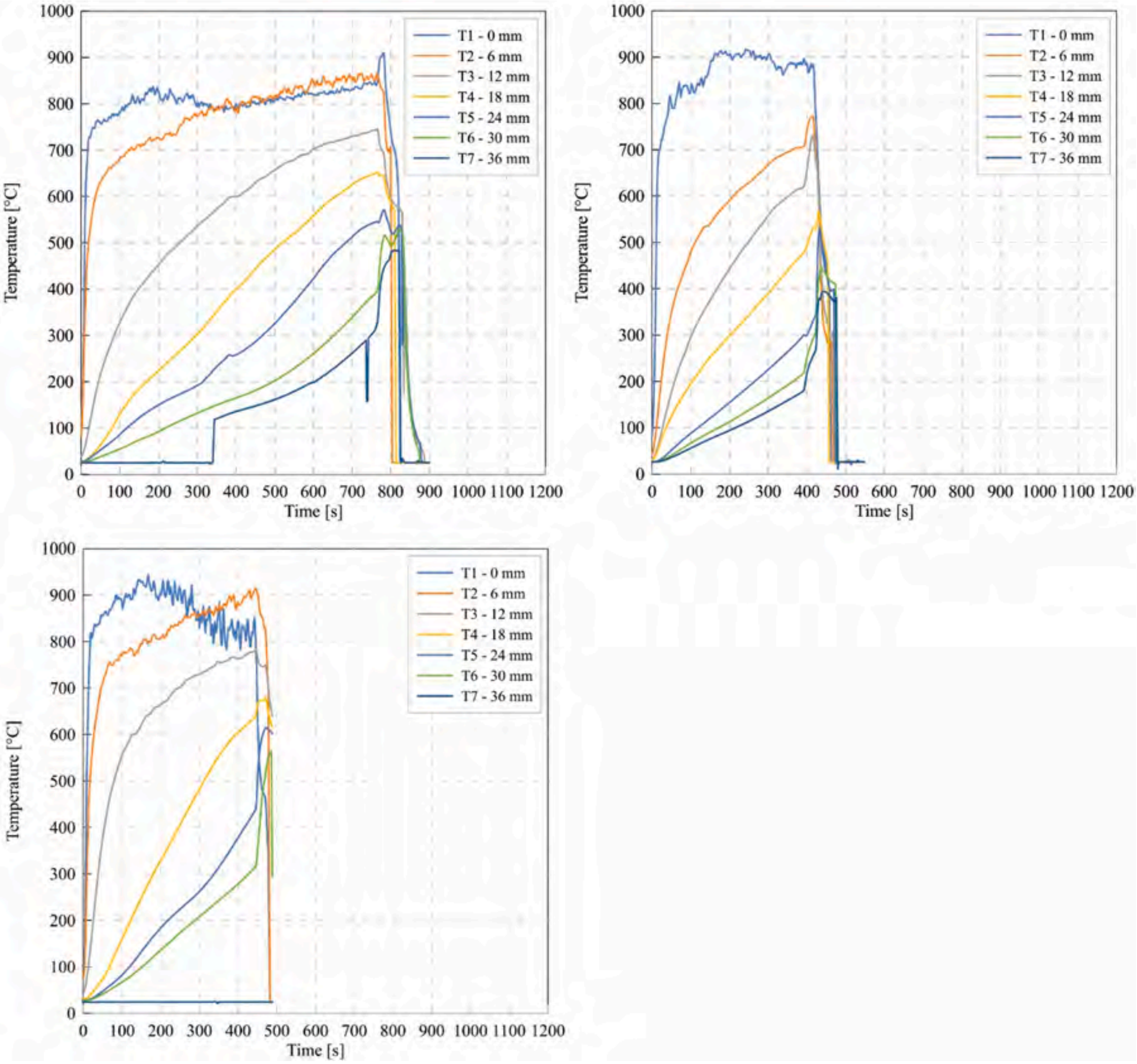

Fig. 12. Plot of thermocouples temperature profiles for series 1: top left) B.1.5; top right) C.1.4; bottom left) S.1.4.

spread rates [87,88]. The majority of authors found that charring rates decreased with increasing density, as expected and as seen from experiments under direct radiant heating. By comparing the charring rate (Fig. 15) of beech and spruce specimens, it is possible to confirm this statement, but the behavior of chestnut diverges from this assumption.

Different authors highlighted the unique behavior of chestnut in environmental conditions as well as the pyrolysis stage [89–92]. In spite of being a hardwood species, chestnut is characterized by the lower level of holocellulose (the total amount of hemicellulose and cellulose) than beech, and has high extractive content (introducing significant deviations with respect to the basic characteristics of the hardwood category) [89]. The main constituents of chestnut extracts are both saccharides and polyphenols. This latter are hydrolyzable tannins and most notably ellagitannins. Ellagic acid may also be present in high amounts [91,93].

The amount of wood fiber strongly affects both the mechanical and the chemical-thermal features of chestnut timber. In particular: *i)* cellulose is responsible for strength in the wood fiber because of its high degree of polymerization and linear orientation and hemicellulose acts as a matrix for the cellulose increasing the packing density of the cell wall [94]; *ii)* holocellulose and extractives are low-temperature components that led to a complete endothermic degradations before (around 300°C) the exothermic degradation of high-temperature lignin (a wide range from 300 up to 900°C) [89].

During the pyrolysis, solid, liquid and gas products are generated due to the wood degradation. In addition, heat and mass transfer processes are affected by volume variation and structural changes undergone by wood while degrading. In particular, for chestnut De Blasi et al. [89] observed that for a heat flux higher than 40 kW/m^2, large swelling occurs. The sample diameter increased by factors of 3–9 % and it was also accompanied by crack formation (contrary to beech and spruce). Structural failures and swelling can be due to intraparticle gas overpressures, which are enhanced by the increase in the devolatilization rate associated with successively higher external temperatures [95,96]. Moreover, it is supported by the speculations [89,92,97] that the extractives intrinsically contribute to product distribution (rate of formation of solid/liquid and gas) from the wood degradation. They have also been reported [92,98] to favor the formation of gaseous and solid (char) products (at the expense of liquids), owing to physical effects, that is, the prolonged residence times of vapors within the reacting sample.

To summarize, the combination of holocellulose degradation, the vapor stagnation and the cracks formation led to a reduction of timber strength with a consequent wood failure.

In addition, the extracts displayed significant char yield at 700 °C (the end temperature of these tests) [91] with significant increases in the amounts of saccharides and ellagitannins decreases while the ellagic acid content increases. The higher the saccharide and ellagitannin contents were present in the chestnut extract, the more important char

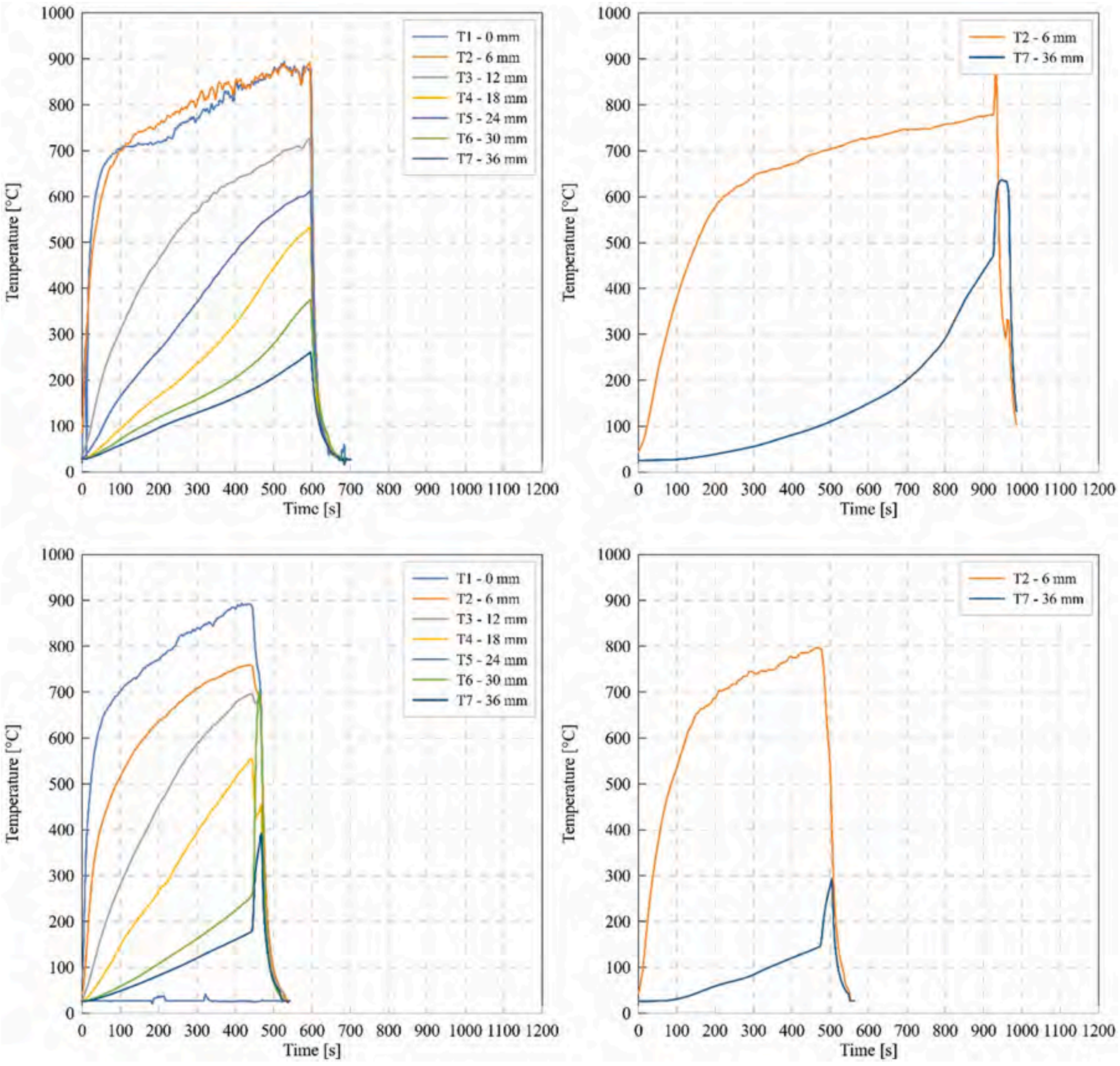

Fig. 13. Plot of thermocouples temperature profiles for series 2: top left) B.2.4; top right) B.2.6; bottom left) C.2.5; bottom right) C.2.6.

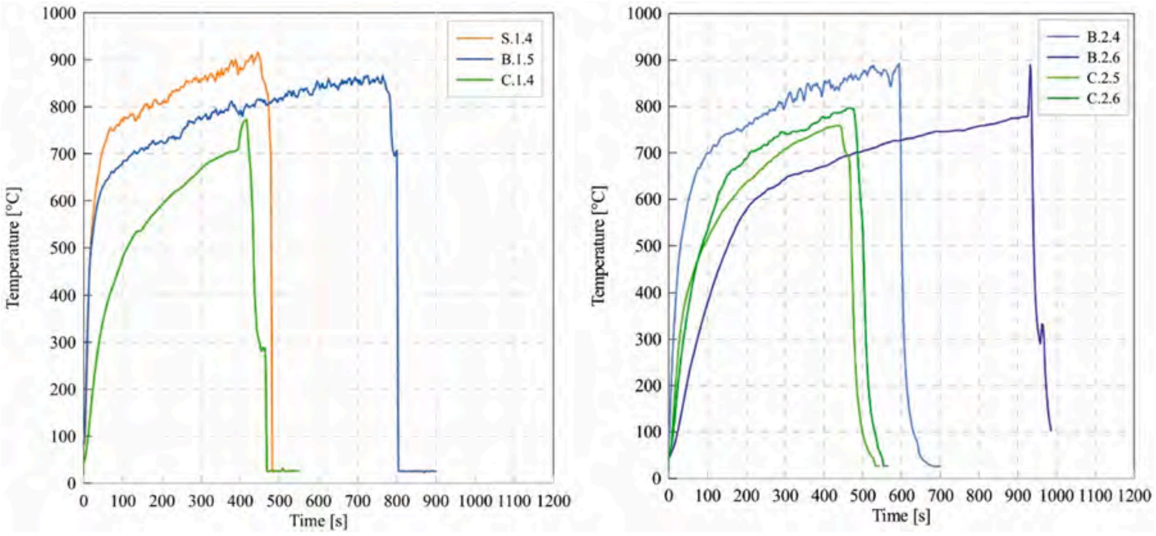

Fig. 14. Plot of thermocouples T2 temperature profiles: left) Series 1; right) Series 2.

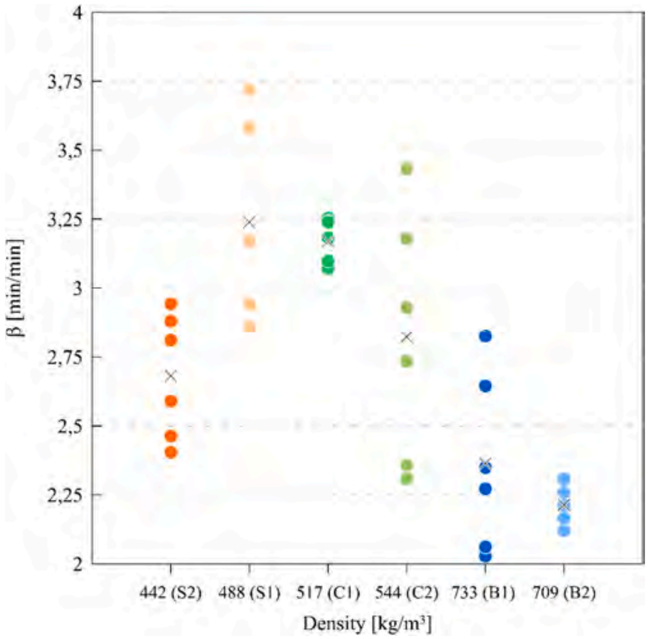

Fig. 15. Plot of charring rate vs density B1 – beech with PRF, B2 – beech with MUF, C1 – chestnut with PRF, C2 – chestnut with MUF, S1 – spruce with PRF, S2 – spruce with MUF.

Table 4
Densities and tensile strengths from tensile test at ambient temperature.

	Mean density [kg/m^3]	COV %	Tensile strength [N/mm^2]	COV %
B1	733	1,7 %	57,1	27,8 %
B2	709	3,8 %	65,0	24,6 %
C1	517	2,3 %	25,6	16,2 %
C2	544	2,7 %	19,5	22,8 %
S1	488	3,9 %	35,5	22,4 %
S2	442	2,6 %	38,6	24,3 %

yield was observed.

The premature wood failure combined with the aforementioned effect could explain the formation of reduced charring layers in the tested chestnut specimens (Fig. 10c). The evaluation of the recordings from thermocouple #T2 (Fig. 14), confirm that close to the exposed surface (6 mm from the exposed surface), the maximum temperature reaches a value of 773 °C for C.1 series and 777°C for C.2 series.

5. Tensile tests

The average tensile strength of finger-jointed and the relative densities are summarized in Table 4.

Typical specimen failures are shown in Fig. 16.

The failure modes were the failure of a clean glue joint, the failure of the net cross-section of the wood, and their combination. For chestnut, despite its higher density than spruce, is mostly characterized by timber failures at ambient temperature which mostly occurred outside the glued area which remained intact.

The distribution of the tensile strength of the finger-jointed specimens as a function of density when tested at ambient temperature is shown in Fig. 17. A large scatter for beech specimens bonded both with PFR and MUF is evident. From the tensile test at ambient temperature it is possible to confirm that the average tensile strength of chestnut specimens are lower than the spruce ones nevertheless their densities are sometimes comparable.

6. Statistics

To achieve a complete understanding of the test results, statistical analyses have been performed. At first the correlation between TTF, charring rates and stresses has been proved to determine the independent variable. The correlation between the TTF, charring rate and stress was proved via partial factor correlation matrices for each species and adhesive type. For each combination the correlation factor between TTF and charring rate was negative and varied between very strong to perfect since it ranged between −0.96 and −1. The correlation factors between TTF and stress were very strong ranged between 0.91 and 0.99, and the correlation factors between the charring rates and the stress ranged between 0.80 and 0.99 demonstrating a strong/very strong correlation between the aforementioned parameters. Then, an analysis of variance (ANOVA) was conducted. ANOVA groups differences by comparing each group's mean values and includes spreading the variance into diverse sources. The term type I error is a statistical concept that refers to the incorrect rejection of an accurate null hypothesis. A null hypothesis is a type of statistical hypothesis that proposes that no statistical significance exists in a set of given observations. Hypothesis testing is used to assess the credibility of an assumption by using specimen data. The result of the ANOVA formula, the *F* statistic (also called the *F*-ratio), allows the analysis of multiple data groups to determine the variability between specimens and within specimens. Consequently, the closer the *F* ratio is to 1, the lower the significance of the difference between the groups tested [55]. In our case the aim was evaluating the impact of both the species and the adhesive on the TTF which is generally assessed by a two-factor ANOVA. Nevertheless, since the sample sizes for the various factors were unequal (this condition is known as "unbalanced model") so the most appropriate approach is the ANOVA using regression. The alpha-factor was set to 0.05 and the most significant values are summarized in Table 5.

Since the p-value (crops) =.057 >.05 = α, we can't reject the null hypothesis, and so conclude (with 95 % confidence) that there are no differences between the effectiveness of the two adhesives. Additionally, since the p-value (crops) =.7,6E-08 <.05 = α so conclude (with 95 % confidence) that there are significant differences between the effectiveness of the employed species. We also see that the p-value (interactions) =.052>.05 = α, and so conclude there are not significant differences in the interaction between species and adhesives.

At last, the correlation between the density, tensile strength and stress was proved via partial factor correlation matrices for each species and adhesive type. In this case, the matrices provide an unclear reading, since the coefficients varied randomly even among the same species (in particular for spruce), so it is not possible to provide accurate conclusions for this.

7. Summary and conclusions

In this paper, small-scale fire tests on finger joints were proposed as a simplified and cost-saving chance to standard fire tests to study the behaviour of bond lines in fire.

Three timber species (beech, chestnut and spruce) and two adhesives (MUF and PRF) were combined in finger-jointed specimens and tested. The results give indications for the fire behaviour of bond lines when PRF and MUF adhesives are used in engineered wood products made of beech and chestnut.

The main novelties concern:

- the use of hardwood species
- the modification of the cutting direction of finger joints, which allowed to neglect the finger's bending strength contribution during the test and to focus on the adhesives' features and their interaction with the wood species.

The fire conditions were reproduced by exposing the specimens to a

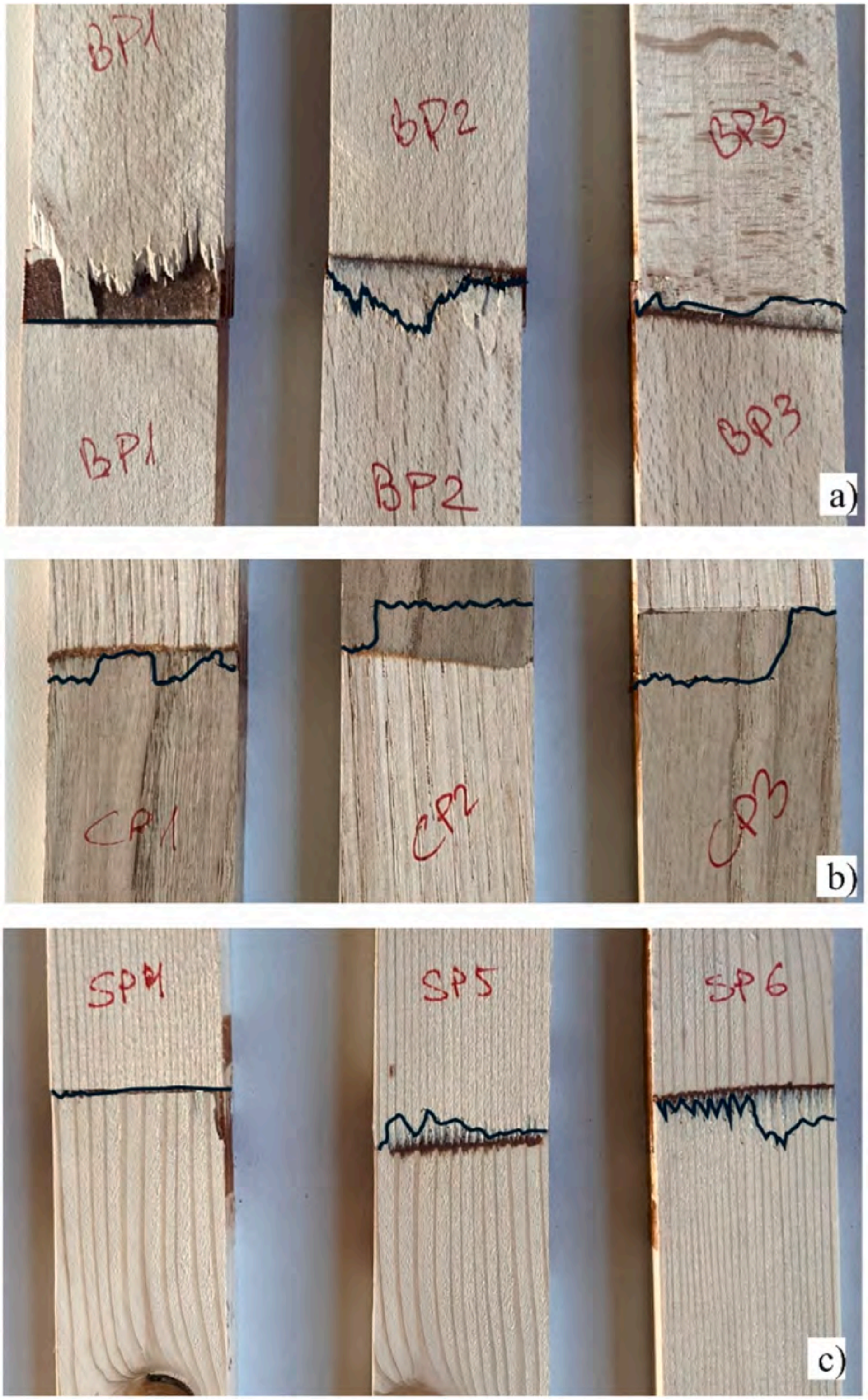

Fig. 16. Typical failure modes from tensile test at ambient temperature: a) Beech; b) Chestnut; c) Spruce.

constant heat-flux with a constant dead load application. From the obtained outcomes, some comparisons can be made between the fire performance of PRF and MUF adhesives as well as between the different timber species. The most interesting parameters to analyze for the comparisons were the time to failure and residual cross-section of the specimens.

Concerning the adhesive role, in particular:

- the finger-joints made of beech and bonded with MUF, experienced slightly higher TTFs, whereas the residual cross-section was almost equivalent as well as the stress level. ANOVA test didn't highlight specific differences in the effectiveness of the two adhesives.
- A higher residual cross section was observed for chestnut and spruce specimens bonded with PFR glue. Despite being a hardwood species with a medium-high density, chestnut reached lower TTFs compared

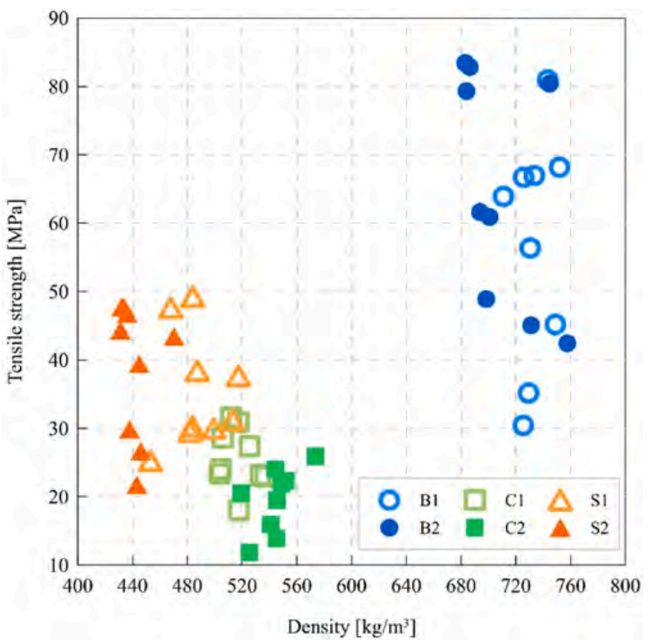

Fig. 17. Correlation between the tensile strength and the density; B1 – beech with PRF, B2 – beech with MUF, C1 – chestnut with PRF, C2 – chestnut with MUF, S1 – spruce with PRF, S2 – spruce with MUF.

Table 5
Two Factor ANOVA (via Regression).

	SS	*df*	*MS*	*F*	*p-value*	*p eta-sq*
Rows (ADHESIVES)	4,1E+04	1	4,1E+04	4,0	0057	0,2
Columns (SPECIES)	8,0E+05	2	4,0E+05	39,6	7,5E−08	0,8
Inter	6,9E+04	2	3,4E+04	3,4	0053	0,2
Within	2,1E+05	21	1,0E+04			
Total	1,1E+06	26	4,2E+04			

to beech and even to spruce, while, the charring rates of both chestnut and spruce were almost the same. The singular outcomes from chestnut tests were explained by considering not just its density but also some specific conditions, such the development of overpressures in gas linked to the heat conditions during the tests and the presence of abundant extractives which produce char over 700°C. This hypothesis was also enforced by examining the temperature profiles from the thermocouples and the residual cross-section.

- ANOVA didn't highlight significant differences in the interaction between the three species and the two adhesives since the most significant differences are mostly due to the species themselves.

The bond lines with MUF and PRF adhesives with beech specimens showed a good fire resistance of the bond lines and therefore a great potential for developing engineered wood with improved fire resistance. The bond lines with MUF and PRF adhesives with chestnut specimens showed varying behaviour in terms of fire resistance. Compared to beech and spruce, the fire resistance of the bond line with chestnut was less. That is partly caused by properties of chestnut. Further investigations of properties of chestnut and bond line integrity should be carried out to develop engineered wood products with chestnut with improved fire resistance. Moreover, the proposed method requires, at a current stage, further reasonings and researches prior to be standardized; the principal test-parameters (i.e load level, heat flux, specimens 'geometrical features) which heavily affect the outcomes, could vary considerably among species. In particular, due to the setup configuration, the initial centric loading of the joint clamps shifts during charring to an eccentric loading with additional and increasing bending moment depending on charring progress. The bending moment increases the applied tensile stress then depending on the residual cross-section being different in the different species. The issue is clearly multifactorial since it depends on the species, the charring-rate and the initial load level. FEM could be calibrated on those test and further analyses (and tests) could be carried out numerically to achieve the increment of stress due to the cross-section reduction. Concerning the load level, it will be deeply investigated since an alternative choice would be to adopt an initial load level proportional to a certain percentage of the tensile strength at ambient temperature for each species. The idea would be to achieve the same tensile stress percentage for each specimen; the amount of this percentage should be carefully addressed since in our case the beech tensile stress level was 3,6 % and spruce and chestnut ones were respectively 5,9 % and 9,6 %, and this last level could be an additional cause of early failure.

At the early stage of this research involving hardwoods, the fire behaviour of finger made of different species was still poorly investigated and the bench-scale fire tests represented a quick method to differentiate and evaluate the quality of different adhesives for finger joints using different species for structural use in fire conditions. Further tests are needed to verify the results of this bench-scale fire test in comparison to the standard full-size fire test and to find a correlation. At present, constant charring rate with time is commonly used in fire design with the assumption that non-linearity does not significantly influence the resistance of timber structures when exposed to fire.

CRediT authorship contribution statement

Massimo Fragiacomo: Supervision, Conceptualization. **Eero Tuhkanen:** Writing – original draft, Methodology, Investigation, Formal analysis. **Martina Sciomenta:** Writing – original draft, Resources, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Jane Vihmann:** Investigation, Formal analysis. **Alar Just:** Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare no conflicts of interest.

Data availability

Data will be made available on request.

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