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Thermomechanical Behaviour of Bonding Joints of Wood and Wood-based Panels at Room Temperature and Elevated Temperatures

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Abstract. Wood is a natural material traditionally used in the construction industry. In recent decades, developments in scientific research have turned wood into a high-tech construction resource. Increased interest in bonded joints in wood construction is due to the advantages of adhesive technology compared to traditional mechanical joining techniques. It is very important to understand the influence of elevated temperatures on adhesives due to their use in multilayer systems such as compartmentation walls and fire-resistant doors, which require adequate mechanical and thermal resistance in fire situations. The purpose of this study is to investigate the mechanical behaviour of different structural adhesives on bonded connections of wood and wood-based panels at room and elevated temperatures through experimental testing. The performance of the adhesives was evaluated at room temperature and at 50 °C, 100 °C, 150 °C, and 200 °C. The resins tested were a polyurethane prepolymer resulting from the reaction between polyols and diphenylmethane diisocyanate (MDI), Flexpur151, and urea resin glue for hot pressing. The tensile shear tests with lap joints were performed using combinations of pinewood-pinewood and MDF-MDF. The experimental tests were done according to EN 205:2016, which allows for determining the tensile shear strength of bonded joints. The failure mode of the tested specimens was classified according to ASTM D5573. The results show that the bonding strength and the displacement of the specimens decrease with the increase of the temperature. The failure mode presents a different result for different temperatures. For example, for the urea resin, the shear resistance of MDF-MDF panels decreases about 50 % when exposed to 100 ºC with the failure mode usually occurring on the panel, and 98 % when exposed to 200 ºC with the failure mode in the adhesion plane. For the MDI based resin, the shear resistance of MDF-MDF panels decreases about 35 % when exposed to 100 ºC with the failure usually occurring on the panel, and 65 % when exposed to 200 ºC with the failure mode occurring in the adhesion plane.

INTRODUCTION

Wood is a natural material traditionally used in the construction industry. In recent decades, developments in scientific research have turned wood into a high-tech resource. Increased interest in bonded joints in wood construction applications is due to the advantages of adhesive technology compared to mechanical joining techniques.

Bonding of wood is the most used process in the wood industry and during this process complex physical and chemical phenomena occur simultaneously as a consequence of the proprieties of the adhesives and wood [1].

Synthetic adhesives are used in the production of wood-based products to bond wood particles and other lignocellulosic materials. Most synthetic resins are made from formaldehyde, namely urea-formaldehyde (UF) and

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melamine-urea-formaldehyde (MUF) and phenol-formaldehyde (PF), polyurethanes derived from diphenylmethane diisocyanate (MDI) and others [2]. These synthetic resins have improved properties of resistance to water absorption, resistance to fungi and bacteria, amongst others [3].

The urea-formaldehyde resin is used by several industries in the manufacturing of wood-based panels, accounting for 90 % of the adhesives used [4]. This low-cost resin is mostly applied in the production of particleboard panels for indoor use, given that it does not have a good resistance to humid environments [5]. Cured urea-formaldehyde resins can be hydrolysed under the action of water or humidity, causing bond breaks due to the presence of water molecules and a loss in the physical-mechanical characteristics of the material [3]. The addition of melamine gives them greater resistance to moisture, giving rise to melamine-urea-formaldehyde (MUF) based resins, which have the advantage of introducing hydrolysis-resistant amino groups, resulting in a more resistant adhesive. However, this modification of the adhesive results in an increase in its cost, so it is common to use mixtures of UF/MUF adhesives in the manufacturing of panels, as a strategy to increase moisture resistance[6].

Polyurethane (PU) based reactive adhesives are produced from the reaction between an alcohol and an isocyanate. This adhesive has free isocyanate groups (-NCO) characterized by high reactivity, being able to react with hydroxyl groups (-OH) present in wood-based substrates and can also react with water. Compared with water-based urea-formaldehyde resins and phenol-formaldehyde resins, the polyurethane adhesive has a high bonding capacity resulting in bond formation with high cohesion, short press time, water resistance and excellent resistance to environmental factors. In addition, compared to resins that contain formaldehyde, a volatile organic compound known for its high toxicity in its composition, PU-based resins present lower environmental risks [4], [7].Additionally, and from a technical point of view, the PU-based adhesive results in the formation of covalent bonds through the reaction of the NCO group with the moisture existing on the surface of the wood, generating a cohesive and durable bond and, ultimately, preventing degradation of wood cells due to the presence of moisture.

The bond strength between the substrates and the adhesive develops during the hardening or curing of the adhesives, which involves the conversion of a liquid adhesive through gelling and vitrification into fully cured adhesive [2]. Shear strength of the bonded joint is an important indicator of the quality of adhesion. Fracture strength means the maximum shear strength in the grain direction when using high-quality adhesive fracture occurs at the interface wood-glue [8]. Moreover, the bonding performance of adhesives is affected by the temperature. Experiments have shown that wood bonding strength decreases with the increase in temperature [9], [10].

This paper presents the results obtained from the experimental campaign conducted to assess the bonded strength of wood adhesives in high-temperature situations. It is important to understand the behaviour of the adhesives because of the applications in systems such as compartmentation walls and fire doors, which requires adequate mechanical and thermal resistance in fire situations.

MATERIALS AND METHODS

The experimental procedure was based on EN 205 [11], which aims to determine the shear strength of lap joints of wood and wood-based products. Pinewood-pinewood and MDF-MDF were the combinations tested using two different adhesives, where in each combination 10 specimens were tested at room temperature, and 5 specimens were tested for each elevated temperature level: 50 ºC, 100 ºC, 150 ºC, and 200 º C.

Materials

Urea-based resin and MDI-based resin adhesives were used in the experimental campaign. The urea-based resin is a hot-pressing glue in powder form. This resin, supplied by Wurth, has a density of 0.5 g/cm^3, a working time between 15 and 20 minutes, with a pressing temperature ranging from 80 ºC to 100 ºC, and pressing times between 7 and 4 min. A relation 2:1 (resin: water) was used to make the resin, which was spread over the entire surface of the panel with a spatula. The MDI-based resin was supplied by FLEXPUR and is a polyurethane prepolymer resulting from the reaction between polyols and diphenylmethane diisocyanate (MDI). It has a brown appearance, transparent liquid with no suspended materials. Due to its low viscosity, which facilitates the mixing and homogenization, this prepolymer is commonly used to produce granulated cork panels. It has a density of 1.18 g/cm^3, with a solid content of 95-100 % and the optimum working temperature ranges from 130 ºC to 140 ºC.

The pinewood, *Pinus pinaster Ait*., originally from Southwest Europe and North Africa, was supplied by a local manufacturer, and MDF panels produced by Finsa were used in this study. The main characteristics of the panels are presented in Table 1. Other panels and combinations are being studied but only the referred ones are analysed in this work.

TABLE 1. Pinewood and MDF panels main properties.

Panels	Moisture Content [%]	Thickness [mm]	Density [kg/m^3]
Pinewood	12	20	565
MDF	7+/-3	19	770

Methods

Overlapped bonded panels were cut with dimensions of 600 mm in length and 150 mm in width, with the surfaces cleaned before spreading the adhesives. Table 2 shows the main characteristics relating to the bonding procedure for the adhesives studied.

TABLE 2. Urea and MDI resin properties and application conditions.

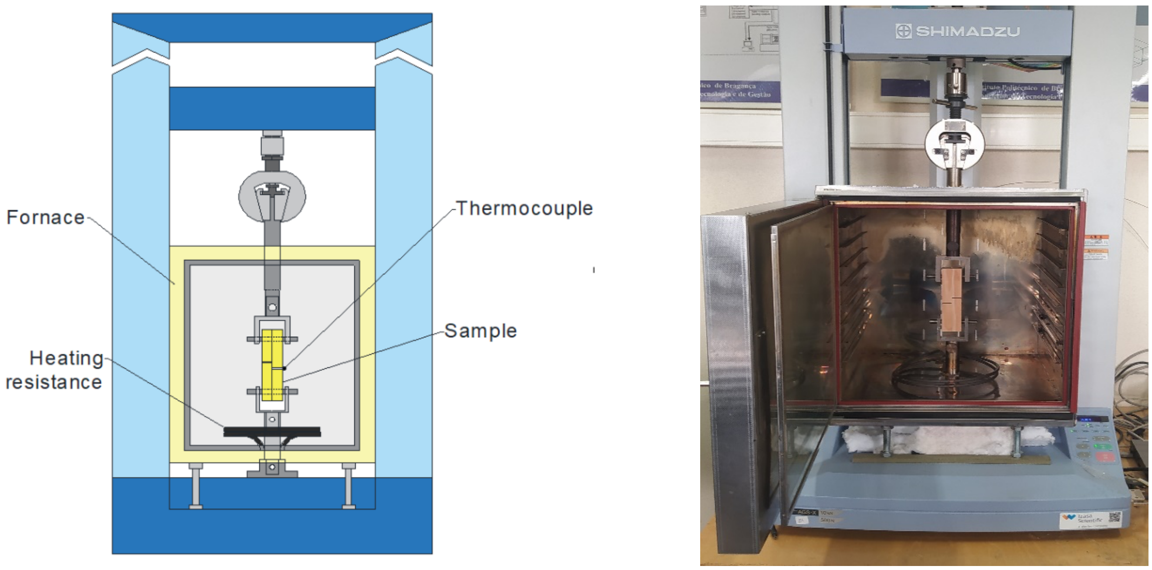
Adhesives	Flexpur151	Wurth
Base	MDI	Urea
Adhesive spread [g/m^2]	150	150
Application on both sides	Yes	No
Pressing pressure [N/mm^2]	0.7	0.4
Pressing temperature [ºC]	80	130
Pressing Time [minutes]	8	120
Open assembly [minutes]	2	2
Closed assembly [minutes]	3	3

a) b) c)

FIGURE 1. a) Pressing of the panels. b) Atmospheric conditioning. b) Specimen's dimensions.

The pressure and temperature were applied and controlled by a MonTech LP 3000 hydraulic press, as shown in Figure 1a. A thermocouple was inserted between both panels to ensure the correct temperature at the resin layer during the specified pressing time. After pressing the panels, the test specimens were cut in the configuration shown in Figures

1b and 1c and were conditioned at a temperature of 20 ºC and 65 % of relative humidity for a minimum of 7 days in a climatic chamber, see Figure 1b. The experimental tests follow the same procedure at room temperature and at elevated temperatures. In the last case the specimens were placed inside a furnace, where the interior temperature was controlled by a PID device. A tensile test machine was used to apply the load on the test specimens, see Figures 2a and 2b.



(a) (b)

FIGURE 2. a) Tensile test machine. b) Furnace.

The tensile load was applied with a displacement control using a velocity of 1 mm/min. until failure. The shear strength was calculated according to Equation 1, where the shear strength τ, in [MPa], is calculated with the maximum load applied, F_{max} [N], and the bonded area defined by l_2 [mm], the length of the bonded test surface, and b [mm], the width of the bonded test surface.

$$\tau = \frac{F_{max}}{l_2 \times b} \quad (1)$$

The primary objective of any structural adhesion bonded joint is to assure that it never fails before the joined structural elements. Depending on the design, a bonded joint can fail under different ways, as shown in Figure 3. Failure can occur by detachment at the interface between the adhesive and the adherent elements (adhesive failure), failure at the bond line (cohesive failure), tear of the adherent near the adhesion surface (panel tear failure) and stock-break failure, where the bond strength is higher than the element's strength. The classification of the failure modes is addressed in the standard ASTM D5573 [12], where six main failure modes are considered. This practice provides a simple means of classifying failure modes for adhesively bonded fibre-reinforced- plastic (FRP). Each failure mode classification is based solely on visual observation of the failure surface without the aid of a microscope or other means to magnify the surface. Figure 3 shows the failure modes considered in this study.

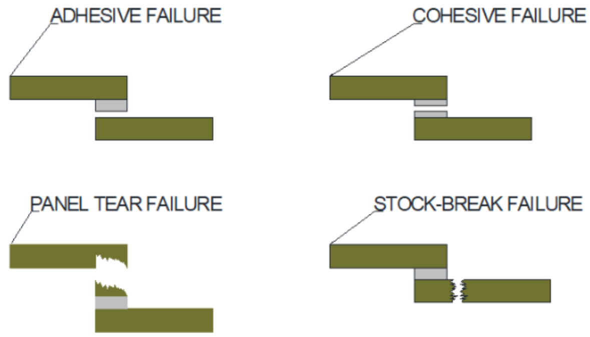
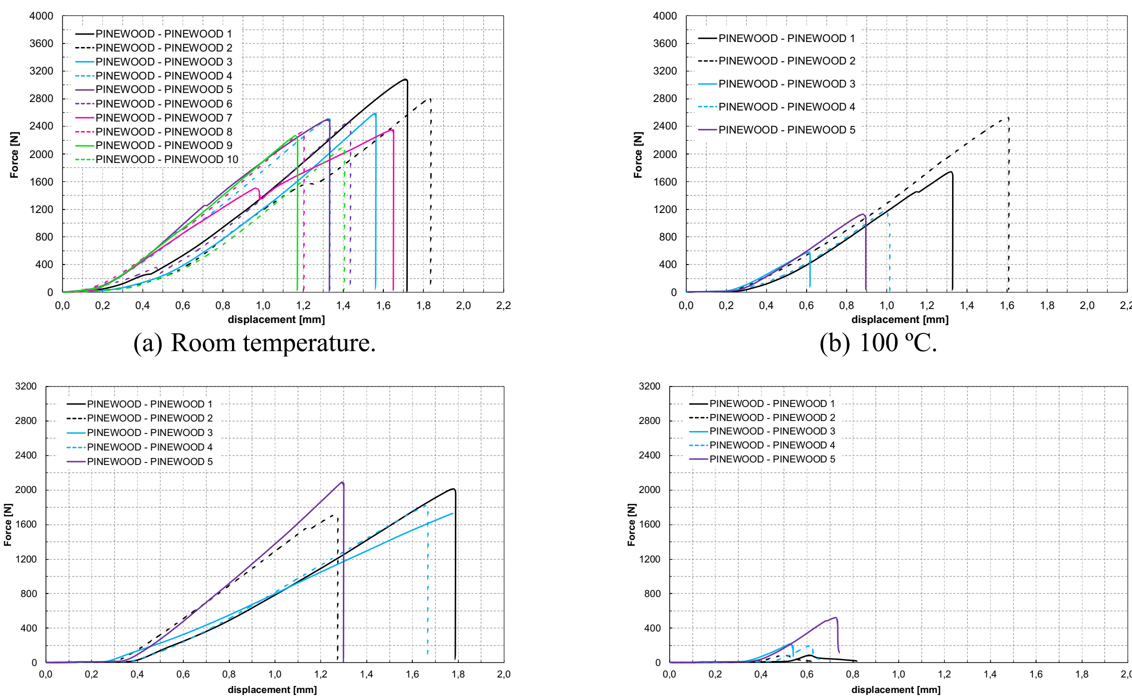


FIGURE 3. Classification of failure modes.

RESULTS

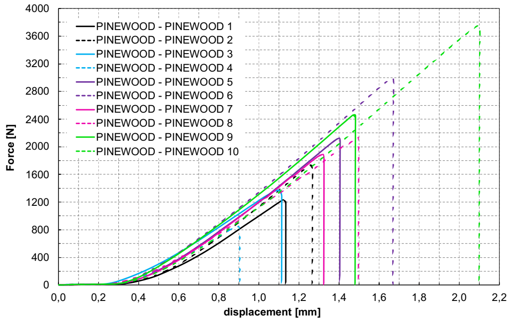
The applied load versus the axial displacement of the specimens is shown in Figures 4 through 7, for all tests performed with pinewood and MDF panels for the two resins analysed.



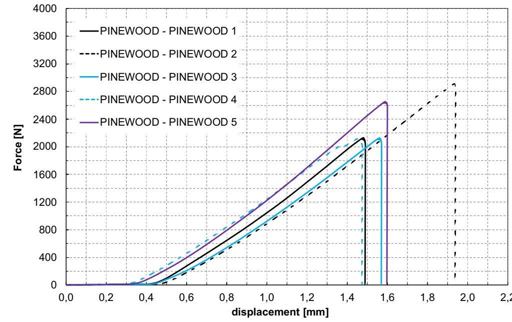
(a) Room temperature. (b) 100 ºC.

(c) 150ºC. (d) 200ºC.

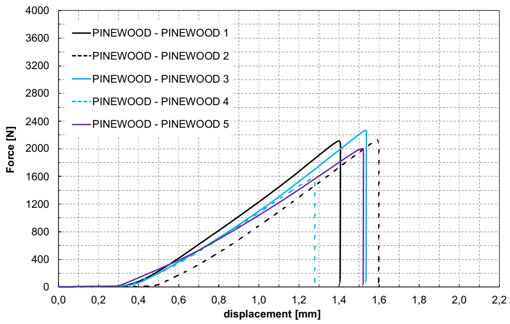
FIGURE 4. Results from pinewood-pinewood panels using urea resin at different temperature levels.



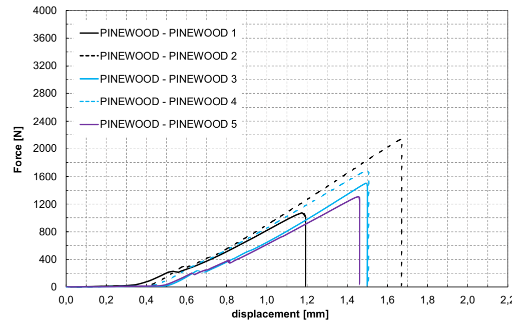
(a) Room temperature.



(b) 100 ºC.

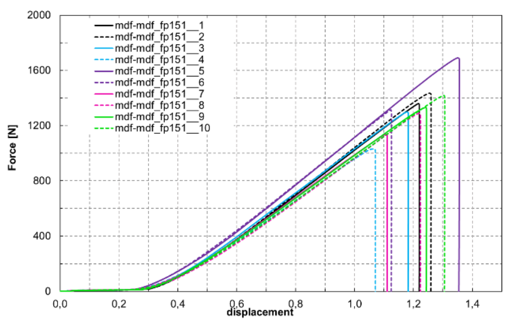


(c) 150ºC

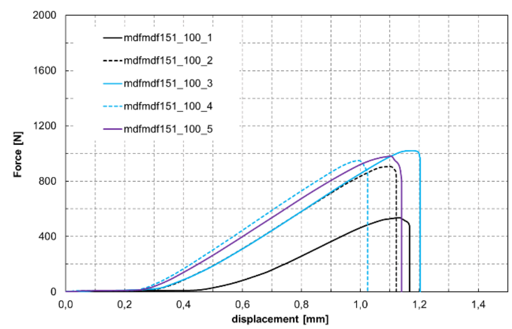


(d) 200ºC

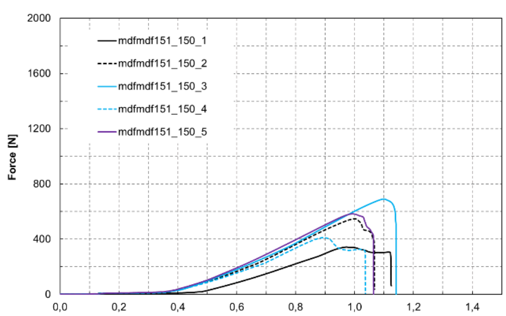
FIGURE 5. Results from pinewood-pinewood panels using MDI resin at different temperature levels.



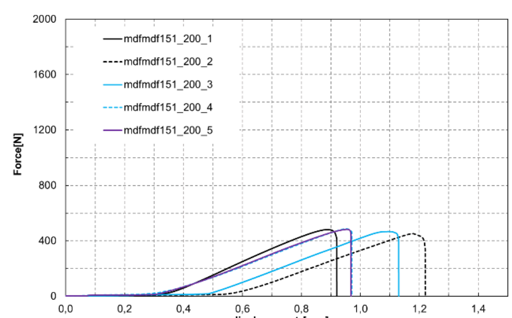
(a) room temperature.



(b) 100 ºC.

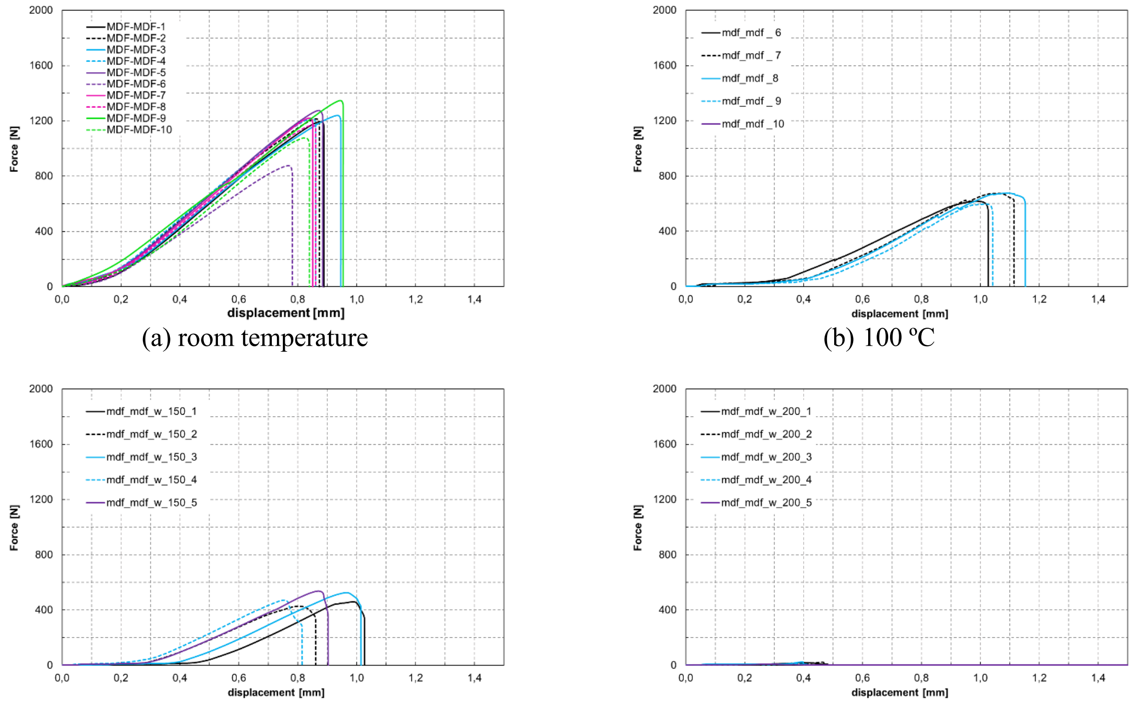


c) 150ºC



d) 200ºC

FIGURE 6. Results from MDF-MDF panels using MDI resin at different temperature levels.



(a) room temperature

(b) 100 ºC

c) 150ºC

d) 200ºC

FIGURE 7. Results from MDF-MDF panels using urea resin at different temperature levels.

The shear strength was calculated from Equation 1 and the average value was obtained for all tests, for the same temperature, resin, and adherent combination. The average values are presented in Table 3 and shown graphically in Figure 8, with standard deviation bars for comparison.

TABLE 3. Shear strength experimental average values, in [MPa].

Temperature	Pinewood-Pinewood		MDF-MDF	
	MDI-Resin	Urea-Resin	MDI-Resin	Urea-Resin
25	10.31	12.54	6.65	5.91
50	11.46	7.74	5.31	4.96
100	11.99	7.19	4.40	3.12
150	10.13	9.41	2.58	2.42
200	7.72	1.13	2.37	0.08

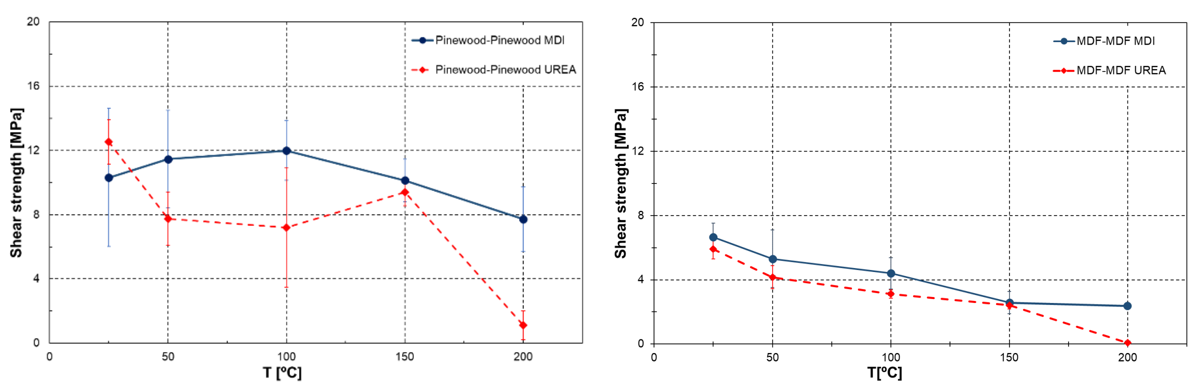


FIGURE 8. Shear strength temperature variation for different resins and adherent panels.

These results show a more significative shear strength reduction after a temperature of 150 ºC, for the case of pinewood panels, being more significative when urea resin is applied. An adhesion of MDF panels shows an almost linear reduction from room temperature to 200 ºC. In both cases, for temperatures above room temperature, the shear resistance obtained by urea resin was always smaller than the one obtained with MDI resin.

From the failure mode analysis and its surface appearance, for room temperature, 50 ºC, 100 ºC and 150º C, the failure mode of all MDF-MDF and pinewood-pinewood tests occurred by panel tear failure for both adhesives. For 200 ºC, the failure mode for all the specimens was by cohesive failure.

CONCLUSION

The performance of two adhesives, urea and MDI based, was evaluated at room temperature and at 50 °C, 100 °C, 150 °C, and 200 °C.

The shear tests with lap joints were performed using combinations of pinewood-pinewood and MDF-MDF. The experimental tests were done according to EN 205:2016, which allows for determining the shear strength of bonded joints.

The failure mode of the tested specimens was classified according to ASTM D5573. Except for the temperature of 200ºC, where the failure mode was due to cohesive failure, all the cases show a failure due to panel tear failure, for both resins.

The results show that the bonding strength and the displacement of the specimens decrease with the increase of the temperature. For example, for the urea resin, the shear resistance of MDF-MDF panels decreases about 50 % when exposed to 100 ºC with the failure mode usually occurring on the panel, and 98 % when exposed to 200 ºC. In the case of the MDI based resin, the shear resistance of MDF-MDF panels decreases about 35 % when exposed to 100 ºC and 65 % when exposed to 200 ºC.

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