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Effect of temperature on the mechanical performance of glued-in rods in timber structures

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ABSTRACT

Structural bonding technology has proven to be an economically and attractive connection process in timber engineering. Within old or historical wooden buildings, local reinforcement of weak zones is often performed with glued-in rods. This kind of connection typically allows the transfer of loads within wooden elements by means of threaded steel rods glued with a structural adhesive. This paper relates to experimental and numerical investigations on small sized specimens, with the aim of providing a better knowledge about the elastic behavior according to temperature. Experimental results reveal that stiffness of bonded-in rods significantly decreases once the glass transition temperature of the adhesive is reached. However, the ultimate shear strength is constant and sudden failures occur in the wood close to the adhesive whatever the temperature is. Then, an elastic finite element model allows the evolution of the Young modulus of the adhesive with temperature changes and also reveals the stress distribution along the glued-in depth during the elastic regime.

1. Introduction

Structural bonding technology and connections in timber engineering have undergone an important growth in the last few years. Connections with concealed rods bonded into timber are often used for rehabilitation (repair or reinforcement) of wooden structural members. This process appeared for the first time in French historical monuments in 1979. Such connections make the transfer of loads within wooden elements possible. They also offer esthetic benefits; the joint is inconspicuous and rods are hidden in the cross sections of the members. A large part of the original timber is preserved, since only the damaged part of the member is changed and replaced by a sound one.

Many experiments have been carried out to understand the short-term behavior of connections by glued-in rods and their dependence on geometric or material parameters [1–4]. The durability of structural adhesives, when bonding secondary materials into wood, has been examined by some researchers in relation to combined thermal moisture effects [5,6]. Aicher et al. [7] and Cruz and Custodio [8] revealed that glue lines inside timber structural members followed the outer temperature regime both in heating and cooling phases. Temperature inside roofs, recorded in summer 2004 in Portugal, did not exceed 45 °C, but peak temperatures of 75 °C have been measured in the USA [9]. The European standard EN301 [10] accepts 50 °C to be the limit between normal conditions and hot service conditions, to which different requirements are imposed concerning the adhesives performances (type I and type II). Currently, the European structural timber code [11] does not cover the design of structures subject to prolonged exposure to temperatures over 60 °C. Besides, other studies [12,13] disclosed that the load bearing capacity of bonded-in rods significantly decreased when the epoxy resins reached an intrinsic critical temperature also called the glass transition temperature (T_g). Once this temperature was attained, irreversible modifications of the inner structure of the polymer occurred. From this temperature, it is known that mechanical properties of the adhesive, and consequently of the corresponding connection, significantly decrease. Design rule proposals, predicting the pull-out strength of glued-in rods, are available [14,1,15] but the temperature is not taken into account in design. The lack of information regarding the performance of these connections under temperature changes is still a drawback for their use and the influence of temperature needs to be further analyzed.

In this work, the effect of temperature on the mechanical behavior of glued-in rods is studied through experiments and

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finite element computations. The inherent mechanical properties of each component of the connection are reported in a first part: the characteristics of rod and adhesive are investigated through experiments, whereas those of wood are deduced from its density and its moisture content. Then, an experimental campaign is carried out on glued-in rod connections. Tests were performed under pull-compression configuration because this set-up is more prejudicial for the mechanical study of glued-in rods. Indeed, the stiffness and strength of the connection were roughly 20% upper under pull–pull configuration [16]. At last, a finite element model (FEM) is calibrated in elasticity from experimental results. The numerical analysis provide information which is difficult to evaluate with experiments only. For instance, the stress field at wood–adhesive interface can be estimated and the evolution of elastic properties of the adhesive due to temperature changes can also be assessed. The main goal of this paper is to check the mechanical performance of the adhesive in conditions of use.

2. Materials: physical and mechanical properties

Seventy seven wooden specimens, with a $50 \times 50\ \text{mm}^2$ cross-section, made with spruce (*Picea Abies L.*) were used. After 2 weeks in a climate enclosure room with a controlled atmosphere, their moisture content (MC) was around 12%, which corresponds to the optimal humidity for the gluing process. Their average density was close to 0.42 with a coefficient of variation of 5%. Wooden specimens were longitudinally drilled in their full length (50 mm) with a hole diameter of 12 mm, in order to insert both rod and adhesive. Elastic characteristics of spruce were not measured directly but were estimated from the value of the density for $T=20\ ^\circ\text{C}$ and from the value of the MC for temperatures above through the usual relationship proposed by Guitard [17] (Table 1).

One threaded steel bar, with a nominal diameter of 8 mm and a length of 160 mm, was bonded in the wooden specimen with a two-component structural epoxy. Such a diameter was chosen in this study because it was recommended in design proposals that the minimal edge distance for rods glued-in parallel to grain should equal two and a half times the diameter of the rod. Besides, specimen's geometry was selected with regard to test machine and oven capacities. In practice, the diameter of the rod was also selected according to the wooden cross section, the edge distance, the distance between rods and the bearing load. An annular bondline thickness of 2 mm was created and the anchorage length was equal to 50 mm. The inherent mechanical properties of rod and adhesive were investigated through tensile tests for $T=20\ ^\circ\text{C}$; the coefficients of variation for each average value are indicated in Table 2. The results on both equivalent and tensile strengths of the rod take into account the thread rod and are similar to a 8.8 grade. The use of such a grade allows avoiding the plastic behavior of rod bars during pullout tests.

The estimate of mechanical characteristics of each component will allow an accurate implementation in a further finite element model. Authors are aware that it would have been ideal to measure directly the mechanical properties of wood, adhesive and rod at different temperatures; but, with regard to experimental equipment, it was unfortunately impossible to perform it.

In addition, differential scanning calorimetry was used to evaluate the glass transition temperature of the adhesive. The principle of this experiment consists in measuring the difference of exothermicity between the adhesive and a reference (air) as a function of temperature in the enclosure chamber. The evolution of the heat flow versus temperature is illustrated in Fig. 1. This graph clearly exhibits an inflexion point: a glass transition temperature of 58 °C is revealed, with an onset of the phase change, from glassy to rubbery, close to 52 °C.

If the temperature of the glued interface is above 58 °C or for higher temperatures (fire exposure), a significant decrease of mechanical performance can produce irreversible damages in the connection. Thus, the influence of temperature on mechanical performance of the connection should be investigated.

Table 1
Elastic characteristics of wooden specimens. T is the temperature, MC is the average moisture content, $\rho^{12\%}$ is the density for a MC of 12%, E is the modulus of elasticity, G is the shear modulus and L, R, T are the three orthotropic directions of wood.

T (°C)	20	30	40	60	80
MC (%)	12 (0.02)	12 (0.02)	11 (0.05)	7 (0.11)	3 (0.13)
$\rho^{12\%}$ (kg/m^3)	410 (0.05)	412 (0.02)	422 (0.03)	432 (0.03)	428 (0.05)
E_L (MPa)	11,430	11,430	11,600	12,290	12,460
E_R (MPa)	905	905	930	1040	1070
E_T (MPa)	560	560	580	645	660
G_{LR} (MPa)	780	780	800	900	920

3. Experiments on glued-in rods

3.1. Experimental set-up

Experiments have been carried out in order to study the influence of temperature on the short-term behavior of small-sized glued-in rods [16]. They were performed in two steps: first, connections were heated in an oven until the glue line reached the target temperature (30, 40, 60 or 80 °C) and then they were tested under pull-compression configuration (Fig. 2) outside the oven. In each batch of tests, a thermocouple was introduced at the moment of bonding in the annular bondline thickness of one specimen. With this device, it was possible to ensure that the adhesive well reached the target temperature. However, specimens were not insulated during the heating process which inevitably induced a loss of their MC (Table 1). Then, bonded-in rod connections were tested at constant cross-head displacement rate equal to 0.5 mm/min, producing a short-term failure. Displacement control tests

Table 2
Mechanical properties of rod and epoxy (average values). f_y is the equivalent yield strength, E is the elastic modulus, ν is Poisson's ratio and σ is the tensile strength.

Rod		Epoxy	
f_y (MPa)	580 (0.07)	E (MPa)	4,270 (0.11)
E (MPa)	180,390 (0.04)	ν	0.343 (0.02)
σ (MPa)	835 (0.02)	σ (MPa)	28 (0.20)

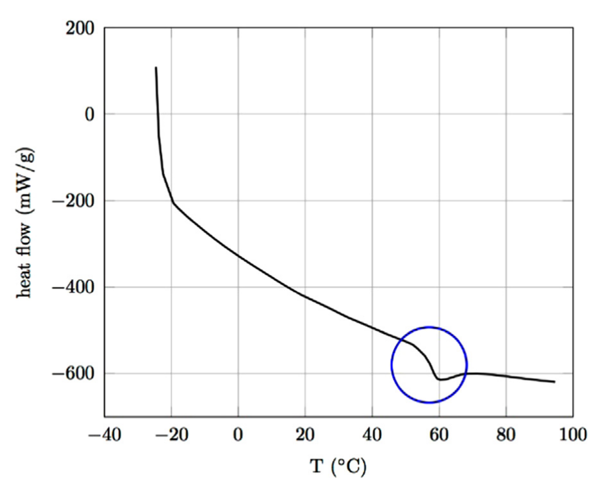

Fig. 1. Glass transition temperature emphasis.