Construction and Building Materials 186 (2018) 438–453

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Temperature effect on the mechanical behavior of glued-in rods intended for the connection of timber elements

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HIGHLIGHTS

- Characterization of the properties of epoxy adhesive at high temperature.
- Pull-out tests at high temperature, parallel and perpendicular to the wood grain.
- Two different pull-out test methods at stabilized temperature and at constant load.
- Analysis of the failure modes of the tests specimens.

ARTICLE INFO

Article history:
Received 13 March 2018
Received in revised form 13 July 2018
Accepted 17 July 2018

Keywords:
Glued-in rods
Bond strength
High temperatures
Glued laminated timber
Parallel and perpendicular to grain
Glass transition temperature

ABSTRACT

The application field of glued-in rods (GiRs) has been extended over the years to include new timber constructions thanks to their high stiffness and to the technical solutions they offer to achieve high mechanical performance. However, the mechanical behavior of GiRs seems to be affected by several parameters, and in particular by temperature changes. This paper presents an experimental investigation on the mechanical behavior of GiRs bonded parallel and perpendicular to wood grain by means of pull-out tests at stabilized temperature and at constant load. In addition, complementary physico-chemical and mechanical characterizations were carried out on the bulk epoxy adhesive which was used for the fabrication of the GiRs specimens, in order to correlate the temperature behavior of the overall GiR connection to that of the polymer adhesive. Results of pull-out tests revealed a gap between experiments performed at stabilized temperature and those at constant load. Such a gap was attributed to physical, chemical and mechanical phenomena occurring in the epoxy resin at high temperature, and highlighted the major influence of the resin glass transition (*Tg*) of the polymer adhesive on the temperature behavior of the GiR connection.

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1. Introduction

There are three general methods to connect timber structure elements: traditional methods using carpentry connections, mechanical methods using fasteners, and modern methods using adhesives [1]. Glued-in rods (GiRs) is now commonly used for connecting timber structures, but only in few European countries, in Australia and in North America [2]. It was developed for the first time in Denmark by Riberholt in 1986 [3] and consists in gluing a rod, often made from steel or glass fibers reinforced polymer (GFRP), into a timber element using a structural adhesive [4]. This technology belongs to a wide range of hybrid joints since it involves three different materials (timber, rod and adhesive).

The efficiency of glued-in rods in transferring load between the structure elements depends on several parameters such as the geometry of the adhesive joint, the materials used, and the loading and boundary conditions [2]. Fig. 1 shows a non-exhaustive list of these parameters. Many researchers were interested in studying the influence of each of these parameters on the global behavior of the GIR connection at ambient temperature. The research work was focused on studying the influence of material properties, such as wood species and products [4,5], and timber density on modifying the mechanical behavior of GiRs [6,7]. Indeed, the timber density modifies the stress distribution along the bonded area, and therefore, may affect the mechanical behavior of GiRs [8]. However, researchers have staffed different opinions [7]. Some of them managed to establish a relationship between timber density and

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https://doi.org/10.1016/j.conbuildmat.2018.07.122
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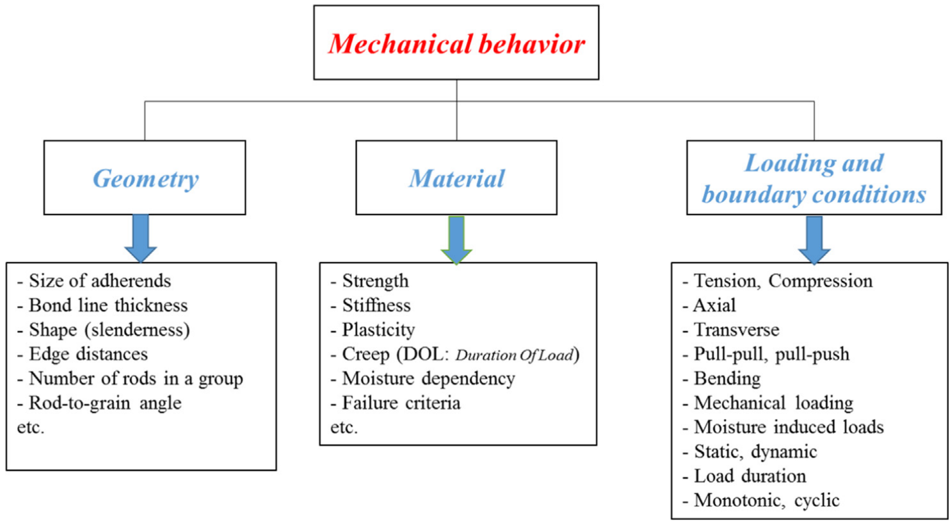

Fig. 1. List of parameters affecting the mechanical behavior of glued-in rods [8].

mechanical properties of GiRs [9,10,11,12], while others asserted the mechanical properties to be independent of timber density [13] or to exhibit poor correlation [14,15,16].

The orientation of the rod with respect to the wood grain direction is of major influence on the mechanical behavior of GiRs. Indeed, it was demonstrated by Rajcic et al. [9] that when the rod is glued parallel to the grain, the glued-in rod connection exhibits a brittle failure mode, while, when the rod is glued perpendicularly to the grain, it exhibits a ductile failure mode. Pull-out tests carried out on both directions showed that the bearing capacity of GiRs is 20% to 50% higher when the rod is set perpendicular to grain [6].

Several types of structural adhesives were also tested for bonding rods into timber. These systems are mainly polyurethane (PU), phenol-resorcinol-formaldehyde (PRF) and epoxy (EPX) adhesives [10]. All the researchers agreed that the epoxies achieve the best mechanical performance regardless of the test conditions and configurations [11,10,12,13,14].

Studies concerned with geometric parameters of GiRs have also been reported in several publications. They showed that the increase in the embedment depth leads to an increase in the bearing capacity of GiRs [6,7]. However, it was reported in [15] that no changes in the bearing capacity of GiRs could be observed when the embedment depth exceeds 20 times the diameter of the rod.

The effect of the adhesive joint thickness on the mechanical performance of GiRs has generated contradictory opinions [16]. Several researchers believe that the increase in the adhesive joint thickness leads systematically to an increase in the bearing capacity of glued-in rods since the bonded surface area increases [10,17]. In addition, it was demonstrated that the increase in the joint thickness reduces the amplitude of the stress peak at the edge of the bonded area [10] and leads to a more uniform shear stress distribution along the rod [2]. However, the current trend in the literature consists in reducing the thickness of the adhesive joint [18] since, according to some researchers, increasing this thickness does not lead to significant improvements in the mechanical performance of GiRs, and besides it is possible to increase the bonded surface area in a more economical manner by simply increasing the diameter of the rod.

Tests carried out on GiRs with different diameters of rods confirmed that increasing the rod diameter improves the bearing capacity. According to Broughton et al. [10], increasing the rod diameter decreases the stress peak amplitude at the steel/resin interface near to the top of the bond. However, studies showed that the relationship between the bearing capacity of GiRs and the rod diameter is not linear and is rather difficult to establish [19]. Some tests have been carried out on GiRs with a hole diameter equal to the nominal diameter of the rod minus the depth of the threads in order to benefit from the mechanical locking in addition to adhesive bonding. Unfortunately, this technique was found to be very difficult, even impossible to implement and does not ensure that the resin covers the entire surface of the rod [20].

To summarize, several studies have shown the dominance of the embedment depth and the rod diameter (hence the thickness of the adhesive joint) on the bearing capacity of GiRs [21,22]. Aicher et al. [23] and Steiger et al. [7] have grouped these two parameters in a single parameter that they called slenderness, equal to the ratio between the embedment depth and the hole diameter($\lambda = \frac{l}{d_h}$). Parametric studies have shown that a high slenderness leads to steel rod yielding and therefore to a ductile failure mode [4], and to an increase in the bearing capacity of the glued-in rod connection as well, by decreasing the stress peak at the beginning of the rod [6].

Despite the numerous national/international projects and despite the widespread use of GiRs for the connection of timber elements, it should be noted that there is no unified test method for assessing the mechanical behavior of GiRs so far [24]. Fig. 2 represents the results of a statistical study carried out by Stepinac et al. [25] on various experimental methods used to assess the mechanical behavior of GiRs. Some of these test methods are illustrated in Fig. 3. Results show that even though the pull-pull and pull-compression configurations do not correspond to the practical application of GiRs [2], they remain the most popular test methods.

Despite the abundance of the research work dedicated to the influence of geometric and material parameters, only few studies deal with the impact of environmental factors, and especially exposure to high temperatures, on the mechanical behavior of GiRs [27,28]. Some of these studies highlighted an important decay of the mechanical performance of GiRs for relatively low temperatures reached in the adhesive joint (40 °C–60 °C) [3,27,28,29,30]. These studies emphasized the vulnerability of GiRs in the case of fire event and showed a link between the fire resistance of GiRs and the mechanical behavior of the adhesive joint at high temperature. Therefore, with the growing use of GiRs in timber structures, there is a strong need to identify factors involved in the loss of mechanical performances at elevated temperature since it is a regulatory requirement for most of the buildings.

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