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Resistance-curves and wood variability: Application of glued-in-rod

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ABSTRACT

The current study investigates the withdrawal strength of glued-in rods as part of linear elastic fracture mechanics. An experimental campaign was performed in order to observe the effect of the specie (spruce and oak) on the axial strength of glued-in rods for given geometrical configurations. Finite elements modelling was presented in order to consider the progressive damage and the crack propagation located at the wood-adhesive interface (failures obtained during experiments). The approach aims at separating the progressive failure due to mode I and mode II. For this, Resistance-Curves, regarded as material properties, were used to characterize the peeling and the shear effects at the ultimate state. The study reveals that the mode I initiates the damage in the glued interface. Using several finite element runs, the predicted pull-out strengths were estimated from the elastic properties of substrates (wood, adhesive and steel) and the fracture properties of wood. Numerical results show the dependence of the strength according to the stiffness of the materials. Moreover, the scattering of the results is also affected by the variability of the fracture energies of the wooden substrates. The investigation leads to propose a robust approach which is able to predict the axial strength of glued-in-rods, considering the variability of each material and combining damage and crack propagation of the wooden substrate. It reveals that the prediction of the ultimate load cannot be performed considering only the failure mode II.

1. Introduction

The glued-in rods technique has been developed for 50 years for repairing ancient and decayed timber structures. It has also a high potential for new constructions, such as multi-storey or large span structures. Numerous advantages widen the scope of timber connection design: hidden steel elements, high prefabrication level, high stiffness, low loss of working timber ratio. This technique consists in sticking steel rods (or glass fibre rods), mainly axially loaded, to timber members with structural adhesives like epoxy or polyurethane. Nevertheless, it still requires a better understanding of their mechanical performance, know-how and quality control. Many research projects have been carried out to assess this process and aimed at the proposition of design formulas [1–5]. However, no reliable modelling of the mechanical performance is yet available. The lack of understanding increases as duration of load and effect of temperature are involved. Riberholt's attempt, once as informative annex in the European pre-Standard Eurocode 5 [6], has then been removed at early stage, preventing a recurrent use in timber engineering. Consequently, companies performed private investigations and research projects [7], demonstrating the need of application and the great potential of this technique in timber building. The first step is the enhancement of consistent models in order to understand better the failure mechanisms of the glued interface for short-term loading. It aims at assessing the contribution of the mechanical properties of each component on the resulting axial strength. It may offer a large variety of configurations with a required safety index for designers. Structural adhesives used in timber engineering should be designed taking into account the variability of the substrates.

Experimental investigations and theoretical approaches were currently proposed in literature in order to predict the load bearing capacity of such connections. In most of experimental studies, the axial load bearing capacity of glued-in rods were typically investigated according to geometric and material parameters. The thickness of the interface and its anchorage length are investigated in [8,9]. The studies revealed mainly that the anchorage length and more particularly the slenderness of the rods was a relevant parameter for the design. Different species were also tested [10,11], illustrating the potential effects of the density, which modifies the elastic properties of wood. All studies focused on the strength of the joint (axially and perpendicular to the grain [12]), in order to have design formulas developed by curve fitting of

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Nomenclature

a	length of the crack along the interface as part of LEFM (mm)
a_c	length of the crack producing a crack propagation at a constant critical energy released rate (mm)
a_u	length of the crack at ultimate load (mm)
A_s	area of the rod (mm^2)
COV	coefficient of variation (%)
$G^*(a)$	critical energy released rate induced by damage and crack growth (J/m^2)
$G_I(a)$	energy released rate in mode I for a load equal to 1 N (J/m^2)
$G_{II}(a)$	energy released rate in mode II for a load equal to 1 N (J/m^2)
$G^*_I(a)$	critical energy released rate in mode I when G*(a) is reached (J/m^2)
$G^*_{II}(a)$	critical energy released rate in mode II when G*(a) is reached (J/m^2)
$G_{RC,I}$ (a)	critical energy released rate in pure mode I (J/m^2)
G_{RI} (a)	R-curve in mode I according to a (J/m^2)
K	ratio between critical energy release rates in mode I and mode II
l_a	anchorage length (mm)
P_u	failure load of the single bonded-in rods (N)
S	initial stiffness of the connection (N/mm)
r	radius of the rod (mm)
$S(a)$	stiffness of cracked specimen (N/mm)
$S'(a)$	derivative function of $S(a)$
$R_I(a)$	part of mode I in function of the global energy released rate

empirical data. Most of experimental investigation exhibited adhesive failure of the glued interface (wood/adhesive), and few information are given concerning the quasi-brittle behaviour obtained during tests, since ultimate load was regarded as the crucial parameter. Similar observations were present in experimental campaign led for timber components reinforced longitudinally with glued-in rods for instance [13–15]. The quasi-brittle behaviour indicates the potential damage in the interface producing a loss of stiffness before the ultimate failure of specimen.

Tlustochowicz et al. [16] published also an interesting state of the art overview concerning glued-in threaded steel rods from European studies. With a scope more general, Custodio et al. [17] examined the factors influencing the durability of structural bonded timber joints. The ultimate load of a single glued-in rod is then associated to the shear strength of graded timber and its related density [18–20]. The delamination of the wood-adhesive interface is often considered as the failure due to the shear stress distribution. This assumption reduces the number of parameters for the design, but the accurate calibration of such a model becomes difficult, since the stress state is more complex along the glue line [21–24]. The second proposal consists in using fracture mechanics. In this kind of approach, the assumption of a pre-existing crack in the joint induces a stress singularity and then a traditional maximum stress criterion can be no longer applied. For instance, using linear elastic fracture mechanics (LEFM), Serrano et al. [25,26] proposed an evaluation of the load bearing capacity of a glued-in rod assuming that failure of the joint occurred when the energy release rate was equal to the fracture energy in mode II. Gustafsson et al. [27] took into consideration the initial damage preceding the failure of a joint by using non-linear fracture mechanics (NLFM). This approach combines both the strength of the bond-line and the fracture energy. Such analysis required knowing the fracture energy of the materials that is unusual for designers. It is also currently assumed that the degree of anisotropy of species is constant [24,27]. Variability of the materials on the resulting strength of the connection cannot be assessed. Three theoretical approaches were used in literature to describe the strength of connections: traditional strength analyses, LEFM and NLFM analyses. Their corresponding benefits and disadvantages were well described in a recent paper [28]. The quasi-brittle behaviour of glued-in rods demonstrated clearly that design considering stress analysis and/or Linear Fracture Mechanics (using fracture energy) only are not sufficiently appropriated. Consequently, NLFM has the advantage to describe the mechanical performance of these connections, but other approaches are possible and it is the interest of the investigation. As part of fracture mechanics, the assumption that the glued-in rods failure is mainly due to the shearing mode (mode II) is often made. Nevertheless, some recent studies [29,30] reveal significant peeling at the beginning of the anchorage length. In this study, the failure mechanism of glued-in rods is investigated by combining two approaches: LEFM and Resistance-Curves. The use of R-Curves considered as mechanical properties of materials is useful to reproduce and to describe the quasi-brittle behaviour [31]. The interest is to apply the concept to the design of glued interface when the failure is adhesive. It is proposed to use a previous mixed mode fracture criterion on different glued-in rods configurations. The aim is to study the effect of the fracture energies and the elastic properties of materials on the withdrawal strength of a single glued-in rod. The pertinence of this method is discussed according to the studied species (spruce and oak) and for different anchorage lengths. Finite element (FE) computations are used to provide design concepts taking into account the variability of materials. The interest is to demonstrate that the proposed method is a useful means to investigate the failure mechanism at a meso-scale. A comparison of this numerical approach with experimental results is also discussed.

2. Experiments

A preliminary experimental campaign [31] was carried out on spruce and oak in order to understand the effect of their mechanical properties on the axial strength of a single bonded-in rod. Thirty-five cubic specimens of spruce (*Picea abies* L.) and thirty-six specimens of oak (*Quercus* L.) with an edge of 50 mm were used. The wooden specimens were seasoned for 7 days in a climate enclosure room with a temperature of 20 °C and a relative humidity of 65%. So, their moisture content reached a value close to 12%, which corresponds to the optimal humidity for the gluing process. The average density of spruce and oak was respectively 0.46 and 0.75, which correspond to a grade of C30 and D40 [32]. The characteristic shear strength values for spruce and oak are similar and equal to 4 MPa. Concerning the strength perpendicular to the grain the values are respectively 0.4 MPa and 0.6 MPa. These values are conservative, and they are used for design application. Consequently, if the failure is only due by shear, the glued-in-rods strength (characteristics value) would be the same for both species. The experimental campaign aims at investigating the mechanical performances obtained for spruce and oak for similar configurations. The potential differences will be analysed by means of fracture mechanic in order to extract additive properties