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Experimental and analytical analysis of moment-resisting connections with glued-in rods

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ABSTRACT

The advances of timber engineering in the field of tall buildings raised a need for high performance connections that can accommodate increased demands due to higher loads and longer spans. A semi-rigid connection with glued-in rods was designed to fulfill these requirements. Moment-rotation behavior of this connection was investigated in a series of quasi-static cyclic tests. A moment-resisting connection was established between timber columns and steel base plates. Three different timber products, including hardwood and softwood species, and two different rod diameters were used. The columns were subjected to shear force and bending, to simulate the loading conditions of a column in a frame under lateral loads. The tests were performed with increasing rotation demand on the column until the failure.

The connections provided high moment capacity and rotational stiffness. All of the tested specimens demonstrated ductile response, while the connections with hardwood performed especially well. No strength degradation was observed in multiple cycles, therefore the hysteretic energy dissipation was significant in cycles with high target displacement.

The nature of the connection response was studied in detail and an analytical model was developed to describe the relationship between the moment and the rotation at the column base. The model is capable to predict the envelope of the cyclic response and corresponds well to the experimental results.

1. Introduction

Recent developments in timber engineering resulted in an increased interest in use of this material for tall buildings [1]. There are multiple benefits in choosing timber for the load bearing structure over concrete or steel, as the material production is sustainable, the material stores CO_2 from the atmosphere and the structural elements can be recycled after the intended life-time of the building [2,3]. Although in the past timber buildings were mainly limited to few stories, new reliable timber products and massive elements can nowadays be found also in multi-story buildings [1]. In order to comply with the requirements of the codes, strong and stiff connections are needed to promote the construction of timber buildings. The strength of the connection has to be sufficient to address the increased force demand, while an adequate stiffness is necessary to limit the structural displacements.

One of the solutions for a strong and stiff connection is to use glued-in rods. Different products are available on the construction market, including steel rods, as well as the fiber reinforced polymers, with glass [4] or carbon fibers [5]. Extensive investigations were made in this field in the last 30 years, resulting in different proposals for the estimation of pull-out strength. The design proposals are mainly based on fitting the experimental data from the pull-out tests [6], and are valid only for specific types of connections tested, i.e. timber products and geometries. Experiments showed that the timber species is an important factor in determining the pull-out strength of the connection, since significantly higher strengths were achieved with hardwood [7]. However, adequate models to calculate the pull-out strength in hardwood are currently not available.

Connections with glued-in rods can be found in axially loaded elements, but also in beam and column elements, thanks to their high moment capacity and rotational stiffness. Already in the early stages of research in the field of glued-in rods, Riberholt pointed out the possible application of moment stiff column-foundation connections [8]. Riberholt clearly distinguished between the connection that relies only on the capacity of the rods, without contact between the timber column and the base, and the connection with tampered mortar, where a close contact is established. Moss et al. studied moment-resisting connections between beams made of glued laminated timber (glulam) and steel supports [9]. They successfully applied three different types of connection capable to

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Nomenclature

b	width of the column section
c	modulus of subgrade reaction
c_t	deformation of timber at the compressed edge of the column
$d_{s,i}$	distance of the row i from the compressed edge of the column
$f(s_i)$	stress-displacement relationship for the steel rods
f_u	ultimate strength of steel
f_y	yield strength of steel
$f_{c,0}$	strength of timber in compression parallel to the grain
h	height of the column section
s_i	elongation of the steel rods in the row i
x_c	depth of timber section in compression
$A_{s,i}$	area of the steel rods in the row i
D	ductility
$E_{c,0}$	modulus of elasticity of timber in compression parallel to the grain
F_t	force in timber
$F_{u,mean}$	ultimate strength of the steel rod, mean value
$F_{u,nom}$	ultimate strength of the steel rod, nominal value
$F_{y,mean}$	yield strength of the steel rod, mean value
$F_{y,nom}$	yield strength of the steel rod, nominal value
$F_{EN,k}$	pull-out strength according to prEN1995–2, characteristic value
$F_{Rib,k}$	pull-out strength according to Riberholt, characteristic value
$F_{Ros,k}$	pull-out strength according to Rossignon et al., characteristic value
$F_{St,mean}$	pull-out strength according to Steiger et al., mean value
$F_{s,i}$	force in the steel rods in the row i
K	unloading rotational stiffness of the connection
M	bending moment at the base of the column
N	number of rows of steel rods
ν_{eq}	equivalent viscous damping ratio
ρ	density of the timber product
σ_t	stress in timber at the compressed edge of the column
θ	rotation at the base of the column

withstand the combination of bending and shear force, with center bar, angle bar and tie bar to accommodate the shear stresses. Tomasi et al. devoted their research to the investigation of a steel-to-timber joint suitable for implementation in seismic resistant timber structures [10]. The shear force transfer was ensured by means of end-plates glued into the slots in timber elements and the bending moment was transferred via glued-in rods. Numerical and experimental investigations were performed to describe the moment-rotation behavior of such connections. Jensen and Quenneville expressed their interest into connections with hardwood rods [11]. They evaluated theoretical models for design of connections with glued-in rods subjected to combined bending and shear actions through an experimental campaign performed on moment-resisting connections subjected to pure bending and pure shear. Gehri showed different applications of high performing jointing technique using glued-in rods [12]. GSA®-technology was used to establish a ductile beam joint capable to provide almost full moment capacity and stiffness of the timber beam. Gehri also emphasized the importance of using hardwood, which allows higher pull-out strength to be reached with the same rod size. Gattesco et al. investigated the performance of connections with glued-in rods under pure bending, considering both monotonic and cyclic load application [13]. They showed that ductile behavior can be achieved without significant pinching in hysteretic loops, and came to the conclusion that the joint ductility is significantly larger for monotonic, compared to cyclic loads. Xu et al. analyzed the behavior of timber connections with glued-in rods in bending experimentally and numerically [14]. Furthermore, they proposed analytical models to predict the initial stiffness and the moment capacity of the connections. A series of experiments on timber moment connections using glued-in steel rods was performed by Oh [15]. The main objective of the study was to determine the requirements that will ensure ductile failure of the connection, investigating the impact of different parameters.

A three-bay frame with pinned column supports was tested under horizontal loads, concluding that the limiting factor for the structural design is the horizontal displacement [16]. A base connection with glued-in rods was suggested to improve the performance of the frame. The aim of the experimental campaign presented here was to quantify the response of such connection to loading conditions that would be expected in a real frame structure. Preliminary tests were made to determine the mechanical properties of timber and steel. Pull-out tests were performed on single rod specimens to verify the design that assumes failure by yielding of the steel. The performance of connections with multiple rods and different timber products was investigated under quasi-static cyclic load.

2. Preliminary tests

The response of a composite connection with timber and glued-in rods is influenced by the mechanical properties of both materials and the behavior of the bond between them. The preliminary tests were conducted on the components of the connection. The tests aimed to verify the behavior of the rods in tension, confirming the mechanical properties given by the manufacturer, and behavior of the timber products used in the campaign in compression. Furthermore, pull-out tests were performed on specimens with a single glued-in rod to verify that the failure mode of the connection will be ductile.

2.1. Tests on the steel rods

The first series of tests was performed on single steel rods to determine their actual yield and ultimate strength. Knowing the exact properties of the reinforcement is significant for the adequate design of the connection. One must ensure that the yielding of the rods will occur before the pull-out failure, since only in this way the connection will have a ductile behavior.

Two groups of six metric rods M12 and M16, nominally of grade 4.8, with length of 500 mm were tested in the universal testing machine Schenck 480 kN. The rods were tested with a uniform displacement rate of 1 mm/min up to approximately 40% of the estimated tensile strength, unloaded, and finally tested until the failure. After yielding was detected, the displacement rate was increased to 4 mm/min. The test results are listed in Table 1, confirming the grade [17]. The yield strength was measured at the end of the linear range, while the ultimate strength was calculated based on the maximum tensile force in the test. High discrepancy was observed between the nominal and the measured strength of the steel rods (Table 1). Although designing the connection with nominal steel properties results in conservative estimation of capacity, it must be ensured that failure mode does not change