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Behaviour and repair of carpentry connections – Rotational behaviour of the rafter and tie beam connection in timber roof structures

Pedro Palma [a,*], Helena Garcia [b], João Ferreira [c], João Appleton [d], Helena Cruz [a]

[a] National Laboratory for Civil Engineering, Timber Structures Division, Avenue Brasil 101, 1700–066 Lisboa, Portugal
[b] Tecnovia–Sociedade de Empreitadas S.A., Casal do Deserto, 2740–135 Porto Salvo, Portugal
[c] Technical University of Lisbon, Department of Civil Engineering and Architecture (ICIST/IST/UTL), Avenue Rovisco Pais, 1049–001 Lisboa, Portugal
[d] A2P Consult Estudos e Projectos, Lda, Rua Acácio de Paiva, 27, 2°, 1700–004 Lisboa, Portugal

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ABSTRACT

An extensive experimental campaign on structural carpentry connections, namely the rafter and tie beam connection, was conducted to assess their rotational behaviour and the effectiveness of some common repair and reinforcement techniques. The mechanical behaviour was appraised for different geometries, metal fastening devices and moisture content of timber. After the mechanical tests, some of the connections were repaired and tested again, which allowed comparing the performance of the original and the repaired connections. The compressive internal force in the rafter influences the connection's behaviour, being crucial in maintaining the integrity of some of these carpentry joints. This aspect required a complex test apparatus and the design of specific equipment to simultaneously apply the compression force and the rotations in the rafter specimen. The experimental results show that some configurations exhibit enough rotation stiffness and load bearing capacity to be accounted for when appraising the roof structures they belong to, enhancing the common assumption of hinged joints. The connection's behaviour is different when opening or closing the skew angle. Each connection typology exhibits specific load bearing mechanisms which dictate different performances and failure modes, which should be considered when devising a repair.

1. Research aims

The research presented in this paper aims at characterizing the mechanical behaviour of structural carpentry connections in timber roof trusses and appraise the effectiveness of some common repair and reinforcement techniques. The results are intended to provide guidance to the engineers involved in the structural assessment of existing timber structures and planning the repair or reinforcement interventions, regarding the performance of the carpentry connections, which play a major role in the overall structural behaviour.

2. Introduction

Connections in old timber structures, namely in roof structures, usually rely on notches on the structural elements, through which the internal forces are transmitted by compression and friction in the contact surfaces. These connections are often complemented with metal parts, some added during construction, e.g. to allow the connections to withstand tensile forces, or to increase their strength or stiffness, and some are added later, to repair or strengthen underperforming connections.

As current design standards [1] and building codes focus primarily on modern industrialized mechanical or bonded timber connections, they provide little or no guidance to engineers involved in the assessment of existing structures, who often face difficulties when making assumptions about the behaviour of carpentry connections. In addition, current guidelines and standards point towards maintaining the connections' "original stiffness" [2,3], reserving stiffening intervention techniques to extreme degradation scenarios, because of their influence in the overall structural behaviour. Likewise, the growing interest in carpentry connections has increased the demand for design methods, in part due to the development of CAD/CAM systems and CNC machinery which makes it possible and affordable to produce complex and accurate timber members and connections.

Therefore, it is necessary to establish design and detailing rules and to provide criteria for the assessment of carpentry connections in existing structures, as well as recommendations for repair or strengthening interventions.

* Corresponding author. Tel.: +351 21 8443893.
E-mail addresses: ppalma@lnec.pt (P. Palma), helena.garcia@tecnovia.pt (H. Garcia), joao.ferreira@civil.ist.utl.pt (J. Ferreira), joao.appleton@a2p.pt (J. Appleton), helenacruz@lnec.pt (H. Cruz).

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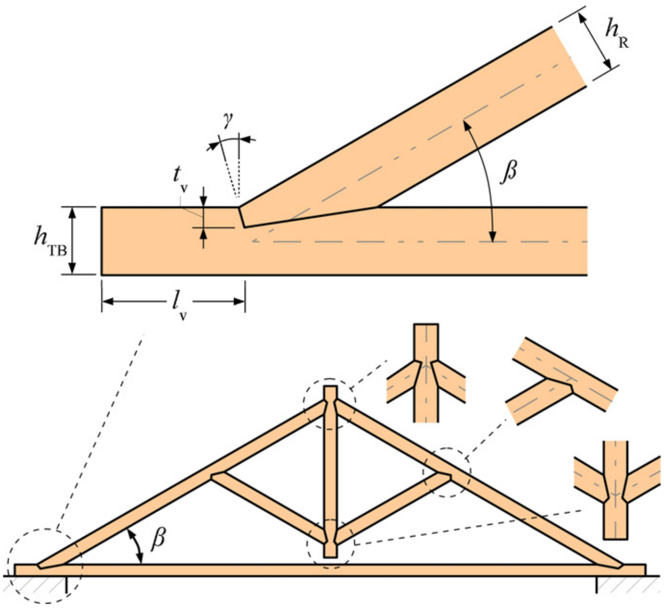

Fig. 1. Traditional roof truss and rafter and the tie beam connection.

This paper presents the results of an extensive experimental campaign, carried out at the Portuguese National Laboratory for Civil Engineering (LNEC), aimed at characterizing the rotational behaviour of the most frequently observed configurations of the rafter and tie beam connection in timber roof trusses. The experimental campaign comprised two stages: a first stage, in which the connections' behaviour was characterized, regarding the influence of geometry (notch depth and presence of mortise and tenon), of commonly employed metal fasteners (bolted steel plates and clamps), and moisture content of timber in the connection behaviour; and a second stage, where some of the previously tested connections were repaired using traditional techniques (thicker steel plates, through bolt, new clamps, wood wedges to fill gaps in the contact surfaces) and tested again. The results allow evaluating the influence of different factors in the connections' behaviour and the effectiveness of some techniques in restoring or improving the connections' performance.

3. Rafter and tie beam connections

3.1. Typologies

3.1.1. Connections without metal parts

Carpentry connections join timber elements through notches in the connected members. In the absence of metal parts, these connections rely exclusively on the compressive and friction stresses transferred trough contacting surfaces. Since friction is highly dependent on the compression level in the rafter and in the characteristics of the contact surfaces [4], the use of carpentry connections without metal parts in roof trusses is restricted to a limited number of situations, particularly to transfer compression and shear internal forces between members and where tensile or alternating loads are not expected to occur. Only some old roof trusses still in service today have carpentry connections with no metal parts.

The connection between the rafter and the tie beam, in a common timber roof truss, is usually located near the eaves and its purpose is to take the horizontal component of the rafter's thrust off the supporting wall and redirect it to the tie beam. This connection withstands the highest internal forces (particularly the compression in the rafter and the tension in the tie beam) in the entire truss and the support reaction (Fig. 1).

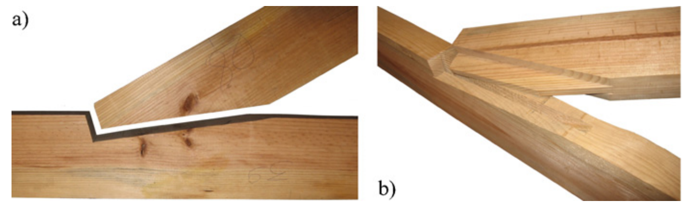

Fig. 2. Front notched connections without metal parts: a: simple front notch connection; b: front notch connection with mortise and tenon.

In single member trusses, the most widespread rafter and tie beam carpentry connection is the 'front notch connection', also called 'cogged joint', with a V-shaped indentation in the upper face of the tie beam, where the notched end face of the rafter rests (Fig. 2a). This layout requires, in the absence of devices that prevent the members from separating, that the rafters carry a minimum compression level to maintain the integrity of the connection.

Some connections exhibit, in addition to the V-shaped indentation, a lengthwise stub mortise and tenon (Fig. 2b). The mortise is the cavity cut in the tie beam and the tenon is the complementary projection in the end face of the rafter. This typology hinders out of plane displacements of the members in the connection, but it is more complex to manufacture.

3.1.2. Connections with metal parts

Carpentry rafter and tie beam connections are often complemented with metal parts, which can play a decisive role in the load transfer between members. Some are incorporated during construction to strengthen the connections (allowing them to withstand higher rafter thrust loads), or increase their rotational stiffness (allowing them to withstand bending moments between the rafter and the tie beam), or simply to ease the erection process; others are fastened later to repair or strengthen underperforming connections, when there is already some localized damage or excessive deformation. The connections' performance can be very different in these two situations.

Regarding the design of new structures, the European standard EN 1998:2004 [5] states that carpentry connections "shall be designed in such a way that they are prevented from separating and remain in their original position", and the use of metal parts is probably the most common way to comply with this requirement, in both existing and new structures.

The most common metal fastening systems are bolted steel plates (Fig. 3a) and clamps, namely external clamps (Fig. 3b) and 'through bolts' (Fig. 3c).

Bolted steel plates are steel-timber-steel dowelled connections, in which the side members are steel flat bars aligned with the members' longitudinal axis and welded together. They prevent out of plane displacements and the undocking of the joined elements and are very common in both repair/reinforcing interventions and in new structures.

Clamps are devices that clasp the rafter and the tie beam in the notched area. They can be materialized in different ways, such as external braces or internal through bolts, but their action is essentially the same: restrain the relative displacements between the

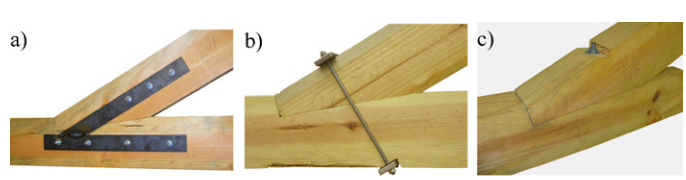

Fig. 3. Front notched connections with metal parts: a: bolted steel plates; b: external clamp; c: through bolt.