Construction and Building Materials 97 (2015) 34–47

Contents lists available at ScienceDirect

Construction and Building Materials

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

Analysis and strengthening of carpentry joints

Jorge M. Branco [a,*], Thierry Descamps [b]

[a] ISISE, Dept. Civil Eng., University of Minho, Guimarães, Portugal
[b] URBAINE, Dept. Structural Mech. and Civil Eng., University of Mons, Mons, Belgium

HIGHLIGHTS

- Joints play a major role in the structural behavior of old timber frames.
- Lack of design rules regarding the reinforcement of carpentry joints.
- Some calculation rules and possible strengthening techniques are presented.

ARTICLE INFO

Article history:
Received 28 December 2014
Received in revised form 8 May 2015
Accepted 11 May 2015
Available online 23 May 2015

Keywords:
Carpentry joints
Analysis
Reinforcement
Design

ABSTRACT

Joints play a major role in the structural behavior of old timber frames (Descamps et al., 2014) [1]. Current standards mainly focus on modern dowel-type joints and usually provide little guidance (with the exception of German and Swiss NAs) to designers regarding traditional joints. With few exceptions, see e.g. [2–4], most of the research undertaken today is focused on the reinforcement of dowel-type connections. When considering old carpentry joints, it is neither realistic nor useful to try to describe the behavior of each and every type of joint. The discussion here is not an extra attempt to classify or compare joint configurations (Gerner, 2012) [5,6], (Seike, 1977) [7]. Despite the existence of some classification rules which define different types of carpentry joints, their applicability becomes difficult. This is due to the differences in the way joints are fashioned depending, on the geographical location and their age. In view of this, it is mandatory to check the relevance of the calculations as a first step. A limited number of carpentry joints, along with some calculation rules and possible strengthening techniques are presented here.

1. Timber frameworks and carpentry connections

Timber frameworks are one of the most important and widespread types of timber structures. Their configurations and joints are usually complex and testify to a high-level of craftsmanship and a good understanding of the structural behavior that has resulted from a long evolutionary process of trial and error. A simplified analysis of (old) timber frameworks, considering only plane parts of the system, is often hard to realize. Nowadays, a considerable number of timber structures require structural intervention due to material decay, improper maintenance of the structure, faulty design or construction, lack of reasonable care in handling of the wood, accidental actions or change of use. While the assessment of old timber structures is complex, it is an essential precursor to the design of the reinforcement of the joints. Owing to a lack of knowledge or time, the species and/or grade assumed are often an overly conservative estimate which can lead to unnecessary replacement, repair and retrofit decisions along with associated superfluous project costs.

For the design of the reinforcement of old timber structures or joints, the first step is to understand fully how the structure and the joints work. Old timber structures are usually highly statically indeterminate structures. This means that loads applied to the structure have different pathways to reach the supports. Resolving the indeterminate system involves looking for additional equations that actually express the relative stiffness of all those pathways. To illustrate how the differential stiffness of elements, joints or supports may influence the behavior of the structure, a simple collar-braced roof is presented in Fig. 1. In the absence of buttressed walls, under vertical loads, the collar (or the tie-beam) is under tension because it prevents the roof from spreading. If buttressed walls restrain the feet of the rafters, the collar is in compression. The only difference between these situations is the horizontal stiffness of the supports (zero or infinite). The mass of the walls to resist the outward thrust is not the only influencing factor. Most of the time, principal rafters are connected to wall plates that

* Corresponding author.

http://dx.doi.org/10.1016/j.conbuildmat.2015.05.089
0950-0618/

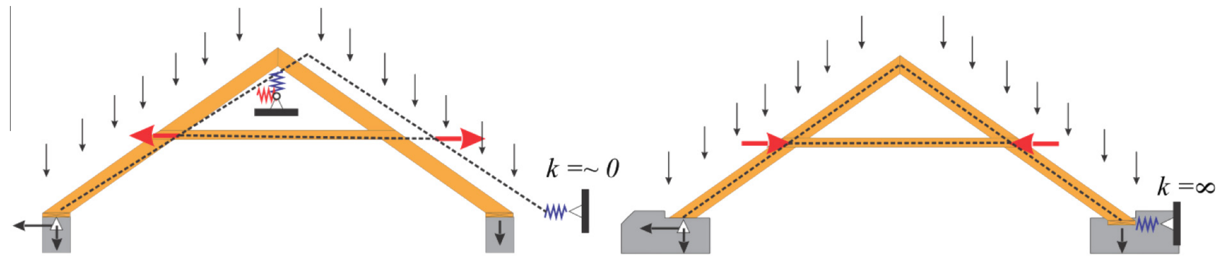

Fig. 1. Collar-braced roof.

have to be stiff enough to act as a beam in the horizontal plane spanning between two fixed ends in the walls. If the rafters are notched, for example, with birdsmouth joints, over the plate at the top, the roof can be hung from the ridge purlin, depending on the stiffness of the wall plate. The stiffness determines the ability of the wall plate to act as an additional support. This is valid for most types of carpentry joints as they usually are statically indeterminate. In conclusion, when working on old carpentry joints, it could be useful, when possible, to look at the joint as an assembly of equivalent springs. This model allows a better understanding of how the joints behave and deform and determines where the major stresses will occur. This could help to avoid incorrect positioning of the reinforcement and thereby circumvent poor design.

The main challenges for the structural assessment of carpentry joints are [8]:

- Stiffness and strength of joints depend on the type of loading. As an illustration, the rotational stiffness of a joint is mostly different under positive and negative bending. Moreover, within most joints there is an interaction between the different pathways in which the forces are transferred in terms of stiffness and strength. This interaction should be considered to define the mechanical behavior of the connection.
- Despite most current standards not declaring any rules for the assessment of the material strength under combined stresses, their appearance in carpentry joints is inevitable.
- The design of traditional joints essentially involves a check of the contact pressure between the assembled elements. It is not easy to calculate the value of contact pressure in the following situations: unknown contact surfaces and non-uniform stress distributions (because of non-uniform elastic support due to local defects like knots for example). The values of compressive strength of timber are different in the direction parallel and perpendicular to the grain. In order to calculate the strength at any intermediate value of the load angle to the grain Hankinson's formula, which has been presented in many standards, may be used. SIA 265:2003 [9] suggests a different expression that takes into account a reduction because of the difference between the strength of early wood and latewood. In addition, some standards allow enlarging the real contact surface by taking into account a so-called effective length [10]. Those slight differences about the definition of the compressive strength at an angle to the grain highlight a lack of knowledge, which fortunately, is not of major importance for compression at angles between 30° and 60° (which represent the most common values).

2. Old carpentry joints

Common traditional carpentry joints found in old timber frames can be categorized in four main types, according to their arrangement and geometry:

- *Tenon and mortise joints:* There are countless examples of this type of joint. Tenon joints connect members that usually form an "L" or "T" type configuration. The joint comprises two components: the mortise hole and the tenon tongue. The tenon formed on the end of a member is inserted into a square or rectangular hole cut into the corresponding member. The tenon is cut to fit the mortise hole exactly and usually has shoulders that sit when the joint fully enters the mortise hole. The joint may be pinned or locked into place. In the traditional fashion, the pin hole in the tenon is bored a little closer to the shoulder than in the mortise and the pin pulls the joint together very tightly. This kind of joint is mainly used when the adjoining pieces connect at an angle between 45° and 90°. When the angle between the two jointed elements is different from 90°, the nose of the tenon can be cut off and is called a skewed tenon (see Figs. 3a and 6a).
- *Notched joints:* This kind of joint is linked to the development of king post and king post-like frames. In order to work successfully, these frames need appropriate joinery at a multitude of locations. A notch is a "V" shaped groove generally perpendicular to the length of the beam, as seen in Fig. 3. Examples where notched joints are used include cases where secure footing is required for the toe of a rafter (or strut) or between the rafter and the king-post. A tenon can be added to the notched joint to essentially keep all the beams coplanar but the notch is what creates the strength of the joint (because it is stiffer than the tenon).
- *Lap joints:* In a full lap joint, no material is removed from either of the members to be joined, resulting in a joint whose thickness equals the combined thickness of the two members. The members are held in place by a pin (Fig. 4a). In a half-lap joint, material is removed from each of the members so that the thickness of the resulting joint is the same as that of the thickest member. Most commonly, in half-lap joints, the members are of the same thickness and half the thickness of each is removed. The cogged half-lap joint is a half-lap with additional cogs. The dovetail-lap joint (named after the shape of the tenon being similar to the tail of a dove) is another way to fashion the joint in an attempt to reinforce its tensile strength (Fig. 4c).
- *Scarf joints:* Scarf joints (and splice joints), shown in Fig. 5, allow the joining (splicing) of two members end to end [11,12]. They are mainly used when the material being joined is not available in the length required. This technique is recognized as being the strongest form of unglued member lengthening [13]. The halved-scarf joint is a lap whose surfaces are parallel with the members. It is similar to a half-lap joint with co-axial members. The scarf joint is simply a pair of complementary straight sloping cuts secured to each other with pins (also called pegs). Another type of scarf joint is known as the *Trait-de-Jupiter* or *Bolt of lightning*, in view of its resemblance to lightning. It is more efficient in the presence of a key (or several keys, depending on the number of indentations – see Fig. 23d) made of hardwood to improve contact and to simplify fabrication. From a mechanical point of view, it is an excellent scarf, since the