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# Design of three Step Joint typologies: Review of European standardized approaches

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ABSTRACT

When assessing timber roof structures on-site for any restoration project, engineers can be faced with elements that, over time, were poorly preserved, especially damaged joints in contact with moist masonry walls. Before dealing with any intervention technique, the mechanical behaviour of such carpentry connections must be properly understood. Therefore, it has to be determined how the joints fail, which parameters (i.e. geometrical configurations and mechanical properties of the joint) influence the appearance conditions of failure modes, and the way how the internal forces are distributed within the connection. Therefore, the present paper aims at overviewing three different typologies of Step Joints (SJ) which can often be encountered within traditional timber carpentries between the rafter and the tie beam: the Single Step Joint, the Double Step Joint, and the Single Step Joint with Tenon-Mortise. Regarding each SJ typology, some design rules and geometrical recommendations can be gathered from European Standards and from authors of works on the subject, but no design equation is conventionally defined. Hence, new design models have been determined through the Analytical Campaign for the investigated Step Joints according to their geometrical parameters and to both failure modes: the shear crack in the tie beam and the crushing at the front-notch surface. In order to check the reliability of new design models and the emergence conditions of both failure modes, future experiments and numerical analysis on the three SJ typologies are going to be performed.

## 1. Introduction

In the field of Built Heritage Restoration, engineers have to work with existing timber carpentries made of poorly preserved elements and connections. Being located at the foot of timber trusses, Step Joints (SJ) are common connections used by carpenters to link the rafter to the tie beam as shown in Fig. 1. Within the former and contemporary timber carpentries, three SJ typologies can often be encountered [1,2]: the Single Step Joint, the Double Step Joint, and the Single Step Joint with Tenon-Mortise. Because they can constantly be in contact with moist masonry walls functioning as a support of the roof structure, these carpentry connections over time may be subjected to biological degradation (i.e. insect attacks, fungi decay,…), which can lead to the collapse of the whole timber truss.

Therefore, the health assessment of Step Joints on-site is a major issue for engineers involved in any restoration project dealing with existing roof structures. Before thinking about any intervention technique, the mechanical behaviour of Step Joints must be properly understood [1]. In other words, it has to be determined how the three SJ typologies fail, which parameters (i.e. geometrical configurations and mechanical properties of the joint) significantly influence the appearance conditions of the failure modes, and how the internal forces are distributed inside the connection.

Although the mechanical behaviour of existing structures is badly estimated during their on-site assessment, over time the knowledge about traditional timber carpentry connections has grown. Indeed, some geometrical and design recommendations can be obtained from European Standards (e.g. [3–5]) and from authors of other works (e.g. [2,6–12]). However, no conventional and reliable SJ design model exists in the technical literature. Furthermore, these analytical recommendations need to be checked, optimized (if necessary) and formalized through the definition of new design models in the current Standards with respect to the appearance conditions of failure modes inside the investigated Step Joints.

In the last three decades, available scientific reports (e.g. [13–16]), recent research (e.g. [17–22,24,25]) and state-of-the arts (e.g. [6,7,12,23,26]) have focused on determining the mechanical behaviour of the three SJ typologies through analytical, numerical and

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**Fig. 1.** Step Joint and elements constituting the traditional timber carpentry (King-Post truss).

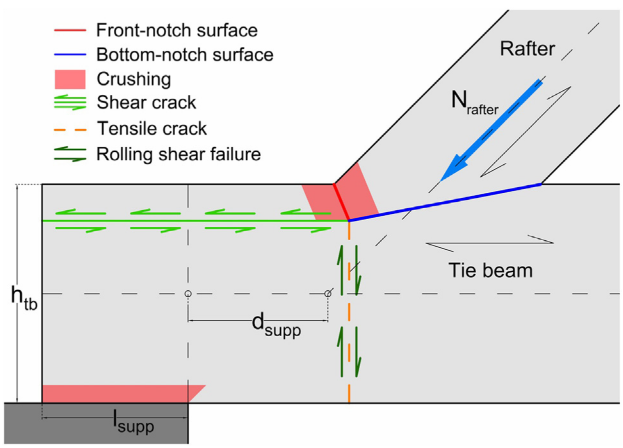


**Fig. 2.** Illustration of different failures modes likely to occur in the Single Step Joint.

experimental assessments. When considering only the axial force in the rafter ($N_{rafter}$) due to the weight of roof coverings or other permanent loads, two main failure modes illustrated in Fig. 2 may occur inside the three SJ typologies: the crushing at the front-notch surface, and the shear crack in the tie beam [24]. While the former leads to high local deformation within the roof structure, the latter features a brittle failure mode that entails the collapse of the whole timber truss. Therefore, it is urgent to prevent the emergence of both failure modes, especially the shear crack, when designing and assessing on-site Step Joints. So far, the reliability of such design models for the Single Step Joint have been discussed and checked by comparing the analytical with the experimental results [24]. Besides, the design models related to the Double Step Joint have been defined in respect with both failure modes [25] whereas the design of the Single Step Joint with Tenon-Mortise has not yet been tackled.

## 2. Research method and assumptions

In order to fill the existing gaps in the current literature, the proposed research method consists of carrying out the Analytical Campaign on the design of three Step Joints (SJ) typologies: the Single Step Joint (SSJ), the Double Step Joint (DSJ), and the Single Step Joint with Tenon-Mortise (SSJ-TM). In the first step, the Analytical Campaign consists of gathering all the geometrical and design recommendations related to the three SJ typologies from European Standards [3–5], authors of works [2,6–12] and recent research [23–25]. In the second step, the SJ geometrical parameters and new design models will be defined in respect with both investigated failure modes: the shear crack in the tie beam, and the crushing at the front-notch surface. Before going ahead, several research assumptions as shown below must be firstly be established:

- As a first research assumption, only the axial force in the rafter will be considered when designing Step Joints against both failure modes [24,25]. In other words, dynamic and out-off-plane loadings due to wind loads or earthquakes are out-of-scope. Meanwhile, this research hypothesis is highly suitable for the former carpentries without structural disorders in which timber elements are only subject to axial forces of compression or tension. Conversely, the presence of structural disorders (e.g. roof sagging, weakness or failure in support points of the structure…) and/or the current design of contemporary timber trusses may introduce significant in-plane lateral loadings in the rafter which has then to bear axial compression, bending moment and shear stresses;
- Because the rafter skew angle $\beta$ highly conditions the emergence of failure modes, the three SJ typologies investigated must be characterized by a low or moderate rafter skew angle ($\beta \leqslant 50°$) [9]. If this research assumption is not met, another failure mode may appear such as a crushing at the bottom-notch surface within Step Joints due to the high vertical component loadings transferred from the rafter;
- In case of SJ bad design, other failure modes illustrated in Fig. 2 may occur: the crushing perpendicular to the grain at the bottom of the tie beam along the support, the tensile crack and the rolling shear failure at the SJ heel in the tie beam cross-section. While the crushing can be avoided by increasing properly the support length $l_{supp}$ at the foot of timber truss, the tensile and rolling shear failures can be prevented by checking the geometrical recommendations on the heel depth [6] for each SJ typology. Otherwise, further design equations (not detailed in the present paper) should be established to prevent these extra failure modes;
- Because the mathematical equations from the SJ design models have to be as simple as possible, friction forces can be neglected because they are usually weak at unreinforced contact surfaces of such traditional carpentry connections. On the other hand, friction forces should be considered when designing any SJ strengthening at the contact surfaces;
- Furthermore, when designing Step Joints the eccentricity between the joint node (i.e. intersection between the rafter and tie beam axes) and the support area of timber trusses ($d_{supp}$) shown in Fig. 2