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Historic timber roofs modelling: prosthesis and resin repairs

Modele zabytkowych dachów drewnianych: protezy i naprawy z wykorzystaniem żywic

Słowa kluczowe: naprawa z wykorzystaniem żywicy, połączenie pół-sztywne, ocena

Key words: Resin repair, semi-rigid connection, assessment

1. INTRODUCTION

1.1. Structural analysis of old timber frameworks

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.

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 behaviour that has resulted from a long evolutionary process of trial and error. A simplified analysis of old timber frameworks, considering hinged joints and only plane parts of the system, is often hard to realize. 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 behaviour 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 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.

This simple example illustrates how the stiffness of joints may influence the force distribution inside the structure. This also points out that when restoring

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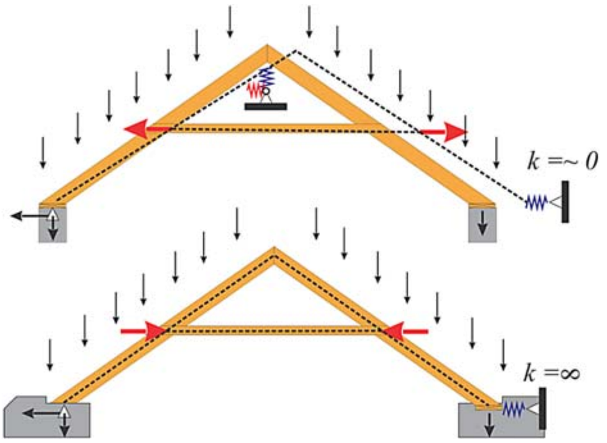

Fig. 1. Collar-braced roof [6]

an old timber frame, major attention has to be led to a modification of the joints stiffness. In statically indeterminate structures, replacing a joint by a new one, stiffer, may act as a "magnet" for forces what could lead to other pathologies or new local overload problems. In conclusion, when working on old timber frames, it is useful 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 helps to avoid incorrect positioning of the reinforcement or a wrong design in terms of stiffness of the prosthesis and its connection to the timber beam.

1.2. Typologies of carpentry joints

Common traditional carpentry joints found in old timber frames can be categorized in four main types, according to their arrangement and geometry (see Fig. 2):

- *Tenon and mortise joints*: Tenon and mortise joints comprise two components: the mortise hole and the tenon tongue. The tenon is inserted into the mortise cut into the corresponding member. These joints usually form an "L" or "T" type configuration.
- *Notched joints*: A notch is a "V" shaped groove generally perpendicular to the length of the beam. This kind of joint is linked to the development of king post and king post-like frames where secure footing is required for the toe of a rafter (or strut) or between the rafter and the king-post.
- *Lap joints*: Lap joints are joints in which an end or section of one element is overlapped by an end or section of the other. In a full lap joint, no material is removed from either of the members to be joined and a pin hold the beams in place. In a half-lap joint, material is removed from each of the members (Fig. 2).
- *Scarf joints (and splice joints)*: This is a method of joining two members end to end. The halved-scarf joint 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).

1.3. Prosthesis for end beam repairs

The use of one prosthesis made of timber is of course a good solution because it allows the possibility to create a new joint using the same geometry and the same materials than the older one and so guarantee the same stiffness. However, its cutting is complex because it can not be fully prefabricated in a workshop and it requires high skills labour.

Glued-in rods are widely used in historical buildings for columns, trussed rafters or beam-ends repairs. For instance, glued in rods are used to replace decayed beam-ends, by cutting the rotted part, drilling the sound part of the beam and gluing rods into it, and finally gluing these rods with a new piece of wood or a prosthesis made of resin. An example of an epoxy resin repair to replace the end of a decayed tie beam is illustrated in Fig. 3. The rods are made of stainless steel bars. However, other materials as wood, basalt rods, glass or carbon fibres rods can be used.

Epoxy resin is often considered as the best choice to glue threaded steel rods in timber. Its advantages are quite numerous [1]:

- Little shrinkage, leading to no cracks or voids in the bond line
- Fast polymerisation (quick implementation)
- Low pressure required during application, room-temperature cure
- Excellent durability, good tolerance to moisture content changes, good adhesion with a lot of materials, and especially with steel, good strength
- Can be used in thick bond line.

Epoxy resin can be used to make prosthesis but in that case, sand is used in addition to reduce de cost.

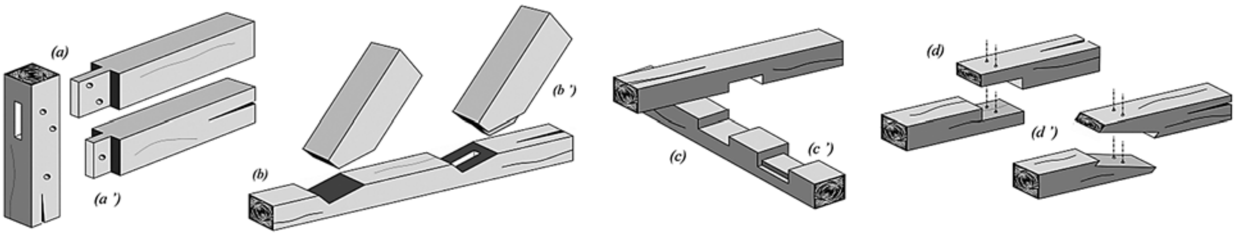

Fig. 2. Example of carpentry joints: (a) Through pinned mortise and tenon (a') blind pinned mortise and tenon, (b) Notched joint between main rafters and tie-beam.(b') A skewed tenon may be used to help in keeping all timber pieces co-planar. (c) Half-lap joint. (c') Cogged half-lap joint. (d) Halved-scarf joint (or half-lap splice joint). (d') Scarf joint with under-squinted ends

Fig. 3. Example of resin repairs for notched joint: the end beam is cut off and a new ends is poured in epoxy resin. Restauration of the Old castle of Ecaussines-Lalaing, Belgium

The main advantage of epoxy resin is that pouring the prosthesis is much easier to implement than fashioning a wooden prosthesis. Some studies has proved the epoxy strength to be greater than those of PU and PRF, for instance in fatigue tests [2], [3]. The failure modes are different as well. The reason of the out-performance of the epoxy on all other adhesives is that PU and PRF have poorer gap-filling capacities. In the GIROD project, tests have confirmed that the pull-out strength obtained when using epoxy is greater than with PUR, which is itself better than the PRF performances [4]. However, many stakeholders use nowadays PUR and PRF adhesives to produce engineered wood products (glulam beams, CLT…) and are thus quite experienced with these adhesives, and may probably use it more easily than epoxy. Moreover, PUR and PRF seems to become more and more popular for gluing rods in timber, probably because they are easier to implement.

This paper presents the preliminary results of a research carried out to better understand how the stiffness of joints may influence the global behavior of old timber frames and second, to design a new prosthesis with a control of its stiffness. To ease the presentation, we will focus on one important joint in restauration works which is the step joint (notched joint between the main rafters and the tie-beam in kingpost trusses).

2. METHODS

2.1. Component method

The component method gives an estimation of the joint stiffness according to only geometrical and mechanical properties. Frequently used in steel construction, it has already been used with success for traditional timber joints studies [12]. If a tenon joint is loaded in bending, contact appears between wooden parts of the joint what contributes to the global stiffness of the joint. It is assumed that the wooden peg resists shearing and fix the position of the centre of rotation (CR). No friction is taken into account. The rotational stiffness can be easily calculated. The total displacement δ_k in the normal direction to surfaces i,j is:

$$\delta_k = \delta_i + \delta_j = \frac{F_k}{k_j} + \frac{F_k}{k_i} = \frac{F_k}{k_k} \tag{1}$$

The equivalent spring constant of the stiffness k_i and k_j acting in series is simply:

$$k_k = \frac{1}{\sum_{ij} \frac{1}{k_{i,j}}} \tag{2}$$

If M is the applied bending moment and q the relative rotation between the connected members, the rotational stiffness of the joint can be written as:

$$\begin{aligned} k_{rot} &= \frac{M}{\theta} = \frac{\sum_k F_k z_k}{\theta} = \frac{\sum_k k_k \delta_k z_k}{\theta} = \\ &= \frac{\sum_k k_k (z_k \theta) z_k}{\theta} = \sum_k k_k z_k^2 \end{aligned} \tag{3}$$

As the distances $z_{i,j}$ are simply defined when the CR is known, the rotational stiffness only depends on the stiffness k_k of each couple of surface i,j in contact. To get this stiffness, a first attempt has been made by means of laws used in soils mechanics engineering to calculate the settlement under a rectangular foundation supported by a semi-infinite half space.

$$k_i = \frac{E_\alpha \sqrt{b\,h}}{0{,}85} \tag{4}$$

Where $b\ h$ is the contact surface. E_α is estimated from $E_{perpendicular}$ and $E_{parallel}$ according to the Hankinson's relation frequently used in timber engineering. This method can be enhanced. Several researches led to the following proposal:

New definition of the stiffness k_i of the surfaces that are in contact to take into account an "edge effect". Actually, the assumption of an infinite half space is caught out and specific boundary conditions of free surface surrounding the contact area cannot be neglected. To take this into account, a cut factor must be applied to the modulus of elasticity E_α in Eq. 4. This cut factor has been defined from FE models (anisotropic, contact and friction between elements).

New definition of the position of the centre of rotation of the joint. Actually, the broken pegs observed on-site attest that the peg is not the centre of rotation of the joint. This explains the importance to look for the real position of the CR. In this work, a conservative assumption has been made assuming that the CR is in an area that corresponds to a lower limit of the joint stiffness.

2.2. Influence of the stiffness on the force distribution

When restoring a joint with a prosthesis, three new joints are actually designed. The first one is the carpentry joint itself between the two (or more) connected members as presented in Fig. 4. Most of the time, its design is simply a replica of the decayed joint. The second and third ones are the continuity joints between the prosthesis and the sound parts of the existing timber beams. Those connections are most of the time made with glued-in rods which have also a stiffness that should be checked.

How the stiffness of carpentry joints influence the force distribution in timber frames has been previously studied [45]. Only a summary focussing on step joints will be presented here to enlighten how much it is important not to neglect that point when studying old timber frameworks. To evaluate the sensitivity of old timber frames in case of modification of the stiffness of the step joint, a parametric study has been carried out on three non-statically determined frames (x7) from major patrimonial buildings. Only the results of the study of the Old castle of Ecaussines-Lalaing, Belgium are presented here.

The stiffness of the old step joint has been evaluated with help of the enhanced component method [45]. The stiffness of the new joint depends of course of the type of joints which is chosen for the restoration. For this parapmetric study, two different approaches have been considered: the first one is a wooden prosthesis with the same design as the old decayed joint. The second one is a contemporary joint made with dowel type fasteners and sloted-in steel plates. This two ways of doing define respectively one lower limit and one upper limit of the joint stiffness. Actually, if the question that arises is whether it is required to focus on a possible modification of the stiffness of the connection after restoration, it is important to know the range within which the stiffness may vary. Fig. 5 presents those upper and lower limits for the step joint.

For any modification of the connections stiffness between those limits (steps of 5% between the limits), the new distribution of the stresses has been calculated. Fig. 6 shows how the bending moment in the rafter changes according to the step joint stiffness. The maximum bending moment in the rafter is slightly influenced by the stiffness of the step joint, decreasing from 9600 N·mm/rad (hinge assumption) to 9000 N·mm/rad for a stiff joint (infinitely stiff). The second graph shows what actually happens if the stiffness varies within the feasible domain from the lower bound (old carpentry joint) to the upper bound (dowel type fasteners and slotted-in steel plates). One may notice that all the influence of the joint stiffness on the forces

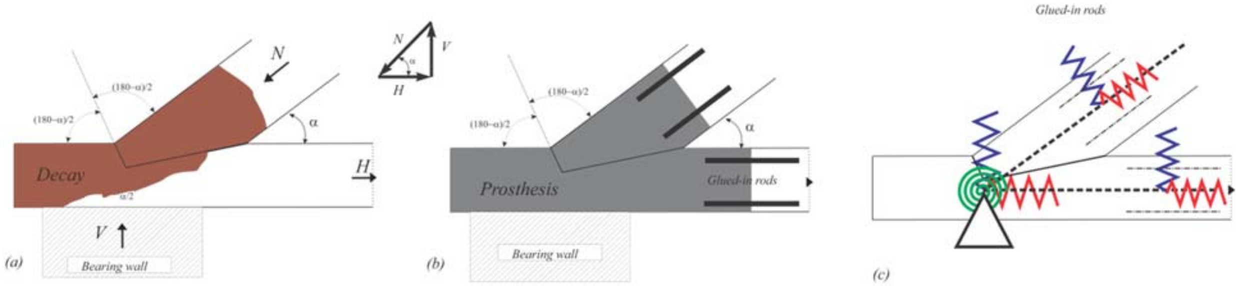

Fig. 4. Timber frame of the Old castle of Ecaussines-Lalaing, Belgium

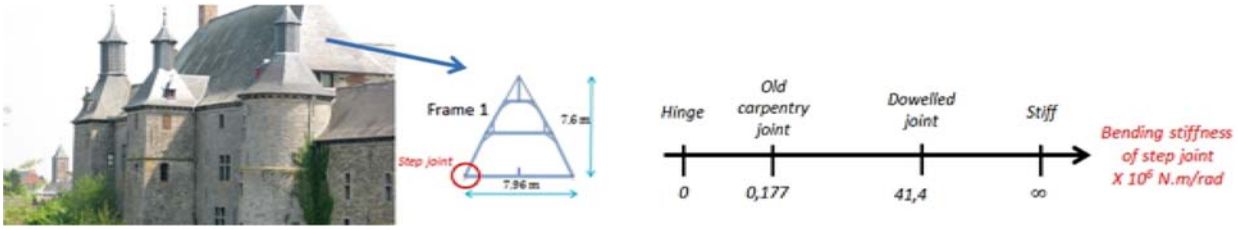

Fig. 5. Timber frame of the Old castle of Ecaussines-Lalaing, Belgium: upper and lower bounds of bending stiffness of the step joint

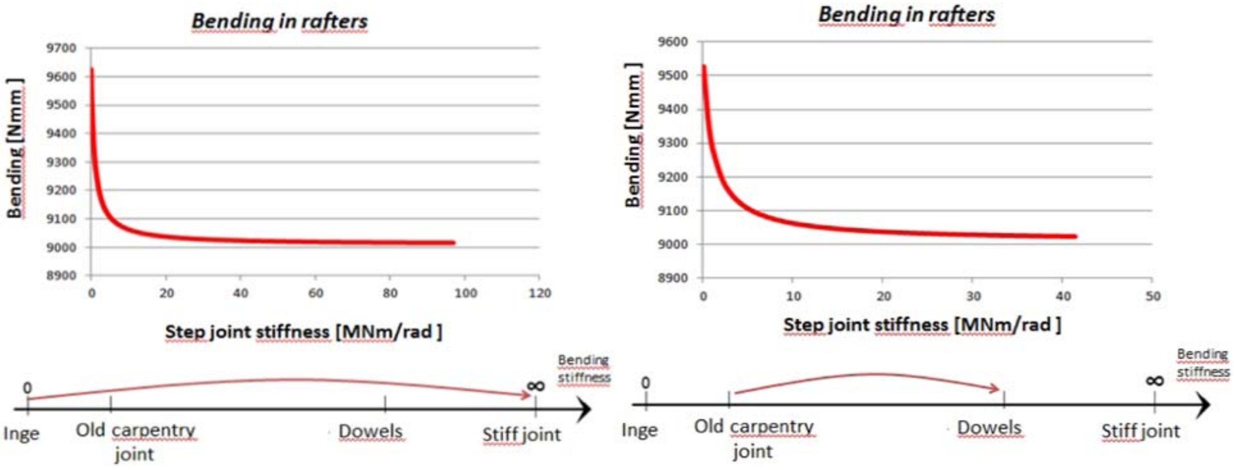

Fig. 6. Influence of the stiffness of the step joint on the bending moment in the rafters of the frame 1

in the rafteris due to a variation of stiffness within this domain. So we could not directly reject the influence of the stiffness on the global design of the structure however the range within which the bending moment varies is small.

Such studies have been done for all the beams of the framework and the results have been summarized on colored maps showing the variation from a reference (hinge or stiff assumption) as showed in Fig. 7.

The reference is the hinge model. All stresses (bending, shear and axial) are expressed as a variation from that reference. Some observations can be done:

- There is a slight influence on the shear stresses, expressing a slight influence on the slope of the bending diagram. The influence on bending stresses is higher than on all other stresses.
- From the design point of view, the variation of the bending stresses in some elements may reach up to 18% which is significant for the check of the whole structure.
- All the influence of the joint stiffness on the stresses is due to a variation of stiffness within the feasible domain of stiffness.

2.3. Modelling of glued in rods for continuity joints

The component method is not suitable for glued-in rods joints. With the goal to to develop a FE model which can predict the behaviour, e.g. the strength and the stiffness of glued-in rods axially loaded, we investigated the possibility to use a "cohesive surface" approach:

- *Cohesive surface*: a cohesive surface models the glue through a zero-thickness element (i.e. an interaction) taking into account all successive behaviours of the adhesive (cohesive behaviour, failure criterion and damage evolution). For this fidelity study, we need to characterize the glue in shear and tension and so have used experimental resulst. The advantage of this model is that the behaviour of the adhesion is fully described and predicted with quick computation.
- *Shear failure in wood*: the wood failure is modelled by using a "fictional cohesive surface" which introduces a "favoured failure surface" in the wood, located where the wood usually breaks. The idea is thus to use the interaction "cohesive surface" (that we also use to model the adhesive) to model this fictional cohesive surface. Here, the characteristics encoded for the "cohesive surface" are not the bondline's properties, but the wood properties, i.e. its Young modulus, shear modulus, shear strength…
- *Loading and boundary conditions*: The model "axisymmetric" benefits from the symmetry of the specimens and models only half the sample. The model is fixed at the bottom of the wood section and the tension is applied as a pressure on the end of the

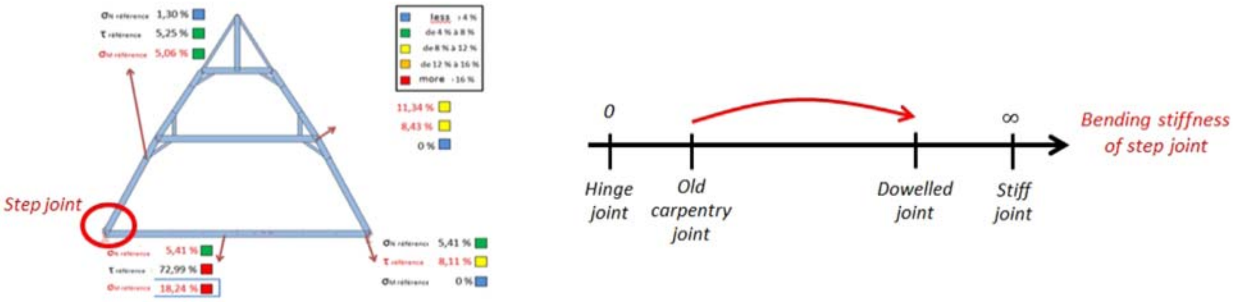

Fig. 7. Range of variation of the stiffness of the step joint for frame 1 (design under ULS loading)

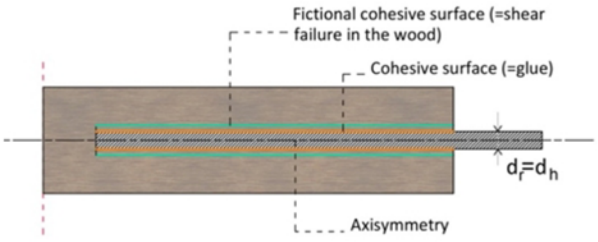

Fig. 8. Finite element model of one glued-in rod

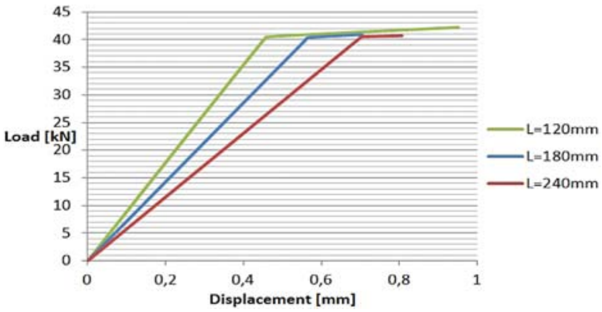

Fig. 9 *Stiffness of Glued-in rods with different anchorage lengths*

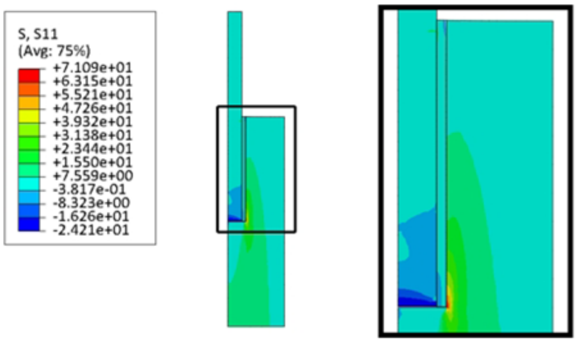

Table 1. Properties of glued-in rods for the continuity connection

Timber	D30	
Rods	Steel	E = 210 000 MPa f_y = 480 ou 640 MPa
	CFRP	E = 127 500 MPa f_y = 1860 MPa
	Aramide reinforced polymer	E = 85 000 MPa f_y = 1410 MPa
	GFRP	E = 35 000 MPa f_y = 470 MPa
	Nylon	E = 2930 MPa f_y = 80 MPa
Glue	Pliogrip 7779	E = 1184 MPa; G = 414 MPa; σ = 29 MPa τ_f = 5 MPa, G_f = 2 N/mm

rod. The parts are then meshed by quad-dominated elements. The mesh is thinner near the edges and the interactions between parts

We first use the experimental results from specimens with steel rod diameter d_r = 12,7 mm and length of 60 mm to calibrate the model. To validate the model, we have successfully compared the numerical results with the experimental data available for different rod diameters (12,7 mm and 19 mm) and different anchorage length (l = 120, 240 mm and l = 95, 190, 380 mm respectively). The model thus gives information regarding the stiffness of the glued-in rod modelled, its strength, failure mode and the stresses occurring in the joint (i.e. in the wood, steel or bondline).The stiffness of the glued-in rods modelled with d_r = 12.7 mm and l = 60 mm can be compared to the stiffness of the tested specimens, using the load-displacement curves recorded with a LVDT during the test. The stiffness of the FE model is in the same range as the tested samples. The same comparison model/experiments can be made for d_r = 12.7 mm and l = 120 mm, with the same favourable conclusion. We can also check that the stiffness of a glued-in rod decreases when the slenderness ratio increases (see Fig. 9), which makes sense.

4. RESULTS

In an attempt to sketch a continuity joint that would have a certain stiffness, different materials (steel, CFRP, Aramide, GFRP and nylon) and diameters (20, 13 and 10 mm) of rods have been studied. Properties of rods, timber and glue are presented in Table 1.

For example, Fig. 10 presents load slip curves of axially loaded rods of 10 mm of diameter and made of different materials. One may notice that Aramide, steel and GFRP rods have almost the same stiffness for short anchorage length. The lower strength of GFRP rods could make their use problematic.

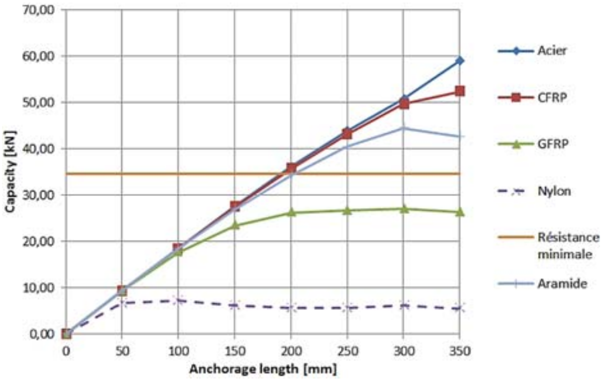

Fig. 10. Load displacement curves for 1 rod, diameter = 10 mm

For example, let's consider the stiffness of a tie beam whose section is 20 × 20 cm, length is 8 m and which is graded D30:

$$K = \frac{E \cdot A}{l} = \frac{10000 \cdot 200^2}{8000} = 50 \text{ kN/mm} \tag{5}$$

If the ULS load is 550 kN, 7 sketches can be proposed for a continuity joint made with glued-in rods, all resulting in a large range of stiffness (from 393 to 873 kN/mm) according to the diameter and the anchorage length chosen. One may notice that when designing the joint, both parameters diameters and anchorage length may be adjusted to get a stiffness target.

For example, the following sketches can fit all strength (550 kN) and stiffness requirements (50 kN/mm):

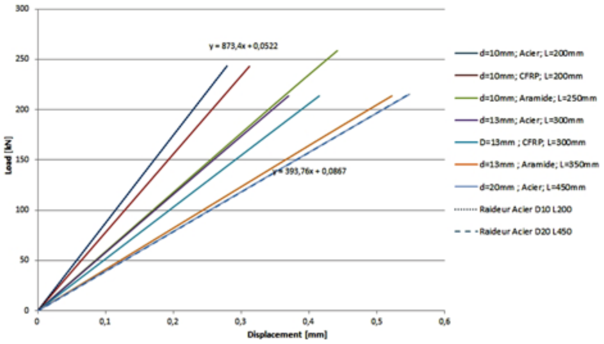

Fig. 11. Stiffness for different configurations

- 16 steel rods, diameter 10 mm, anchorage length 200 mm:

$$\frac{1}{K_{tot}} = \frac{1}{K_a} + \frac{2}{K_{TOT,ass}} + \frac{1}{K_b} \tag{6}$$

$$\frac{1}{K_{tot}} = \frac{(7000-400)}{10000 \cdot 200^2} + \frac{2}{873400} + \frac{(1000-400)}{10000 \cdot 200^2}$$

$$K_{tot} = 49285.6 \text{ N/mm}$$

- 4 steel rods, diameter 10 mm, anchorage length 450 mm:

$$\frac{1}{K_{tot}} = \frac{(7000-900)}{10000 \cdot 200^2} + \frac{2}{393760} + \frac{(1000-900)}{10000 \cdot 200^2}$$

$$K_{tot} = 48592.7 \text{ N/mm}$$

4. CONCLUSIONS

Depending on the type of structure studied, the stiffness of the joints may influence the way that the forces are spread in the frame in such a way that this parameter cannot be neglected when studying timber frameworks. The component method allows to easily getting the stiffness of any old carpentry joint. However, this method is not suitable for glued-in rods joints.

When restoring a beam with a prosthesis, a continuity joint between the prosthesis and the sound parts of the existing timber beams has to be designed. Those connections are most of the time made with glued-in rods. Their stiffness should be checked too. In an attempt to sketch a continuity joint that would have a certain stiffness, different materials (steel, CFRP, Aramide, GFRP and nylon) and diameters (20, 13 and 10 mm) of rods have been studied.

To develop a FE model which may predict the behaviour, e.g. the strength and the stiffness of glued-in rods axially loaded, we investigated the possibility to use a "cohesive surface". This method has been calibrated with the help of laboratory tests. This tool allow to design any configurations of glued-in rods, axially loaded, whatever the material, the glue or the anchorage length.

Finally, the developped tools have been applied to the design of a continuity joint, with a target in terms of strength and stiffnes. Two configurations of joints made with steel glued-in rods have been proposed. Those first results are very encouraging but further researches on that topic are required. Indeed, at the moment, the developed FE model does not enable any shear loadings. However, one may assume that the shear stiffness should be considered too.

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Streszczenie

Obowiązujące standardy i normy koncentrują się na współczesnych połączeniach kołkowych i zazwyczaj nie zawierają zbyt wielu wytycznych dla projektantów wykorzystujących tradycyjne połączenia. Skuteczna naprawa elementów drewnianych wymaga złożonych i interdyscyplinarnych działań, uważnych badań i realizacji. W obszarze odnowy historycznych budynków inżynierowie pracują na dawnych konstrukcjach, zbudowanych ze źle zachowanych elementów drewnianych, połączonych różnymi tzw. „tradycyjnymi złączami'. Połączenia odgrywają kluczową rolę w pracy konstrukcji starych drewnianych obiektów. Konieczne jest przeprowadzenie dalszych badań w tym obszarze, aby wypracować rzetelne specyfikacje dla projektantów, protokół procedur naprawczych oraz rekomendacje dla przyszłych interwencji renowacyjnych lub wzmacniających. Zabytkowe dachy drewniane odgrywają istotną rolę z punktu widzenia historycznego i estetycznego oraz wymagają dogłębnego zrozumienia oryginalnie zastosowanych zasad i technik, w celu wybrania właściwej strategii naprawczej. Podczas renowacji belki za pomocą protezy konieczne jest zaprojektowanie ciągłego połączenia pomiędzy protezą a zdrową częścią starej belki drewnianej. Połączenia takie wykonuje się najczęściej z wykorzystaniem wklejanych prętów. Artykuł opisuje badania przeprowadzone w celu opracowania Modelu Elementów Skończonych, który będzie w stanie prognozować pracę i zachowanie, np. wytrzymałość oraz sztywność wklejanych prętów wykorzystywanych w złączach ciągłych.

Abstract

Current standards mainly focus on modern dowel type joints and usually provide little guidance to designers regarding traditional joints. An effective timber repair needs a complex interdisciplinary work with careful investigation and execution. In the field of restoration of patrimonial buildings, engineers have to work with old structures made of badly preserved timber elements connected by particular connections known as "traditional connections". The joints play a major role in the structural behaviour of the old timber frames. Further studies in the area are deemed necessary to establish a reliable design specification, the protocol of the repair procedure, and recommendations for the future rehabilitation or strengthening interventions. Patrimonial timber roofs are of considerable historic and aesthetic significance, and demand a thorough understanding of the principles and techniques involved to choose a suitable repair strategy. When restoring a beam with a prosthesis, a continuity joint between the prosthesis and the sound parts of the existing timber beams has to be designed. Those connections are most of the time made with glued-in rods. This paper presents a research carried out to develop a FE model which may predict the behaviour, e.g. the strength and the stiffness, of glued-in rods used for continuity joints.