Experimental characterisation of the behaviour and the rotational stiffness of Hornbeam (*Carpinus betulus L.*) bifurcations for structural applications

BREBAN Marius[1,3], FRÉCHARD Victor[1,2]

[1]Equipe CRAI, URM MAP, ENSA Nancy, 2 Rue Bastien Lepage 54000 Nancy, France
[2]Université de Lorraine, LERMAB, France
[3]ENSTIB, 27 Rue Philippe Séguin, 88000 Epinal, France
victor.frechard@nancy.archi.fr

Key words: bifurcation ; raw-timber structures; tensile tests ; rotational stiffness

Context and objective

In the context of both forest ecosystem disturbances and growing demand for timber, the need to find new strategies to add value to the entire forest biomass, including resources that are currently disregarded for long-term structural applications. Such strategies align with a sustainable, circular and locally sourced approach to the architectural projects. The rapid development and the spread of scanning, parametric design and digital fabrication technologies has encouraged researchers in the architecture field to rethink the use of wood resources in its natural form even when exhibiting highly variable geometric and mechanical properties, such as curved members or tree forks (Bukauskas et al 2019). Bifurcations are particularly interesting for structural applications due to their presumptive natural mechanical capacity and their geometric similarity to bracing systems. The angles formed at the bifurcation require only the addition of a single element to create self-stable triangular configurations within the structures. The current research mainly focuses on geometric design and digital fabrication methods, but lack addressing engineering or materials science issues. Despite this research gap, tree forks are often considered, in architectural science, as rigid connections based on the ability of the natural junction to transfer bending moments induced by both wind and eccentric gravity load. In civil engineering, a rigid connection requires that its deformation does not significantly influence the distribution of internal forces or the overall deformation of the structure, i.e., it must have a significant bending moment transfer capacity without significant relative rotation. Although the ability of natural bifurcations to transfer bending moments has been studied in recent years in the arboriculture and the urban forestry field (Drénou et al 2020**;** Slater, 2016), their rotational stiffness has not yet been well documented to the authors' knowledge. The aim of this study is to provide architects and engineers data on the bifurcation rotational stiffness, determined through mechanical testing, investigating their bending moment resistance behaviour and comparing them to the civil engineering requirements. These initial experimental campaign focuses on small-diameter specimens, in order to critically discuss the often poetically attractive classification of the bifurcations as rigid connections and to prevent inappropriate structural applications.

Materials and methods

Sample

Thirty-six hornbeam (*Carpinus betulus L.*) bifurcations harvested from forestry by-products were used for this study. Hornbeam bifurcations were studied for their resource availability, their branching tendency and their complex behaviour including its dimensional instability and its sensitivity to cracks. These properties help to identify key issues that will be useful for conducting a broader investigation of the mechanical behaviour of bifurcations from other hardwood species. Each bifurcation had two branches, free from visible cracks and was relatively flat. The stem diameter ranged from 60 to 142 mm while branch diameters ranged from 39 to 111 mm. The moisture content, measured at the fracture surface post-testing varied moderately between 30 and 36%. The aspect ratio of the specimens was 0.812±0.010, indicating a high proportion of codominant stems in the sample. Three bifurcations with included bark were preserved for the analysis of the results, as no significant deviation was observed in the measured data in comparison to the rest of the sample.

Tensile test

For each branch junction, the canonical reference point C, i.e. the point of application of the resultant force and the bending moment, was physically determined by tracing the neutral axes of the two branches with strings. Two 14 mm diameter holes were drilled perpendicular to the bifurcation plane, located 200 mm from the canonical reference point. The distance between the two holes was measured using an engineer's scale ruler. The tensile test protocol is based on the method proposed by Slater and Ennos (2013). Each sample was fixed in the INSTRON testing machine using two custom-made steel U-shaped brackets. A 12 mm bolt held the two arising members of the bifurcation within the centre of each U-shaped bracket. The crosshead of the testing machine was displaced upward at a constant rate of 10 mm.min^{-1}. The force and the displacement were recorded using a 100 kN load cell and an integrated displacement sensor. The failure modes were observed and documented photographically.

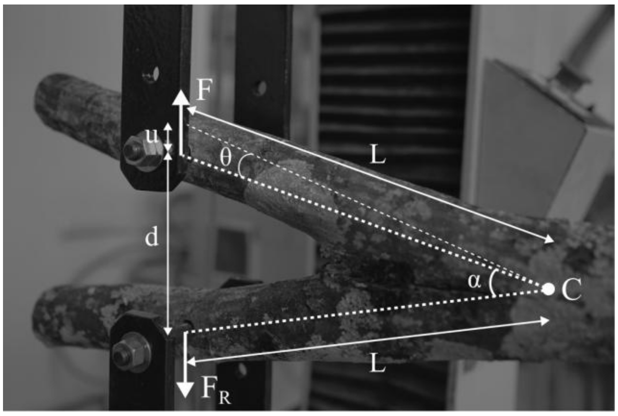

Fig. 2 : Test protocol and measures for calculation

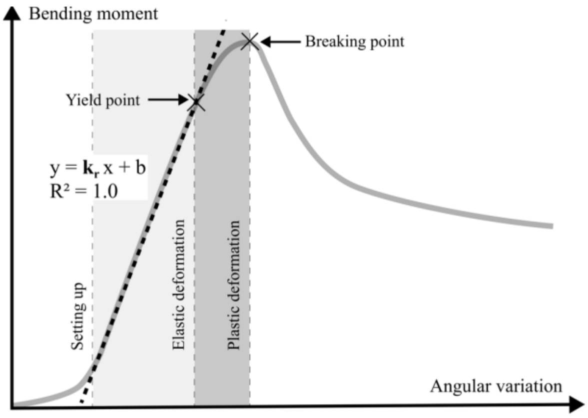

Fig. 3 : Rotational stiffness (k_r) determination

The maximum breaking stress was calculated according to the protocol proposed by Slater and Ennos (2013), based on the Euler-Bernoulli beam theory, modelling the branch with the smaller diameter as a cantilever beam, fixed at the bifurcation apex and loaded by an inclined force. The rotational stiffness k_r is defined, for elastic behaviour, as the ratio between the bending moment M and the angular variation ϑ, which, considering Fig.2, are expressed at the canonical reference point with the following equations (1,2) :

$$\mathrm{k_r} = \frac{\mathrm{M}}{\theta} \quad (1)$$

$$\text{with } \mathrm{M} = \mathrm{FL}\cos\left(\frac{\alpha}{2}\right) \text{ and } \theta = 2\left(\sin^{-1}\left(\frac{\mathrm{d}+\mathrm{u}}{2\mathrm{L}}\right) - \sin^{-1}\left(\frac{\mathrm{d}}{2\mathrm{L}}\right)\right) \quad (2)$$

The constitutive relation between the bending moment and the angular variation is represented for each specimen. The rotational stiffness was determined as the slope of the elastic portion of the curve, using the least square linear regression method, applied to the relevant recorded data points.

Results

The failure modes observed confirm the results of the experiments conducted by Kane et al (2008) with failures occurring exclusively via embedded branch (Fig.4a) and flat surface (Fig.4b) for diameter ratios exceeding 0.70. The stress – displacement curves revealed two distinct failure behaviours (Fig.5). The first one is described as a progressive damage due to crack development, for branches with minimal diameter less than 60 mm. This behaviour is characterised by a peak stress value reached after an elastic and a brief plastic phases, followed by a more or less pronounced fall to a plateau level where the displacement continues to decline slowly. The second behaviour, described as brittle, occurs in specimens with larger branch diameter (Fig.6), for which a sudden fall is observed after reaching the peak stress value.

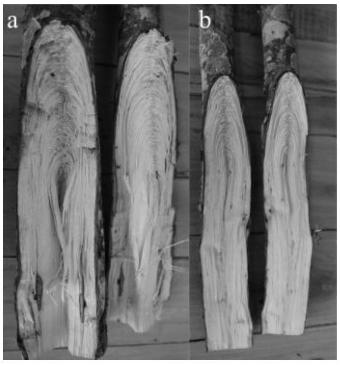

Fig. 4 : Failure mode

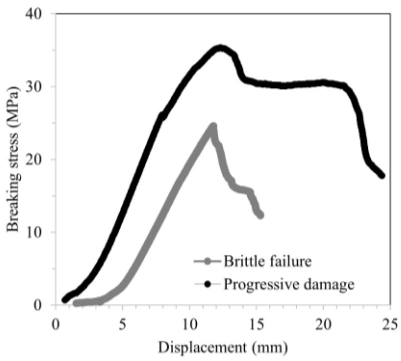

Fig. 5 : Illustration of the two significant failure behaviours

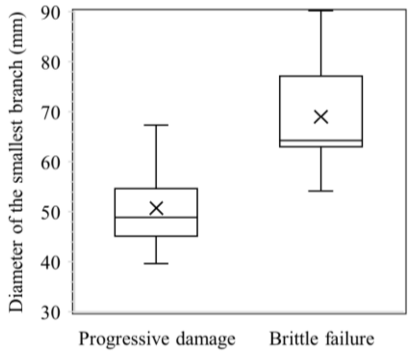

Fig.6 : Branch diameter dispersion according to the failure behaviours

The measured breaking stress have an average value of 26.40 MPa with a standard deviation of 7.95 MPa and extreme values ranging from 12.36 MPa to 4s1.88 MPa. The rotational stiffness have an average value of 21.11 kN.m/rad with a standard deviation of 10.75 kN.m/rad and extreme values ranging from 5.91 kN.m/rad and 42.71 kN.m/rad (Fig.7). The rotational stiffness is significantly positively correlated with the diameter of the smallest branch of the bifurcation (R^2 = 0.68 ; $P<0.001$). Furthermore, specimens exhibiting highest measured rotational stiffness values tended to fail in a brittle manner (Fig.8). For bifurcations whose smallest branch diameter is larger than 0.60 mm, brittle failure behaviour, increased rotational stiffness and reduced breaking stress are observed.

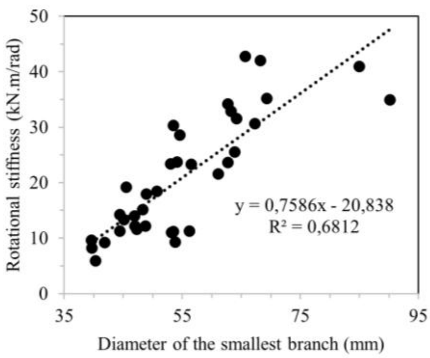

Fig. 7 : Scatterplot for the prediction of rotational stiffness from the diameter of the smallest branch

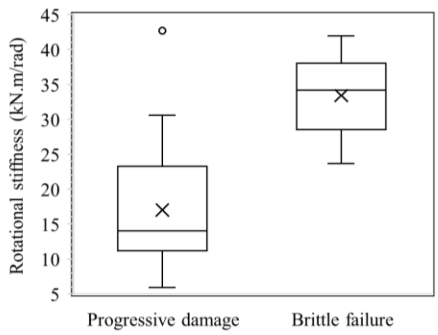

Fig. 8 : Rotational stiffness dispersion according to the failure behaviors

Discussion

The principle of rigid connection, according to the civil engineering requirements, refers to a significant capacity to transfer bending moments and high rotational stiffness values, minimizing the rotational displacement within the structures. Although the samples tested have small diameters and would need to be supplemented by larger diameter bifurcations, at the scale of a large load-bearing structure, their measured rotational stiffness are $\sim 10^{-3}$ of that typically reported for rigid connections in the timber construction industry (Johanides et al 2021). The capacity to transfer bending moments has been confirmed but the very low rotational stiffness of the bifurcations means that they cannot be classified as rigid connections.

The design of high-quality timber structures relies on ensuring that the structural elements deform in a ductile manner, thereby dissipating energy under load. In the present study, larger bifurcations exhibited brittle failure, primarily due to perpendicular tensile stresses in the fibres. Such failure modes represent a critical safety limitation for the use of natural junctions in structures when subjected to bending. Consequently, these configurations should be avoided. The findings support the use of this forest resource only in schemes where bifurcations are loaded axially, either in compression or in tension. If a natural junction is to be subjected to bending, reinforcement would be required to enhance both ductility and rotational stiffness.

Conclusion and perspectives

The mechanical tests conducted in this study clearly contradict the poetical classification of natural junctions as rigid connections, in terms of civil engineering requirements, due to the very low rotational stiffness measured. The use of bifurcations in structural elements subjected to bending stress should therefore be avoided unless adequate reinforcement is provided. The opportunities for long-term structural applications of bifurcations appear to be restricted to elements subjected primarily to axial stress, either in compression or in tension.

Further experimental work is required to assess the compliance of the bifurcations mechanical properties with engineering criteria, for larger diameters, different species and axial loading conditions. In addition, research on the non-destructive analysis methods and on the modelling approaches should be pursued with the aim of facilitating the integration of bifurcations into the architectural and the engineering design practices thereby improving predictions of their structural performance in buildings, beyond research-scale pavilions.

References

Bukauskas A, Mayencourt P, Shepherd P, Sharma B, Mueller C, Walker P, Bregulla J (2019) Whole timber construction: A state of the art review, Construction and Building Materials, 213:748-769.

Drénou C, Restrepo D, Slater D (2020) demystifying tree forks: vices and virtues of forks in arboriculture, Journal of Botany Research, 3(1): 100-113.

Johanides M, Kurbincova L, Mikolasek D, Lokaj A, Sucharda OL, Mynarcik P (2021) Analysis of rotational stiffness on the timber frame connection, sustainability, 13(1), 156.

Kane B, Farrell R, Zedaker SM (2008) Failure Mode and Prediction of the Strength of Branch Attachments

Slater D (2016) The anatomy and biomechanical properties of bifurcations in Hazel (Corylus avellana L.), PhD, The University of Manchester, 262 p.

Slater D, Ennos R (2013) Determining the mechanical properties of hazel forks by testing their component parts, Trees 27:1515-1524.