



# A Minimal Invasive Anchoring Technique for the Foundation of Technical Structures in Trees

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**Abstract.** We present motivation, ideas, experiments, and numerical results for the anchoring of buildings or technical elements into trees. The task here is interdisciplinary since the tree with its biological tissues does not represent a building material in the classical sense but is used for building by the intended use. Therefore, as in medicine, a minimal invasive procedure must impart forces into the hard tissue layers via a technical connector, considering the metabolism as well as the growth processes of the tree. Our hypothesis is, that in this context only a two-bolt solution offers an acceptable anchoring technique to fulfill building laws. The consideration of biological aspects into the solution also has relevance in terms of the building law, as well as the durability and reliability of the connection depends on the vitality of the tree. However, an anchoring technique like that sets up new and ecologically oriented construction methods, which enable the preservation of tree populations in civil development areas.

First, by analysis of existing anchoring techniques different concepts are discussed. Then, the load capacity of a minimally invasive anchoring technique is investigated in a series of load tests including interpretation. Finally, we propose a solution based on two bolts with rigid coupling in order to increase significantly the load capacity of the connection.

**Keywords:** Construction with trees · fastening · anchoring · tree house building

## 1 Introduction

### 1.1 Motivation for Building with Trees

The importance of forested areas for mitigating global problems such as climate change, species extinction, soil erosion and flood events is of increasing importance for our society and is prompting the development of novel concepts such as “urban greening” in the building sector as described in [1], among others. In this context, the preservation and use of existing trees for this new generation of buildings is little discussed, even though such building development only requires a defined intervention and not a complete transformation of the ecosystem.

Yet neither in Germany nor in other countries, building laws or technical standards regulate the use of trees. Although wood (technically prepared) has always been important as building material, the use of living trees for the implementation of professional building projects is unusual. One reason for this is, that the development of civilization has had no need for tree-preserving construction methods up to date [11].

Another barrier to use trees for construction is the risk of strong wind events. Official guidelines rely primarily on the trees vitality or simple models but do not serve like engineering models as suggested in [2]. The same issue applies to the anchoring of technical loads into trees. To the best of the authors knowledge, neither technical guidelines nor documented deterministic models on this topic can be found so far.

### 1.2 Anatomy of Trees and Intervention by Fasteners

Anchoring techniques in trees can be summarized basically into **three categories**:

1. Form-locking force transfer via the stems surface into the wood matrix
2. Friction-based force transfer via the stems surface into the wood matrix
3. Form-locking force transfer directly into the wood matrix

Methods of category 1 & 2 do not remove or penetrate any layer as necessary in category 3. The basic structure of tissue layers in a tree are sketched in Fig. 1. The thin and soft vascular cambium positioned between the inner bark (phloem or cortex) and the sap wood (xylem) as described in [3] divide and diversify new cells to create vascular bundles of transporting tissues and increase stem girth [4, 5]. As a result, trees possess the distinctive and inherent characteristic of secondary thickness growth in radial direction  $r$  of the stems cross-section, which we define as  $r$ - $\varphi$ -plane. The (primary) extension growth of trees in height is made principally from just below the topmost apical bud (growing point or “leader”) [4]. The stem itself does not elongate in  $z$ -direction since it is solid wood.

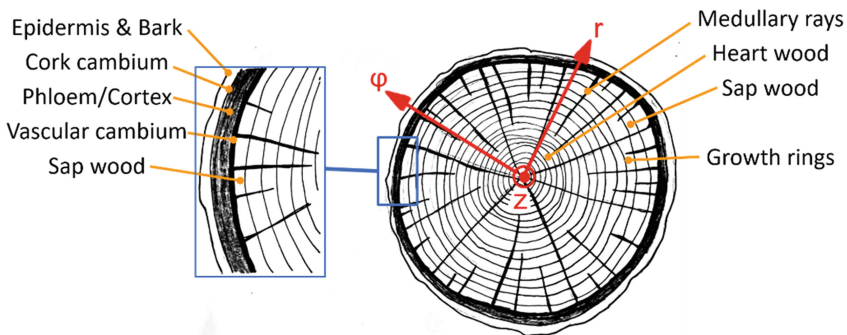


Fig. 1. Cross-section of a stem with layer structure and coordinate system.

The outer bark defines the surface of the stem and protects the soft tissues within [4]. It is more or less resilient to mechanical impact depending on the tree species. While

oak trees (*Quercus*) in general exhibit a thick and robust outer bark, beech trees (*Fagus*) provide generally a thin and fragile outer bark, although both types belong to the same family (Fagaceae). It implies that any force transfer via the surface of a stem have to pass a series of tissue layers, which are

- different in thickness, strength and load capacity depending on the tree species
- thin and soft in relation to the heartwood.
- subject of the growth process.

**Category 1:** Methods of form-locking force transfer via the stems surface can be split up in a) anchoring techniques for the initiation of predominantly **vertical** forces and b) anchoring techniques for the initiation of predominantly **horizontal** forces.

a) Form-locking force transfer in predominantly vertical direction via the stems surface is often found in practice by laying textile slings over the shoulder of branch forks, see Fig. 2 a). Due to the natural rounding of the fork, for a wide range of force vectors a sling-position can be found such that the surface normal corresponds to the direction

(a)



(b)



(c)



**Fig. 2.** a) Form-locking force transfer through the stems surface under usage of textile slings. b) Result of form-locking force transfer under usage of textile slings when contact stress is greater than the cambium growth pressure. c) Result of form-locking force transfer under usage of (covered) steel cables when contact stress is greater than the cambium growth pressure.

of the force vector. Thus, the force transfer takes place almost without friction and thus without shear forces, provided that local effects due to the finite width of the sling as well as friction between the first contact of the sling to the surface and the actual pressure point in the branch fork are disregarded.

If the contact stress between the sling and the stems surface is less than the growth pressure of cambium and cork cambium, which is about  $0,7 \text{ N/mm}^2$ , see [6], natural thickness growth can continue, lifting the sling by the newly grown layers. If the contact stress between the sling and the stems surface is greater than the growth pressure of the cambium, only the layers next to the sling can continue to grow. As a result, unnatural ingrowth and even death of tissue layers occurs, see Fig. 2b). In case of steel cables - even when they are covered with rubber hose as supposed protection of the tree- the contact stress between the sling and the stems surface in the most load cases is greater than the strength of cork or cortex or both, leading to immediate damage of layers, see Fig. 2c).

The mechanical strength of the wood matrix in the area of the branch fork is another complex issue, which is only predictable through exact knowledge of the local geometry as well as an estimation of the fiber course in the wood [10].

- b) Form-locking force transfer in predominantly **horizontal** direction via the stems surface is often found in practice by wrapping techniques. To protect the tree in most cases wooden strips were placed between the steel cable and the outer bark of the tree, see Fig. 3a). In fact, the resulting forces are transferred radially into the tree directly through the wooden blocks.

(a)



(b)



**Fig. 3.** a) Form-locking force transfer through the stems surface using wrapping techniques. b) Different grades of failure under usage of wrapping techniques.

Depending on the contact stress between the wooden stripes and the outer bark the tree shows a wide range of reactions, that are from slight damage up to total failure, see Fig. 3b).

**Category 2:** Especially in adventure parks established in forests the attachment of technical equipment to living trees via friction-based force transfer very common, see Fig. 4a).



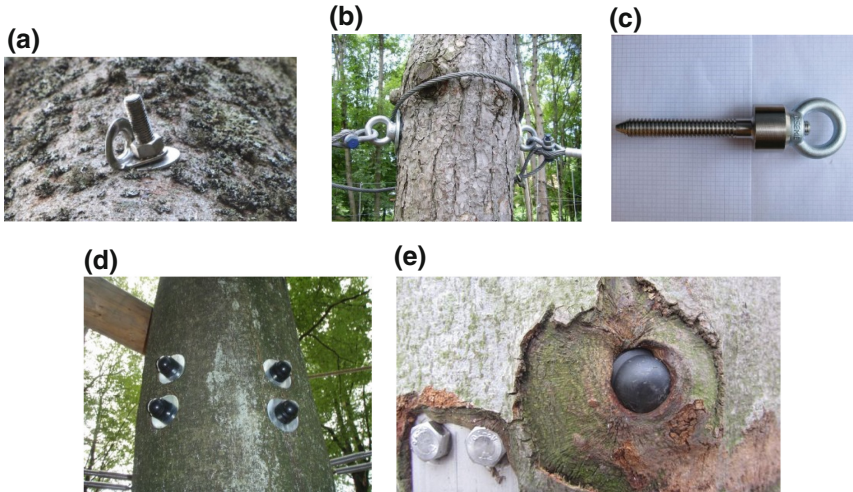
**Fig. 4.** a) Examples of different methods of friction-based force transfer b) Failure mechanism of a friction-based force transfer.

For construction projects, friction-based force transfer across the stems surface into the wood matrix is critical for two reasons. First, the coefficient of friction must be provided on the surface. Since the surface is exposed to weathering and the bark can be attacked by fungi, this aspect is problematic. For solid friction (Coulomb friction), furthermore, the frictional force is proportional to the normal force, so that this must also be secured, for example when the trees move in the wind and actually requires clamping. Clamping, however, leads in principle to unnatural growth, damage to the growth tissue, waterlogging, etc., as described in [7–9].

Second, the low shear strength of the outer stem layers calls into question any **category 2** connection. In Fig. 4b) one can see how the cambium layer is peeled away from the wood core by shear stresses from vertical force components.

**Category 3** anchorage methods bridge the outer tissue layers through stiff elements and thus the uncertainties and weaknesses listed above. However, tissue layers and wood matrix must be removed locally. Thus, minimally invasive elements are advantageous in order to spare the organism. For practical reasons, the assembly is prepared by drilling holes. Expansion anchors, through rods, and moderately long threaded pins, see Fig. 5 a)–c), are discussed below.

- a) **Expansion anchors** achieve their anchoring effect by expansion, which compresses the material around the anchor. This deformation generates ring tensile stresses in the wood matrix above and below the drilled hole, which can cause fibers to delaminate locally in the longitudinal direction and lead to large-scale splitting of the wood matrix. If such splitting occurs, this leads to a loss of the anchoring effect of the expansion anchor, which speaks against its use.
- b) **Through rods** require drilling through the complete stem to anchor on the opposite side of loading by means of compressive contact stress. Disadvantage of the usage of



**Fig. 5.** a) Expansion anchor, b) Through rod, c) moderately long threaded pin. d) Through rods after mounting. e) and 3 years after mounting.

through rods is, that the accessibility and detachability of the connection is getting lost after some time and cannot be monitored any longer, see Fig. 5d) and e).

To make the drill hole as thin as possible, the bolt can be oriented in the direction of the load so that it is only subjected to tensile normal forces, allowing efficient small diameter design. However, the drilled hole will always create a continuous entry point for microorganisms and other subcellular pathogens, which can thus cause widespread decay in the wood. If the drilling is carried out professionally and in a sterile manner, the rod fills the drill hole completely sterile and airtight. If rod and anchor are made of non-corrosive steel, this type of anchoring technique can meet the requirements for safety and durability. But it cannot be called minimal invasive.

c) **Moderately long threaded bolts** are screwed into a blind hole and injure the tissue layers only at one side of the stem [12]. The bolts establish the form fit to the wood matrix via shaft and thread. In principle, the orientation of the bolt is selectable and can follow the loading direction in order to be free of shear force and bending moment. Thus, the angle between the bolt and the wood fiber direction is varied in our experiments in Sect. 2. We usually align the bolt in the  $r$ - $z$  plane, see Fig. 6. But it can be inclined by an angle  $\beta$  with respect to the  $r$ - $\varphi$  plane. If the load direction and the centerline of the bolt do not coincide, shear force must also be transferred into the stem via the bolt. This results in contact forces with the wood matrix especially in the outer regions (i.e. new annual growth rings).

The flanks of the thread yield form-locking to the wood matrix. It is recommended to ensure that the blind hole can absorb the displaced wood matrix through the flanks of the thread. Otherwise, undesirable ring pull forces will occur below and above the blind hole, as discussed for expansion anchors.

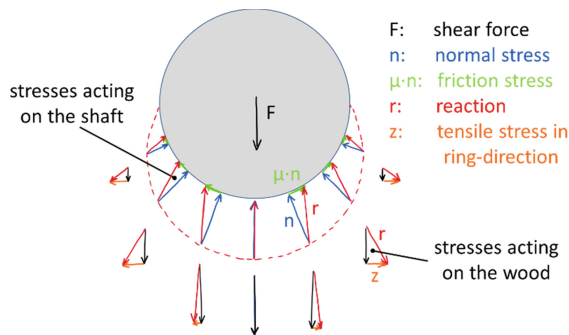
## 2 Anchoring with Moderately Long Threaded Bolts

### 2.1 Basic Structure

Anchoring devices with moderately long threaded bolts are available from various suppliers. They differ in material, thread type, diameter, shaft and other geometric features. The limited length of the thread is due to aspects of minimal invasive drilling and to the technically justifiable screw-in resistance. Generally, such anchors have the following areas and features:

**The shaft and thread** establish form-locking to the wood in longitudinal (via the thread) and transverse (mainly via the shaft) direction of the bolt. The pull-out resistance can be associated with the form-locking of the thread. In case of shear forces, complex mechanical processes occur, which are primarily based on bending and bedding of the bolt by the wood matrix.

The cause of tensile stress in ring direction of the stem is explained in Fig. 6. This kind of tensile stress can easily delaminate the vertical wood fiber structure below and above the bolt.



**Fig. 6.** Formation of ring tensile stresses by compression force

The shaft is followed by the so-called growth reserve section (GRS) of the anchor. Since this section is installed outside the bark or cambium, no or fewer tissue layers have to be removed. Thus, the diameter of the GRS is usually larger than the diameter of the shaft. Due to the secondary growth of the stem, this section becomes gradually enclosed by callus tissue and wound wood, see Fig. 7. Thus, the spatial inclusion of the GRS provides a significantly larger surface for the transfer of shear forces after appropriate time.

The **load connection point** is at the end of the GRS in order to couple construction components like ropes. For pure normal force loading, the distance between the shaft and the load connection point has no influence on the load-bearing capacity of the anchor. However, when shear forces act, this distance leads to a linear increase in the resulting bending moment.

## 2.2 Specification of the Test Body

In the following experiments threaded bolts with a total length of 220 mm are used. The shaft is 36.5 mm long and has 20 mm in diameter. The trapezoidal thread is 103.5 mm long with 20 mm outer and 16 mm core diameters. The GRS is 80 mm long with 50 mm in diameter. A movable swivel joint with eyelet is used as load connection point.

## 2.3 Specification of the Test Setup

The anchors are inserted into trunk sections of freshly cut copper beech (*Fagus sylvatica*). The bark and phloem is removed from the center of these sections by face milling and the hole is drilled for the shaft and thread.

For inclinations  $\beta \neq 0^\circ$ , a wedge-shaped washer mediates between the face milling and the GRS, compare Fig. 7. We use a servo-hydraulic cylinder with 5 mm/min speed for displacement-controlled loading onto the movable swivel joint. The experiments vary the load application angle  $\alpha$  in the interval  $[0^\circ; 90^\circ]$ , and the inclination angle  $\beta$  in the interval  $[0^\circ; 30^\circ]$ .

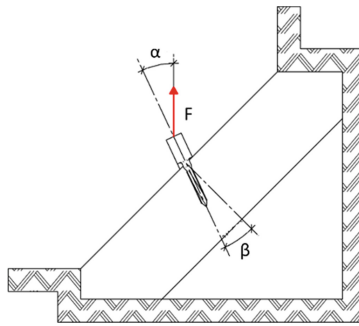


Fig. 7. Schematic representation of the experimental setup

## 2.4 Axial Pull-Out Test

The axial pull-out test for the anchor is obtained by the load application angle  $\alpha = 0^\circ$ . We observe decreasing pull-out resistance for increasing inclination angles, see Table 1.

Table 1. Pull-out resistance of the anchor for different inclination angles  $\beta$

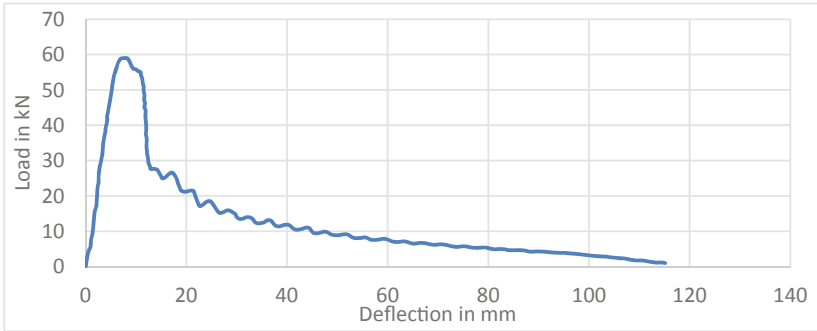
Inclination angle $\beta$	$0^\circ$	$15^\circ$	$30^\circ$
Pull-out resistance	58 kN	51 kN	47 kN

A typical force-displacement curve of this test can be seen in Fig. 8 and can be observed similarly for all inclination angles  $\beta$ . After reaching the maximum resistance



of approx. 58 kN the load curve drops abruptly to less than half (28 kN). This is explained by the loss of the form-locking due to shear-failure of fibers in the area of the thread, since the thread on the anchor presents itself undamaged after the test.

The slightly wavy course after failure has a wavelength of 4 mm, which corresponds to the thread pitch of the anchor. Since the amplitude of the wave is small and continues to decrease with increasing pullout, the residual stiffness of the connection can be attributed to friction between the thread and the wood matrix.



**Fig. 8.** Typical load deflection curve in the axial pull-out test.

## 2.5 Shear Force Test and Combined Loading

The pure shear force test requires the load application angle  $\alpha = 90^\circ$ . Decreasing angles  $\alpha$  yield combinations of tensile and shear loading.

**Table 2.** Shear load resistance of the anchor for different loading angles  $\alpha$

Loading angle $\alpha$	$90^\circ$	$60^\circ$	$45^\circ$
Load resistance $FE,k$	5 kN	6,5 kN	7,5 kN
Bending moment in the shaft $ME,k$	62,5 kNcm	58,8 kNcm	66,3 kNcm

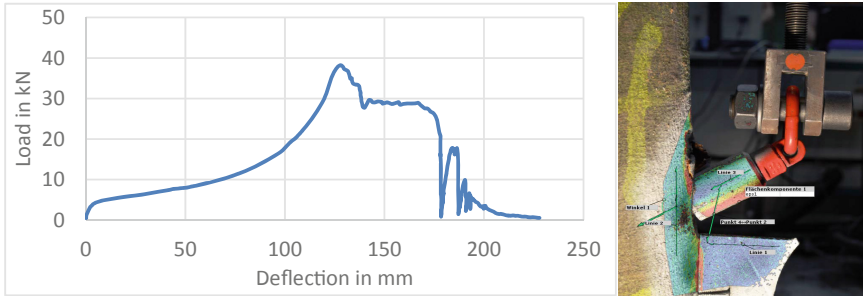
Under pure shear loading, a system change in the mechanical behavior becomes apparent at approx. 5 kN, which already limits the ultimate load of the anchor, see. Fig. 9 This system change is identified by the attainment of the plastic cross-sectional load capacity of the shaft, which is correspondingly low for a diameter of 20 mm. Neglecting strain hardening effects in the yield zone the shafts plastic moment reads

$$M_{pl} = w_{pl} \cdot f_{y,k} = 1,33 \left[ \text{cm}^3 \right] \cdot 35,5 \left[ \text{kN/cm}^2 \right] = 47,2 \left[ \text{kNcm} \right] \quad (1)$$

The distance between the load connection point and the shaft can be used to determine its bending moment listed in Table 2:

$$M_{E,k} = F_{E,k} \cdot \sin(\alpha) \cdot 12,5 \left[ \text{cm} \right] \quad (2)$$

Obviously, for all loading angles the shafts plastic load capacity is already exceeded at ultimate load  $F_{F,k}$ . This is in accordance to the significant loss of stiffness at the beginning of the force-displacement curve (less than 5 mm deflection).



**Fig. 9.** Typical load deflection diagram (left) and image (right) of the GRS

In the sense of building regulations, the present system (cantilever) must not exceed the ultimate load from the elastic-plastic verification method. This confirms our hypothesis that at least a second anchor is required for practically efficient anchor systems.

Although the load deflection curve in Fig. 9 (left) considerable load increase as well as rotational capacity, such configurations are unacceptable for the state of use. For example, tissue layers close to the surface are damaged by the rotation of the GRS, Fig. 9 (right).

## 2.6 Basic Conceptual Design of the Coupling

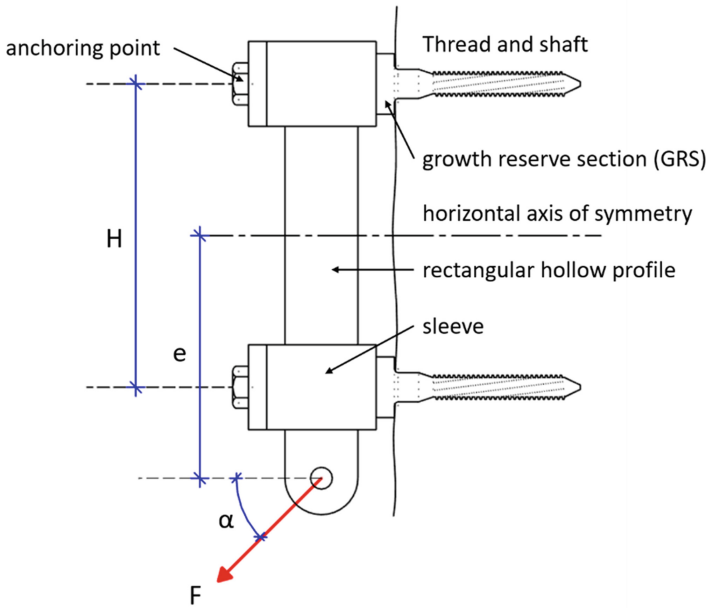
The tests in Sect. 2.5 reveal the strong limitation of the load capacity of a single anchor. An increase of the shaft diameter is undesirable in terms of the minimally invasive anchoring technique. It would also increase the risk of greater ring tensile forces in the stem. However, the load capacity of the connection can be significantly increased by bending-resistant coupling of two anchors via an appropriate coupling element.

The rigid coupling is provided by a sleeve that clamps the GRS of the anchors. Thus, the coupling element is radially expandable and can follow secondary growth of the stem. Furthermore, the sleeves are rigidly connected to a square hollow section, see Fig. 10.

Up to the ultimate load, four yield hinges are necessary in the plastic-plastic verification method. The sequence in which the yield hinges occur depends primarily on the load application angle, the square hollow section and the bedding of the shaft by the wood matrix, which will be discussed in the next chapter using numerical simulations.

## 2.7 Specification of the Numerical Load Capacity Tests

Our simulations vary the load angle  $\alpha$  within a simplified 2D model as suggested by the scheme in Fig. 10. The material properties of the coupling element and the anchors are



**Fig. 10.** Scheme of the coupling element

modeled as elastic-plastic material with linear strain hardening following the material data sheet *I.4301*. The material data of the green wood follow a bilinear Drucker-Prager model with values from Table 3. These values are in accordance with literature [13, 14] but partially determined from own experiments.

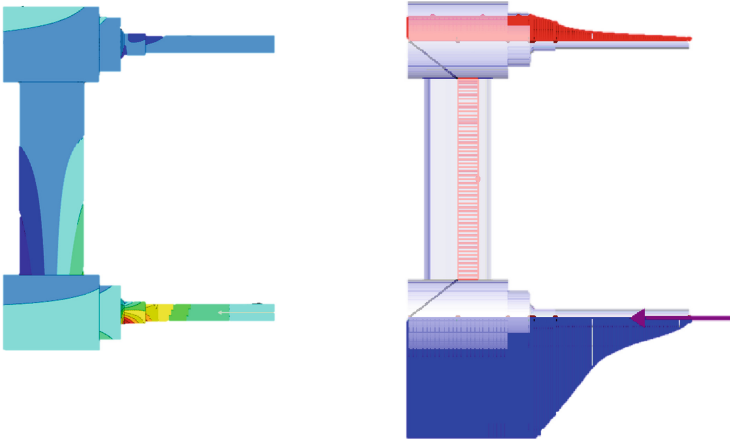
**Table 3.** Material parameters of the numerical model for beech

Modulus of elasticity $E$	7500 kN/cm <sup>2</sup>
Shear modulus $G$	2586 kN/cm <sup>2</sup>
Yield point (tension) $f_{y,t}$	2,7 kN/cm <sup>2</sup>
Yield point (compression) $f_{y,c}$	1,6 kN/cm <sup>2</sup>
Modulus of hardening $E_p$	0,038 kN/cm <sup>2</sup>

## 2.8 Calibration of the Model with Horizontal Loading

The model of the coupling element is calibrated with the axial pull-out resistance of a single anchor for purely horizontal loading with  $\alpha = 0^\circ$ . We account the fact, that the load eccentricity  $e$  with respect to the horizontal axis of symmetry increases the pull-out force in the lower anchor. Thus, the horizontal limit load is  $F_{max} = 47.3$  kN - generating the maximal pull-out force of 58 kN in the lower anchor.

The load eccentricity also causes a bending moment in the shaft of the lower anchor. However, this is not yet sufficient to close the yield zone, as shown in Fig. 11.

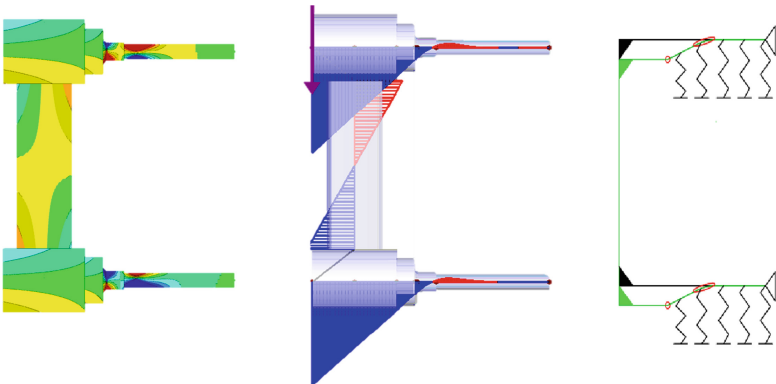


**Fig. 11.** Equivalent stress (left) and normal force distribution (right) for horizontal limit load.

## 2.9 Transverse Load

Under pure transverse load with  $\alpha = 90^\circ$  the system remains in the elastic state up to a load of 62 kN. The ultimate load is reached at  $F = 85$  kN by closing four yield zones. The formation of the yield zones starts in the lower anchor.

The failure mechanism at the limit load is remarkable. The formation of yield zones in both – in the shaft and in the thread - leads to the kinematic sketched in Fig. 12.



**Fig. 12.** Equivalent stress (left), bending moment (center) and kinematics (right) at the limit load.

### 3 Summary and Outlook

We motivate building in and with trees in accordance with building law and technical guidelines. On the one hand, this construction technique can reduce resource consumption and protect the used trees. On the other hand, the used trees can be damaged in the short or long term by improper anchoring techniques. Furthermore, safety-relevant aspects have to be considered, motivating our experiments on the load capacity. They confirm the working hypothesis that professional anchoring in trees requires at least two anchors per point to be safe. Both anchors should be coupled with a bending-resistant device to fully exploit an efficient and minimal invasive anchor system. This is supported by numerical simulations and analysis.

Further work aims load tests for the proposed anchor system in situ. It may result in further optimization of the simulation parameters as well as anchor geometries. Experiments should be performed in different tree species to extend the range of applications.

### References

1. Shu, Q., Rötzer, T., Detter, A., Ludwig, F.: Tree information modeling: a data exchange platform for tree design and management. *Forests* **13**, 1955 (2022)
2. Loske, S., Muench, I.: Experiments and Modelling of the Load Capacity of Green Wood. Accepted for publication in *Proc. Appl. Math. Mech.* 20(1) (2022)
3. Shigo, A.L.: *Tree Anatomy*, Shigo & Trees Association (1994)
4. Brickell, Chr., Joyce, D.: *Pruning & Training*, Royal Horticultural Society (2017)
5. Shigo, A.L., Lang, J., Bernatzky, A.: *Die neue Baumbiologie*, Haymarket Media (1990)
6. Masselter, T., Speck, T.: Quantitative and qualitative changes in primary and secondary stem organization of *aristolochia macrophylla* during ontogeny: functional growth analysis and experiments. *J. Exp. Bot.* **59**, 2955–2967 (2008)
7. Jaffe, M.J.: *Thigmomorphogenesis: The response of plant growth and development to mechanical stimulation*. Ohio University, Department of Botany (1973)
8. Telewski, F.W.: A unified hypothesis of mechanoperception in plants. *Am. J. Bot.* 93(10), 1466–1476 (2006). Botanical Society of America
9. Markovic, D., Glinwood, R., Olsson, U., Ninkovic, V.: Plant response to touch affects the behaviour of aphids and ladybirds. *Arthropod-Plant Interact.* **8**(3), 171–181 (2014). <https://doi.org/10.1007/s11829-014-9303-6>
10. Mirabet, V., Das, P., Boudaoud, A., Hamant, O.: The role of mechanical forces in plant morphogenesis. *Annu. Rev. Plant Biol.* **62**, 365–385 (2011)
11. Ludwig, F., Schönle, D.: *Wachsende Architektur – Einführung in die Baubotanik*, Birkhäuser, Basel, 2023
12. Zeller, M., Muench, I.: Befestigung von Bauwerken in Bäumen mit Baumankern und doppelter Umreifung. *Bautechnik* **99**(S1), 13–22 (2022)
13. Niklas, K., Spatz, H.: Worldwide correlations of mechanical properties and green wood density. *Am. J. Bot.* **97**, 1587–1594 (2010)
14. Lavers, G.: *The Strength Properties of Timber*. Bulletin of the Forest Products Research Laboratory Princes Risborough, England (1969)