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Comparison of unit cell-based computational methods for predicting the strength of wood

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Wood, as a naturally-grown material, exhibits a highly anisotropic and inhomogeneous material structure, with a complex wood fibre distribution influenced by randomly occurring knots. Thus, for the prediction of effective strength properties of wood, advanced computational tools are required, which are able to predict as well as consider multidimensional strength information at different scales of observation.

Within this work, three such computational methods will be presented: an extended finite element approach able to describe strong strain-softening and, thus, reproduce brittle failure modes accurately; a newly-developed limit analysis approach, exclusively describing ductile failure; and an elastic limit approach based on continuum micromechanics. All three methods are applied to earlywood and latewood unit cells and to clear wood, finally yielding effective failure surfaces for a range of multidimensional stress states. These failure surfaces are compared with each other and with experimental results from biaxial tests. Based on these comparisons, the strengths and weaknesses of the three computational methods are discussed, and their applicability to wood is evaluated.

The extended finite element method is a powerful technique that allows for a very realistic description of strength-governing processes. Nevertheless, its complexity and high computational effort prevent widespread use in the engineering field. The plastic limit analysis and elastic limit approaches, however, show good predictive performance compared with the extended finite element method, coupled with excellent efficiency and stability. In this study it is found that together, the latter two approaches are able to enclose the experimentally-obtained failure regions for clear wood almost perfectly, while also delivering new insights with respect to the ductile failure potential of wood.

The conclusion can be drawn that there exist promising computational methods that are capable of delivering reliable multidimensional strength information for wood and, subsequently, will enable effective strength predictions for wooden boards and wood-based products. Finally, this work is intended as a contribution to performance-based optimisation of wooden structures, a necessity for wood to become competitive with respect to other building materials.

1. Introduction

Traditionally, wood as a structural building material has mainly been used in rural areas for one- or two-storey residential buildings or simple halls and stables. Due to the relatively small dimensions of such buildings and the fact that each structural element only appears in a small number, it has not been necessary to exploit the full mechanical potential of wood. Simple design rules combined with practical experience and considerably oversized components have together met all requirements.

In recent years, this situation has changed dramatically. The excellent mechanical and physical properties of wood, combined with the general trend of growing environmental awareness, have put timber structures into the focus of private as well as public building developers – not just to realise small buildings, but to use wooden building elements for highly sophisticated engineering structures. There has already been a nine-storey tower built in London and a 12-storey wooden building is under construction in Bergen, Norway. A 24-storey wooden skyscraper will be completed in Vienna in 2018, which, with a height of 84 m, will be

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the tallest wooden skyscraper in the world. Another wooden tower, comprising 35 storeys, is planned in Paris, aimed at addressing the French capital's housing challenges in a sustainable, creative and environmentally-friendly manner. Meanwhile, a 34-storey wooden apartment block could be built in Stockholm by 2023 if the planning authorities have their way.

Such projects could, or respectively can, only be realised by the strong initiative of individual responsible authorities, and all of these developers struggle to justify their wooden buildings on economic grounds. Indeed, it is only possible for timber structures to be cost-competitive with steel or concrete structures under ideal planning and executing conditions. A major reason for this is the aforementioned traditional origin of timber constructions, the associated simple design practice, and the resulting conservative dimensioning of wooden structural elements.

This has been the motivation for the present work, which aims at the development and assessment of new computational methods enabling better predictions of the mechanical behaviour of wood. Based on such methods, the great mechanical potential of the 'raw' wooden material should be much better utilised. In this context, simple wooden boards, obtained in sawmills by cutting of logs, are considered as 'raw' material. For use in construction, these wooden boards are typically assembled into wood-based products like glued-laminated timber (GLT) or cross-laminated timber (CLT). The basic steps of this procedure are shown in Fig. 1, together with the principal material directions of the flawless wood. The tubular structure of the wooden cells proceeds in the *L*-direction (longitudinal fibre direction), the *R*-direction denotes the radial direction with respect to the central pith, and the *T*-direction describes the tangent direction to the circular annual rings. These directions of the flawless wood, which is subsequently referred to as clear wood, are disturbed by randomly occurring knots, forcing the fibres to deviate from the global longitudinal direction. Such knots or knot groups, as illustrated in Fig. 1, introduce large fluctuations of wooden board properties, and in general board sections with knots exhibit poorer mechanical behaviour than clear wood sections. For this reason, knot-related characteristics are commonly used for sorting and classifying wooden boards. The more accurately this classification procedure works, the more efficiently wooden boards can be used in wood-based products.

Unfortunately, only empirically derived relationships between knot characteristics and certain board properties have been developed and used in the field so far. These do not show very good prediction quality, especially when it comes to strength properties. This is why a growing amount of effort is being put into the development of numerical simulation methods able to describe the influence of knots and knot groups on the effective behaviour of the associated wooden board section. These simulations need to model knots as well as the fibre distribution around them, as shown schematically in Fig. 2. Suddenly, timber design, which has historically been concerned mostly with beam-like structures, and thus 1D design concepts, has to deal with complex 3D stress and strain fields arising in the vicinity of knots. These stress distributions around knots are often responsible for the initiation of cracks or plastified material zones, and therefore have to be taken into account accurately. This is only possible when a detailed characterisation of the multidimensional strength behaviour of the considered clear wood is available. This is actually never the case, because the enormous experimental programme that would be required is hardly feasible. Furthermore, it would be virtually impossible to determine experimentally the influence of density fluctuations, different moisture contents, and the different characteristics of several wooden species on the multidimensional strength behaviour.

For this reason, the present work focuses on a new approach for determining 2D and 3D strength information for clear wood. Since failure and plastification is strongly influenced by the complex material system of wood, exhibiting cellular and layered structures on different length scales, a conceptual framework in which these different microstructural characteristics are incorporated appears to be necessary. Since the strength behaviour of the individual components of the wood material can be assumed to be far less complex than that of the overall material system, linking microstructural characteristics to each other and to the macroscopic behaviour, respectively, ultimately leads to a significant reduction of the independent unknown material properties. Moreover, the influence of microstructural changes on the macroscopic behaviour can be identified easily, without performing additional experiments.

Thus, the division of wood into meaningful levels of observation is the first objective of the present work. At each level, failure

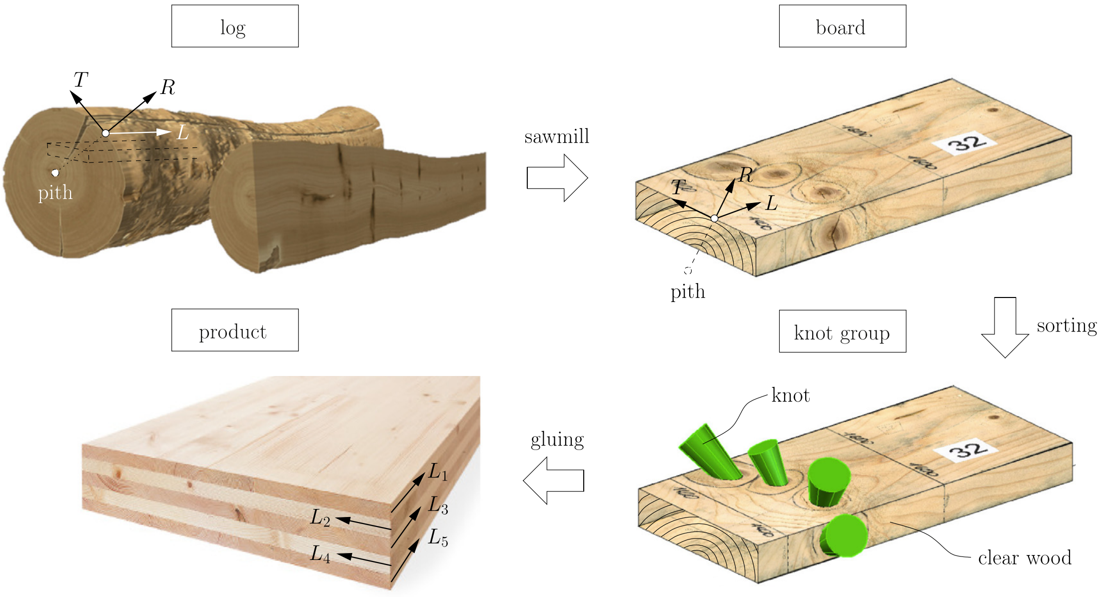

Fig. 1. Basic steps in wood processing. Wooden boards are obtained in sawmills by cutting logs. These boards are sorted and rated according to characteristics like knots and fibre deviations, before they are glued together to create products (like the CLT board shown).