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Heterogenous material simulation in architectural timber design

Tom Svilans[1], Ee Pin Choo[1], Minori Ogoshi[2], Martin Tamke[1], and Mette Ramsgaard Thomsen[1]

[1]Royal Danish Academy
[2]Niigata University

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1 INTRODUCTION

Previous work has focused on the design modelling of timber structures and joints (Svilans 2021) as well as methods of integrating X-ray computed tomography (CT) data of specific timber logs into design modelling environments (Tamke, Svilans, Gatz, and Ramsgaard Thomsen 2021; Tamke, Svilans, Gatz, and Thomsen 2021; Svilans, Tamke, and Ramsgaard Thomsen 2022). The former is aimed at modelling glue-laminated timber elements and their connections from a fabrication perspective; the latter focuses on informing how the physical material is allocated and mapped onto the digital element geometry. While this introduces methods of precisely defining the heterogeneous make-up of a fabricated component before it is cut, this has so far been based on a notional metric of ”material quality”.

This paper presents a continuation of this effort to integrate specific heterogeneous material resources into design modelling with the introduction of mechanical simulation of timber composites into the framework. This shifts the success criteria of the material allocation heuristic from one of mapped ”material quality” matching to a simulated performance-based evaluation under particular loading conditions. This step is significant because it eschews the one-dimensional notion of ”quality” and recognises that different material properties contribute to the overall mechanical performance of timber elements in very localised and situation-specific ways, meaning what may result in a higher performance in one configuration might result in a lower performance in another, even quite similar, configuration. This introduces challenges in how design data is generated for composite timber elements, how this data is transferred between design modelling and simulation software environments, how its semantic structure is retained, how material properties are assigned, and how simulation results are transferred back into the digital modelling environment.

2 DESIGN MODELLING FOR TIMBER

Digital design modelling of timber elements for construction needs to take into account the inherent material heterogeneity and variance present in timber. The boundary representation of the element geometry is taken as a starting point. While this is sufficient information for communicating design intent as well as for other building information modelling purposes, specification of the volumetric makeup of the element is needed. Critical information for predicting the mechanical performance of timber is its orthotropic material orientation throughout its mass, since this has a profound effect on mechanical properties, as well as the inclusion of higher-level features such as knots, since these often present localised material discontinuities. As described in previous work, estimations of these properties and features are derived from CT scans of logs, based on the studied relationship between X-ray datasets and mechanical properties (Freyburger et al. 2009; Shuxia, Lei, and Dawei 2007; Florisson et al. 2022; Gu, Yu, and Wang 2010). Therefore, the modelling of timber elements requires a) a comprehensive breakdown of its constituent timber components (i.e. each lamella in a glulam beam) and b) knowledge of their locations and orientations in relation to the physical timber resource - the mapping of individual timber components onto the log.

3 MODEL TRANSFER AND SEMANTIC PROPERTY RETENTION

In order to assign variegating properties throughout the volume of each timber element, the input boundary representation needs to be three-dimensionally discretised. The challenge here is how to ensure that higher-level features

- such as particular surfaces in the top-level boundary representation that represent joint interfaces - correspond to low-level node and element groups in the generated mesh. In this work, an interface between the design authoring software and the finite element mesh generator Gmsh (Geuzaine and Remacle 2009) is developed to better control the meshing of the element geometry and retention of semantic relationships. Links to top-level surfaces are kept by component-level geometries, for which node groups are created on each component-level mesh. When representing laminated elements, multiple components are merged in a single mesh that represents the entire element, in which case node and element groups are also created for each component. This allows the tracking of nodes and elements between high-level geometries and their constituent parts, and further allows each element group to be placed in a different part of the digital log and augmented with differing properties.

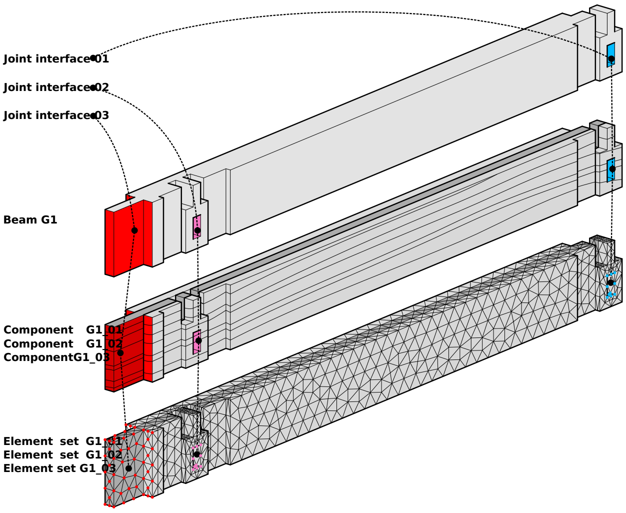

Figure 1: The three different scales and types of models involved: the building element model (top), the broken down component model with individual timber components for fabrication (middle), and the finite-element model for simulation (bottom).

4 TIMBER MODELLING AND ASSIGNMENT OF PROPERTIES

For modelling the mechanical performance of the timber components, an orthotropic material model is used, using values for Norway spruce (*Picea abies*) from Ormarsson 1999. Obtaining the material orientation for each element is done by transforming the element group for each component to its previously-determined position in the physical log. The material orientation is found through one of several ways. The first method uses the model presented by Ormarsson, Dahlblom, and Petersson 1998, which is augmented by also taking into consideration proximity to knots and using a similar model for each knot within a distance defined by its radius. This is the simplest model to implement, however it assumes straight pith and knot axes - a significant abstraction. A second method uses a variation on this model which implements a more irregular pith line, log border, and knot vectors derived directly from the CT scans by Microtec (Sepúlveda, Kline, and Oja 2003; Giovannini et al. 2019), augmented by the fibre deviation models for knots described by Foley 2003, Lukacevic et al. 2019, and Hackspiel, De Borst, and Lukacevic 2014. This model is a more accurate representation of the real pith line and knot axes, since it uses the scanned cross-section of the physical tree to construct the pith line and an interpolation between pith line and outer border to approximate non-circular growth rings. Finally, the third method employs a computer-vision based extraction of material orientations based on detection of growth rings and knots in the CT scan. This model is truest to the individual make-up of the physical log, since it attempts to derive material orientations directly from a localised gradient of the CT-scan dataset. However, this is challenged by noise in the dataset, areas of low variation in density values, or other anomalies that make it difficult to recover an unambiguous gradient direction. Nevertheless, the three methods provide opportunities for varying degrees of speed and approximation in the material orientation calculation, as well as further paths of future improvement.

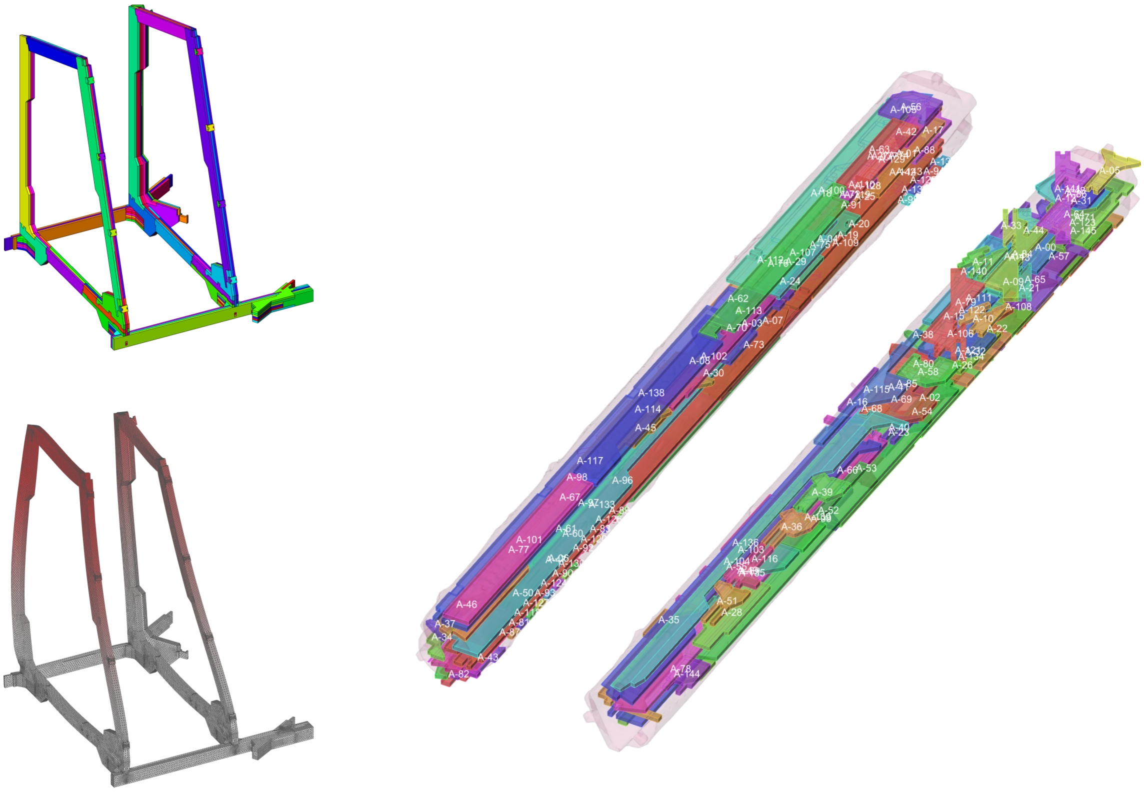

Figure 2: The link between the design model (top left), the distribution of its individual components throughout two CT-scanned logs (right), and the resultant mechanical simulation results (bottom left).

5 MECHANICAL SIMULATION OF HETEROGENEOUS ELEMENTS

Once the element mesh, element orientations, and material properties are defined, the node and element groups that relate to high-level surfaces for joints are used to apply boundary conditions and loads. Element orientations are assigned on a per-element basis according to where in the log the particular element is located. The open-source three-dimensional finite element program CalculiX (Dhondt and Wittig 2023; Dhondt 2004) is used to solve the linear statics problem. Results from the simulation are read back into the design modelling environment to visualise the deformed design model and variations in stress, strain, and displacement. The return to the design modelling environment suggests that further design adaptations could be made and the process repeated to see the effects. As a single round done from beginning to end, the results give an indication of expected behaviour and stiffness of the designed timber element if it were to be fabricated out of a specific timber log compared to any other log. However, an opportunity to iteratively refine the placement of the timber components within the log model or to adjust the designed structure arises by repeating the process as in Svilans, Tamke, and Ramsgaard Thomsen 2022. The simulation results of each iteration therefore provide a ”fitness” value based on, for example, maximum or average simulated strains or displacements, and are therefore used to select a better-performing allocation of material for the design element in question. This feedback loop therefore provides an evaluative framework for informing design decisions in timber structures through high-resolution material simulation.

6 CONCLUSION

The main contribution of this design modelling and simulation framework is a fast and easy exploration of tailored glue-laminated timber assemblies using specific material data acquired through CT-scanning, and the integration of simulated material performance in the design-to-fabrication workflow. Using CT-scan data sources that are aligned with existing technology in active sawmills means that it is useful to speculate about the application of this framework to larger scales of architectural design and fabrication, and how such a workflow could be optimised to reach industrial speeds of processing.

In terms of design exploration, this framework also provides opportunities for simulating new types of timber composites. As one of the biggest challenges for the efficient usage of timber, the anisotropic nature of its properties can therefore be deployed in different and strategic ways to fulfil specific functional requirements by visualising the effect of a changing orientation throughout the constituent components of a glue-laminated element. In this way, a predictive modelling method for non-standard timber composites becomes tractable as a way to develop new and tailored solutions for specific design challenges.

Apart from virgin timber logs, the presented work also offers opportunities for exploring the performance of other heterogeneous entities that possess a high degree of variance and heterogeneity, such as reclaimed timber elements. Further opportunities might also be found in the simulation of other scenarios in which a fast feedback loop between design variation and detailed finite-element analysis would be helpful. For example, these scenarios could include the study of moisture transport and the effects of drying on arbitrary timber composite elements.

Ultimately, the development of this framework is motivated by a belief that, by developing methods for more precisely matching found material properties with their intended use, exploitation of the timber resource and the accompanying pressure on forests can be lessened. Through its deep integration into the digital design-to-fabrication chain, the natural heterogeneity and anisotropy can be leveraged as a design asset instead of a liability, further pointing at novel forms and methods that can challenge the limits of timber construction.

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REFERENCES

Dhondt, Guido (2004). *The finite element method for three-dimensional thermomechanical applications*. John Wiley & Sons.

Dhondt, Guido and Klaus Wittig (2023). *CalculiX - A Three-Dimensional Structural Finite Element Program*.

Florisson, Sara et al. (2022). "Macroscopic X-ray computed tomography aided numerical modelling of moisture flow in sawn timber". In: *European Journal of Wood and Wood Products* 80.6, pp. 1351–1365.

Foley, C. (2003). "Modeling the effects of knots in structural timber". In: 188, p. 188.

Freyburger, Charline et al. (2009). "Measuring wood density by means of X-ray computer tomography". In: *Annals of Forest Science* 66.804.

Geuzaine, Christophe and Jean François Remacle (2009). "Gmsh: A 3-D finite element mesh generator with built-in pre- and post-processing facilities". In: *International Journal for Numerical Methods in Engineering* 79.11, pp. 1309–1331.

Giovannini, Stefano et al. (2019). “Improving Knot Segmentation Using Deep Learning Techniques”. In: *Proceedings 21th International Nondestructive Testing and Evaluation of Wood Symposium*, pp. 40–47.

Gu, Haiyan, Lei Yu, and Yong Wang (2010). “CT number in wood physical properties prediction based on computed tomography technology”. In: *2010 IEEE International Conference on Automation and Logistics, ICAL 2010* 11551111, pp. 279–284.

Hackspiel, Christoph, Karin De Borst, and Markus Lukacevic (2014). “A numerical simulation tool for wood grading model development”. In: *Wood Science and Technology* 48.3, pp. 633–649.

Lukacevic, Markus et al. (2019). “A 3D model for knots and related fiber deviations in sawn timber for prediction of mechanical properties of boards”. In: *Materials and Design* 166.

Ormarsson, Sigurdur (1999). “Numerical Analysis of Moisture-Related Distortions in Sawn Timber”. PhD dissertation. Chalmers University of Technology.

Ormarsson, Sigurdur, O. Dahlblom, and Hans Petersson (1998). “A numerical study of the shape stability of sawn timber subjected to moisture variation Part 1: Theory”. In: *Wood Science and Technology* 32.5, pp. 325–334.

Sepúlveda, Paul, D. Earl Kline, and Johan Oja (2003). “Prediction of fiber orientation in Norway spruce logs using an X-ray log scanner: A preliminary study”. In: *Wood and Fiber Science* 35.3, pp. 421–428.

Shuxia, Han, Yu Lei, and Qi Dawei (2007). “Application of X-ray computed tomography to automatic wood testing”. In: *Proceedings of the IEEE International Conference on Automation and Logistics, ICAL 2007*, pp. 1325–1330.

Svilans, Tom (2021). “GluLamb: A toolkit for early-stage modelling of free-form glue-laminated timber structures”. In: *Proceedings of 2021 European Conference of Computing in Construction (2021 EC^3)*.

Svilans, Tom, Martin Tamke, and Mette Ramsgaard Thomsen (2022). “Integrative strategies across the timber value chain”. In: *Proceedings of the 5th International Conference on Structures and Architecture (ICSA)*.

Tamke, Martin, Tom Svilans, Sebastian Gatz, and Mette Ramsgaard Thomsen (2021). “Tree to Product - Prototypical workflow connecting Data from tree with fabrication of engineered wood structure - RawLam”. In: *Proceedings of WCTE2021*.

Tamke, Martin, Tom Svilans, Sebastian Gatz, and Mette Ramsgaard Thomsen (2021). “RawLam - Probing Tree-to-Timber Workflows”. In: *Climate - Building Resilience in the Era of Climate Change*. Ed. by Susanne Jøker Johnsen and Kristoffer Lindhardt Weiss. Danish Architectural Press, pp. 182–187.