2021 European Conference on Computing in Construction
Online eConference
July 26-28, 2021

GluLamb: A TOOLKIT FOR EARLY-STAGE MODELLING OF FREE-FORM GLUE-LAMINATED TIMBER STRUCTURES

Tom Svilans
CITA (Centre for IT and Architecture), Royal Danish Academy, Copenhagen, Denmark

ABSTRACT

This paper focuses on the integration of material and fabrication parameters into the early-stage digital design of free-form glue-laminated (glulam) timber structures. This integration constitutes an embedding of a *glulam materiality* into digital design modelling tools. This paper presents *GluLamb*, a software modelling toolkit that implements a constrained glulam blank model for the design and fabrication of glulam elements. The general functionality of this toolkit is described and three case studies are presented which show the application of *GluLamb* in different contexts: design simulation in research, design exploration and rationalization in an architectural practice setting, and as the basis for a digital design-to-fabrication workflow.

INTRODUCTION

Digital materiality

As digital design evolves to accommodate bio-based systems and a deeper material engagement, the idea of materiality in digital modelling has gained an important status. In a broader sense, as a set of ”capabilities that afford or constrain action” (Leonardi 2010), digital materiality has sought to imbue models with a sense of the physical substrates that they represent, especially their behaviours and simulated performance. Entwining digital simulation of material behaviour into processes of drawing and making has therefore led to new design practices that shift between the digital and the physical (Ramsgaard Thomsen and Tamke 2009; Ramsgaard Thomsen, Tamke, et al. 2017; Svilans 2020), and has evolved the role of architectural drawing and modelling from being primarily representational to being *functional* (Hensel and Menges 2006). Putting aside the broader questions of how this materiality might change how architecture is imagined, this also has immediate implications for the link between design and its materialization.

The manufacture of timber elements benefits especially from this digital materiality due to the complex behaviours of wood and its highly varying and anisotropic properties. Integrating the material performance of timber into design practice has therefore led to a rapidly expanding field of research, from the computational embedding of material behaviours (Fleischmann et al. 2012; Wood et al. 2016); to exploring the processing of timber in its raw state through robotics, digital simulation, and heuristic methods (Mollica and Self 2016; Self and Vercruysse 2017); to developing new joining techniques and morphologies of mass timber elements (Robeller and Weinand 2016). With the increasing focus on timber construction as a path towards climate resilience and a lower carbon footprint in the built environment, the design, development, and manufacture of timber structures is gaining momentum across the broader construction sector. Although the timber industry has long benefited from developments in automation and process efficiency, the shift towards more preplanning and prefabrication across the AEC industries has put more pressure on the precise alignment of early-stage design and late-stage manufacturing strategies, most often through the generation, bidirectional transfer, and encoding of information (Schindler 2007).

Figure 1: Prefabricated curved glulam beams.

Material data and process knowledge

This exchange of information is crucial to the success of timber buildings, particularly in cases of high geometric and manufacturing complexity. As Scheurer et al. (2013) point out, this entails bringing traditionally late-stage information far forward in the design process, and an early definition of goals, constraints, and coordination between stakeholders. Their observations are based on case studies of large-scale and geometrically-complex timber buildings, often with curvilinear glulam elements (Fig. 1) with extreme and out-of-plane curvatures (Stehling, Scheurer, Geglo, et al. 2017). Indeed, the expressive formal possibilities enabled by free-form glulam construction also require an understanding and careful navigation of its processes and limitations - the earlier the better. The key goal here is both the integration of material knowledge early in the design phase - where decisions are cheap and fluid - as well as, more generally, the interfacing and negotiation of different types of information at different stages of the design-to-production process.

In the manufacture of these types of buildings, challenges still exist in the transfer of features and machining details from design models to fabrication environments. Stehling, Scheurer, and Roulier (2014) point out the typical difficulties encountered when processing curved surfaces with traditional CAM software, and the need for more machine-agnostic methods of describing machining operations to permit abstraction and re-use between projects. While resultant languages such as Building Transfer Language (BTL) and Hundegger BVX are an excellent solution for standardized material formats such as flat panels and straight beams, free-form elements are more often than not still handled through custom CAM interfaces or the direct scripting of toolpaths. Furthermore, apart from machining, free-form glulam elements are constrained by the limitations of the lamination process, something which can have a severe impact on overall fabrication complexity and costs. Software that integrates the glulam lamination process is still the affair of manufacturer-specific vendors and does not interface with the typical CAD environments used in early-stage architectural design.

GluLamb occupies this niche between glulam manufacturing and design, and aims to connect the key parameters that govern manufacturing cost and complexity of glulam elements with the fast exploration of design ideas, in this way embedding a certain *glulam materiality* in the digital model. In this sense, it aspires not to be exhaustive, but integrative, and is therefore made to be a lightweight tool that can provide important indicators of downstream risk and uncertainty.

AIMS AND METHOD

Being developed through a larger practice-based project that employs a research-by-design methodology (Frayling 1993), the development of *GluLamb* follows a similar approach. This is initiated by defining the basic geometric constraints involved in glulam modelling, and incrementally adding further layers of detail in order to address specific constraints and issues.

Previous work explores modelling methods for free-form glulam design and fabrication that consider multiple scales of intervention and the disparate types of information in each scale (Svilans, Poinet, et al. 2017). This sows the seeds for a more coherent and formalized object model, and *GluLamb* develops this further to streamline both its usage and applicability to different contexts. Subsequent work tests the glulam model against other geometric models of complex glulam elements provided by industry partners to ensure the validity of the basic modelling approach. Its flexibility in defining fabrication features and joints is extended into a relational model of glulam assemblies and structures. Its applicability in early-stage design scenarios is tested in an architectural design project in collaboration with industry partners. Finally, its use as an interface between other design simulation models is explored in a research environment.

The development aim is to gradually increase the information density and flexibility of the toolkit to make it responsive to a wider range of parameters, especially where specifications and codes are concerned. For example, the lamella thickness versus maximum glulam curvature relationship in *GluLamb* is calculated using either Eurocode or APA standards, selected by the user, but other standards may be useful.

This paper demonstrates the use of *GluLamb* as a) an interface between design and material simulation, b) as a technique for rationalizing geometrically-complex timber structures in early-design stages in an architectural practice setting, and c) as a viable tool for moving from design through to digital fabrication of a small glulam structure. These uses are each presented through case studies, focusing on the role of *GluLamb* in design performance simulation, early-stage design, and digital prototyping.

GluLamb is a .NET software library, using the RhinoCommon API for the popular McNeel Rhinoceros 3D CAD package.

THE GLULAM BLANK

In comparison to other mass timber products, the curved glulam blank occupies an interesting area within the family of laminated timber elements. Other mass timber products such as CLT panels and straight glulam elements are generally laminated to a particular set of dimensions, and then cut and machined to the desired profiles, in the same way that dimensioned lumber is processed for a particular application. The curved glulam blank, however, requires that the lamination is specific to the designed form. This means that, in more complex cases, each glulam blank must be tailored to the individual beam and cannot be interchanged with its neighbours. In more rationalized cases, the designed beam geometries are similar enough such that the same glulam blank could accommodate multiple shapes of beams, greatly speeding up the lamination process, as the presses would not have to be adjusted for each one.

The cutting of curved geometries out of wood has significant repercussions for the strength of the final elements, again due to the anisotropic strength properties of wood and its fibre direction. Maximizing the strength of a glulam element therefore can be equated to perfectly tailoring its blank to the form of the final designed element. With regard to waste, the closer the form of the blank is to the final form of the element, the less waste arises from the final machining process, however the total amount of waste must also include the intermediate processing steps of planing and dimensioning the laminations, something which drives the bulk of the post-sawmill waste in the manufacture of highly-curved glulam elements. The trade-off - between manufacturing expediency, waste, and structural efficiency - becomes apparent.

Glulam blanks are therefore categorized into straight, single-curved - or planar - and double-curved blanks. These categories reflect the types of pressing infrastructures required for their manufacture, with their accompanying production complexities. For example, the manufacture of straight blanks is largely automated, while double-curved blanks require much more manual labour.

Figure 2: Single- and double-curved glulam blanks.

A CONSTRAINED GLULAM BLANK MODEL

The central focus of *GluLamb* is a constrained glulam blank model. The established methods for producing the three glulam blank types reveal key geometric constraints that can be described using a lightweight generative model. This allows a distinction between straight, single-curved, and double-curved glulams using only centreline curves and dimensional data as inputs.

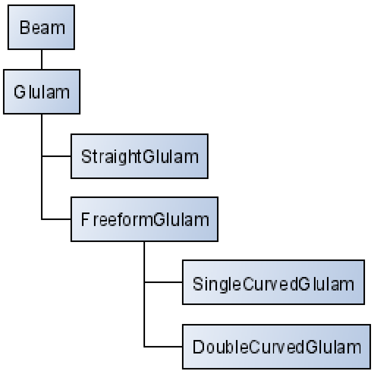

Figure 3: The class diagram of the Glulam element.

The formulation of this model takes advantage of the most fundamental process in industrial timber manufacturing: the sawing of logs into longitudinal timber members with rectangular cross-sections. Given that the geometries of the material inputs in the glulam manufacturing process are rectangular prisms that are stacked in single or multiple columns, some basic assumptions about the digital model can be drawn. As an aggregate of these rectangular cross-sections, a glulam cross-section can be thus conceptualized as a rectangular matrix, whose overall cross-section is also rectangular. The geometric boundary of the whole glulam can therefore be described simply as an extrusion of this cross-section along the glulam centreline, which is straight or curvilinear.

The rotation of the cross-section around the centreline axis then presents a degree of freedom that must be pinned down. An abstract `CrossSectionOrientation` class is therefore defined to allow different types of control over the cross-section orientation.

Finally, the specification of lamination thicknesses and the overall section size as a sum of these thicknesses and number of laminations is provided by a `GlulamData` class.

Linking these aspects together, *GluLamb* therefore implements an abstract `Beam` base class which holds information only about the centreline curve of an element and the orientation of its cross-section along it. From this, a `Glulam` class is derived, adding in glulam-specific data, which is extended into subclasses corresponding to the three main blank types: `StraightGlulam`, `SingleCurvedGlulam`, and `DoubleCurvedGlulam` (Fig. 3).

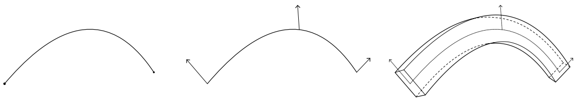

Figure 4: The basic steps for describing a free-form glulam element: defining the centreline curve, defining cross-section orientations, defining the cross-section dimensions.

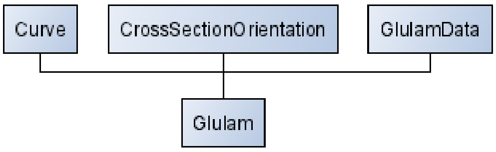

Figure 5: The inputs required to create a Glulam element.

This establishes the three main components of the model: the centreline curve, the orientation of the cross-section, and the material specification of the cross-section (Fig. 5).

The centreline curve

The type of glulam blank - straight, single-curved, or double-curved - is directly related to the type of centreline curve that is used to drive it. A straight curve - a line - describes a straight glulam, with the caveat that its cross-section orientation remains constant. A planar curve describes a single-curved glulam, with the caveat that its cross-section orientation is aligned with its plane of curvature; and a non-planar - or free-form - curve corresponds to a double-curved glulam. Since the processes of manufacturing the different types of blanks differ greatly in cost and complexity, a simple categorization of the glulam centrelines can already reveal impacts in fabrication later on and inform the required manufacturing capabilities.

The generation of the glulam blank model uses this simple distinction. Given the centreline curve used to drive the blank model, a factory method returns the appropriate subclass that would best describe it. This permits an analysis of a set of input curves to determine what type of blank they represent, and also lets common parameters to be shared between all glulam blank types, while allowing specific functions to be specialized or additional parameters to be added.

The cross-section orientation

Since the cross-section is assumed to always be perpendicular to the centreline curve tangent, only a single additional direction vector is needed to fully describe an orthotropic frame of reference at any point along the glulam blank. For describing straight blanks, a single vector is required to orient the cross-section around the centreline. Single-curved blanks similarly have a constant cross-section orientation, where the direction of the major cross-section axis lies on the plane of curvature. Double-curved blanks are less constricted in their cross-section orientation. Furthermore, varying the cross-section orientation of straight and single-curved blanks can describe more complex blanks that introduce torsion or an angled section. To accommodate these different rules for cross-section alignment, *GluLamb* implements several subclasses of the `CrossSectionOrientation` base class that provide interfaces for different orientations:

- `VectorOrientation` attempts to always align the cross-section to a single, user-defined vector, or as close as possible while staying perpendicular to the centreline tangent.
- `VectorListOrientation` uses a list of user-defined direction vectors and curve parameters to distribute multiple orientations along the centreline curve.
- `SurfaceOrientation` holds a reference to a user-defined surface and attempts to always align the cross-section to its closest normal vector.
- `RailCurveOrientation` holds a reference to a user-defined curve and attempts to always align the cross-section to its closest point.
- `PlanarOrientation` attempts to always align the cross-section to a user-defined plane.
- `RmfOrientation` uses the rotation-minimizing frame of the centreline curve to orient the cross-section.

An interesting product of the combination of the centreline curve and the cross-section orientation is a *curvilinear glulam coordinate system*: by considering the cross-section axes as the X- and Y-axes, and the centreline curve as the Z-axis, it becomes possible to map coordinates relative to the laminations as they are bent and twisted throughout the glulam.

Curvature and lamella thickness

The final component of the blank model is the material specification, which is primarily driven by the relationship between the maximum curvature of the blank and its lamination thicknesses. The minimum allowable radii of curvature of a particular thickness of timber are defined in - and differ between - regional standards. These ratios are defined to ensure that laminations of a particular thickness can be safely bent to the corresponding curvature without breaking. For example, the maximum allowable thickness defined in EN 14080:2013 (2013) for a lamination is $1/200^{th}$ of the minimum radius of its curvature; in ANSI 117-2020 (2020) it is $1/100^{th}$ or $1/125^{th}$, depending on the wood species.

The maximum lamella thickness in a free-form blank can therefore be found by first finding the largest curvature vector of its centreline curve, projecting it onto the X- and Y-axes of the cross-section at that point, and thereby finding the radii of curvature in both dimensions. By adjusting these radii by the half-width or half-height dimensions of the cross-section, the radii of curvature of the inner faces of the glulam can be found.

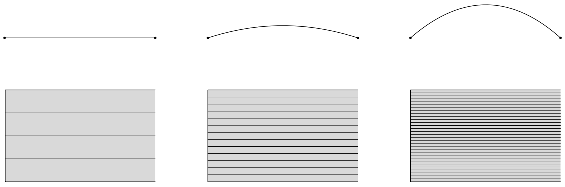

Figure 6: The lamella thickness changes according to the maximum curvature of the centreline curve, following the ratio between radius of curvature and thickness specified in the appropriate standard.

GluLamb uses this relationship between glulam curvature and its lamella sizes in two ways: for estimating a material specification for a glulam blank and for analyzing an existing glulam blank for compliance with this relationship. This means that, by simply adjusting the centreline curve, appropriate lamination thicknesses can be estimated: thicker where the curvature is low, thinner where it is higher (Fig. 6).

An additional `LamellaFactory` base class provides functions for constraining the lamination thicknesses to, for example, a list of user-defined available thicknesses, as well as minimum and maximum thicknesses.

Analyzing material orientation

In the case where the same designed beam element is machined out of two different kinds of glulam blanks, methods are needed to differentiate the two results as well as to provide important information about the integrity of the fibre direction. *GluLamb* offers two analysis methods that reveal fibre *direction* and *deviation* in the final element.

The first method simply encodes the longitudinal material direction vector of the glulam blank as a colour and maps it onto the final beam geometry, in a technique very similar to normal mapping in computer graphics. This allows a qualitative evaluation and differentiation between element geometries that are machined out of straight blanks - a constant fibre direction and therefore a constant colour - and ones that are machined out of curved blanks - a changing fibre direction; a changing colour.

The second method encodes the deviation of the surface normal of the final element geometry from the fibre direction of the blank. This yields important information about the degree to which the wood fibres are cut: if the two vectors are perpendicular, then the fibre direction is parallel to the surface, meaning that the longitudinal material direction is precisely aligned with the beam boundary; if they are parallel, then the surface is cutting across the wood fibres, resulting in a severe decrease in structural integrity and a loss of durability due to the end grain exposure.

These mappings of fibre direction and deviation therefore provide qualitative feedback to the user about the implications of the blank choice for a particular beam element.

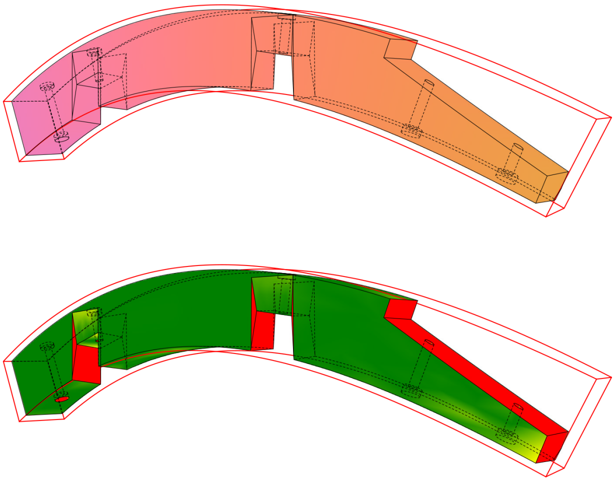

Figure 7: Representation of fibre direction using color (top) and identification of fibre-cutting areas (bottom).

Connections and graphs

To accommodate not only individual elements but their assemblies, *GluLamb* implements an interface for defining connections between glulam elements and an overall `Structure` class that contains these. The `Structure` class contains a list of `Element` objects - each of which holds a reference to a `Beam` object - and a list of `Connection` objects - each of which holds a reference to two `Element` objects with additional metadata and a local coordinate system. The coordinate system is used as a handle to help orient the connection geometry or define connection-specific axes. From the `Connection` class, subclasses are derived for specific connection types.

This effectively creates a connectivity graph (Fig. 8) comprising the total assembly of all connected elements. This is method of managing collections of elements and their interconnections provides an overview of the total scope of the design project and its overall material complexity.

This is particularly useful for developing parametric connections that depend on the relative orientations and angles of connected elements, since each connection has access to the geometry and material specification of the elements. Containing all of these within an overarching `Structure` object allows higher-level storage of metadata as well as functions that consider the assembly as a whole.

In this way, *GluLamb* moves from the scale of material and fabrication to the scale of whole assemblies and structures. Integrating this structure scale into early design stages helps give a fast indication of element interdependencies, potentially informing future steps such as fabrication sequencing and assembly planning.

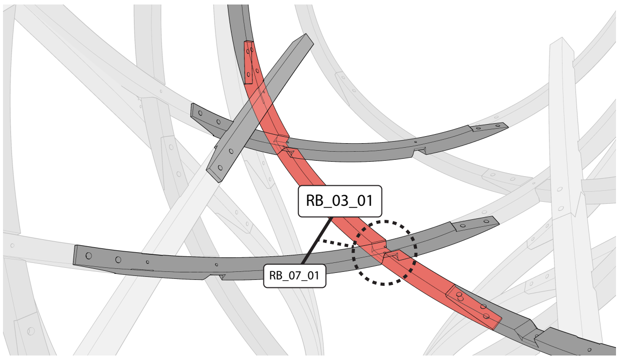

Figure 8: A connectivity graph defined through connections between elements.

CASE STUDIES AND APPLICATIONS

Three different contexts demonstrate the applicability and versatility of *GluLamb*.

RawLam

RawLam is a research project that investigates how connecting technological developments in forestry and sawmilling with design simulation through digital interfaces allows a more thorough usage of wood in engineered timber construction (Tamke et al. 2021). It involves the design and fabrication of a simple glulam assembly - a three-legged prototype, composed of laminations chosen individually through a heuristic that matches a simulated performance demand with inferred material quality in a CT-scanned log. Here *GluLamb* is used to compose and adjust the design object as three `SingleCurvedGlulam` objects for the legs. Since the design is driven by a rough range of lamination thicknesses that can be worked with, the model geometry is adjusted until this range is reached, ensuring that the planarity of the centreline curves is maintained. The overall geometry of the assembly is generated by *GluLamb* and discretized into tetrahedral elements for interfacing with the finite-element analysis (FEA) package ABAQUS (Smith 2009). The structural simulation results from ABAQUS are overlaid onto the design model and, by querying points within the model, the relevant areas of the simulation results are mapped onto the individual laminations by using the curved glulam coordinate system of the *GluLamb* model. *GluLamb* is then used to generate the geometry of each individual lamination with its simulated performance demands for finding its ideal position in the CT-scan dataset using a multi-objective optimization method. The laminations are then cut out of the specific parts of the log material that corresponds to their position in the CT-scan dataset.

In such a way, *GluLamb* can act as a lamination-level interface between fast design geometry, FE simulation,

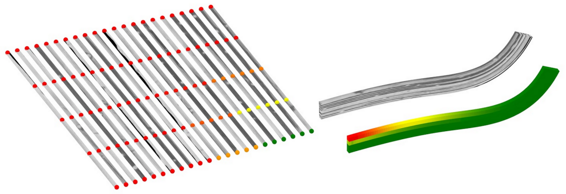

Figure 9: The mapping of performance demands and CT-scanned material properties using GluLamb (Tamke et al. 2021).

and fabrication.

Magelungen Park Bridge

The *Magelungen Park Bridge* tests the development of *GluLamb* within a practice context to evaluate its applicability to agile early-stage design processes. Introduced at the conceptual phase of the project, *GluLamb* is used to help build a case for constructing the bridge out of timber. The fast, centreline-based modelling of the glulam blanks allows quick iterations of various proposals to be developed with an eye to issues of fabrication and durability. Durability is assessed on the basis of the amount of exposed end-grain using the fibre-cutting analysis visualization method.

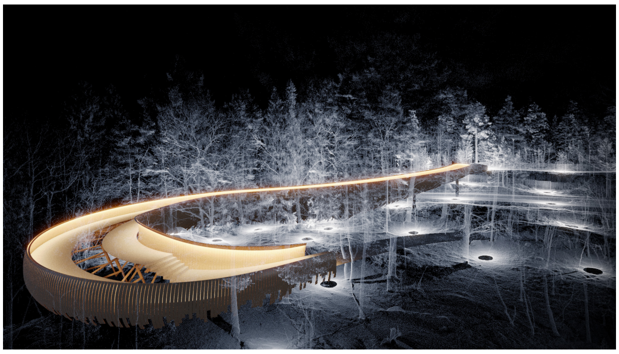

Figure 10: The Magelungen Park Bridge project.

Since the design model of the bridge is composed of a curvilinear hull-like lattice of elements, a major portion of the driving centrelines are non-planar, and therefore are interpreted as being double-curved glulam elements. A rationalization process is therefore explored to try to minimize the amount of double- and single-curved elements. For double-curved elements, centreline curves are compared to their plane-of-best-fit, and those that lie completely within a certain tolerance distance of the plane are projected onto the plane, thereby becoming planar, single-curved elements. Similarly, the centreline curves of single-curved elements are compared to their line-of-best-fit, and those that lie entirely within a distance threshold are converted to straight lines, thereby becoming straight elements. The new elements define the glulam blanks that the original elements would be machined out of, and therefore need to be expanded to ensure that the original double- and single-curved elements fit entirely within the glulam blank volumes. Comparing the difference in volume between the original elements and the glulam blanks, an increase in material volume is calculated. The cost factor of the original elements is compared to the cost factor of the blanks - the straight, single-, and double-curved blanks having factors of 1.0, 5.0, and 15.0, respectively - and the material volumes multiplied accordingly. For a number of different distance thresholds, this rationalization yields significant nominal material cost savings, not to mention the possibility of eliminating double-curved glulam blanks entirely, thus lowering the required fabrication complexity (Svilans, Runberger, and Strehlke 2020).

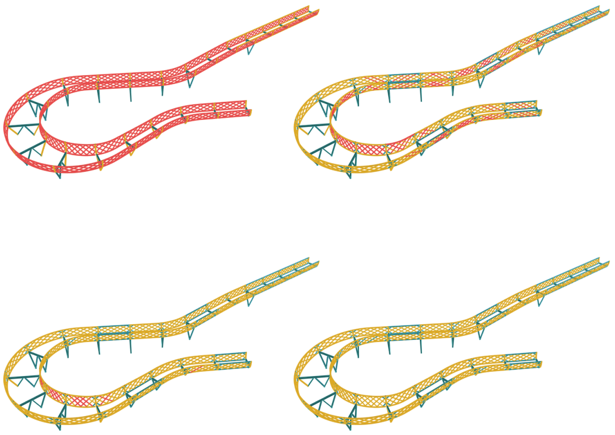

Figure 11: The rationalization process, showing the decrease in double- (red) and single-curved (yellow) glulam blanks as the distance threshold is increased (Svilans, Runberger, and Strehlke 2020).

Since the blanks now describe wood fibre directions that do not completely align with the design elements, the fibre-cutting angle analysis can be further used to inform the consequences of this rationalization for the element strength and durability. This demonstrates how *GluLamb* can be used at early design stages to negotiate feasibility through changes in the type of glulam blank that is used for a curved timber element, without affecting the design geometry itself.

Although the project remains in a schematic stage, the embedding of glulam fabrication and material principles into the design process accelerates discussions with consultants and engineers regarding the feasibility of the bridge, and helps to support the case for building it out of engineered timber.

MBridge Demonstrator

The design of the *MBridge Demonstrator* is derived from the *Magelungen Park Bridge* and represents an effort to implement a design-to-fabrication workflow that capitalizes on the material- and fabrication-led tools in *GluLamb*. The *Demonstrator* extracts a portion of the bridge and focuses on the resolution of interconnected double-curved glulam elements. As a test of *GluLamb*, it evaluates whether or not such a complex structure can be successfully realized within the constraints of the available fabrication environment (Fig. 12).

Since the fabrication cannot make use of double-

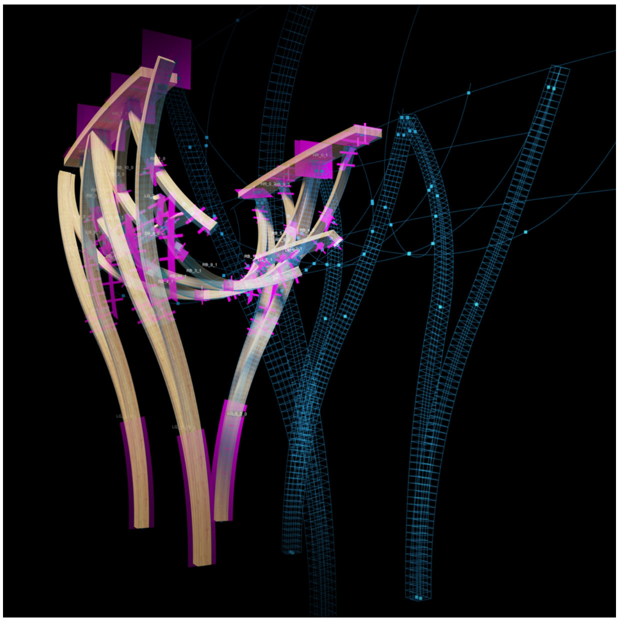

Figure 12: The MBridge Demonstrator with overlaid GluLamb data.

curved glulam presses or heavy infrastructure, the blanks are rationalized in the same way as in the *Magelungen Park Bridge* so that they are all single-curved and thus much easier to fabricate with the limited means available. *GluLamb* provides the necessary thicknesses of lamination which are used to adjust the overall design geometry until a feasible option is found (Fig. 13).

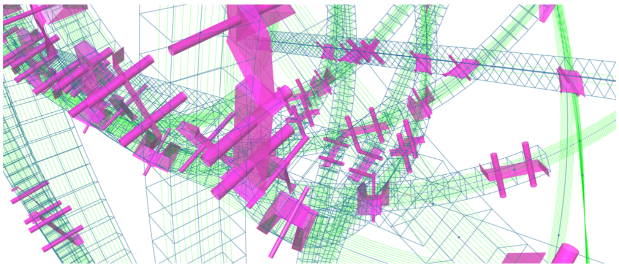

Figure 13: GluLamb is used to rationalize and verify the material specification of its elements, and to generate machining features for joints.

The design is organized as a `Structure`, facilitating the parametric generation of crossing lap joints and end-to-end lap joints - which use the data provided by `Connection` objects and their related `Element` objects to inform their specific geometries. In this case, the connectivity helps to sequence the elements for fabrication and, as fabrication begins, allows later joint geometries to still be adjusted by ensuring they do not depend on parts being currently manufactured.

Using the material specifications provided by *GluLamb*, material is ordered and resawn to the required lamination thicknesses for each element. The modelled blank geometries are used to position formwork for the lamination of the single-curved blanks. Using the structured geometry given by the `Connection` objects, toolpath strategies are defined parametrically and adaptively for each joint, preventing the need for programming each part in CAM software. The final glulam elements are machined with a 5-axis CNC machining centre and assembled with steel bolts (Fig. 14).

Overall, the ability to control the design with simple inputs - centreline curves and some geometry for orienting the cross-sections - while delegating the generation of geometry and fabrication information to *GluLamb* - greatly facilitates changes and adjustments throughout the process. This demonstrates the ability of *GluLamb* to fit into a streamlined design-to-fabrication workflow and remove some of the risk for modelling error and inappropriate material specifications.
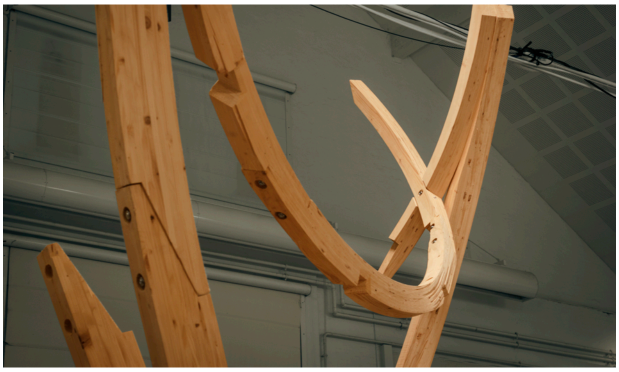
Figure 14: The finished MBridge Demonstrator.

CONCLUSIONS AND OUTLOOK

This paper formalizes an effort to embed a *glulam materiality* in digital design modelling tools through the toolkit *GluLamb* and its constrained glulam model. The three case studies demonstrate its use as an interface for design performance simulation and FEA in a research context; as a tool for evaluating early-stage design iterations in a practice setting; and as the basis of flexible design-to-fabrication workflows for glulam structures.

In terms of fabrication, while it does not offer a fully-defined language for describing machining operations, the extendable classes for defining connections encourage the reuse of adaptive fabrication geometries - across each model as well as across projects - so that they do not have to be scripted or processed in CAM software individually. The most important benefit of *GluLamb*, however, is its ability to integrate material and fabrication concerns into a design workflow and to highlight aspects of an early design that might pose problems later on. This focus on a breadth of integration and information transfer also highlights its role as an interface between more specialized tools and processes.

Further work aims to explore this interface in more detail and how *GluLamb* can be made more robust and adaptable to a wider range of design and fabrication scenarios, as well as a more detailed set of integrated material parameters. The ultimate goal is to find ways of systematizing more key aspects of free-form glulam design and production, so that the design space of free-form timber structures can be explored more agilely, productively, and imaginatively.

ACKNOWLEDGEMENTS

The development of *GluLamb* was initiated at *CITA (Centre for IT and Architecture)* at the *Royal Danish Academy* during a PhD research project as part of the EU-funded *InnoChain* research network (ITN). The project received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 642877. The author is very grateful for the generous collaboration with and support from *White Arkitekter*, *Blumer Lehmann AG*, and *Design-to-Production GmbH.*

REFERENCES

ANSI 117-2020 (2020). *Standard Specifications for Structural Glued Laminated Timber of Softwood Species*. Tech. rep. American National Standards Institute (ANSI), p. 62.

EN 14080:2013 (2013). *Timber structures - Glued laminated timber and glued solid timber - Requirements*. Tech. rep. European Committee for Standardization (CEN).

Fleischmann, Moritz et al. (2012). "Material behaviour: Embedding physical properties in computational design processes". In: *Architectural Design* 82.2, pp. 44–51.

Frayling, Christopher (1993). *Research in Art and Design*. Vol. 1. 1.

Hensel, Michael and Achim Menges (2006). *Morpho-ecologies*. Architectural Association.

Leonardi, Paul M. (2010). "Digital materiality? How artifacts without matter, matter". In: *First Monday* 15.6, pp. 1–13.

Mollica, Zachary and Martin Self (2016). "Tree Fork Truss: Geometric strategies for exploiting inherent material form". In: *Advances in Architectural Geometry 2016*. Ed. by Sigrid Adriaenssens et al. Zurich: Tagungsband, pp. 204–221.

Ramsgaard Thomsen, Mette and Martin Tamke (2009). "Narratives of Making: thinking practice led research in architecture". In: *Communicating (by) Design*, pp. 1–8.

Ramsgaard Thomsen, Mette, Martin Tamke, et al. (2017). "Simulation in Complex Modelling". In: *Simulation Series* 49.11, pp. 80–87.

Robeller, Christopher and Yves Weinand (2016). "Fabrication-Aware Design of Timber Folded Plate Shells with Double Through Tenon Joints". In: *Robotic Fabrication in Architecture, Art and Design 2016* February, pp. 166–177.

Scheurer, Fabian et al. (2013). "Design for Assembly – Digital Prefabrication of Complex Timber Structures". In: *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2013*, pp. 1–7.

Schindler, Christoph (2007). "Information-Tool-Technology: Contemporary digital fabrication as part of a continuous development of process technology as illustrated with the example of timber construction". In: *ACADIA Conference*, pp. 1–21.

Self, Martin and Emmanuel Vercruysse (2017). "Infinite variations, radical strategies". In: *Fabricate rethinking design and construction*, pp. 30–35.

Smith, Michael (2009). *ABAQUS/Standard User's Manual, Version 6.9*. United States: Dassault Systèmes Simulia Corp.

Stehling, Hanno, Fabian Scheurer, Helori Geglo, et al. (2017). "From Lamination To Assembly: Modelling the Seine Musicale". In: *Fabricate 2017*. Ed. by Achim Menges et al. UCL Press, pp. 258–263.

Stehling, Hanno, Fabian Scheurer, and Jean Roulier (2014). "Bridging the gap from CAD to CAM: Concepts, caveats and a new Grasshopper plug-in". In: *Fabricate: negotiating design & making*. Ed. by Fabio Gramazio, Matthias Kohler, and Silke Langenberg, pp. 52–59.

Svilans, Tom (2020). "Integrated material practice in free-form timber structures". PhD dissertation. Royal Danish Academy.

Svilans, Tom, Paul Poinet, et al. (2017). "A Multi-scalar Approach for the Modelling and Fabrication of Free-Form Glue-Laminated Timber Structures". In: *Humanizing Digital Reality*. Springer, pp. 247–257.

Svilans, Tom, Jonas Runberger, and Kai Strehlke (2020). "Agency of Material Production Feedback in Architectural Practice". In: *Design Transactions: Rethinking Information Modelling for a New Material Age*. Ed. by Bob Sheil et al. UCL Press, pp. 98–105.

Tamke, Martin et al. (2021). "Tree to Product - Prototypical workflow connecting Data from tree with fabrication of engineered wood structure - RawLam". In: *Proceedings of WCTE2021*.

Wood, Dylan Marx et al. (2016). "Material computation — 4D timber construction : Towards building-scale hygroscopic actuated , self-constructing timber surfaces". In: *International Journal of Architectural Computing* 14.14.