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# BEAVER: A PARAMETRIC DESIGN FRAMEWORK FOR TIMBER ENGINEERING

**Renan Prandini[1], João Tavares Pini[2], Márcio Sartorelli Venâncio de Souza[3]**

**ABSTRACT:** Developments in digital modelling tools and requirements for low-carbon buildings have produced increased complexity in the field of timber structural engineering. This paper presents advancements and applications of the on-going development of Beaver, an open-source plugin for Rhino3D and Grasshopper environment, which allows live-fed parametric analysis and design of timber structures (elements and connections) according to "Eurocode 5 – Design of Timber Structures". With the help of Grasshopper and finite element analysis plugins such as *Karamba3D*, structural data can be fed to Beaver for integrated timber ULS and SLS analysis allowing a Performance-Based Design (PBD) and therefore integrates structural conception and timber structural engineering in a single decision-making step.

Case studies are presented using the proposed framework to discuss about how timber engineering practice can benefit from a computational engineering toolbox when integrated to a variety of design methods such as form-finding, genetic algorithms and spatially associative problems to explore various design possibilities and while ensuring structural safety.

**KEYWORDS:** parametric design, timber engineering, Eurocode 5, engineering software, beaver, grasshopper, karamba3d, moment-stiff, semi-rigid, timber design, timber connections, performance-based design, structural optimization, genetic algorithm, form-finding.

## 1. INTRODUCTION

Generative processes have marked the current avant-garde experimentations in architecture and engineering. Contemporary tools have allowed designers to explore new spatial tectonics in architecture, which is also presented as an added layer of geometrical complexity to the physical behaviour of structures. To deal with these non-standard solutions, engineers have increasingly adopted parametric tools for the design and analysis of structures. Although many computational methods are available for handling complex geometry, timber-engineering design is still identified as setback on the interdisciplinary design-to-production process to data exchange [1].

In that context, a commonly used tool for dealing with early-stage design validation is Karamba3D [2], a Grasshopper finite element analysis plug-in used to analyse structures such as: spatial trusses, frames or shell structures. With a simple algorithm, it allows the designer to explore a range of structural arrangements and instantly have structural feedback on the design. The live-fed structural output is one of the key features of Karamba which allow for further spatial explorations and information-aided design, such as cost or environmental impact of the designed structure.

Although the structural data output from Karamba and other visual programming tools are decisive for validation of concepts, it also relies on the experience of the structural designer to develop further parametric routines to evaluate if the output renders a valid result in terms of building structural safety codes.

In a previous paper [3], the authors proposed a beta version of Beaver: a Grasshopper plugin developed to evaluate the necessary safety Eurocode 5 checks, which assists the design of feasible timber-framed structures and the exploration of optimal solutions in terms of topology, aesthetics, costs and global structural behaviour.

Beaver is now presented in its first official version, with an improved workflow that allows a more straightforward usage of the tool as it is now completely integrated with Karamba3d, requiring minimal steps to connect both tools. Beaver software architecture was recreated to enable coupling of Beaver functionality not only inside Grasshopper, but also any other .NET application. The tool is now open sourced to promote the collaboration between professionals on the field as well as for research and educational purposes.

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## 2. BOUNDING STRUCTURAL ENGINEERING AND SOFTWARE DEVELOPMENT

One of the main issues in the practical field of structural engineering and design is mainly due to compatibility between computational models. It is difficult or almost impossible to find end-to-end solutions to design, analysis and detail buildings. Common practice is to transfer models between different software applications specialized to their needs, which can be detailing, structural analysis, thermal analysis, and so on. This is a well know issue of CAD (Computer Aided Design) and CAE (Computer Aided Engineering) systems. Most of integration issues relate to loss of data, compatibility during the process and lack of automation [4]. Those issues arise due the different characteristics between the processes. A CAD model is mainly a computational representation of the geometry, not necessarily having attributes and properties. These features are crucial inside CAE environment, as it needs data such as material properties, physical interfaces, and element types.

Grasshopper3d appeared as a good candidate to enable integration between CAD/CAE systems. It offers a convenient way to create scripts for geometry processing and automation in a powerful CAD environment, and many research is being applied in developing CAE systems inside it, such as Karamba3D [2], Kiwi3D [5] and BATS [6] for structural analysis, Ladybug [7] for Thermal/Solar Analysis, Butterfly [7] and Eddy3d [8] for CFD analysis.

Beaver first conception was to overcome one of the limitations of structural design inside of Grasshopper which was the lack of structural design tools according to valid design codes [3]. Its beta version was composed of a series of Grasshopper components that worked based on element internal forces and displacements provided by a structural frame analysis software. Generic routines were conceived in C# in order to evaluate the Limit States according to Eurocode 5 procedures [9]. As inputs, along with internal forces and displacements, the nominal strength, modification coefficients for load duration, service class and material uncertainties are considered. As outputs one can access actions and resistance ratios and considered analysis information such as failure mode of elements or fasteners, along with specific evaluation reports.

However, this implementation has shown some limitations. All design check routines were implemented individually in a series of Grasshopper components that communicate thought the connection of many individual parameters, which made quite challenging to transfer data between components as well as to implement new features, such as new design codes and direct integration with Grasshopper structural analysis plugins. The lack of structured data also made it demanding  to filter values such as utilization data, based on combination and/or design check type, making it difficult to select data to display in colour and display graphs.

Also, while parametric design environments display great advantages for integrated structural design and analysis, the development of a C# library for the design of timber structures could also be beneficial to many other .NET applications. This is particularly important since many modern engineering companies are promoting in-house software development teams, both by dedicated software engineers but also by use of structural engineers with software development skills. This also may support the extension and creation of structural analysis software for academic purposes.

To overcome those limitations, a full refactor of Beaver software architecture was made. The first decision was to make Beaver functionality independent from Rhino and Grasshopper API's, creating a .NET Standard library named *BeaverCore* [10]. This library provides an object-oriented-model to assign and evaluate structural design checks.

On top of that layer sits BeaverGrasshopper [11], which is the actual Grasshopper plug-in. It provides data wrappers to pass BeaverCore objects between Grasshopper components, making the design process simpler and with less Grasshopper components. Also, a Beaver object-oriented model enables the conversion of structural analysis models, such as Karamba3d models, into an evaluated Beaver model in a simple straight-forward manner.

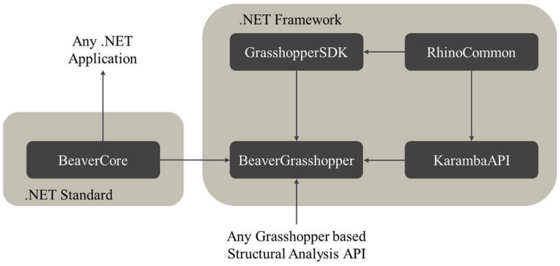

***Figure 1:*** *Beaver dependencies flowchart*

### 1.1 BeaverCore: A open-source .NET library for structural timber engineering design

BeaverCore is a .NET library that contains an object model to properly assign structural members and its internal forces to apply the desirable design checks for timber members and connections.

Beaver functionality was split from the original GH plug-in to easen the development of additional features on design checks and proper structural models independent from any platform. This enables the use of BeaverCore in any other .NET application, such as FEA software and web/cloud-based platforms. BeaverCore has its code totally open-sourced, in a wish to assist designers to potentially enhance its functionality for other design codes, national annexes and further developments regarding other timber-based structural materials. The reliability of the tool is promoted by the development of unit tests that assures that the results provided by Beaver

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can be verified by the community and allow awareness of the methods and algorithms used in its formulation.

### 1.2 BeaverGrasshopper: A Grasshopper plugin for parametric timber design

BeaverGrasshopper is a Grasshopper layer built on top of BeaverCore library to fulfil the original Beaver purpose of enabling parametric structural timber design according to official structural codes. The Grasshopper plug-in now only deals with managing BeaverCore object data between the Grasshopper components, that just queries data from BeaverCore object model. With this object model it is also possible to integrate Beaver fully with third-party FEA plug-ins such as Karamba3d by translating their API object model to BeaverCore model. This makes the use of Beaver way simpler since you can define all properties in your FEA model and automatically check the results of the Eurocode checks.

The presented workflow is integrated to *Karamba3D* by assigning element-related parameters of *Eurocode 5* such as span length, cantilever considerations, service classes, buckling lengths and other necessary parameters to *Karamba* beam elements.

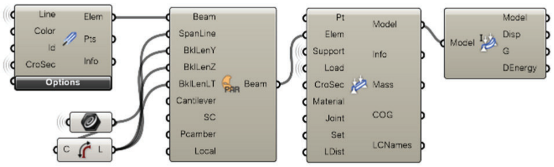

***Figure 2:*** *Typical model setup for Beaver consists in using native Karamba elements and including necessary inputs for EC5 calculations.*

After the FEA analysis is performed by *Karamba*, all Beaver input data can be retrieved directly from *Karamba's* model to allow the final limit state timber analysis and further result displays. It is also possible to filter the load-case and bending direction to be displayed.

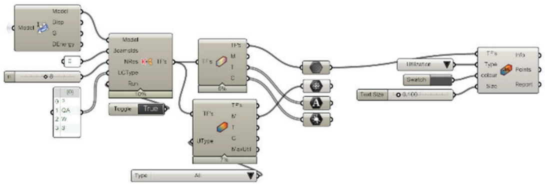

***Figure 3:*** *A Karamba3D analysed model can be directly fed into Beaver components for displaying the limit state analysis.*

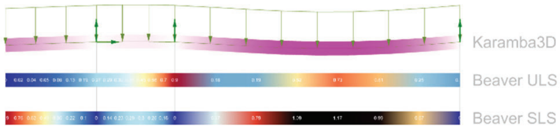

***Figure 4:*** *Example of the ULS and SLS displayed results for a loaded beam with two spans and a cantilever.*

In addition, calculation reports are now available for result checking of Beaver analysis of elements and connections, which avoids the "black-box" perception of users, allows better benchmarking processes and promotes an educational usage of the software.

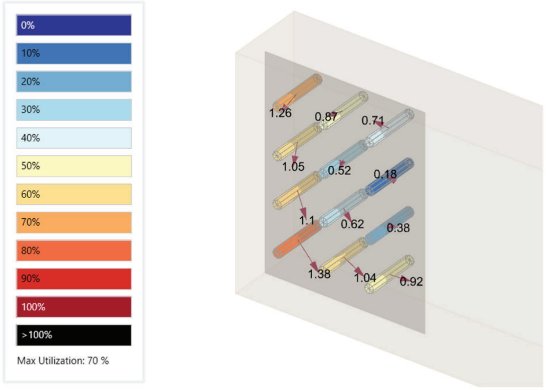

***Figure 5:*** *A parametric dowel-type moment-stiff connection can be generated and verified in real time*

Having a generic solver for timber structure validation allows for exploration of new tectonics of construction and experimentation on problems whose physical properties are directly associated with geometrical constraints. This is all done through a live-fed calculation with intuitive outputs.

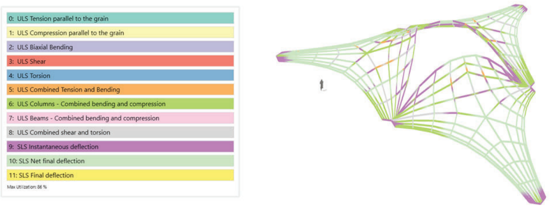

***Figure 6:*** *Dealing with complex geometry requires deeper understanding of the governing checks of the structural analysis.*

Also, parametric processes are generally very useful for designers which perform specific design methods on multiple projects which are not necessarily complex structures. Grasshopper, along with *Karamba3D*, have shown to be increasingly used by the industry in all stages to fasten design processes from the concept to documentation, and a complete timber limit state analysis is also beneficial is this perspective.

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## 3. APPLIED PROBLEM-SOLVING

Three study cases are presented in order to highlight the benefits of computational design approach to timber engineering and to illustrate how specific designs can be achieved through topological optimizations, form finding and integration between connection detailing and global structural behaviour.

### 1.3 Fishbelly trussed beam form-finding

This structure was designed Ita construtora, Brazil, to be a competitive alternative to typical steel and precast concrete structures usually employed for Boat Hangars located in tropical areas. With modular spans of 6 by 20 meters, permeable façades and lightweight steel sandwich panel roofs, the structural arrangement will mainly be affected by low permanent load case, low imposed load cases, high wind load cases and no earthquake or snow consideration.

To achieve this product, the structural concept goals were:

- *Minimal timber volume*
- *Minimal use of steel*
- *100% CNC machining*

The project started with the intuition that those goals would be achievable with a trussed beam for the long span and secondary beams for the short spans, where the roof sandwich panels are to be attached. Considering critical variable wind load scenarios, all structural elements were conceived in timber, in order to allow both tension and compression resistance.

A Grasshopper algorithm was written to generate multiple trussed beam arrangements. Karamba3D and Beaver were used to allow an on-time Eurocode 5 analysis considering all load case scenarios.

The variable structural arrangement parameters where:

- *Main beam division ratio*
- *Truss height*
- *Elements cross sections*

In terms of main beam division ratio, from a one-post trussed beam to a multiple posts fish-belly beam, there is an optimal cross section for each arrangement in order to employ minimal timber volume. Less posts scenarios generate larger buckling lengths and larger spans on upper chord, resulting in larger cross sections. In the other hand, multiple posts scenarios will allow smaller buckling lengths and chord cross sections, but the volume of the added posts and the number of timber connections will also be incremental.

Also, minimal beam division ratios will generate obtuse angles on lower chord that demand timber segmentation and steel connections, while higher beam division ratios will allow straighter angles that may allow lower chord continuity with the use of a curved glulam beam.

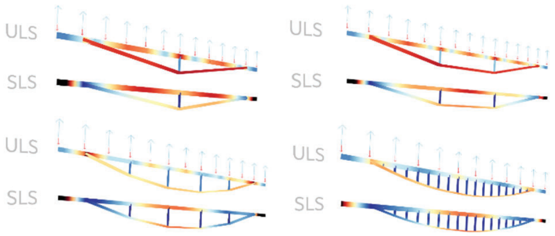

***Figure 5:*** One to multiple posts trussed beam geometries with adjusted acceptable cross sections.

In terms of truss height, considering ULS analysis, a higher truss will allow smaller cross sections by reducing normal forces on upper and lower chords, but will also increment the lower chord length. Considering SLS analysis, higher truss heights will result in less deformation and SLS may be critical, demanding cross sections with higher bending resistance.

***Figure 6:*** *Different truss heights with adjusted acceptable cross sections.*

Based on the presented parameters, this Grasshopper script allows multiple acceptable solutions in terms of structural safety, and the genetic algorithm [12] was used to generate and compare those arrangements in terms of timber volume and safety, resulting in the optimal arrangement bellow.

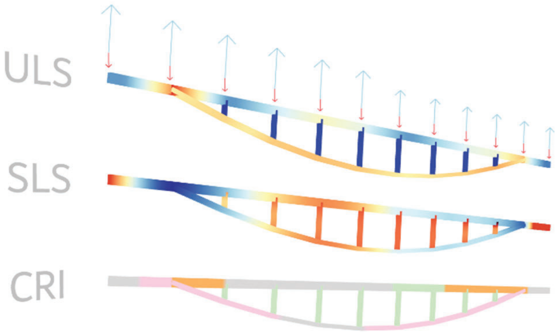

***Figure 7:*** *Optimal genetic algorithm solution considering asymmetrical wind load cases*

Considering the main project goals presented above, minimal timber usage would be achieved with this solution. In the other hand, the minimal use of steel would only be achieved if the lower chord is made of a continuous beam, resulting in only two main connections between lower and upper chord, and this would be easily possible by considering a curved continuous glulam beam.

In the other hand, the third project goal is develop a 100% CNC machined timber structure, and for most production plants this allows only straight timber elements.

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Considering those goals, the best concept would be to develop the correct geometry to allow both upper and lower chords to be continuous and also straight members, pretensioned together in pre-assembly process, in a way that curvature will be generated by posts lengths.

Karamba3D is a parametric tool that allows the consideration of imposed curvature strain loads, developed to allow the analysis of timber grid shells, for example. With the of this method, it is possible do model the structure correctly, considering the bending moments generated by the initial imposed curvature. This pretension adds permanent bending moment to both chords, which must be considered at the ULS analysis, and will result in a too high pre-camber that will affect SLS analysis.

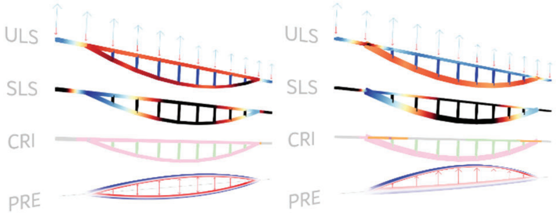

***Figure 8:*** *Imposed curvature bending moment and pre-camber are governed by the inertia relation between upper and lower chords and the overall truss height.*

With this new script that includes pretension forces and deformations for the Beaver ULS and SLS analysis, Grasshopper genetic algorithm should converge to an optimal solution that will meet the main project goals of minimal timber volume, minimal use of steel and 100% CNC machining.

What is interesting about this study-case is that we realized that a very a large spectrum of the inputs will result in not acceptable structures, and depending on the imposed loads the form-finding process will never converge to a possible safe result, because of three main reasons:

- *Higher truss heights will simultaneously result in better SLS ratios and worse ULS ratios due to incremental imposed curvature bending moments.*
- *To generate acceptable imposed pre-camber, the Y-axis inertia relation between upper and lower chord must be drastically different, while section areas tend to be similar due to axial loads.*
- *Incrementing cross sections will not necessarily minimize ULS ratios, since they also increment bending moments due to the imposed curvature loads.*

Thankfully to the minimal loads of this typical scenario, the genetic algorithm found a small spectrum of possible results and could finally reach the optimal relation for the main beam division ratio, truss height and element cross sections.

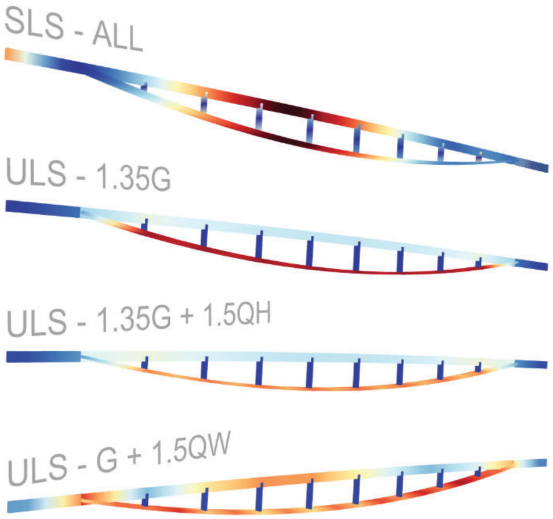

***Figure 9:*** *Design ratios from critical load-cases displayed at the optimal structural arrangement generated by the algorithm. Imposed curvature strain load bending moment and precamber considered, along with and asymmetrical wind load cases.*

But there was one more topic that could be developed for a last optimization. The script was built based on a parabolic curvature, ant that is not perfect since it generates a peak bending moment at the first and last fish belly posts, and this affects directly the lower chord ULS analysis.

A last script was written to allow a fine manipulation of truss height and curvature for the now defined division ratio and cross sections, in order to find the optimal curvature. After this last analysis, a greater safety margin was achieved without incremental production costs.

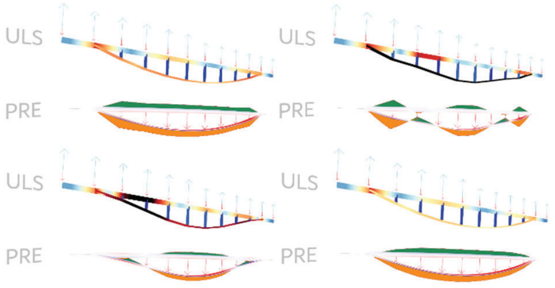

***Figure 10:*** *Genetic algorithm playing with curvature to find the minimal peak bending moment, generated by the imposed curvature strain load.*

With the help of Karamba3D and Beaver, the final structural arrangement was achieved. In the next steps, before reaching the final product, a double check on the structural safety will be made along with the connection detailing. Later, a 1:1 mock-up will be produced to allow an evaluation of pre-assembly process and to be load-tested in order to verify that safety standards are met as expected.

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## 1.4 Doubly curved roof with straight elements

Reciprocal beams have an intimate relationship with structural behaviour and the spatial arrangement of beams. Defining the correct pattern for a structurally sound structure can be a calculation-intensive process with many design possibilities. The roof in Franz Masereel Centre has undergone several topology optimizations based solely on global deflections because workflows regarding structural verifications according to code were be too time-consuming for an integrated design approach [13].

Applying Beaver into a geometrical formulation within Grasshopper will immediately offer feedback on the structural feasibility of the structure, while also allowing for topological optimizations. This is essentially true to reciprocal systems where each element is dependent on each other for achieving global stability and thus have no structural hierarchy between elements.

In the example below, a doubly curved surface is subdivided in a diagrid subdivision to form a reciprocal grid where two subsequent lines of the diagrid are joined together to form one continuous element. A script for moving each start and end node of these joined lines to the middle of the next continuous line was built so that an iterational procedure can occur until a geometrical convergence is reached. This allowed for an approximation of the double curvature surface while maintaining strictly straight elements connecting at middle points of the next element on the reciprocal grid.

A design exploration can take place where the reciprocal grid can vary in terms of subdivision in the u and v domains of the NURBS surface. Different designs are then tested against code in Beaver and a structurally sound solution can be chosen where a balance between number of connections and suitable cross section sizes is achieved.

***Figure 11:*** *Design explorations are possible where the structural arrangement is critical to the final solution.*

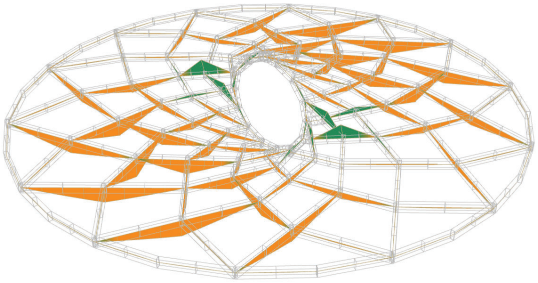

***Figure 12:*** *Bending moment around the y-y axis of each member.*

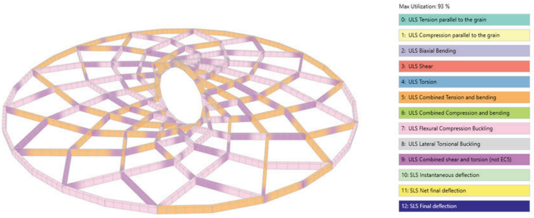

***Figure 13:*** *A Color-coded plot shows the critical SLS or ULS verification according to code for each FE node of the structure.*

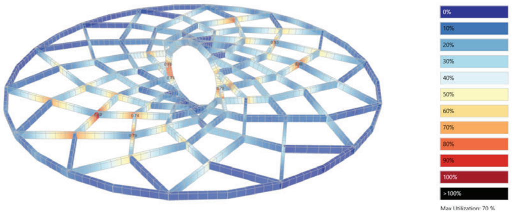

***Figure 14:*** *ULS utilizations according to EC5.*

## 1.5 Integrated calculation of semi-rigid moment stiff connection

Since serviceability requirements often determine element sections in timber structures, optimization processes can occur by implementing semi-rigid connections in early design stages. On the other hand, engineering practice often neglects the effects of semi-rigid timber connections due to the several iterations needed to ensure proper structural behaviour.

The implementation of rotational stiffness on FE models represent a time-intensive task of the detail design since the resulting moment affects not only the forces acting the connection but also the resistance of each fastener due to a change in the angle between the acting force and the relative angle to the grain in the timber element.

Beaver proposes an integrated process of semi-rigid connection design where the rotational stiffness can be live verified and fed back to the finite element software, resulting in an automated iterative approach on the design of the timber structure and its connections. This integration is particularly important because every change made on the connection design affects the bending moment acting upon it. Since the resistance of each fastener depends on the angle between the grain direction and the fastener force, it is difficult to infer whether a change in the connection design is conservative or not. In most cases, a recalculation of the connection is necessary.

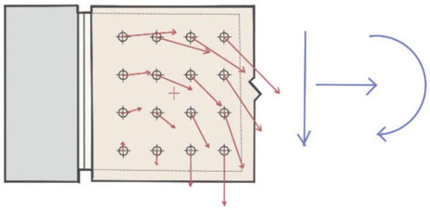

***Figure 15:*** *The resistance of each fastener is calculated separately since the vectorial sum of forces affects the angle between force and grain.*

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Designers can often oversee the effects of semi-rigidity of the connections especially when they are designed for pure shear and tension. The choice in arrangement and type of fasteners and number of shear planes affect deeply the behaviour of the connection, which may lead to an undesirable moment-stiffness in the connection. An integration between a global model and the connection detailing is desired to ensure the compliance of the connection to standards.

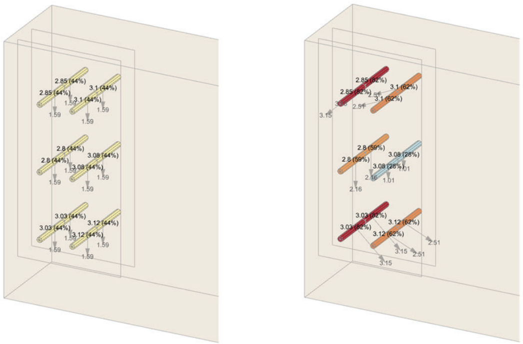

***Figure 16:*** *Calculated fastener utilization on a simple-span beam for a steel-to-timber connection adopting hinged (left) and semi-rigid (right) hypothesis*

In the previous paper [3], the authors presented another geometrical optimization of a truss system where Beaver was used for an early stage engineering design of a 40m span roof for a horse arena, designed and executed by Ita Construtora, Brazil, in 2020. A benchmark is presented to demonstrate how Beaver is able to produce reliable results also at later-design stages.

Not only optimizations in truss geometry and member cross-section design have been optimized but also the connection design was considered in early stages. Fasteners geometry at the critical multiple shear plane tensile connections affected greatly on section design due to possible block shear failure and there was a concern that the effect of moment semi-rigidity and sliding of the dowels would effect on deformations and on the integrated design of each fastener.

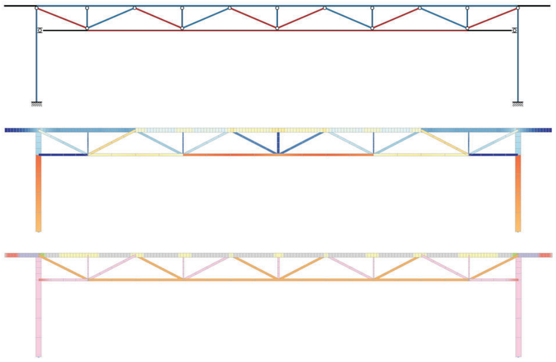

***Figure 17:*** *Structural principles, Beaver utilizations and critical check according to code.*

A high number of fasteners and steel plates were needed to take tensile forces on the connections of the truss, inherently creating a semi-rigid moment-stiff connection between elements. This affects not only global deformations and actions on each member but also the design of the connection, leading to an iterative process on the engineering design.

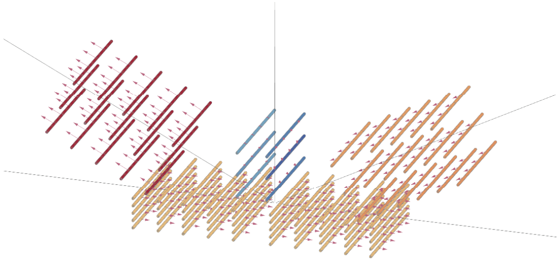

***Figure 18:*** *The connection nodes of the structure were modelled in 3D and verified according to EC5 in real time.*

The workflow adopted integrates both timber engineering member design, connection design and 3D model documentation into one single interface, making sure the fastener arrangement is compatible with the cross-section and facilitates the coordination between draftsmen, engineers and builders.

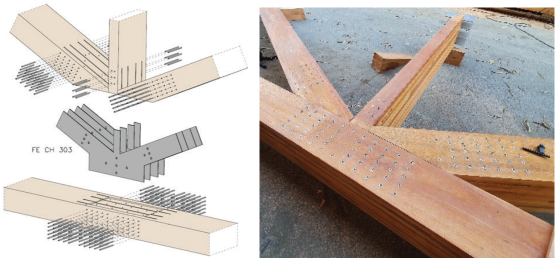

***Figure 19:*** *Project and pre-assembly of one of the multiple shear connections used as a benchmark in Beaver.*

***Figure 20/21:*** *Final structure after truss geometry and section optimization along with connection design.*

## 4. CONCLUSIONS

The framework and case studies presented in this paper display an integration between computational design tools – i.e., evolutionary solvers, multi-objective optimizations and form-finding processes – and timber engineering calculations, allowing for a broad variety of design methods and its associated performance in relation to current standards.

The improved integration with *Karamba3D* allows the designer to evaluate its results easily by performing a structural safety evaluation. By managing *Karamba*'s data directly from a back-end integration, Beaver is able to perform live limit state evaluations, which suits well with computational design workflows and early design phases. Furthermore, Beaver combines the limit state analysis for timber elements and its respective connections in a live-fed calculation, assisting designers to consider a variety of spatially associative problems such as the effects of semi-rigid stiffness and fastener arrangements on global structural behaviour and member design.

After all, Beaver aims to assist designers to integrate geometrical formulations, finite element analysis, safety structural checks and solver algorithms in order to simplify structural design in a parametric environment. The latest improvements of the tool deliver a better user experience of the tool, as well as invite the field to use and collaborate with it by making its core logic open-source, and independent from Grasshopper. The authors hope that this step will provide a tool to develop new systems as well to help improve its features either by professional collaboration as well inside scientific research in the areas of structural engineering and software development.

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