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Built Environment Research Ireland

TimberFlow

Enhancing Efficiency in Mass Timber Construction through Innovative Design Practices and Capacity Building

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Timberflow: Enhancing Efficiency in Mass Timber Construction Through Innovative Design Practices and Capacity Building

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Table of Contents

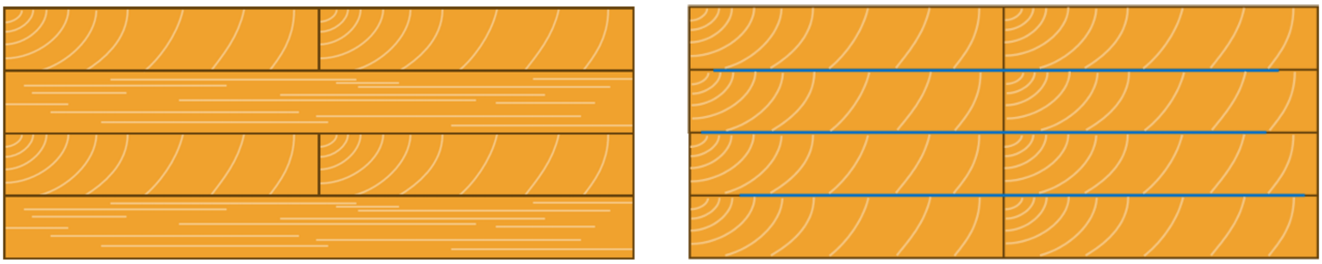
1 Introduction

1.1 Need for Timber Construction

In our modern world, where populations and construction continue to grow and the climate emergency is increasingly pressing, finding new techniques and construction materials is gaining more importance. In this context, Timber Construction is perceived as a sustainable alternative to traditional contemporary building materials such as concrete and steel. Timber construction is proving to be environmentally friendly, structurally sound and appropriate for a variety of building types because of advancements in engineered wood products. In several countries, including *Austria, Canada and Sweden*, Timber has been successfully integrated into the construction sector for a few decades, demonstrating its potential for all types of buildings, including mid- and high-rise structures. However, timber construction is still underutilized in *Ireland,* despite the country's long history of forestry and the increased focus on sustainable development.

1.2 What is Timber?

Timber refers to a family of engineered wood products with large cross-sections that provide the construction industry with a viable alternative to steel and concrete. While primarily describing thick panel products, the term can also include large-section glued or block-laminated linear elements, Timber products are used for structural components such as walls, floors and roofs. These products and building systems have gained a significant interest over traditional uses of wood that relies on lumber of smaller dimensions, due to their technical capabilities, cost effectiveness, and mostly environmental benefits. Timber is made by gluing layers of wood together to form a more robust material. The most popular types of Timber include *cross-laminated timber (CLT), glued-laminated timber (glulam or GLT), laminated veneer lumber (LVL), and nail-laminated timber (NLT)*. These materials are prefabricated on site, which allows precision and efficient on-site assembly. *Cross-laminated timber (CLT)* has received the most attention among Timber products in recent years with *Glulam*. *CLT* and *Glulam* are manufactured by glueing at least three layers of parallel boards together under pressure. For CLT, the boards in successive layers are perpendicular to each other, resulting in strong in-plane stability (Fig. 1a). The cross-lamination improves the material's load-bearing capability and dimensional stability. Glulam, on the other hand (Fig. 1b), has boards aligned parallel to each other and is commonly used for beams and columns due to its high strength-to-weight ratio. These qualities allow architects and engineers to create open, flexible layouts with little internal supports.



(a) CLT element (b) GLT element

Fig.1: Schematic sections of Timber elements

Another significant advantage of Timber is its fire resistance. While wood is intrinsically combustible, when exposed to fire, the thick, dense panels used in Timber Construction char on the surface, providing a protective layer that delays combustion and reduces the loss of strength. This charring action permits Timber structures to remain structurally sound during a fire, meeting or exceeding safety standards. These materials have been used in a variety of building types, particularly low-rise construction. From 2003 to 2011, around 100 educational buildings in the UK were built with CLT [1].

1.3 Challenge

Ireland has experienced significant growth in housing demand and is currently facing a housing crisis. Between 1991 and 2006, the Irish population increased by approximately 20%, while the number of households increased by approximately 43%, creating substantial pressure on housing supply and construction capacity (see Fig. 2) [2]. This rapid growth generated large-scale construction activity but also resulted in sharp increases in housing prices and mortgage debt, highlighting systemic inefficiencies in meeting long-term housing demand. Despite periods of housing oversupply during economic downturns, more recent years have been characterized by insufficient new housing construction, particularly in urban regions such as *Dublin* and surrounding commuter counties. Limited new housing supply, combined with rising demand, has resulted in increasing rental and property prices, rising homelessness, and growing social housing waiting lists [3].

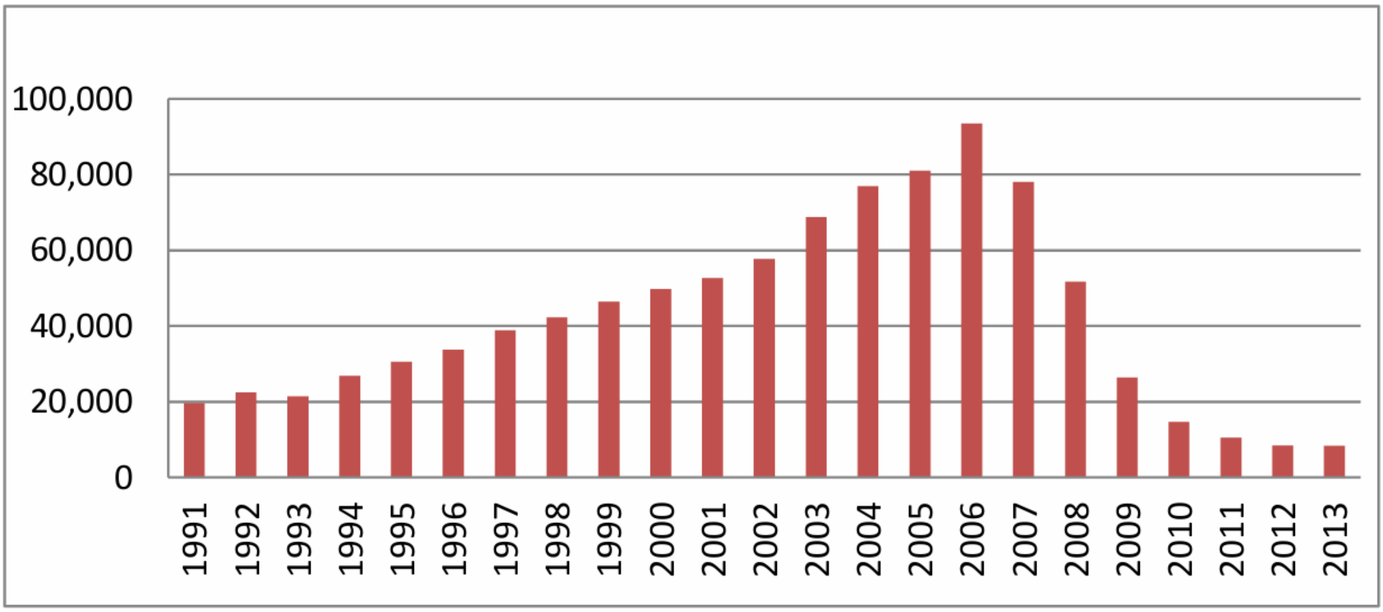


Fig. 2: Number of completed housing units per annum, 1991-2013. Source: DECLG 2014 [2]

Another major challenge is the slow pace and high cost of traditional construction methods, which often struggle to respond quickly to fluctuating housing demands. Economic constraints, financing limitations, and planning complexities further restrict the ability of developers and government agencies to deliver housing at the scale and speed required. Additionally, fragmented housing policies and inconsistent construction planning strategies have historically delayed implementation of long-term housing solutions, exacerbating supply shortages and affordability concerns.

Timber construction presents a promising alternative approach to addressing these challenges. Compared to traditional concrete and steel construction, Timber systems offer advantages such as faster prefabrication, reduced construction time, improved sustainability, and lower carbon footprint. However, implementing Timber construction at scale requires reliable and efficient structural design tools that comply with relevant building standards, including *Eurocode 5 and relevant National Annexures.*

Therefore, the above factors triggered the motivation to develop a Timber Design and Analysis tool (we named it *TimberFlow*), which will help streamline the structural design process, reduce manual calculations, minimize design errors, and support rapid housing development. Timber structural design involves multiple limit states *(ULS/SLS*), material-dependent modification factors, load combinations, and connection detailing rules. In day-to-day engineering practice, these checks are often performed across multiple spreadsheets and references. The objective of this software tool is to provide a single, structured desktop environment where engineers can define geometry and material, enter load cases using a consistent table format, run Eurocode-style combinations, and obtain transparent utilization checks and diagrams.

By providing automated design calculations, improved efficiency in structural verification, and standardized compliance with Eurocode-based timber design requirements, this tool aims to contribute towards accelerating ease of Timber adoption in Ireland. In turn, such technological support can assist stakeholders in delivering housing projects more efficiently, helping to address supply shortages while maintaining structural safety, cost-effectiveness, and environmental sustainability.

1.4 Background and Feasibility

The increasing adoption of timber as a sustainable structural material has created a growing demand for reliable and efficient digital design tools. Engineered timber products such as *Glulam, Laminated Veneer Lumber (LVL), and Cross-Laminated Timber (CLT)* are increasingly used in modern construction due to their favorable *strength-to-weight ratio*, carbon sequestration benefits, and prefabrication potential. However, the complexity of timber design often creates a steep learning curve for both students and practicing engineers.

Python was selected as the primary programming language for the tool development due to its strong ecosystem for scientific computing, numerical analysis and graphical user interface development. The “*PyQt”* framework provides a robust and scalable desktop interface that supports modular design architecture, enabling separate functional modules to interact seamlessly while maintaining user accessibility.

The feasibility of this tool is supported by several factors:

1.4.1 Computational Feasibility

Modern Python libraries allow rapid implementation of structural analysis algorithms, load combination logic and numerical methods required for beam and column members and frame analysis. The scripting environment enables flexible integration of future analytical methods such as Finite Element Modelling (FEM) and optimization algorithms.

1.4.2 Engineering Feasibility

The *Eurocode design philosophy* is well-structured and lends itself to algorithmic implementation. Material strength reduction procedures, load combination rules, and interaction expressions can be reliably translated into deterministic computational routines. This ensures that engineering judgement is preserved while automation reduces calculation errors.

1.4.3 Educational Feasibility

The tab-based modular interface allows users to isolate structural design tasks, improving conceptual understanding of individual design components. The transparency of calculation steps makes the tool particularly suitable for academic instruction and training of early-career engineers.

1.4.4 Expansion Feasibility

The modular software architecture supports future extension into:

• National Annex implementation
• Additional connection types
• Advanced frame modelling
• Automated reporting and verification systems
• Integration with *Building Information Modelling (BIM)* workflows

Overall, the project demonstrates strong technical and practical feasibility due to the synergy between modern computational tools and standardized structural design procedures.

2 Project Scope, Objectives and Limitations

2.1 Project Scope

The software is designed to provide comprehensive structural verification for timber structural elements using *Eurocode 5*. The primary scope includes:

i. Design verification of beams, columns, frames and connections
ii. Implementation of Ultimate Limit State (ULS) and Serviceability Limit State (SLS) checks
iii. Automated load combination generation
iv. Integration of material modification factors
v. Support for continuous beam analysis
vi. Stability and interaction check for compression members

vii. Connection verification using dowel-type fastener design provisions

The tool primarily targets structural engineers engaged in (i) residential and mid-rise timber structures, (ii) Timber modular construction, (iii) preliminary and detailed design verification, (iv) educational and research applications.

2.2 Objectives

One of the core objectives of developing this software is to make Eurocode-style timber design workflows more transparent and practically usable by providing an accessible, modifiable tool that supports both educational learning and early-stage engineering checks. A major advantage of the project is that it is open source, meaning it can be freely accessed, reviewed, and customized to suit specific industrial or academic requirements (e.g., preferred assumptions, national annexure parameters, reporting formats, or institutional teaching needs). To ensure long-term availability and straightforward dissemination, the complete software code with all supporting materials have been deposited in the Zenodo repository under DOI : https://doi.org/10.5281/zenodo.18518598 , from where it can be downloaded and adapted for use [4].

2.2.1 Engineering Objectives

Provide accurate timber structural design calculations in full compliance with Eurocode standards, ensuring that all structural elements meet the required safety, serviceability, and performance criteria. The approach enhances the transparency of design verification results by presenting clear, traceable, and well-documented calculation outputs, allowing engineers and stakeholders to easily understand and validate the design process. Additionally, the methodology significantly reduces the time required for iterative structural optimization by streamlining calculation procedures and enabling faster evaluation of multiple design alternatives. It also delivers clear and intuitive graphical representations of internal force diagrams and utilization ratios, helping engineers quickly assess structural behavior and identify critical design conditions.

2.2.2 Industry Objectives

Support the widespread adoption of Timber in housing infrastructure by promoting efficient, reliable, and standardized structural design practices that align with modern construction requirements and sustainability goals. The approach enhances the productivity of structural engineering workflows by automating repetitive calculations, reducing manual effort, and improving overall design efficiency. It also proves as a good solution for structural design verification by minimizing the need for extensive manual checking while maintaining high levels of accuracy and compliance with relevant design codes and standards. Furthermore, it facilitates rapid structural feasibility assessments during the early stages of design, enabling engineers and designers to quickly evaluate multiple concepts, identify viable structural solutions, and make informed decisions that optimize both performance and cost.

2.2.3 Educational Objectives

TimberFlow will provide students and researchers with accessible structural design tools that simplify complex analytical procedures and allow them to perform reliable and efficient structural evaluations. These tools enhance the understanding of Eurocode-based timber design methodology by offering step-by-step calculations, transparent verification processes, and practical examples that bridge theoretical concepts with real-world applications. Additionally, they support academic training in timber structural engineering by enabling learners to develop strong analytical skills, gain hands-on experience with industry-relevant design standards, and strengthen their ability to interpret and apply structural design principles effectively.

2.3 Limitations

The current implementation assumes linear elastic structural behavior, meaning that material and structural responses are considered proportional to the applied loads, which may not fully capture complex real-world nonlinear effects. Dynamic loading conditions and seismic design provisions have not yet been incorporated, limiting the framework's applicability to structures subjected to time-dependent/dynamic or earthquake-induced forces. Additionally, fire resistance design requirements in accordance with Eurocode 5 Part 1-2 are not included, restricting the evaluation of structural performance under fire exposure scenarios. Long-term creep behavior is modeled using simplified service class factors, which provide a generalized approximation but may not fully represent time-dependent deformation characteristics under varying environmental conditions. Furthermore, advanced nonlinear connection behavior is approximated using empirical formulations provided in Eurocode guidelines, which may not capture highly detailed connection responses under complex loading conditions. The current scope also excludes large-scale three-dimensional structural modeling, focusing instead on simplified structural configurations to ensure computational efficiency and ease of implementation.

3 Tool Development and Key Features

3.1 Software Architecture and User Interface

The application employs a tab-based GUI structure that separates structural components into independent modules, including beams, columns, frames, connections, and continuous beams. The interface allows engineers to input geometry, loading, and material properties in structured formats consistent with professional structural design workflows.

3.2 Embedded Material Database and Eurocode factors

The tool incorporates a comprehensive material database that includes essential mechanical and physical properties required for accurate structural design calculations. It provides characteristic bending strength ($f_{m,k}$), enabling reliable assessment of timber elements subjected to bending loads. It also includes characteristic compression strength parallel to the grain ($f_{c,0,k}$), which is critical for evaluating load-bearing capacity under axial compression. Additionally, the database contains shear strength values ($f_{v,k}$) to support the analysis of shear resistance in timber members. The inclusion of the mean modulus of elasticity ($E_{0,mean}$) allows for precise estimation of stiffness and deformation behavior under loading conditions. Furthermore, density values are incorporated to facilitate accurate load calculations, including self-weight estimation and other gravity-related loading considerations.

Material properties are modified using Eurocode 5 factors:

$$f_d = \frac{k_{\text{mod}} \cdot f_k}{\gamma_m}$$

Where:

f_d is design strength

f_k is characteristic strength

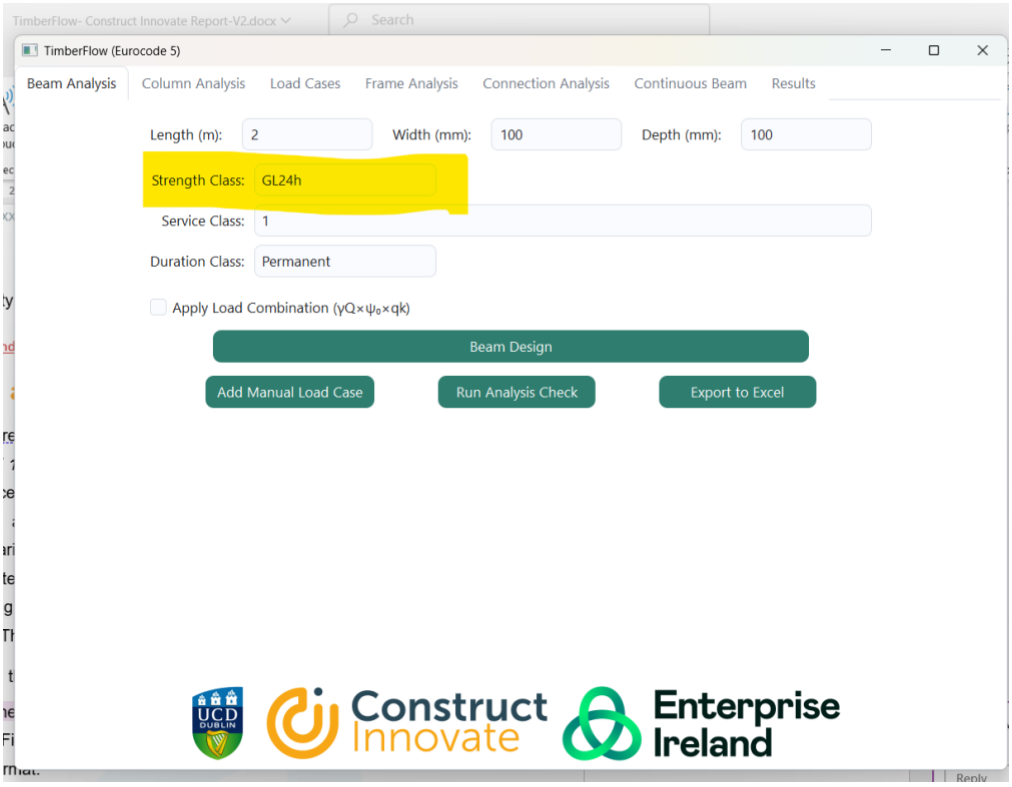
k_{mod} is load duration and service class factor

γ_m is material partial safety factor

What about strength classes and the explanations? This tool is proposed as an MET tool that speaks about CLT and Glulam, but then does not discuss the strength profiles of any of these as implemented in the tool?

What is meant by MET here, also the technical data regarding to tool is avoided to not confuse the general audience and minimum technical supporting data is provided.

3.3 Load Cases and Design



Combination Engine

The Load combinations are generated in accordance with the fundamental load combination rules specified in Eurocode EN 1990, ensuring that structural designs are evaluated under code-compliant loading scenarios. The tool considers a wide range of loading conditions, including permanent loads, which account for the self-weight of structural elements and other fixed components, as well as variable loads that represent fluctuating actions during the service life of the structure. It also incorporates imposed loads associated with occupancy and usage conditions, along with environmental loading such as snow loads and wind loads, which can significantly influence structural performance.

The tool automatically applies the appropriate combination factors ($\Psi_0, \Psi_1, \Psi_2,$) as specified in the Eurocode framework and systematically generates governing design envelopes, enabling users to efficiently identify critical load cases and ensure structural safety and serviceability. Below Fig. 3 shows the Load Cases tab which includes the Added Manual Load Cases data in a tabular format.

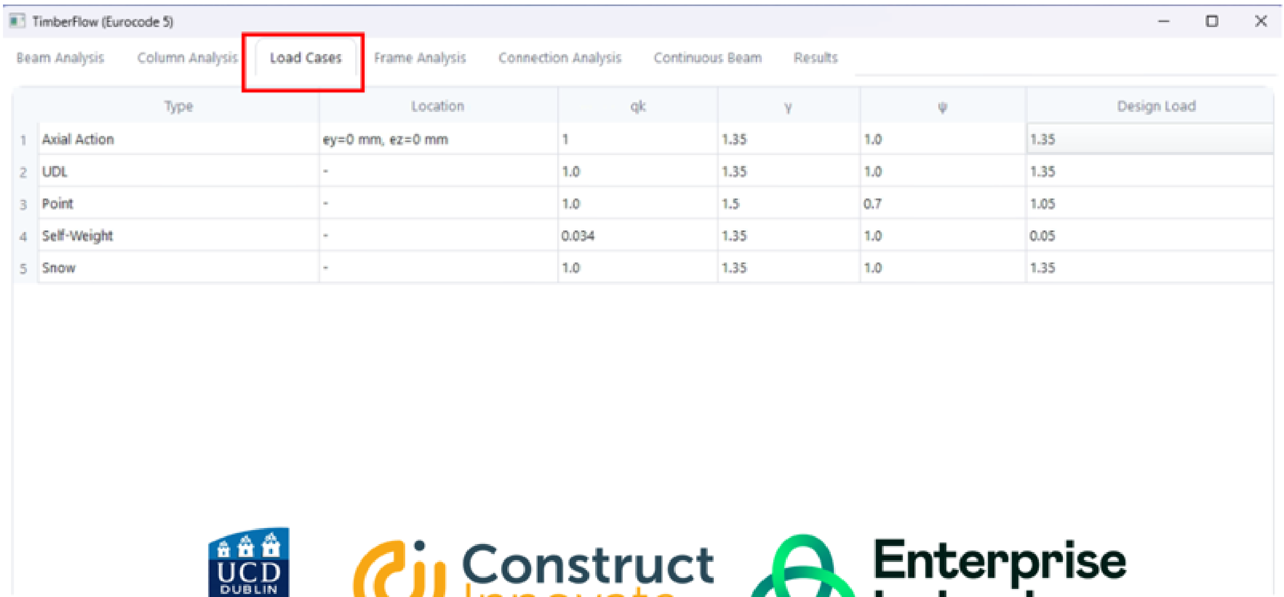


Fig. 3: Load Cases tab user interface window

3.4 Beam Analysis and Design Checks

Beam modules perform structural analysis to evaluate the performance and safety of timber beam elements under applied loading conditions. The modules conduct shear force and bending moment analysis to determine internal force distributions along the beam length, enabling accurate identification of critical sections. Deflection calculations are performed using elastic beam theory to estimate structural deformation under service loads and to ensure compliance with serviceability requirements.

The modules also carry out bending strength verification by ensuring that:

$\sigma_m \leq f_{m,d}$

Similarly, shear verification is conducted by checking that:

$\tau \leq f_{v,d}$

In addition, the modules evaluate serviceability performance by verifying deflection limits in accordance with span-based criteria, ensuring that beam deformations remain within acceptable limits for functionality, durability and user comfort. Figs. 4-5 down below is the image of the User interface used for entering input and output for Beam Analysis, respectively.

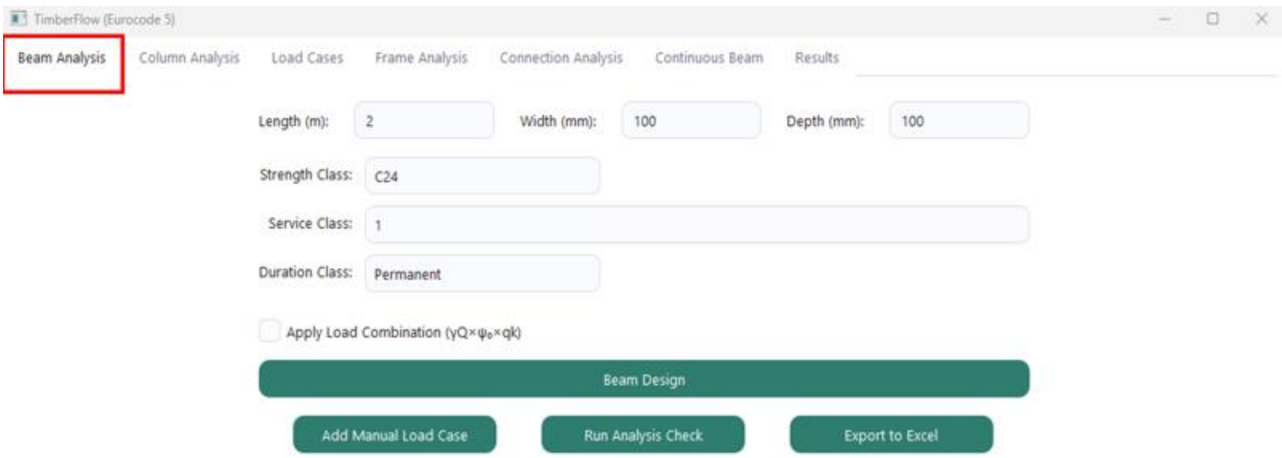


Fig. 4: Beam Analysis Input User Interface window

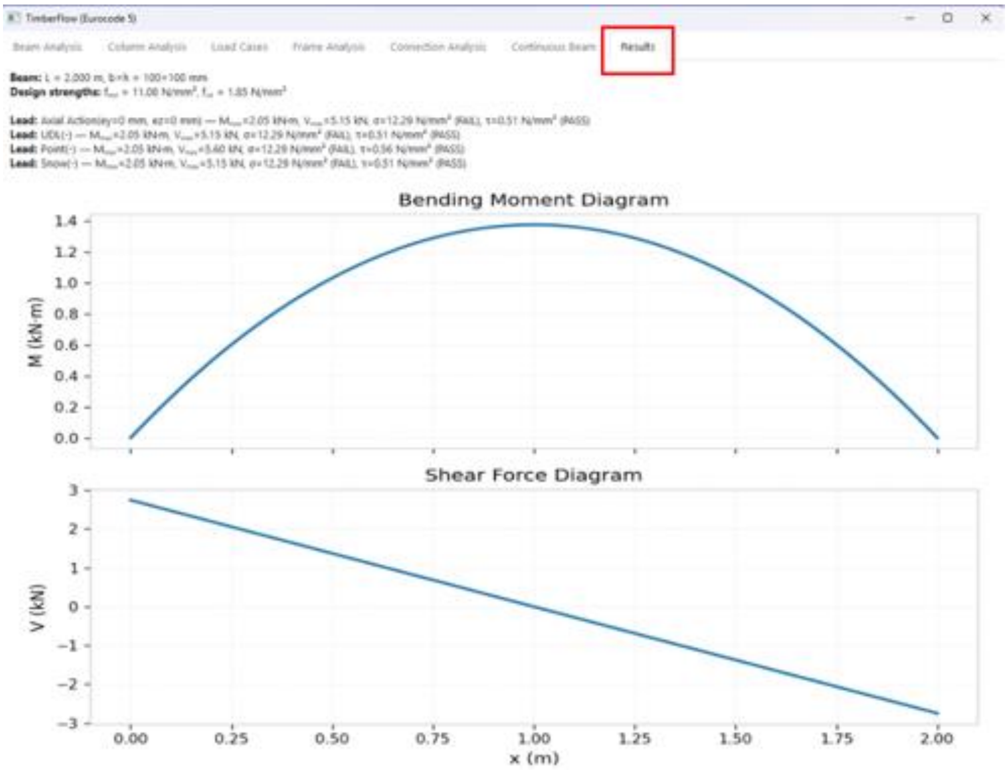


Fig. 5: Beam Analysis Output User Interface window in Results tab

3.5 Column Analysis, Stability and Interaction Checks

Column verification includes a comprehensive assessment of structural performance under axial and combined loading conditions to ensure stability and safety. The process evaluates axial compression resistance to confirm that the column can safely carry the applied compressive loads without exceeding its design capacity. Buckling analysis is performed using slenderness ratios to assess the susceptibility of the column to instability under compressive forces, ensuring that global and local buckling risks are adequately addressed. The verification procedure also includes interaction checks between bending moments and axial compression forces, enabling accurate evaluation of column behavior under combined loading scenarios commonly encountered in practical structural systems. Additionally, effective length calculations are carried out based on the column's boundary conditions, allowing precise determination of buckling resistance and improving the reliability of stability assessments. Fig. 6 below shows what the image of the user interface of Column Analysis in the software.

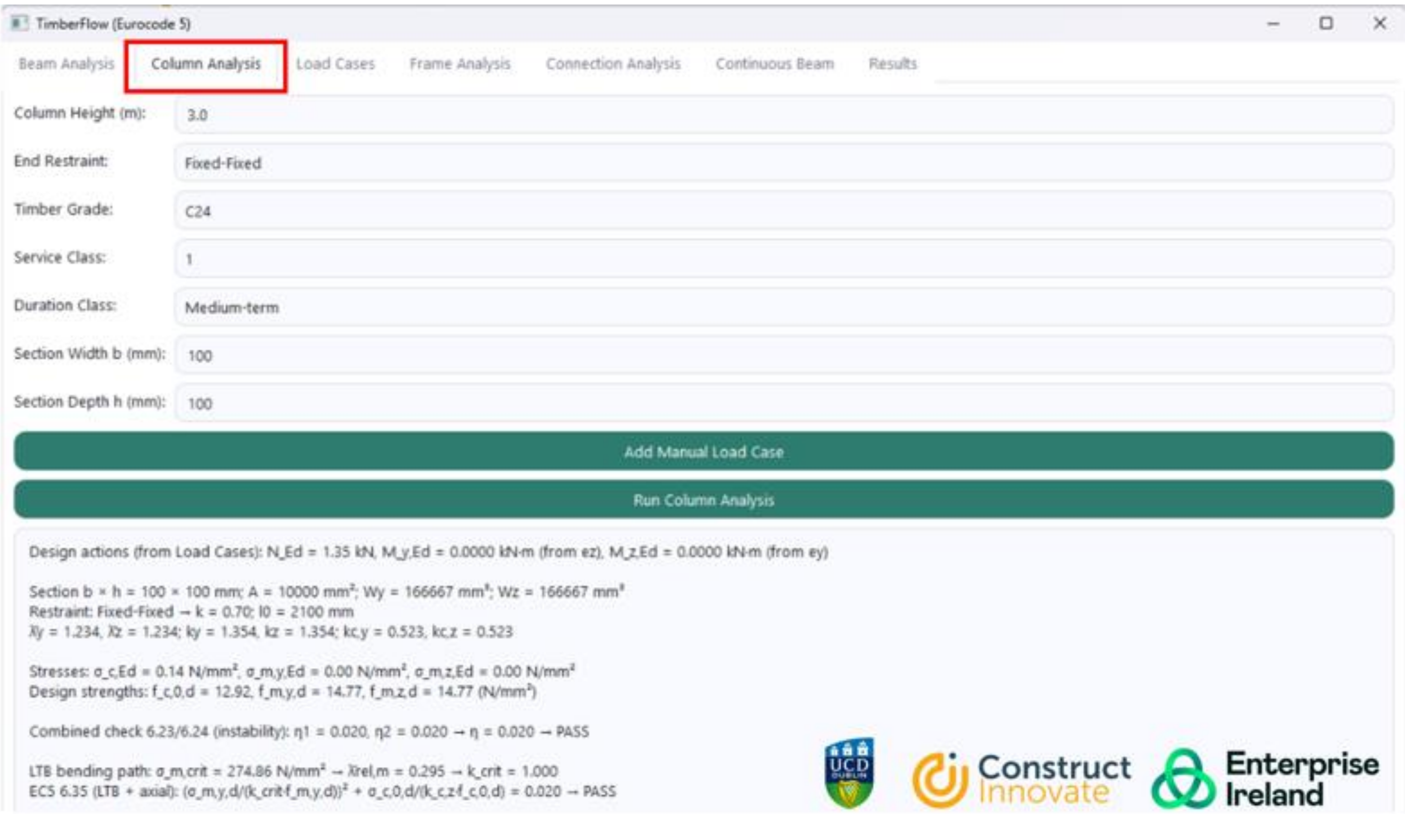


Fig. 6: Column Analysis user interface window

3.6 Connection Analysis Module

Connection design is carried out in accordance with Eurocode 5 provisions for dowel-type fasteners, ensuring reliable and code-compliant evaluation of timber connection performance. The design process includes embedment strength calculations to determine the resistance of timber material against localized bearing stresses generated by fasteners. It also applies Johansen yield theory to verify the load-carrying capacity of connections by evaluating potential failure modes associated with fastener yielding and timber crushing. In addition, withdrawal resistance checks are performed to assess the capacity of fasteners to resist pull-out forces, which is critical for maintaining connection integrity under tensile loading conditions. The design procedure further considers group action effects, accounting for the interaction between multiple fasteners within a connection to ensure accurate prediction of load distribution and overall connection strength. Fig. 7 shows one of the equations for Characteristic capacity check in single shear conditions. Further, Fig. 8 shows the Connection Analysis user interface window as an image.

Table 10.2 Characteristic load-carrying capacity per fastener per shear plane for timber–timber and timber–wood based connections*

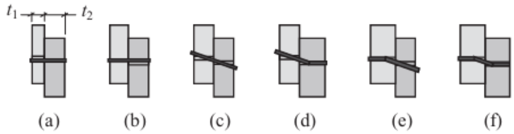
Connections in single shear		
Failure modes		
Characteristic load-carrying capacity per fastener per shear plane, $F_{v,Rk}$, is the minimum value from the mode failure equations: (EC5, *equations (8.6)*)	$F_{v,Rk} = f_{h,1,k} \cdot t_1 \cdot d$	mode (a) (10.1)
	$F_{v,Rk} = f_{h,2,k} \cdot t_2 \cdot d$	mode (b) (10.2)
	$F_{v,Rk} = \frac{f_{h,1,k} \cdot t_1 \cdot d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1+\frac{t_2}{t_1}+\left(\frac{t_2}{t_1}\right)^2\right]+\beta^3\left(\frac{t_2}{t_1}\right)^2} - \beta\left(1+\frac{t_2}{t_1}\right)\right] + \frac{F_{ax,Rk}}{4}$	mode (c) (10.3)
	$F_{v,Rk} = 1.05\frac{f_{h,1,k} \cdot t_1 \cdot d}{2+\beta}\left[\sqrt{2\beta(1+\beta)+\frac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k} \cdot t_1^2 \cdot d}} - \beta\right] + \frac{F_{ax,Rk}}{4}$	mode (d) (10.4)
	$F_{v,Rk} = 1.05\frac{f_{h,1,k} \cdot t_2 \cdot d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\frac{4\beta(1+2\beta)M_{y,Rk}}{f_{h,1,k} \cdot t_2^2 \cdot d}} - \beta\right] + \frac{F_{ax,Rk}}{4}$	mode (e) (10.5)
	$F_{v,Rk} = 1.15\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,Rk} \cdot f_{h,1,k} \cdot d} + \frac{F_{ax,Rk}}{4}$	mode (f) (10.6)
		(*continued*)

Fig. 7: Exemplar equations (from Eurocode 5) for Characteristic capacity check in Single Shear conditions used in the logic of the tool

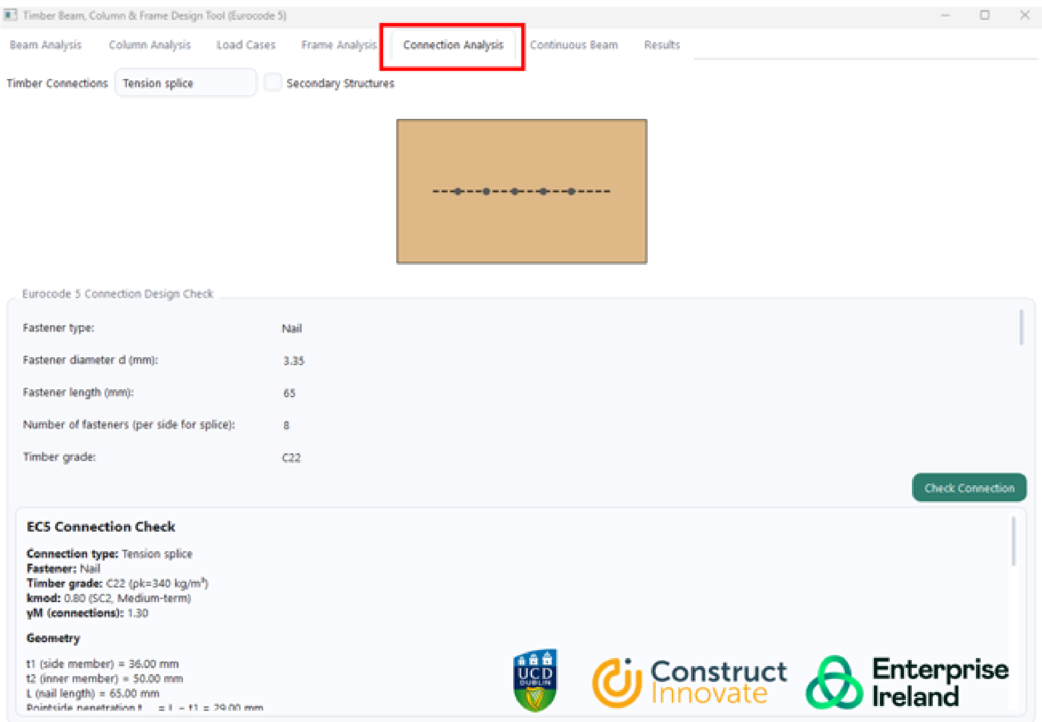


Fig. 8: Connection Analysis user interface window

3.7 Frame Analysis Module

The Frame module provides a separate workflow for frame-level response and visualization (geometry, restraint choices, and analysis output). It is implemented as its own tab, enabling later expansion to more complex frame types and boundary conditions. Fig. 9 below shows the Frame Analysis user interface screen for providing input. Fig. 10, which shows the Frame Analysis output displayed in a separate “Results” tab.

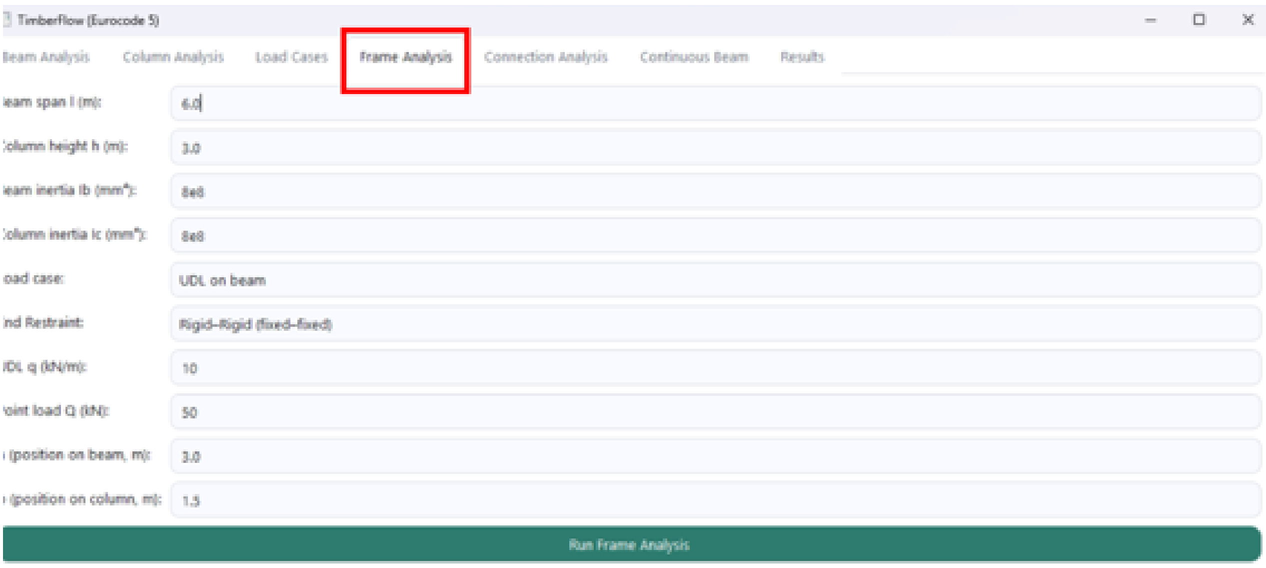


Fig. 9: Frame Analysis input user interface window

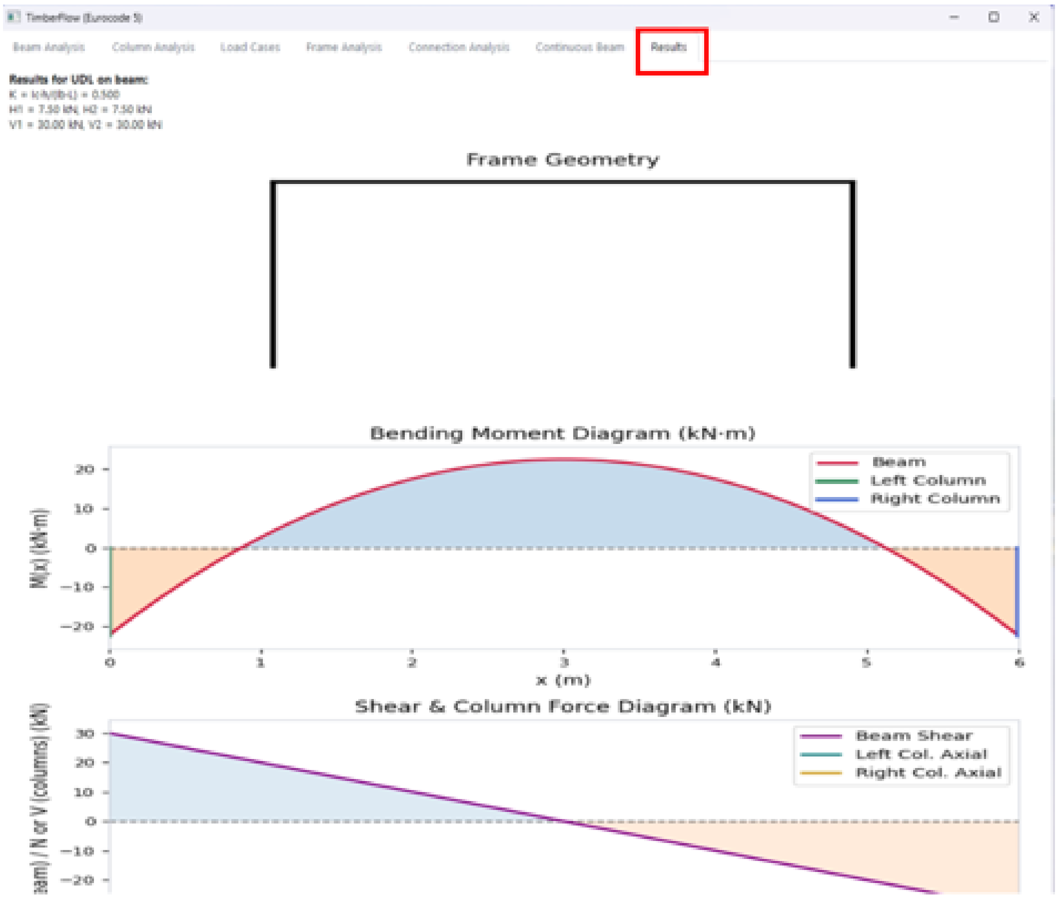


Fig. 10: Frame Analysis output user interface window

3.8 Continuous Beam Analysis Module

A Continuous Beam tab is included to facilitate the analysis of multi-span beams, offering flexibility by allowing users to select between the Three-Moment method and a finite element–based stiffness method as the preferred analysis approach. The module accepts comprehensive user inputs, including lists of spans, support conditions, uniformly distributed load (UDL) segments, and point loads, enabling accurate representation of realistic loading and boundary conditions. Based on these inputs, the module computes support reactions and identifies peak design effects such as maximum bending moments and shear forces, with integrated support for plotting internal force diagrams to aid in visual interpretation of structural behavior.

However, while the module is designed to perform all the functions described above, the code developed to implement this functionality was not fully completed due to time constraints. As a result, the Continuous Beam module was considered a work in progress at the conclusion of the project. Nevertheless, the foundational code structure and core analytical framework have already been established, providing a solid base for future development. Any candidate who takes up this project in the future to expand and advance this module will be able to build upon the existing foundation, extending its capabilities to a more advanced and fully realized level. Fig. 11 below shows the Continuous Beam user interface screen.

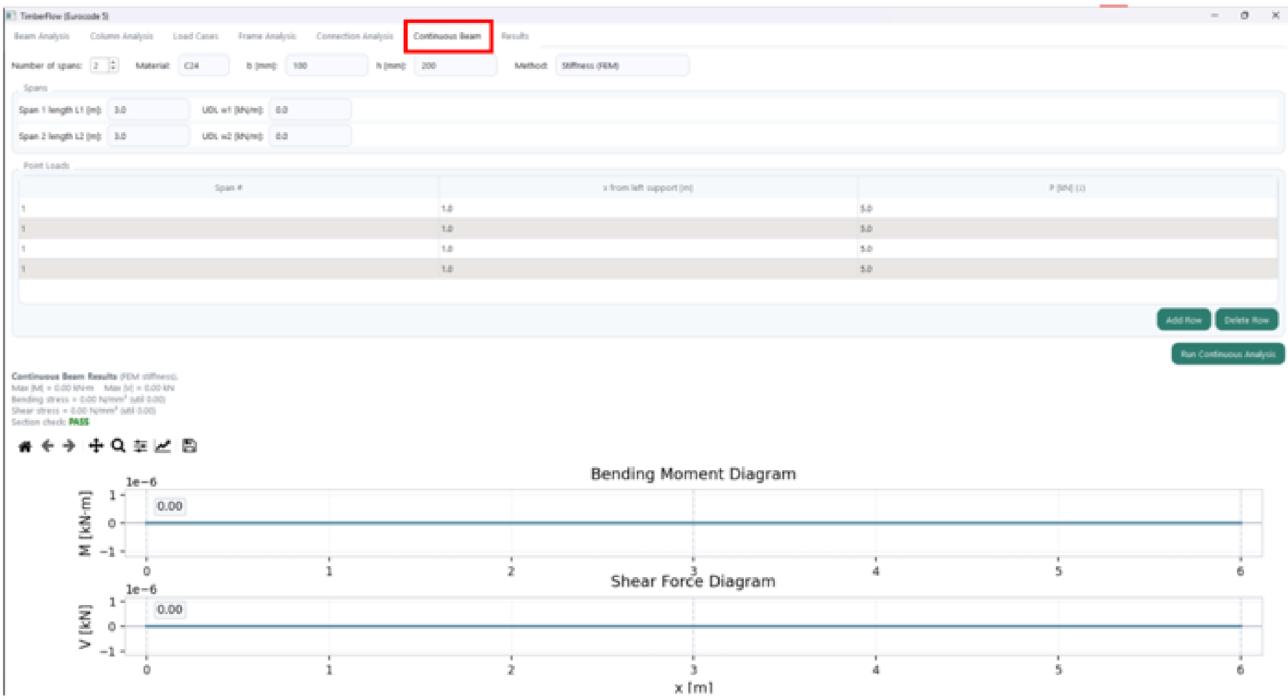


Fig. 11: Continuous Beam Analysis user interface window

3.9 Output, Export and Reporting

The Output, Export, and Reporting functionality includes an Excel export feature that allows the load table and all associated user-entered data to be saved into an ".xlsx" file, ensuring traceability, documentation, and ease of external review. The Results tab is designed as the central interface for presenting formatted outputs generated by the various analysis modules, enabling users to view key structural results in an organized and accessible manner.

At the current stage, the exported reports are generated in a raw Excel sheet format, primarily intended for data verification and internal review. These outputs require further editing, formatting, and refinement before they can be presented or submitted within a professional or industry-standard reporting . This limitation also highlights an opportunity for future enhancement, where automated report formatting and presentation-ready exports could be developed.

Educational Dissemination

The tool is well-suited for educational dissemination in Eurocode-based timber structural design, supporting both teaching and training applications. It enables effective instruction of Eurocode timber design workflows, including clear separation of ULS and SLS checks, application of k_{mod} and k_{def} factors and load combination logic, while also demonstrating the sensitivity of utilization ratios to material grade, service class and load eccentricity. Through transparent calculation procedures and clear visual representation of structural performance, the tool helps students and junior engineers develop a deeper understanding of how design assumptions and parameters influence structural capacity and compliance. Additionally, it serves as a valuable platform for training junior engineers on the impact of connection detailing constraints on structural behavior and design limits, and it can be effectively integrated into structural engineering coursework and research projects focused on timber structures and sustainable construction practices.

In addition to the development of the software itself, a series of structured tutorial videos has been created to support educational dissemination and professional adoption (which can be accessed through the repository link - https://doi.org/10.5281/zenodo.18518598). These videos provide step-by-step guidance on the use of each module within the application, including beam design, column stability checks, frame analysis, connection verification, and load combination generation. Each tutorial briefly explains the required inputs, underlying Eurocode 5 design logic, interpretation of outputs, and common design considerations. The videos are intended to assist students, early-career engineers, and industry professionals in understanding both the operational workflow of the software and the structural principles embedded within it. By combining computational implementation with explanatory guidance, the tutorials enhance accessibility, reduce the learning curve, and promote effective and accurate use of the tool in academic and professional environments.

4 Impact and Future Directions

The developed timber design tool has the potential to improve efficiency, accuracy, and accessibility in structural timber design. By consolidating multiple verification procedures into a unified environment, the tool reduces dependency on fragmented calculation workflows and improves design traceability.

From an engineering practice perspective, the software enables rapid evaluation of alternative design scenarios, allowing engineers to optimize structural performance and material usage. From a research perspective, the modular codebase provides a flexible platform for incorporating advanced modelling techniques such as long-term creep analysis and probabilistic reliability assessment.

Future development of the tool is expected to focus on:

- Automated generation of detailed engineering reports with calculations.
- Implementation of National Annex customization for design compliance
- Expansion of connection modelling capabilities, including steel-timber hybrid connections
- Integration of advanced finite element analysis for complex structural systems Development of cloud-based collaboration and data storage features

What about continuous beam analysis?

The long-term vision is to transform the software into a comprehensive digital ecosystem supporting both professional engineering design and academic research in timber structural systems.

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