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DEVELOPMENT OF AN INNOVATIVE STRUCTURAL SYSTEM FOR MULTISTOREY TIMBER BUILDINGS WITH INCREASED SERVICE LIFE – THE CRESTIMB PROJECT

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ABSTRACT: CRESTIMB aims to develop an innovative timber system for multi-storey buildings with open spaces. The system includes softwood or hardwood glued-laminated timber (glulam) columns and beams connected with innovative moment resisting connections, and dowel-cross laminated floors. This paper focuses on the description and identification of the structural system, in addition to the experimental programme that aims to assess the short- and long-term performance of the system components, which includes mechanical tests on small wood samples, and full-scale tests. Test results will serve as input to advanced numerical modelling to investigate the long-term behaviour of the selected components considering the complex rheological behaviour of wood under variable indoor climates, with the objective to ensure an increased service life and also the possibility of reuse of components.

KEYWORDS: Glued-laminated timber, moment-resisting connections, dowel-cross laminated floors, threaded rods

1 – INTRODUCTION AND BACKGROUND

Timber structures have gained increasing attention in the European construction field due to their sustainability, reduced self-weight, and speed of erection, which can make them cost effective with respect to traditional cast-in-situ reinforced concrete systems [1]. Particularly beneficial is the low carbon footprint of wood compared to other construction materials such as concrete and steel [2]. Wood products can achieve high mechanical performance not only at material level [3], but also at structural level, as proven by the efforts to design and construct tall timber buildings in Europe, e.g. [4]. Currently, the indicative service life of buildings is 50 years according to EN1990 [5, 6]. Although structural timber is able to retain and even increase its strength over time, its service life is strongly affected by environmental conditions and their variations.

During the last two decades, the vast majority of multistorey timber buildings have been constructed with cross laminated timber (CLT) wall and floor elements (either platform or balloon type construction). This type of construction results in space limitations and low-utilization of structural components and thus it is material-intensive and not very resource-efficient. In addition, this structural system is suitable only for residential buildings as it requires many shear walls to resist the lateral load, whereas architects typically require more open spaces for office buildings.

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Similar issues can be highlighted for light-frame building systems, again characterized by many walls to resist the lateral loads. Another typology used for multistorey timber buildings is the post-and-beam (PAB) system, consisting of beams and columns which carry the gravity loads and a separate bracing system – typically composed of diagonals or a solid core - which carries the lateral loads (e.g. wind, earthquake). However, the bracing system of PAB buildings may also result in space limitations and should be strategically located. Another possibility is the use of moment-resisting frames, which on the one hand provide an excellent solution for open spaces as they limit the obstruction in the building plan to a minimum.

However, moment-resisting frames made of wood are rather flexible leading to increased size of beams and columns, and potential problems of excessive deflection in the short- and long-term, and vibration control. Only a few solutions with moment-resisting frames have been proposed [7] and they are fairly complex and expensive as they require the use of post-tensioning. Moreover, in CLT buildings, the structural components are typically connected with metallic plates and self-tapping screws or nails that result in holes in the timber elements. In PAB systems the structural components are typically connected with steel plates and dowels or bolts inserted in predrilled holes with small tolerances. Although connections with bolts and dowels are more reversible than screws and nails [8], it is questionable if they will be suitable for disassembly and re-assembly in the long-term, considering the effect of creep deformation and moisture-induced effects (dimensional changes, cracks, mechano-sorption) during the service life of a building.

CRESTIMB is a research project funded by the ForestValue2 network. The consortium consists of: VTT (Finland), NTNU (Norway), University of L'Aquila (Italy), University of Galway and Trinity College (Ireland), University of Ljubljana (Slovenia), Ł-PIT and Ł-ITECH (Poland), University of New South Wales (Australia) and several industrial partners. CRESTIMB aims to develop a concept for an innovative structural system for multistorey timber buildings composed of moment-resisting timber frames (MRTFs) made of glulam beams and columns, semi-rigid moment-resisting connections, and dowel-cross laminated floor panels simply supported on the beams of the MRTFs. The columns of MRTFs are continuous. The proposed layout of the system is shown in Fig. 1. The MRTFs are the gravity load-resisting system and the main lateral load-carrying system in one direction and may be used in combination with other bracing elements placed in parts of the building that have less demand for open spaces (e.g. staircases). The lateral stability in the other direction can be achieved with conventional bracing, e.g. by trusswork. Moreover, the floor panels contribute to the lateral stability of the system as they provide the necessary diaphragmatic action. To achieve increased service life and facilitate design for assembly, disassembly and re-assembly (DfADR), the connections must be both reversible and with increased tolerances to accommodate creep deformations, and the components must have quantified long-term properties. This is a main objective of CRESTIMB.

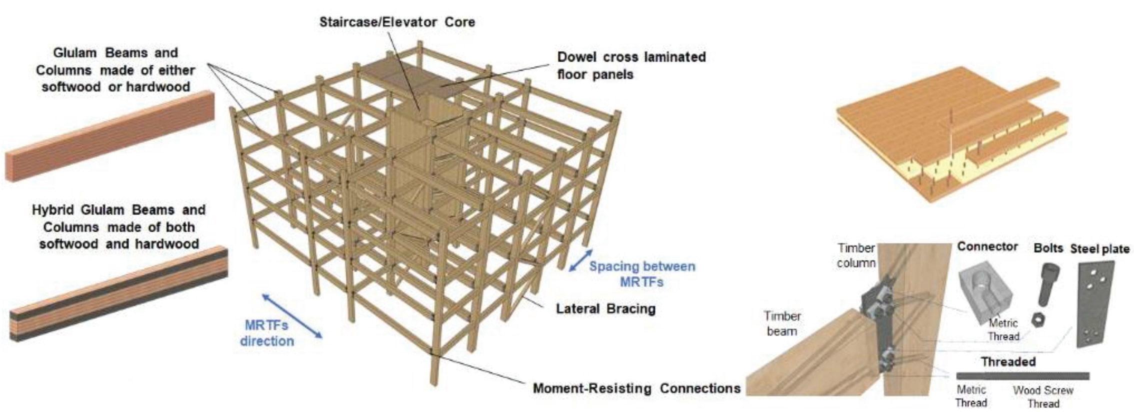

Figure 1 Structural system and its components.

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2 – COMPONENTS OF THE STRUCTURAL SYSTEM

2.1 GLUED-LAMINATED TIMBER

The promotion of alternative and underused timber species, which include hardwoods for structural purposes, has been investigated in the last decade both in Europe and in Italy [9]. In this project, glulam beams and columns made of beech will be fabricated with the aim to characterize them in the short- and long-term, by investigating their mechanical (strength and stiffness) and rheological (creep coefficient) properties. Additionally, the beech glulam elements will be involved in the implementation of a novel moment resisting-connection, which, up to now, was tested by using softwood elements only.

2.2 MOMENT-RESISTING CONNECTION

The connections of MRTFs are based on an innovative moment-resisting, beam-to-column, connection concept developed at NTNU [10]; see Fig. 2. The connection consists of purposely made threaded rods and steel connectors, a steel plate and pre-stressed bolts. The rods, featuring a wood screw thread, are screwed into pre-drilled holes in the timber elements, and they are fastened to steel connectors by using metric threaded ends. Threaded rods are used due to their high axial capacity and stiffness without initial slip [11-13]. The beam and the column are then connected by exploiting the friction between the steel connectors and the steel plate achieved by pre-stressed bolts inserted in over-sized holes. Preliminary short-term tests with softwood glulam elements have shown that moment connections with inclined threaded rods feature suitable stiffness and resistance for MRTFs [14]. Moreover, the aforementioned friction between the steel parts results in ductile behaviour without damage in the timber elements. The connection is reversible, provides easy assembly and disassembly, and can be designed to accommodate the desired tolerances by oversizing the bolt holes.

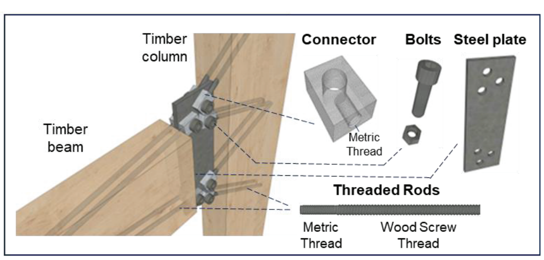

Figure 2. Moment-resisting connection with screwed-in threaded rods

2.3 DOWEL-CROSS LAMINATED FLOOR PANELS

The proposed flooring system will utilise dowel cross laminated timber (DCLT) floor panels, which are adhesive-free and can be a more environmentally friendly alternative to cross laminated timber (CLT) or composite floors [15]. Laminated floor panel systems using vertical dowels have been more commonly investigated in recent years using softwood boards and hardwood dowels. However, while mechanical performance has been studied, knowledge on long-term behaviour remains limited and this project aims to address this gap through experimental testing, leading to the specification of panel configurations that can achieve the intended long service life.

3 – PROJECT DESCRIPTION

The project work to be carried out in CRESTIMB is divided into 7 Work Packages (WP); confer also Fig. 3.

3.1 WP1: COORDINATION AND MANAGEMENT OF THE PROJECT

WP1 is led by VTT, and it concerns coordination and management of the project.

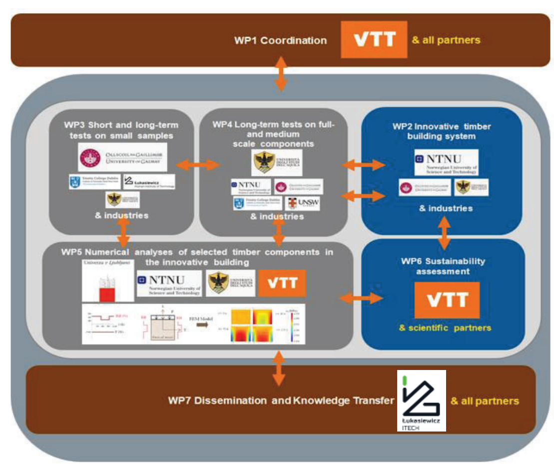

Figure 3. Collaboration among CRESTIMB work packages (large logos: WP leader; small logos: WP partners).

3.2 WP2: INNOVATIVE TIMBER BUILDING SYSTEM

This work package (led by NTNU) aims at the conceptual description and the short-term verification of the innovative timber building system, consisting of MRTFs with semi-rigid connections, glulam elements, and DCLT floor panels. A feasibility study will be carried out resulting in preliminary design of the system both for the Serviceability and the Ultimate Limit State, as well as in estimations the sustained load levels to be used in the long-term experimental programme. Moreover, short-term tests will be performed on all the components of the system, i.e. moment-resisting connections, hardwood glulam elements, and DCLT panels.

Regarding the hardwood glulam elements, beech lamellae will be glued using melamine glue into homogenous glulam members. A hybrid configuration combining beech outer laminations with spruce inner laminations will also be explored. For each configuration, 14 specimens will be produced and tested to destruction in bending (7) and shear (7). In addition, tests on small specimens of spruce and beech will be undertaken to characterize the mechanical properties of the laminations. The fracture properties of the glue (adhesive toughness in mode I, II and IIII) as well as timber will also be experimentally investigated.

Furthermore, short-term full-scale tests of the moment-resisting connection described in chapter 2.2 will also be carried out. To achieve a good degree of reliability, three identical tests will be carried out on specimens with spruce glulam beams and columns. One test will be carried out using hardwood or hybrid glulam to verify the applicability of this connection to hardwood.

Finally, a DCLT floor panel system fabricated without the use of adhesives will be tested in bending (5) and shear (5). DCLT involves the use of dowels positioned within drilled holes to form a tight fit connection between adjacent laminations. Such systems can carry significant structural loads with a limited carbon footprint. However, connection efficiency is reduced compared to adhesively bonded engineered wood products therefore it is important to understand the parameters that affect the strength and stiffness behaviour of DCLT connections. Compressed and hardwood dowels, and variations in dowel spacing, diameter will be considered.

3.3 WP3: SHORT AND LONG-TERM TESTS ON SMALL SCALE WOOD SAMPLES

WP3 is led by University of Galway and concerns material characterization with testing of small-wood samples, both in short-term and in long-term. Small wood samples of the species to be considered will be conditioned and undergo static destructive testing in accordance with EN 408 [16] to determine tension and compression strengths parallel and perpendicular to the grain and shear strength parallel to the grain. Tests will include dowels and both clear wood specimens and laminated timber specimens; Fig. 4 shows test examples. Commercially available adhesive will be used for laminated specimens. The results of these tests will form a reference for (i) the long-term effect of environmental variations applied in the equivalent long-term tests and (ii) the bond and delamination tests associated with bio-based adhesives. Long-term creep tests will be carried out on small clear and laminated specimens under a quasi-permanent load condition, and controlled and uncontrolled environmental conditions to assess the effect of shrinkage/swelling, temperature and relative humidity. Lever-arm test configurations will include the determination of creep parallel and perpendicular to the grain when loaded under tension and compression, and creep parallel to the grain when loaded in shear. Unloaded control specimens will be monitored over time to provide reference measurements. Controlled conditions will include (i) 3-6 months in constant temperature (20 °C) and relative humidity (65%) to identify creep properties (ii) 12-18 months in variable relative humidity cycles to represent seasonal and diurnal variations to identify the mechano-sorption parameters.

Moreover, commercially available bio-based adhesives will be identified for use with the wood species of interest; shear bond performance will be assessed for small laminated samples in accordance with EN 14080 [17]. Novel environmentally friendly adhesives for wood panels will then be produced at lab scale based on carbohydrate polymers, lignin, tannin and thermoplastic biodegradable polymers. Water-based emulsions will be developed based on biobased polymers and additives to improve the surface properties of the wood. Thermoplastic adhesives produced using commercial biodegradable polymers/blends will be considered as alternatives to urea-formaldehyde, melamine-formaldehyde and phenol-formaldehyde systems. Small samples will also be prepared for long-term testing and accelerated aging tests.

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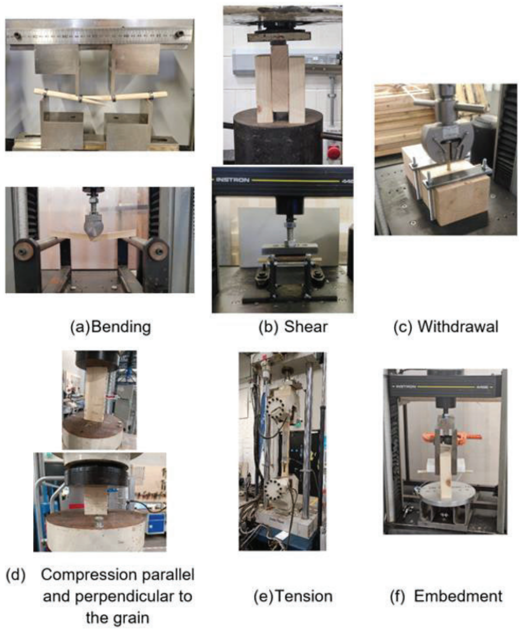

Figure 4. Example test configurations on small-scale wood samples.

Cured samples will be tested as per standard EN13986 for internal bonding, moisture content, thickness swelling, cycle test, modulus of rupture, and modulus of elasticity. Finally, accelerated aging of small laminated samples followed by shear bond performance testing will be carried out in accordance with Method B of ISO 12580 [18], and EN 14080 [17] respectively. This will establish the behaviour of the bio-based adhesives and define parameters for modelling.

3.4 WP4: LONG-TERM TESTS ON FULL- AND MEDIUM-SCALE COMPONENTS

WP4, led by University of L'Aquila, includes long-term testing of medium- and full-scale components. The medium-size components used in the innovative timber system include (i) axially loaded threaded rods-to-timber joints inserted at an angle to the grain, to replicate the loading condition of the rods in the innovative connection, and (ii) timber-to-timber joints with hardwood dowels loaded in shear. Four specimens for each configuration of interest will be tested under constant load (creep tests) in controlled (constant and cyclic humidity) and variable, indoor conditions for 24 months. The deformations (relative slips) will be monitored over time. Control specimens will also be monitored over time in the same conditions to assess the effect of shrinkage/swelling, together with the environmental conditions (temperature and relative humidity) and timber moisture content. The deformations will then be extrapolated over the entire service life to estimate the creep function, mechano-sorptive parameters and the deformation coefficient k_{def} used in design to predict the behaviour in the long-term. At the end of long-term tests, all specimens will be tested to failure, and the mechanical properties (stiffness and strength) compared to those of the specimens tested in the short-term in WP3. A conceptual drawing for long-term testing of threaded rods is depicted in Fig. 5.

The full-size components include (i) the innovative beam-to-column connection with threaded rods using softwood (spruce) and hardwood (beech), (ii) the innovative glulam beams made of hardwood and (iii) the floor solution with hardwood dowels. The specimens will be tested under constant load (creep tests) in variable, indoor conditions for 24 months. The deformations (vertical deflections, relative beam-to-column rotations, relative slips between the timber layers in the floor solution) will be monitored over time together with the environmental conditions (temperature and relative humidity) and timber moisture content. Control specimens will also be monitored. The 3rd country partner UNSW will contribute with long-term tests of an innovative low-grade glulam timber frame with encased steel bars. This system involves horizontal laminations of timber with steel bars placed in grooves similarly to glued-in rods connections. These are suitable for both beams and columns and will be tested under the same indoor environments and constant load of the other full-size components. The deformations of all tested specimens will then be extrapolated over the entire service life with the aim to estimate the deformation coefficient k_{def} used in design to predict the behaviour in the long-term. At the end of the long-term tests, all specimens will be tested to failure, and the mechanical properties (stiffness and strength) compared to those of the specimens tested in the short-term in WP3.

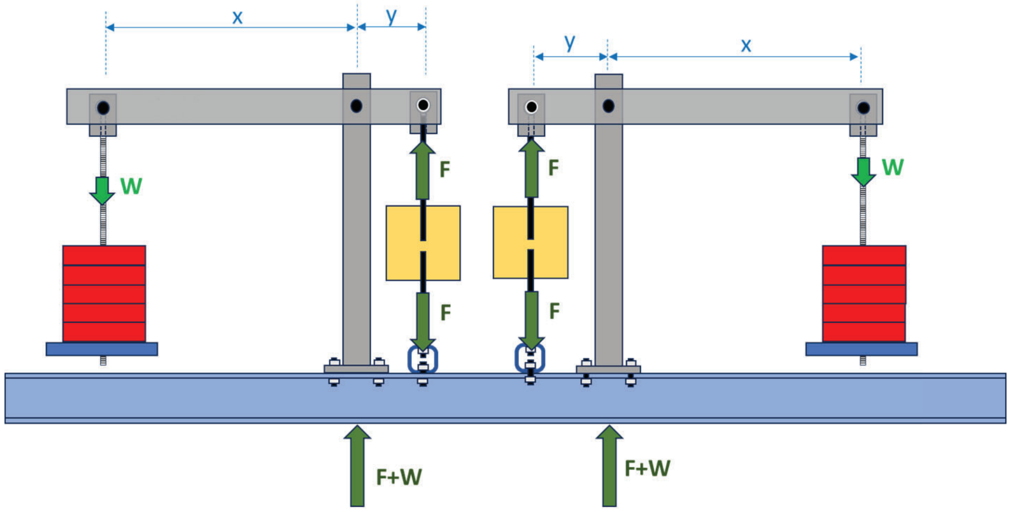

Figure 5. Concept for long-term testing of threaded rods-to-timber joints loaded in tension and compression at an angle to the grain.

3.5 WP5: NUMERICAL ANALYSES OF SELECTED TIMBER COMPONENTS IN THE INNOVATIVE BUILDING

WP5 is led by University of Ljubljana and focuses on Finite Element Modelling. It includes numerical linear elastic analyses of the timber system, advanced hygro-thermal and mechanical analyses of the components considering multi-phase moisture transport in wood, the development and validation of a new rheological model for wood based on the experimental campaign of WP2 and WP3, and the development of a fracture model for the adhesives. The new rheological model for predicting the long-term behaviour of timber members in changing indoor conditions will include a mathematically correct description of irreversible (plastic) deformations in compression and tension in three anatomical directions. Shear deformations will also be accounted for.

3.6 WP6: SUSTAINABILITY ASSESSMENT

WP6, led by VTT, studies the sustainability of the system, defining the product service life and providing a methodology for the service life utilization in life-cycle analysis.

3.7 WP7: DISSEMINATION AND KNOWLEDGE TRANSFER

WP7 is led by Ł-ITECH, and it consists of dissemination and knowledge transfer.

4 – PRELIMINARY RESULTS

4.1 FRAME IDENTIFICATION

The lateral load-carrying system consists predominantly of MRTFs in the one direction, with another bracing type, e.g. typical truss-work with diagonal elements, in the other direction. The scope of the CRESTIMB project is limited to the study of the MRTFs, which consist of glulam beams and columns, made either of softwood or hardwood, and innovative moment-resisting connections with threaded rods. The MRTFs can be analysed as shown in Fig. 6, with linear columns and beams connected through rotational springs which model the semi-rigid connections. Previous theoretical studies on MRTFs [19] have been used as benchmark to identify the structural layout of the frame and perform the preliminary sizing of the components. This preliminary analysis considers exclusively short-term effects, while the long-term effects will be evaluated at a later stage in the project. The MRTFs are designed to fulfil both the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS).

The analysis has been carried out on the following basis:

- The ULS is considered for the fundamental load combination according to EN1990 [5] with wind, according to EN1991-1-4 [20], as the leading variable load for frame elements. Permanent load and live load (residential or office buildings) are considered. Seismic loading is not considered. Properties of connections are estimated/extrapolated based on preliminary experimental results [14, 21]. Where

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relevant EN1995-1-1 [6] is used for the verification of timber components.

- SLS design of MRTFs against wind-induced accelerations. Accelerations are determined according to EN1991-1-4 [20] and the limits specified in ISO10137 [22] are used. For the benchmark frames, this design check is presented in [19] (note: the benchmark frames are a bit heavier than the frames in this project; thus, the accelerations will be higher here and thus closer to the limit).
- SLS design of floors under permanent loads and variable loads (residential or office buildings), according to deflection limits set out in the annex to EN1995-1-1 [3] and against human-induced vibrations. This includes review of the suitability of current design methodology of EN1995-1-1 [3] for the use of wooden dowels in lieu of steel dowels.

Dimensions of glulam elements and connection stiffness

Considering the lateral stiffness of the frame as governing factor, the preliminary analysis resulted in the following dimensions of the glulam elements. The columns are blocked glulam elements with cross-section 430 × 585 mm^2 for strength class GL30c [17] or similar. The beams are double glulam beams with cross-section 2 × 215 × 585 mm^2 for strength class GL30c [17] or similar. Preliminary experimental tests using softwood glulam [14, 21, 23], on connections with beams 400-450 mm high, obtained a mean ultimate moment resistance in the range of 90-130 kNm. This value can be higher by using CLT elements [10]. The connections in the MRTFs will consist of 4 planes of rods. Scaling for the higher lever arm, it is possible to get a rough estimate for the ultimate moment resistance of $2 \cdot (90 \sim 130) \cdot (585 / h_{test})^2 \cong 350 \sim 500$ kNm. Note that the scaling may not apply for brittle failure modes. The static tests to be performed in WP2 will provide more insight into the connection properties. These estimations are preliminary.

Dowel-cross laminated floors

The governing factors for the floors design are human induced vibration and deflections at the SLS. The thickness of DCLT floors is expected to be approximately 250 - 300 mm with at least 5 cross layers of softwood boards (minimum strength class of C16 spruce). Birch dowel diameter and spacing will be varied but existing results indicate that spacings of 100 mm and a dowel diameter of 20 mm may need to be targeted [19]. The aim is to achieve a sufficient response against human-induced vibrations for a span of 4.0 m.

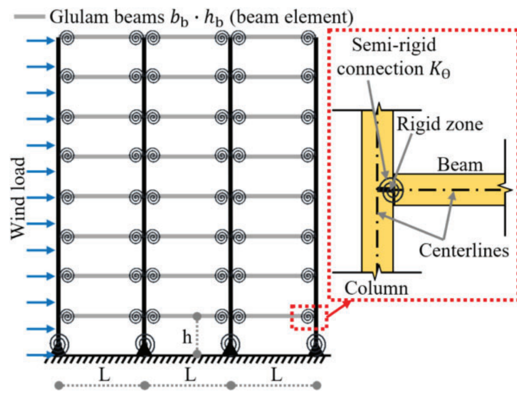

Figure 6. Moment resisting frame [19]

Storeys, bays and frames

The main limiting design criterion for the number of storeys is the wind-induced acceleration, depending on the wind velocity. Using only MRTFs, 4-6 storeys are feasible. To achieve more storeys, double CLT walls may be used instead of some of the glulam columns [24] or additional bracing that may be used (e.g. truss elements or walls located at the staircase/elevator shaft). Another solution is to increase the mass of the floors. This limitation depends largely on the wind velocity. Urban terrain environment according to EN1991-1-4 [20] is used in the benchmark frames which is very beneficial in this regard. Rural terrain is more challenging in this regard. A span of L = 8 m is reasonable value architecturally and feasible structurally. Where relevant from an architectural perspective, also shorter or slightly higher spans may be used. A large number of bays results in 'longer' frames which have a smaller deformation and better SLS performance. A small number of bays (e.g. 2) is more challenging in this regard. A reasonable storey height is approximately h = 3 m, or slightly higher depending on the dimensions of the beams and the floors.

The governing criteria for the distance *c/c* between frames are the fulfillment of SLS criteria of the floors and the lateral stiffness of the frame. With respect to these criteria, a distance of *c/c* = 4 m is the basic choice. The distance should not be much smaller to avoid architectural restrictions. The *c/c* distance is limited by the performance of floors against human induced vibrations and will be increased if test results support this. Considering the lateral stiffness of the frame, a greater *c/c* up to 6 m at max may be considered for a small number of storeys and/or by use of stiffer CLT walls instead of some glulam columns and/or by use of any additional bracing and in case of low wind velocity.

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Estimated load and moments

The quasi-permanent loading acting on the beams has been estimated as follows. The self-weight of the DCLT floor, considering a thickness of 300 mm and a mean density of 390 kg/m^3, is 1.15 kN/m^2. Assuming an additional self-weight of the non-structural elements, such as installations, flooring, ceiling panels, partition walls, of 0.35 kN/m^2 and a distance between frames c/c = 4 m, the load per unit length $g_{k,floor} \approx 6$ kN/m is obtained. Additionally, to obtain the total permanent load, the self-weight of the glulam beams ($g_{k,beams} \approx 1$ kN/m) is also added. Here, the calculation is based on softwood beams of GL30c class with a mean density of 430 kg/m^3. Therefore, the permanent load is equal to $g_k \approx 7$ kN/m. According to EN1991 [25], the live load is 2 kN/m^2 for residential buildings, or 3 kN/m^2 for offices, corresponding to a live load per unit length $q_k \approx 8 \sim 12$ kN/m. Applying the quasi-permanent combination of EN1990 [5], the estimated quasi-permanent load acting on the beams is $q_{qp} = g_k + \psi_2 \cdot q_k \approx 7 + 0.3 \cdot (8 \sim 12) \approx 10$ kN/m. Note that quasi-permanent loads due to snow are neglected at this stage, as they are applied only on the roof. The moments in the connections and the glulam elements due to the quasi-permanent loading are determined by employing, as an approximation, the analytical model of a beam with semi-rigid ends with realistic spring constants, as shown in Fig. 7.

The moments at the beam ends are:
$M_1 = -(qL^2/12) \cdot [k_1(k_2+6) / (k_1k_2+4k_1+4k_2+12)]$ and $M_2 = -(qL^2/12) \cdot [k_2(k_1+6) / (k_1k_2+4k_1+4k_2+12)]$, where $k_1 = K_{\theta,1}/(EI/L)$ and $k_2 = K_{\theta,2}/(EI/L)$.

In the CRESTIMB system the connections in both ends will be similar, i.e. k_1 and k_2 will be similar, with an expected value in the range of $k_1 = 1.5 - 5.0$. Therefore, by using the aforementioned values for the span $L = 8$ m and for the quasi-permanent load $q = 10$ kN/m, the sustained end-moment will be in the range of:
$M_{end} = (0.43 \sim 0.71) \cdot (qL^2/12) = (0.43 \sim 0.71) \cdot (10 \cdot 8^2 / 12) \approx 23 - 38$ kNm.
This corresponds approximately to 5 – 10% of the mean expected capacity of the connection, which can be estimated by experimental results, as described above.

The maximum moment in the span is given by:
$M_{span} = M_1 + (F^2_{z,1}/2q) = M_2 + (F^2_{z,2}/2q)$, where $F_{z,1} = (qL/2) \cdot (k_1k_2+5k_1+3k_2+12)/(k_1k_2+4k_1+4k_2+12)$ and $F_{z,2} = (qL/2) \cdot (k_1k_2+3k_1+5k_2+12)/(k_1k_2+4k_1+4k_2+12)$.
Therefore, the sustained moment in the span will be in the range of:
$M_{span} = (1.57 \sim 2.14) \cdot (qL^2/24) = (1.57 \sim 2.14) \cdot (10 \cdot 8^2 / 24) \approx 42 - 57$ kNm.

This corresponds roughly to 5% of the expected mean experimental capacity of the beam.

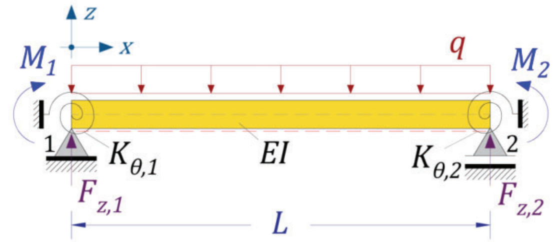

Figure 7. Beam model with semi-rigid ends

Hence, due to the presence of semi-rigid springs at the ends, the maximum end-moment is only 43 – 71% compared to the ideal fixed connection, while the maximum moment in the span is 57 – 114% higher.

4.2 LONG-TERM TESTS PROTOCOL

Four different configurations of the threaded rods-to-timber joints will be tested for about 24 months in a controlled environment. The configurations differ in the rod-to-grain angle: 0° and 90° to characterize the material, 10° representative of the beam side of the connection, and 60° representative of the column side. The temperature will be constant at 20 °C, while the relative humidity (RH) will be variable after an initial constant period up to 6 months at 50%. The initial period will allow for the determination of the creep properties. Then, the RH will cycle between 75% and 25% for shorter intervals of time. The applied load level, constant for the whole duration of the experiments, has been estimated by use of the component method presented in [12]. A reasonable approximation for the permanent axial load of the threaded rods is 10% of their mean withdrawal capacity.

5 – CONCLUSIONS AND RECOMMENDATIONS

The CRESTIMB project funded by ForestValue2 network aims to develop a concept for an innovative structural system for multistorey timber buildings composed of moment-resisting timber frames (MRTFs) made of glulam beams and columns, semi-rigid moment-resisting connections with threaded rods, and dowel-cross laminated floor panels (DCLT) simply supported on the beams of the MRTFs. The moment-resisting connections will be reversible facilitating easy assembly, disassembly and re-assembly. MRTFs are highly statically indeterminate structures, subjected to permanent loads. Therefore, creep deformations and mechano-sorptive effects may affect the distribution and

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magnitude of internal forces and moments over time in the MRTFs. Creep deformations may affect the serviceability of the DCLT floors as well. Finally, when considering the potential for re-assembly of components, the connections should provide sufficient tolerances to accommodate creep deformations. The CRESTIMB project will provide the necessary basis for quantifying long-term effects in all components of the system, developing design recommendations and assessing the service-life of the proposed innovative structural system. When it comes to short-term effects, the MRTF dimensions have been identified fulfilling both ULS and SLS criteria. Based on this analysis, frames with 4 – 6 storeys with storey height of 3 m, 8 m span, and distance between frames c/c = 4 m are deemed feasible in the short term. Moreover, the DCLT floors will have thickness of 250 – 300 mm, while the glulam elements will have cross-section 430 × 585 (columns) and 2 × 215 × 585 (beams). The quasi-permanent load acting on the beams has been estimated as 10 kN/m.

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7 – REFERENCES

[1] M. Yates, M. Linegar, and B. Dujič. "Design of an 8 storey residential tower from KLH cross laminated solid timber panels", In: WCTE 2008 - World Conference on Timber Engineering. Miyazaki, Japan, 2008.

[2] M. Kuittinen, A. Ludvig, and G. Weiss, eds. "Wood in Carbon Efficient Construction - Tools, methods and applications". CEI-Bois: Brussels, 2013.

[3] J. Song, et al. "Processing bulk natural wood into a high-performance structural material". Nature 554.7691 (2018), pp. 224-228.

[4] K.A. Malo, R.B. Abrahamsen, and M.A. Bjertnæs. "Some structural design issues of the 14-storey timber framed building "Treet" in Norway". European Journal of Wood and Wood Products 74.3 (2016), pp. 407-424.

[5] CEN. "Eurocode 0: Basis of structural design", EN 1990:2002. Comité Européen de Normalisation 2002.

[6] CEN. "Eurocode 5: Design of timber structures – Part 1-1: General rules and rules for buildings", EN 1995-1-1:2004. Comité Européen de Normalisation, 2004.

[7] A. Buchanan, et al. "Multi-Storey Prestressed Timber Buildings in New Zealand". Structural Engineering International 18.2 (2008), pp. 166-173.

[8] P. Hradil. "Barriers and opportunities of structural elements re-use", VTT Research Report, VTT-R-01363-14. VTT Technical Research Centre of Finland. Espoo, 2014.

[9] M. Sciomenta, P. Gualtieri, L.Spera, *et al.*Timber-timber composite (TTC) joints made of short-supply chain beech: Push-out tests of inclined screw connectors. *Mater Struct* 57, 171 (2024).

[10] O.A. Hegeir, K.A. Malo, and H. Stamatopoulos. "An innovative slip-friction moment-resisting connection using screwed-in threaded rods in cross laminated timber and steel coupling parts: An experimental study". Engineering Structures 318 (2024), pp. 118654.

[11] H. Stamatopoulos and K.A. Malo. "Withdrawal stiffness of threaded rods embedded in timber elements". Construction and Building Materials 116 (2016), pp. 263-272.

[12] H. Stamatopoulos and K.A. Malo. "Withdrawal capacity of threaded rods embedded in timber elements". Construction and Building Materials 94 (2015), pp. 387-397.

[13] H. Stamatopoulos and K.A. Malo. "On strength and stiffness of screwed-in threaded rods embedded in softwood". Construction and Building Materials 261 (2020), pp. 119999.

[14] H. Stamatopoulos, K.A. Malo, and A. Vilguts. "Moment-resisting beam-to-column timber connections with inclined threaded rods: Structural concept and analysis by use of the component method". Construction and Building Materials 322 (2022), pp. 126481.

[15] A. Sotayo, et al. "Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications". Developments in the Built Environment 1 (2020), pp. 100004.

[16] CEN. "Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties", EN 408:2010+A1:2012. Comité Européen de Normalisation 2012.

[17] CEN. “Timber structures - Glued laminated timber and glued solid timber”, EN 14080:2013. Comité Européen de Normalisation 2013.

[18] ISO. “Timber structures - Glued laminated timber - Methods of test for glue-line delamination”, ISO 12580:2007. ISO, 2007.

[19] H. Stamatopoulos, O.A. Hegeir, and K.A. Malo. “Analysis and design aspects of moment-resisting, beam-to-column, timber connections with inclined threaded rods: from fastener level to construction level”, In: WCTE 2023 - World Conference on Timber Engineering. Oslo, Norway. pp. 1206-1215, 2023.

[20] CEN. “Eurocode 1: Actions on structures – Part 1-4: General actions - Wind actions”, EN 1991-1-4:2005. Comité Européen de Normalisation 2005.

[21] A. Grytbakk, M. Tanum, and K. Tran. “Numerical and experimental analysis of one- and two-sided moment-resisting timber connection using threaded rods and steel coupling parts”, In: Faculty of Engineering, Department of Structural Engineering. Norwegian University of Science and Technology: Trondheim, 2022.

[22] ISO. “Bases for design of structures - Serviceability of buildings and walkways against vibrations”, ISO 10137:2007. ISO, 2007.

[23] A. Vilguts, et al. “A study on beam-to-column moment-resisting timber connections under service load, comparing full-scale connection testing and mock-up frame assembly”. European Journal of Wood and Wood Products 80.4 (2022), pp. 753-770.

[24] O.A. Hegeir, H. Stamatopoulos, and K.A. Malo. “Serviceability performance of timber dual frame-wall structural system under wind loading”, In: WCTE 2023 - World Conference on Timber Engineering. Oslo, Norway. pp. 2940-2949, 2023.

[25] CEN. “Eurocode 1: Actions on structures – Part 1-1: General actions - Densities, self-weight, imposed loads for buildings”, EN 1991-1-1:2002. Comité Européen de Normalisation 2002.

https://doi.org/10.52202/080513-0241