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Robotically-Fabricated Nexorades from Whole Timber

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Abstract

This paper introduces the conceptual design of sustainable timber structures using raw wood. It presents a workflow for systematically generating Nexorades using a tiling method for multi-valence quad subdivided surfaces. The system is designed based on an integrated framework combining resources from local forestry, knowledge from geometry processing, joinery for raw wood, laser scanning and digital fabrication, and structural engineering. Particular focus is given to Cross joint geometry and tool-path generation. Also, the global structural performance of the system is assessed. The results indicate that the proposed design methodology can offer an efficient and sustainable construction technique. Furthermore, the methodology is reflected in a robotically fabricated prototype, demonstrating that the design framework can seamlessly integrate digital tools and construction.

1 Introduction and Prior Study of Nexorades for Raw Wood

Nexorades belongs to a class of self-supporting structures where elements rest on top of each other as Fig. 2, or are interconnected side-to-end, as Fig. 3. One of the key reasons for building these structures is a two-element connection instead of a multi-valence node, as Fig. 1. The Nexorade connection varies from external fasteners to wood-wood connections with additional fabrication effort to adapt to irregular raw woods. The past research-tested panel braced raw wood as Fig. 4. This study focuses on a two-layer system and open-sourcing, an in-depth study of conceptual Nexorades form-shaping methods [5]. In a larger research scope, the raw wood is used due to: a) overstocking of small-radius trees in Swiss forests (Rossiniere), b) added value for decarbonization, c) small radius trees are not considered as a construction material by local saw-mills, d) potential for local-circular economies using local timber for non-standard production, and e) increasing business interest due to low-cost robotic automation. Every raw beam contains certain surface irregularities and natural characteristics, such as knots and non-circular sections. The natural characteristics require subtractive machining operations to unify raw timbers at a connection zone using rectilinear geometries observed in Cross joints. The proposed method follows a rule of not exceeding two-thirds of a beam section [1] to have a sufficient contact zone. Lastly, structural performance is evaluated using a reliable force-flow mechanism. The methodology has four main parts: a) tiling geometry generation, b) local joinery generation, c) structural analysis, d) laser-scanning and robotic fabrication. Accordingly, the system is designed based on an integrated framework combining resources from local forestry, Computer-Aided Design (CAD) for geometry manipulation, joinery of round woods, scanning, digital fabrication, and Computer-Aided Engineering (CAE) and numerical simulations.

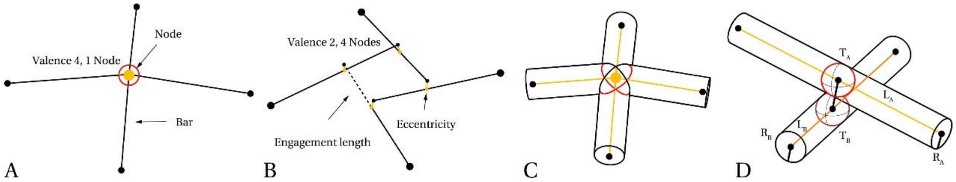

Fig. 1 Nexorades are often used to simplify multi-valence nodes A-C to pair-wise connections B-D.

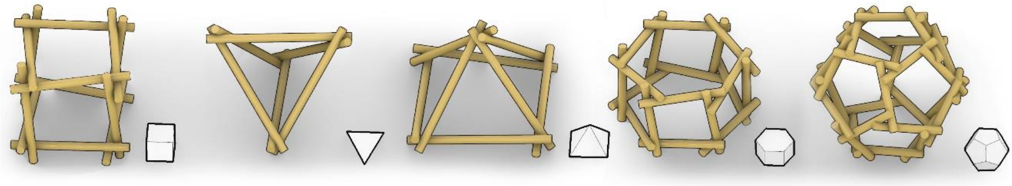

Fig. 2 Mathematical models for simple, platonic objects can be used to define edge rotation angles.

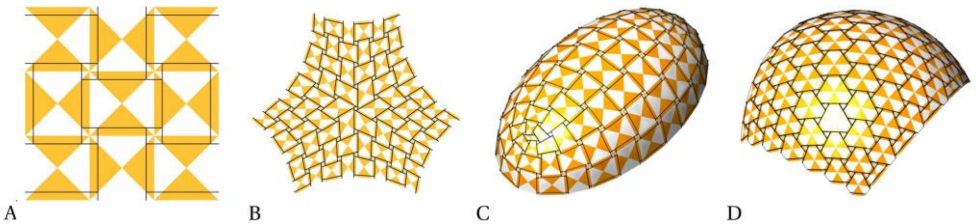

Fig. 3 Translation methods A-C is extended over the past work to an even number of polygons D.

Fig. 4 Fabrication of the panel braced Nexorades is tested using raw wood and translation method.

2 Linear Pattern Generation on a Quad-Mesh

The proposed tiling method aims to obtain a principle pattern representing the rotational Nexorade system using a finite set of tiles [5] as Fig. 5 F. The tiles' set consists of nine tiles drawn as a polygon unit measuring 1x1x1 containing line segments. These line segments represent a part of the Nexorade beam where each side of the polygon is numbered. Colours are used to visualize the indexing to track adjacency between the edges as Fig. 5 A. The sides of the polygon are indexed to identify the rule-set as Fig. 5 B-C. This process improves the visual reflection of the tiles' edges, where each triangle colour represents an index. The rule-set as Fig. 5 C (i.e. [0,1,2,3] – [3,0,1,2]) is then used to match neighbouring tiles. The structure of the tiling is computed using the mesh face-edge graph when matching tile edges. The matching is detailed in the following paragraph. Finally, the tiling workflow is applied to a particular quad-dominant mesh topology as Fig. 5 E composed of mesh patches as Fig. 5 D.

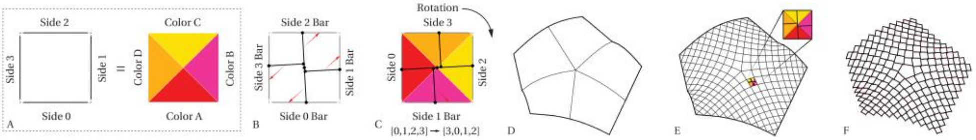

Fig. 5 Tiling notation. A) sides of a Tile are indexed, B) sides are coloured for visualization purpose, C) each side has an associated bar element, D) Mesh topology composed of multiple patches, E) Barycentric mapping, F) linear pattern of the mapped tiles.

The mesh has to be unified in the next step, and the tiling order has to be computed as Fig. 6B-C. The first tile represents a mesh quad-face, and the triangular tiles are used to create the boundary faces. For the mesh generation, the neighbouring edges are directed to have an opposite orientation as Fig. 6B. This condition is obtained by traversing mesh faces and assessing whether edges are opposite to the neighbouring peer. Graph traversing algorithms such as Breadth-First-Seach (BFS) is used to obtain the tiles' sequence. Such an algorithm contain a sequence that indicates the adjacency of the tiles. The BFS algorithm, as Fig. 6C, is used to traverse mesh faces because it explores all the neighbour nodes at the existing depth before exploring the nodes at the next dept level [3]. Then, the 2D tiles, as Fig. 6D, are assigned to the mesh faces according to the BFS sequence algorithm. This is done by checking whether it is possible to choose one of the nine tiles and the number of times a tile has to be rotated. The mapped tiles are coloured by an index (0-9) as Fig 6E. Furthermore, the associated edges are coloured to form triangles (-1:grey, 0:red, 1:pink, 2:yellow, 3:orange) as Fig. 6F. This tiling method produces the Nexorade pattern obtained by duplicating, rotating, and mapping the tile-set as Fig. 6G.

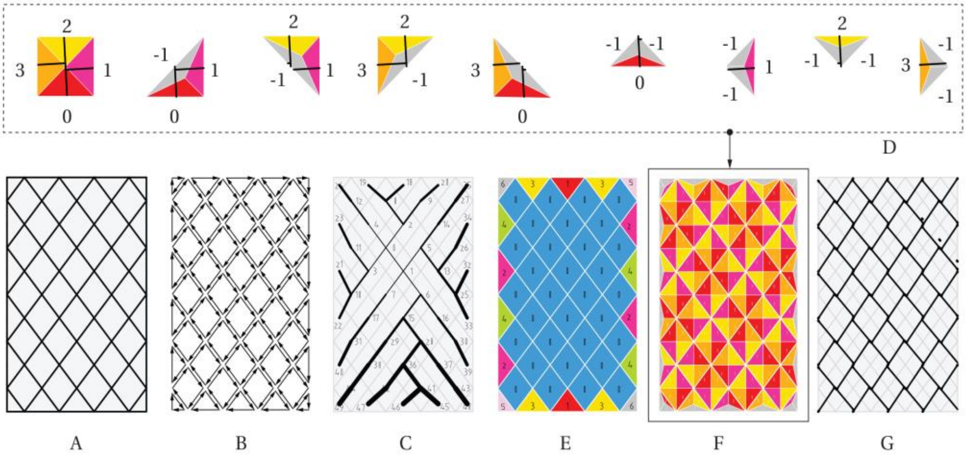

Fig. 6 Tiling method for a planar diamond mesh grid: (A) a diamond mesh, (B) a polygonal mesh with the unified edge winding, (C) Breadth-First-Search, (D) 2D tiles, (E) Tiling, (F) Tiles with coloured edges that show the edge indexing, (G) pattern generated from tiling.

Rotation of the tiles and their appropriate mapping are determined through the adjacency rule as Fig 7C. The rule has a notation of the current-edge-index and the next-edge-index. The indexing follows 0,1,2,3 for the existing tile` face edges and 3,2,1,0 for the next tile. These number pairs say that the quad must be connected, i.e., by edge 0 to the other tiles by edge 3, then 1-3, 2-1, 3-0. The edges that form the boundary are indexed as -1 and empty. The current tile and its rotation in the meshing scheme at each are shown in Fig 7. Fig. 7B illustrates a tile connected with the existing tile following the 2-1 rule (yellow-pink triangles), where index 2 belongs to the tile shown in Fig. 7A. Sequentially, the tile is placed following index pair 3-0 as Fig 7C. Furthermore, it is possible to match several edges as Fig 7D-E, while traversing through the BDS sequence order. To match these sequences, the algorithm compares strings and is determined as true for the tile string (3,2,1,0), if the current mesh faces are indexed as (0,1,2,x) or (x,x,x,3), or (x,x,3,0) or (x,x,x,x). If the tile has a match, then it is selected, and the number of rotations is revised to shift the array of tile-edge indices. The iteration stops when all mesh faces are checked or none of the tiles is chosen. The overall aim of applying such a procedure is to use this methodology for multiple patches where the target geometry is more complex than one rectangular surface.

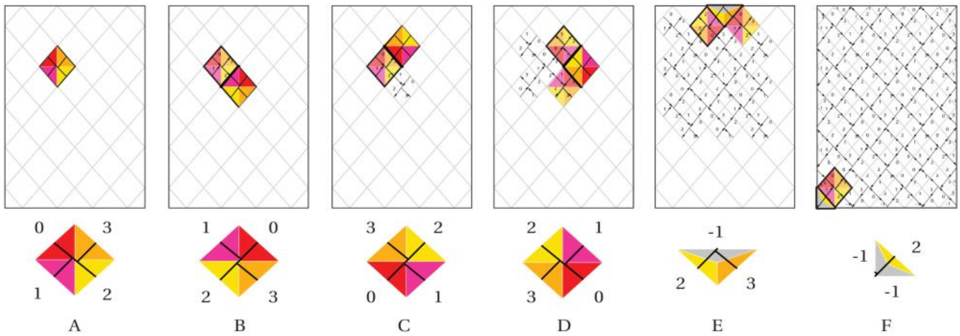

Fig. 7 Tiling based on the Breadth-First-Search: A) first tile, B) the second tile and a common edge, C) third tile and a common edge, D) sixth tile, E-F) boundary tiles.

So far, the tiles are disconnected from each other. However, they contain adjacency information to reconstruct the beam's geometry. Consequently, the tiles are connected, forming a Beam data structure containing ordered line segments, connectivity information, and axes' planes. Tiles are transformed into individual beams by converting the tile's sides into an undirected graph. Subsequently, the connected component method is applied to identify the interconnecting beams. Thus, the connected components are simplified as lines, where the corresponding orientation depends on the sum of the mesh face's normal vectors of the tiles. Next, the axis perpendicular to the plane is determined for each beam. Finally, the line axis is trimmed between the ends of two neighbouring planes. The tiling sequence and the resultant volumetric geometry are tested to correspond within a set of meshes within multiple singularities, including open and closed geometries, as Fig 8.

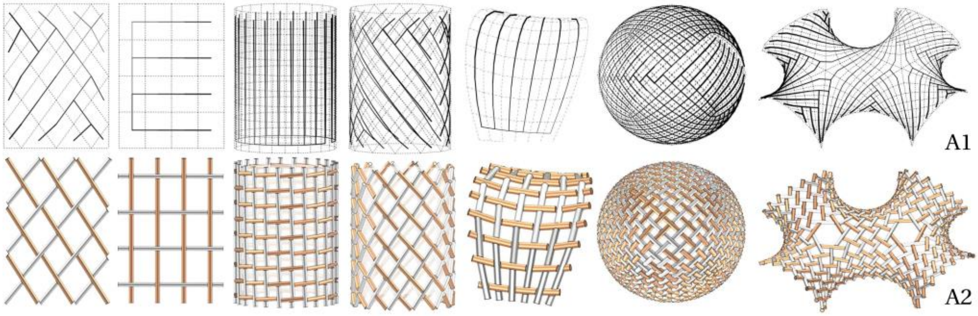

Fig. 8 A1) Visualized Breadth-First-Search and A2) geometry output. Three selected geometries are chosen for further structural analysis: B) planar surface, C) cylindrical shape, and D) a three-valence reciprocal.

3 Dynamic relaxation

Connection zones between beams in Nexorades depends on a mesh curvature, the thickness of elements, rotation of a tile, and the Eccentricity between beams. If the distance between a pair of elements is too large, then the area to connect the two is not sufficient enough. Consequently, either the mesh topology has to be changed, or the distance between bar elements must be reduced. The eccentricities' minimization goal is used, employing a constraint-based solver [4]. In the current study, the dynamic relaxation reduces the maximum deviation between beams, as Fig 9. Beam ends are moved towards each other within the closest vector between the two beam axes. Beams can slide within the neighbour line segments while altering the pair-wise rotation. Thus, the input geometry has to be relatively close to a relaxed one. Tesselated geometries with a changing curvature mostly have different eccentricities unless the input surface has a uniform curvature, for example, a sphere or a plane shape. Therefore, dynamic relaxation aims to reduce or equalize the interval of eccentricities to a given limit, i.e., less than one-third of a given raw-wood diameter. Consequently, the joinery generation adapts to each joint scale depending on a mesh curvature, as Fig. 9 bottom.

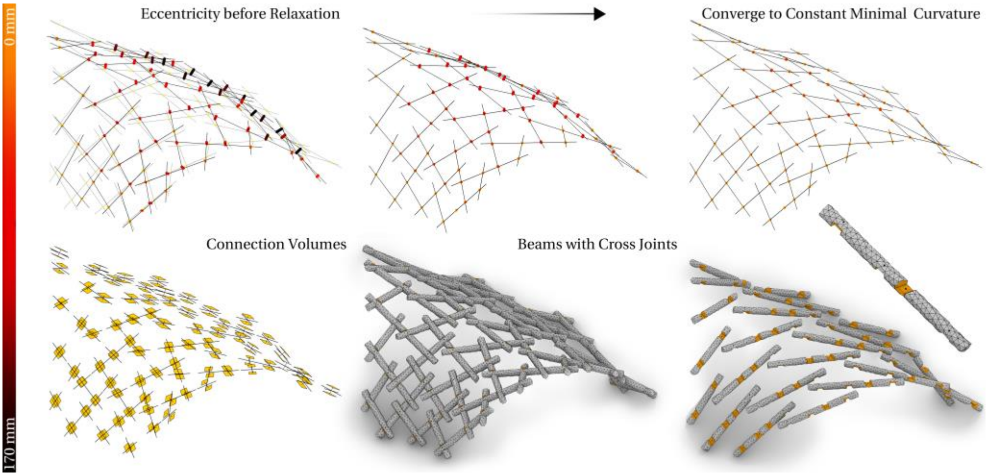

Fig. 9 Top – dynamic-relaxation of central axes to minimize and equalize eccentricities. Bottom – joinery generation at the lowest eccentricities and the connections cut-outs from closed triangle mesh using CGAL mesh boolean difference method.

4 Cross-lap Joint Robotic Fabrication

Two main algorithms can be used in the conceptual tiling method to obtain the Nexorades pattern: a) cross-lap cuts when joints intersect within less than two-thirds of the timber section and b) side-end connection. The current research explores the first option of a cross-lap joint as Fig 12. The digital joinery generation follows timber joinery existing in regular rectangular structures as Fig 11, and it applies this methodology to round sections as Fig. 10A1-A2.

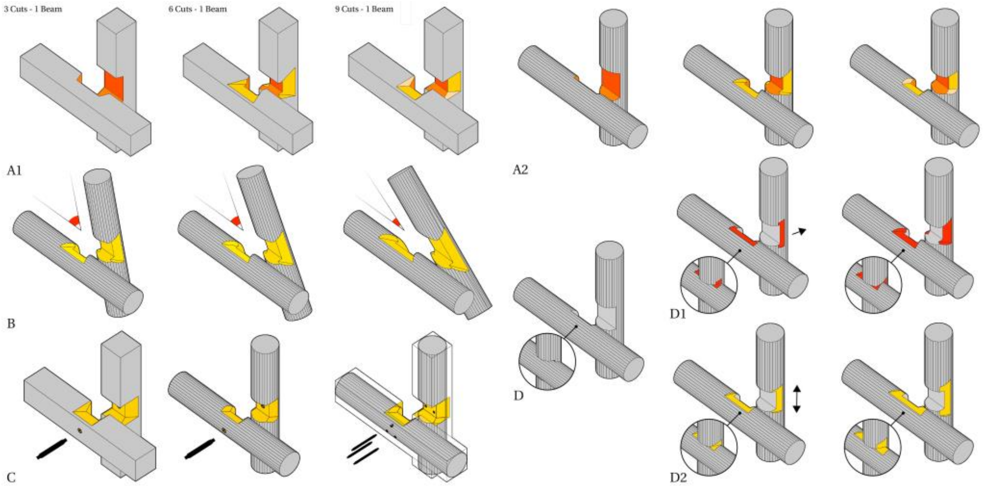

Fig. 10 Cross-lap joint geometry generation: A1-A2) differences between rectangular and circular section, B) changes by angle, C) fasteners, D) conical cuts and its side extensions (D1-D2).

Raw timbers are not generally straight or regular in shape and section, but they stay relatively constant within the connection zone. Also, the definition of joints relies on fabrication tools and their movement relative to a timber piece. The milling tool is limited to its flat cylindrical movement, whereas the saw blade is constrained within the flat surface area resulting in rectilinear cuts. Due to timber irregularities and requirements to have as much contact area as possible, a conical timber joint is proposed as Fig. 10A2 (right). It requires nine cuts comparing to its predecessor that only employs one cut as Fig. 10A2 (left). It is also possible to decrease the number of cuts to six using an extended conical cut, as Fig. 10A2 (middle). The joint is generated using a Joinery Solver that can adapt to various design geometry angles as Fig. 10B and add necessary fasteners to interlock the cross-lap joint as Fig. 10C. The joint can be modified further by controlling side cuts parameters to control from the least contact area as Fig. 10D to the largest possible as Fig. 10 D1-D2. Various wood-wood connections are cut to understand the tool-path generation process concerning limited robotic arm movement, as Fig 13. The cutting process requires scanning because timber shape and location vary, and at least a few centimetres of misalignment can cause issues during the assembly. Consequently, the fabrication workflows require the following steps: a) scanning and point-cloud processing to obtain timber central axis as Fig. 13A b) tool-path that is generated together with the joint geometry as Fig. 13B, c) automatic tool-changer to switch between sawblade and milling as Fig. 13C and d) continuous scanning and fabrication integration after timber is mounter on the rig as Fig. 13D.

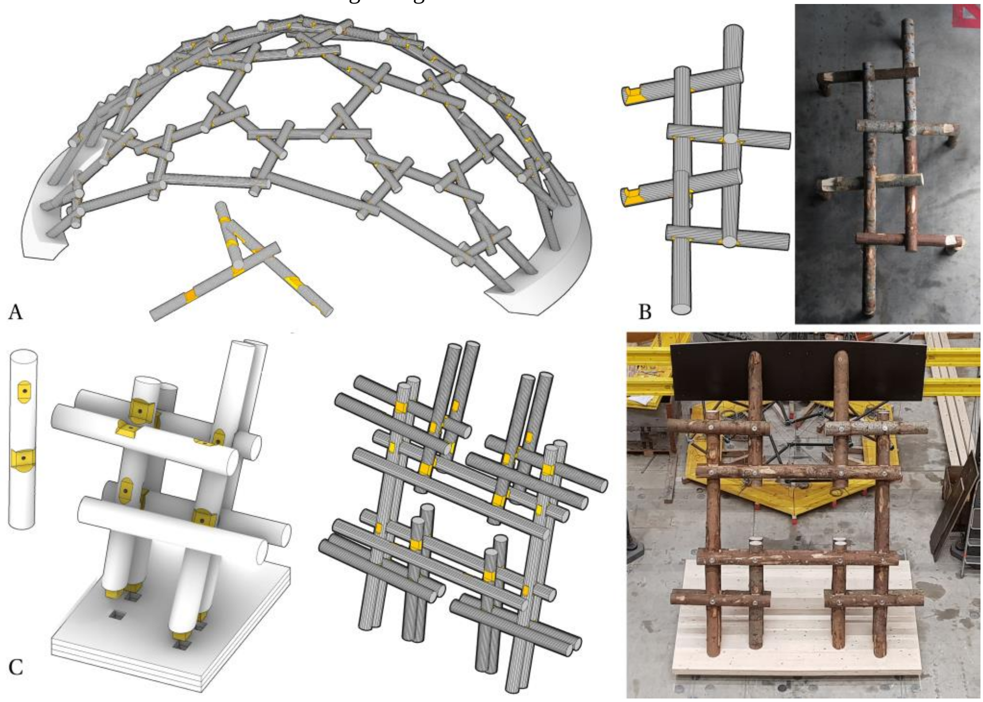

Fig. 11 A) single layer Nexorade, B) Seiwa Bunraku Theater replica in raw-wood, C) two-layer Nexorade.

Fig. 12 Raw-wood cross-lap joints vary from a single dowel, surface flattening to conical cuts.

Fig. 13 Fabrication steps: A) central-axis, B) tool-path, C) cutting process, D) scanning and cutting.

5 Simulation-based Engineering and Design

Given the complex geometry of the Nexorades and variations in the mechanical characteristics of round woods, numerical approximations are preferred to closed-form solutions. Using the Finite Element Method (FEM), the structural design and analysis of the spatial Nexorades structures are performed. The *OpenSees* library [8] is employed as the backend solver for structural analysis and design feedback loop. The geometric information of the structure shown in Fig. 11A is transformed from the *Rhinoceros 3D* CAD environment. Each round wood element is simulated using 1D linear elastic beam elements with orthotropic wood material properties. A uniaxial elastic material associated with C24 timber grade (Table 1) is assigned to the elements. For each joint type, a connector element is defined. The connectors are modelled using a two-node link element. The element consists of six strings, which represent the translational and rotational behaviour of the joint area. The numerical models are analyzed by being subjected to the loads specified by the Eurocode standard. A combination of dead, live, wind, and snow loads is considered, leading to a uniform distributed load of 2814 N/m^2. Once the analysis is complete, the results are post-processed by *COMPAS* and stored back into the original 3D CAD object.

Table 1. Material properties of C24 timber used for round woods.

Description	Unit	Value	Comment
Bending strength	MPa	24.0	$f_{m,k}$
Tension strength	MPa	14.5	$f_{t,0,k}$
Compression strength	MPa	21.0	$f_{c,0,k}$
Shear strength	MPa	4.0	$f_{v,k}$
Modulus of elasticity	MPa	11.0	$E_{m,0,mean}$
Shear modulus	MPa	0.69	G_{mean}
Density	Kg/m^3	350.0	ρ_k

The model is analyzed in 1.26 sec, and the output data is extracted from the backend in 0.119 sec. Furthermore, the data post-processing time is less than 0.005 sec which shows the computational framework's efficiency. The results indicate that the joints' rotational stiffness at the Ultimate Limit State (ULS) has a minimal contribution to the overall load-carrying system. The vertical displacement and Mises stress of the structural elements at the ULS are shown in Fig. 14a-b, respectively. The structure undergoes the ULS deformation of 234 mm at its mid-span, and the maximum Mises stress produced in the elements is 0.32 MPa. This stress state indicates that the Nexorades system with either quad or diamond grid pattern demonstrates a reliable force-flow mechanism. This is mainly related to the multiple numbers of joints within such systems and their ability to distribute the structure's forces. Moreover, given that the system under consideration has low curvature, the stress concentration in particular regions is not considerably high. Furthermore, the deformed shape obtained from the numerical FE models is 37 mm, satisfying the Serviceability Limit State (SLS) since the deflection-based criteria (the span length/300) are approximately 46 mm.

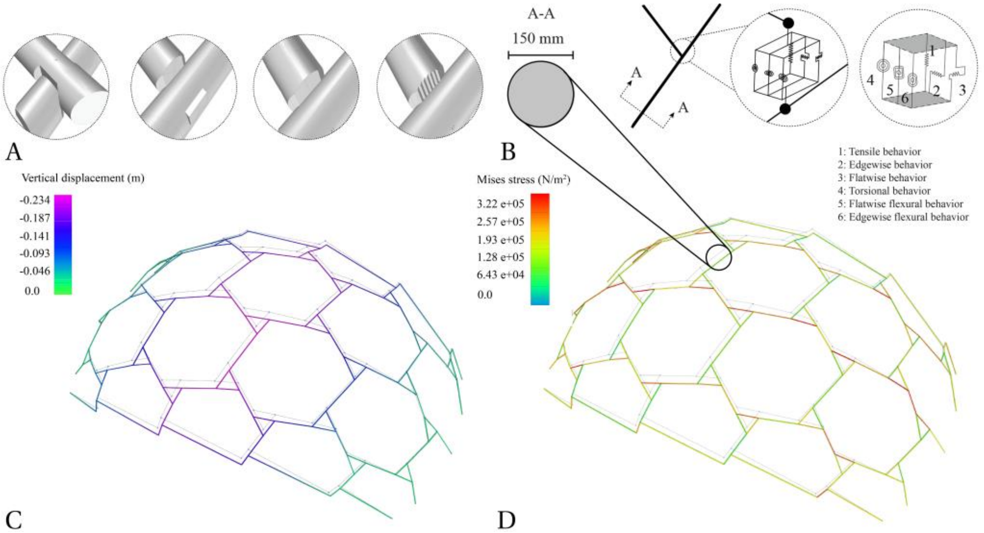

Fig. 14 A – Wood-wood joints with fasteners, B – Macro Joint Model, C – Vertical displacement under ULS load combination, D – Mises stress of elements under ULS load combination.

6 Conclusions

A new methodology to design bio-based spatial timber structures from raw timber is proposed. A series of geometrical steps are employed to obtain a Nexorades pattern, including tiling, dynamic-relaxation, joinery solver, structural calculation, and digital fabrication. The framework enables discrete tile mappings in non-manifold meshes to obtain a Nexorades pattern while reconstructing the beam-like geometry following the graph methods. The beams' volumetric representation included changing radii along the beam axis, and taper assignment based on curvature and elevation is also considered. Meshes with multiple singularities and variation of curvature with optimized Eccentricity are also validated. The geometry generation is open-sourced using NGon tool-set [5]. Experiments have already been conducted using laser-scanner and point-cloud processing to create a raw-wood library and alignment of beams in the robotic workspace. The geometry is also processed in a FE package, COMPAS_FEA. Furthermore, the contact zones of each high-resolution joint have to be studied in further detail. It is recommended that multiple layers of tree trunks or additional fasteners have to be used at the connection points to improve such systems' structural performance due to the non-linear rotational assembly sequence.

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