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Reuse-constrained structural form-finding and construction with VGS tool and reciprocal joint: A Case Study on Traditional Chinese Timber Structures

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This study introduces a computer-aided design methodology that innovatively applies the principles of Vector-based Graphic Statics (VGS) for the adaptive reuse of components in traditional Chinese timber structures. The process synergistically blends reused elements with new materials within the constraints of available resources. Leveraging the form-finding approach of VGS, the method facilitates an intuitive manipulation of pin-jointed structural configurations, ensuring static equilibrium through the computational tool (VGS tool). An integrated algorithm matches the timber structure's component library with the design from VGS tool, and optimizes the usage rate of reusable elements. Further refinement in design detailing is achieved through a reciprocal joint generation technique, tailored to manage diverse angular and dimensional constraints. This is enhanced by the particle physics systems and parametric modeling within a Building Information Modeling (BIM) environment, fostering interactive design and optimization. The culmination of this research is evidenced by a case study on grid shell design, where the practicality and effectiveness of the proposed workflow are demonstrated through a 3D-printed prototype.

Keywords: Vector-based graphic statics, Reuse, Structural design, Circular economy, Timber structure, Adaptive structural joint;

1. Introduction

Construction is one of the largest energy-consuming industries globally, accounting for a significant portion of global carbon emissions. Construction and building activities (including construction, transportation, maintenance, etc.) account for around 37% of global greenhouse gas emissions [1], making emissions reduction in the construction sector a universal challenge. Recycling offers a possible solution as it reduces the production of new materials and the disposal of waste. There are many recyclable building materials, and this article focuses on the reuse of wood. Wood recycling addresses the supply-demand imbalance in building materials, particularly in urban renewal contexts (G. Faraca et al. [2]). As a natural carbon sink and primary construction resource, wood is extensively used, creating significant waste, especially in historic areas. Its recyclability surpasses that of materials like steel and glass due to its moisture-related strength. Naturally air-dried, recycled wood has lower moisture content, increasing its durability and structural stability compared to new wood, making it an advantageous recycling choice (T. Nguyen [3]).

Designing structures with reclaimed timber elements presents significant challenges, primarily due to the constraints imposed by the sizes and lengths of available materials, which dictate the possible spans and spacing in new constructions. Consequently, the design process is effectively reversed, with the mechanical and geometric properties of the available elements exerting a substantial influence on the structural layout (Brütting et al. [4]). According to this question, Bukauskas et al. [5] proposed a "form-fitting" strategy for constructing trusses with a large number of irregular timber elements. The assignment of timber elements to member positions in the truss subject to element length and capacity constraints is carried out using bin-packing heuristics to minimize trim losses. Kim and Kim [6] used a genetic algorithm to optimize the weight, carbon content, and cost of a frame structure made from recycled steel elements. Jan Brütting et al. [7] extended the discrete structural optimization formulation to assign stock elements to truss systems. They validated the proposed design method through two case studies and also presented a method for designing a mesh structure made of newly reused elements with minimal environmental impact [8]. Jonas Warmuth et al. [9] introduced a new computational tool, Phoenix3D, to support user interaction and parametric constraint design workflows for inventory reuse, as well as visualizing solutions and results.

Generally speaking, prior research has mainly concentrated on reuse component adaptation algorithms for various design options to optimize the structure design for reuse. However, the potential of implementing a design constrained interactive structural design computational framework, like vector-based graphic statics (VGS) (P. D'Acunto et al. [10]) is not fully explored. The form-fitting process is designed to accommodate not only stock elements but also to adjust the structure's form to suit the available inventory.

In that regard, the following questions could be addressed:

1.How to design new structural systems interactively while preserving the most of the dimension of the reuse components? This requires a bi-directional synchronized process of the reuse fitting and the structural form-finding.

2.How to take the construction phase into the consideration of the design optimization for the joints of the structure system?

Consequently, this paper takes the reuse of the component from a Chinese traditional timber structure building as the case to exemplify the solution to the questions above. As shown in the Fig. 1, the frame is disassembled to build a new structure. Through the case study the reuse-constrained structure form-finding process and the detailed design is proposed by integrating the VGS tool (J.-P. Jasienski et al. [11]) and BIM.

a) b)

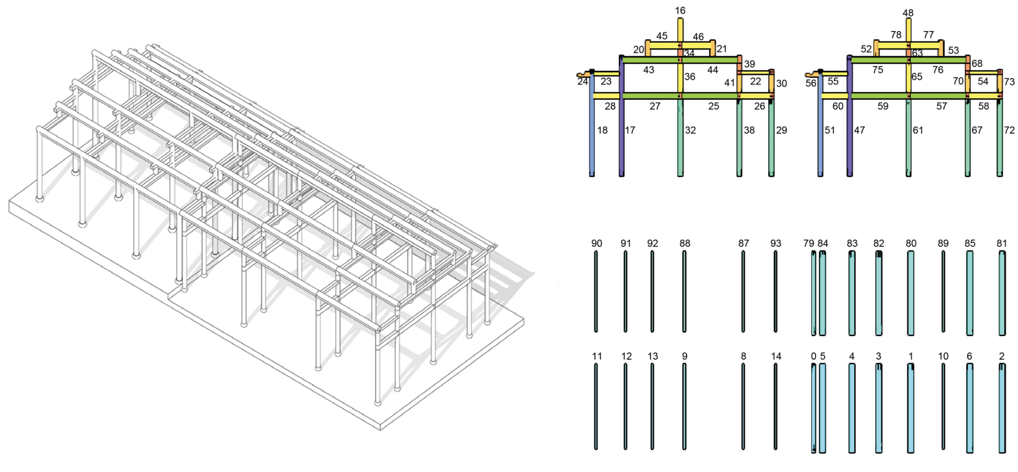

Figure 1: a) the case study is based on reusing timber components from the traditional Chinese timber structure as shown; b) disassembled timber components from the structure, each component is numbered and categorized based on length and cross-sectional dimension

2. Workflow

The workflow illustrated in the Fig. 2 encapsulates a series of methods for adapting usable components within a predetermined structural form during the form-finding process of design. This technique is rooted in the integration of Vector-based Graphic Statics (VGS) tools with Building Information Modeling (BIM) systems. The process initiates with an array of available components (**S**) and a predefined design structural form ($\boldsymbol{F_0}$). Utilizing the VGS tool, form and force diagrams ($\boldsymbol{F}$, $\boldsymbol{F}^*$) can be generated consequently. In the Initial Adaptation phase, where a direct match is sought between the design component set A and the reuse set S. Components are then categorized into fitted ($\boldsymbol{A_f}$) and unfitted ($\boldsymbol{A_n}$) subsets. If a satisfactory fit rate is not achieved, the process advances to the Constraints stage, where similarities between $\boldsymbol{A_n}$ and $\boldsymbol{S}$ are identified to establish constraints for $\boldsymbol{A_n}$ elements. Consequently, a Reuse-Constrained Adaptation is employed to modify $\boldsymbol{F}$ and $\boldsymbol{F}^*$ to enhance the fit rate between $\boldsymbol{A}$ and $\boldsymbol{S}$. The final phase involves a Detailed Design with Reciprocal Joints, where $\boldsymbol{F}$ is transformed to incorporate construction considerations in tandem with BIM, culminating in the conclusion of the workflow. This systematic approach is designed to bridge the theoretical design with practical construction for efficient outcomes.

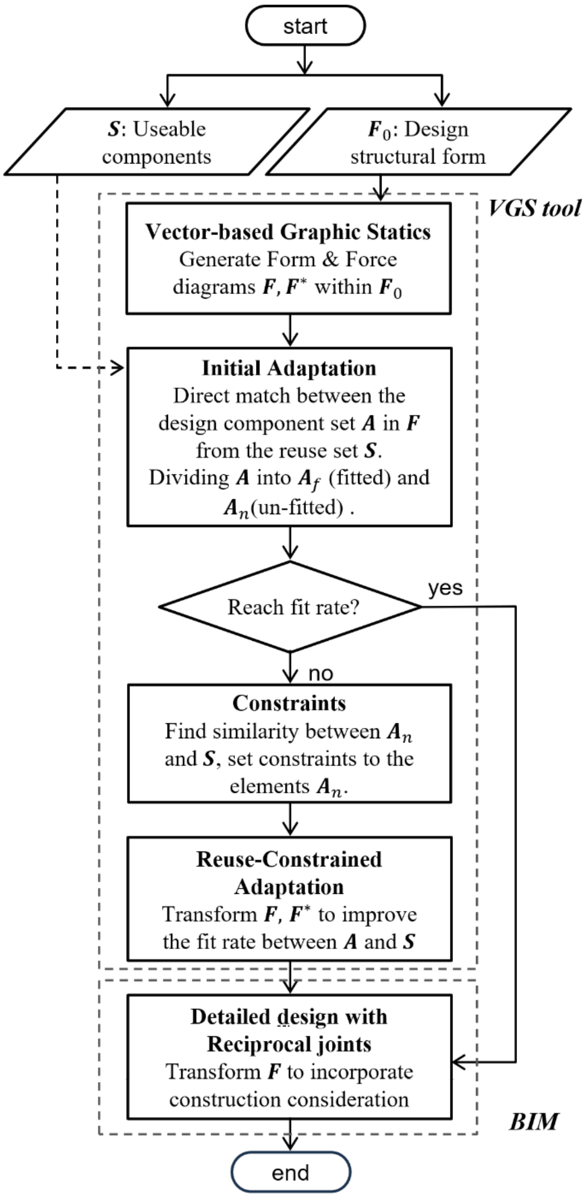

Figure 2: The workflow of the reuse-constrained form-finding with VGS and BIM

3. Method

3.1 Reuse-constrained form-finding with Vector-based Graphic statics

This research implements the Vector Graphic Statics (VGS) method, a shared visualization technique for architects and engineers, employs a computer-aided design tool (the VGS tool) for form-finding and component adaptation in reused structures. Within VGS, the relationship between form and forces in pin-joint network structures is articulated through form and force diagrams. This tool enables the adjustment of specific component lengths and internal forces to meet the limit state requirements of reused components by applying constraints to these diagrams. The process of form-finding for reused structures with VGS is methodically divided into two primary steps, facilitating the efficient adaptation and integration of components within the design framework:

a. Initial equilibrium: As shown in the Fig. 3. The design's intended form, denoted as F, achieves initial equilibrium through the application of either the Force Density Method (FDM) or the Vector-Difference Method (VDM). This process involves all nodes within the structure's network receiving equal point loads, with peripheral nodes serving as support points. To construct the force diagram, a planarization of the structure's non-planar underlying graph is necessary within the Vector Graphic Statics (VGS) theoretical framework, resulting in F*. At this stage, F and F* exhibit a geometric interdependence, characterized by a parallel relationship between each edge in F and its corresponding force vector in F*. This interdependency is crucial for maintaining the structure's static equilibrium.

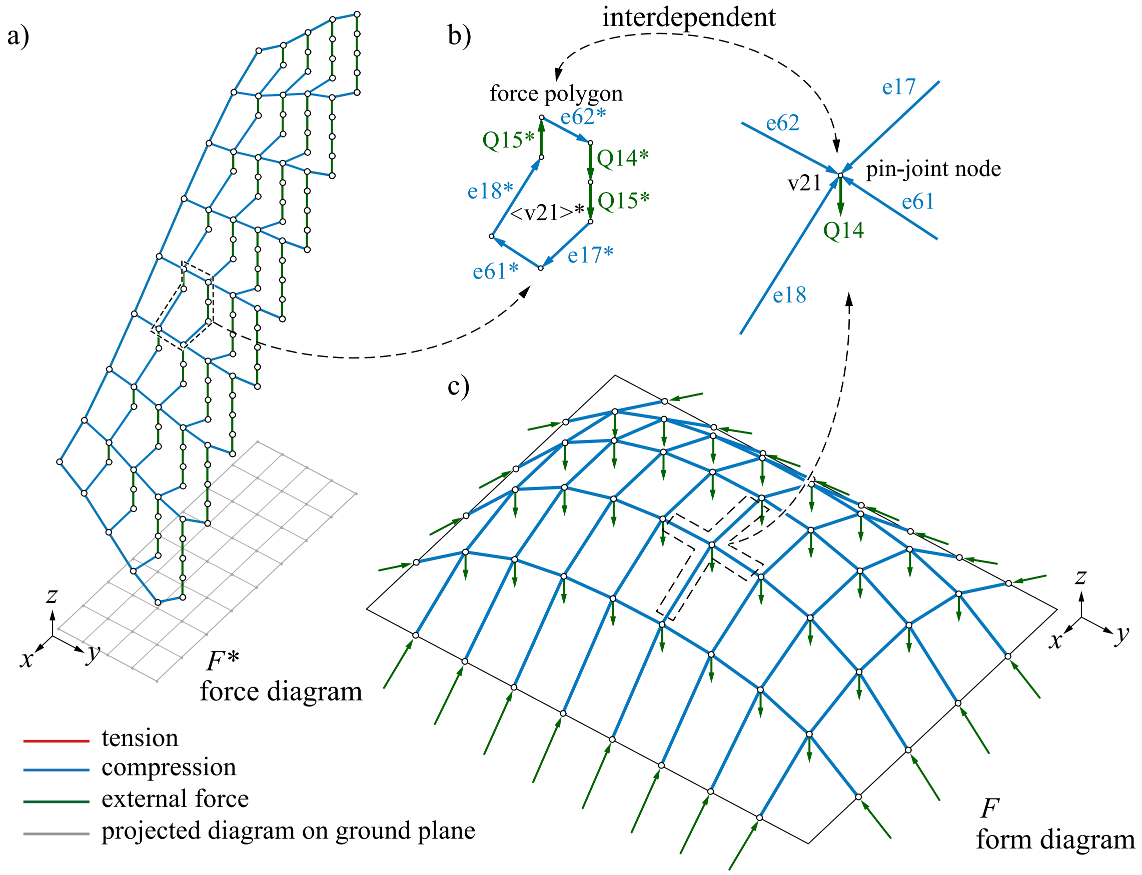

Figure 3: Constructing the initial equilibrium with form and force diagrams by vector-based graphic statics as the initial model for form-finding reuse-constrained structure

b. Reuse component fitting and adaptive transformation: Within the context of reuse component fitting and adaptive transformation, the Vector Graphic Statics (VGS) tool's transformation feature allows for the manipulation of structures while maintaining static equilibrium. Traditionally, component fitting involved using a pre-defined design component set (**A**) to search and match components from a reserve component library (**S**). However, the dynamic adjustability of the VGS tool facilitates a bidirectional fitting approach, enhancing adaptability. As shown in Fig. 4, this process begins with a comprehensive search of the reserve set S based on design set **A**, using component length and internal force as selection criteria for matching. If a direct match is not found, components in set **A** are matched with greater flexibility by setting length and internal force as ranges, rather than fixed values. Upon successful matching, the VGS tool applies constraints to the form and force diagrams based on the actual dimensions and forces of the reused components, thereby aligning the design more closely with these parameters. This iterative process, combined with the dynamic adjustment capabilities of the VGS tool, progressively improves the matching rate and ensures compliance with specific structural design constraints.

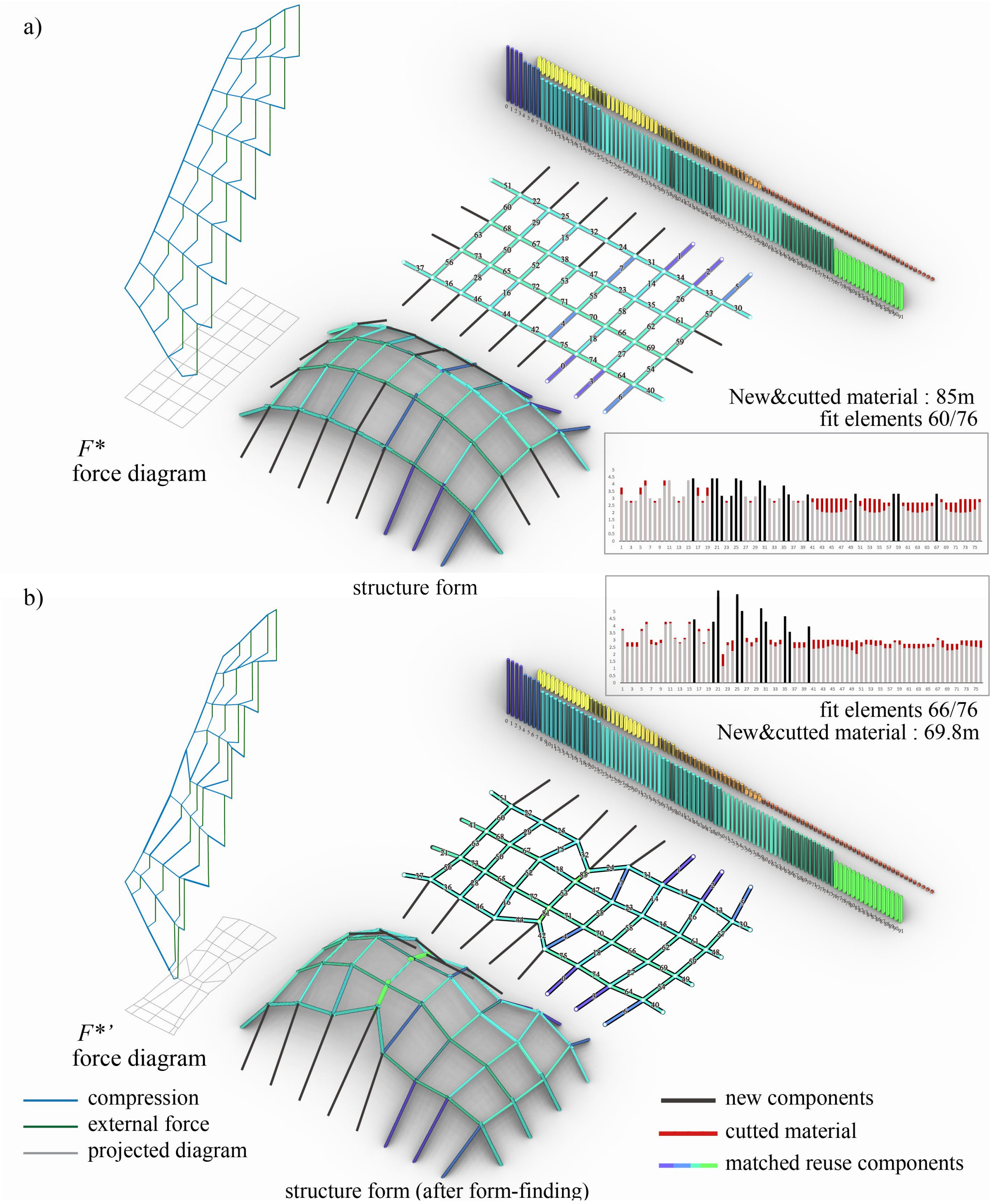

Figure 4: a) The result of the reuse component fitting on the initial form; b) The structure form and force is optimized by transformation to increase the fitting rate

3.2 Joint design approach: Reciprocal Frame as Joint

The initial structural fitted model comprises pin-jointed nodes, with each node connecting multiple struts at varying 3-dimensional angles. The complexity of these nodes is further compounded by the varying sectional dimensions of each strut. While customized structural connections could address this complexity, they risk deviating from the goal of reuse by introducing excessive novelty.
Some presented studies have explored the utilizing of “reciprocal frame joint” to address the problem. For instance, Douthe and Baverel proposed the dynamic relaxation method for form-finding of reciprocal frames [12]. Tachi introduced a technique for designing tensegrity structures by creating reciprocal frames through mesh manipulation and edge rotation [13]. Building on these methods, Daniel Piker and Gennaro Senatore developed a digital tool using Grasshopper and Kangaroo [14].

Given these developments, this study aims to sidestep custom connections by optimizing the initial model based on constructability constraints and employing standard timber connections. It is observed that once the node passes 2-degree, customization is inevitable. Consequently, optimization target is to transform pin-jointed nodes from the initial model into 2-degree nodes. This can be achieved by introducing a small offset from the initial connection point to each neighboring member connection. For instance, a 4-degree node can be converted into four 2-degree nodes (Fig. 5a). This transformation simplifies and standardizes structural connection design. Simple construction methods can then be used at the structural connections, such as using nuts and bolts. The timber members also require very little fabrications – only holes drilled in precise locations are required.

While the terminology surrounding “reciprocal frame structure” stress its structural behavior, with neighboring members structurally interdependent and of equal importance, the "reciprocal joint" in this context focuses on its similarity with the construction of a typical reciprocal frame structure. As shown in Figure 5b), the neighboring member connections at each reciprocal joint are optimized to be close to each other, minimizing deviation from the form-finding result of the initial form.

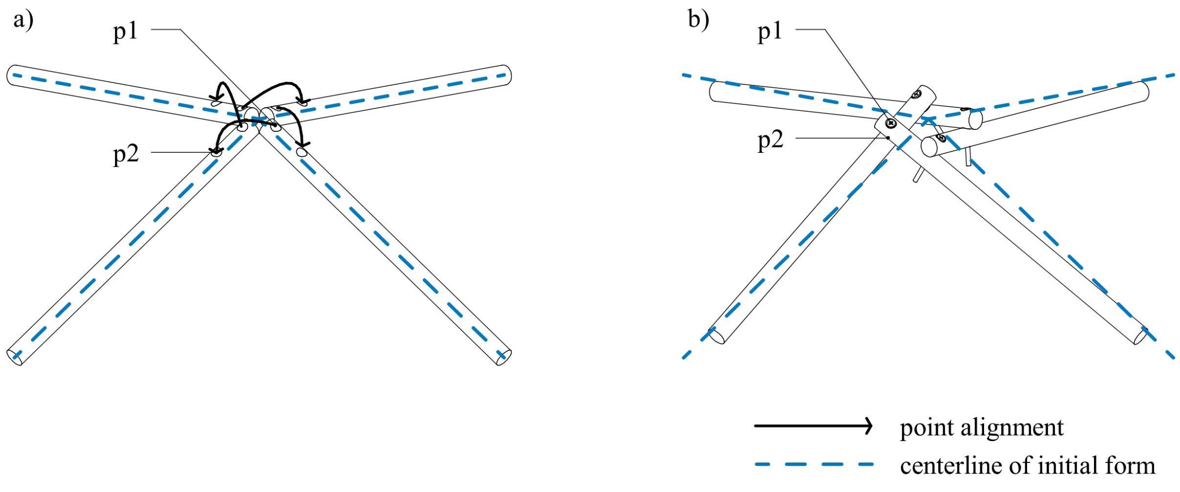

Figure 5: a) Rotation and realignment of members to form reciprocal joint; b) The resultant geometry transforms each 4-degree node to four 2-degree nodes

3.3 Optimization based on the joint design

The slight deviation introduced by the reciprocal frame joint design approach at each joint changes the geometry of the entire structure, making a second form-finding exercise necessary. This optimization is carried out through a custom implementation of Kangaroo Physics. Note that in this context, the application is purely to satisfy geometric constraints for form finding and geometry optimization, without concerning physical meaning. For example, the structural connections of each pair of neighboring members are nuts and bolts drilling through holes on the members. Within Kangaroo Physics, this is prescribed as points colinear with lines, constrained using a method which combines the Dynamic Relaxation Method and Projective Dynamics, and set as “goals”. Multiple goals are set with different weights and feed into the solver to find the optimal results.

The initial VGS model is a discrete network, which can also be represented as a mesh. Based on the development of Daniel Piker, a mesh can be transformed to a reciprocal network by extending and rotating the edges around the nodes of the mesh, resulting into crossings between elements at the joints. However, Daniel's method fails to account for the potential excess in the elements at the reciprocal nodes, representing an unacceptable deviation that could lead to unforeseen outcomes. Therefore, we make further constraints to the transformation to impose reciprocal nodes in the structure:

Goal 1: We represent each member using four nodes: two endpoints corresponding to the extremities of the member, and two additional points indicating intersections with other members, ensuring that all four nodes remain collinear.

Goal 2: Utilizing the half-edge data structure, we determine the clockwise sequence of edges at nodes, subsequently directing each edge towards the intersection point of the following edge (Section 3.2).

Goal 3: The separation between edges is set to match the combined radii of the member cross-sections.

Following the goal above, as shown in Fig. 6, the discrete network can be transformed to a reciprocal jointed network.

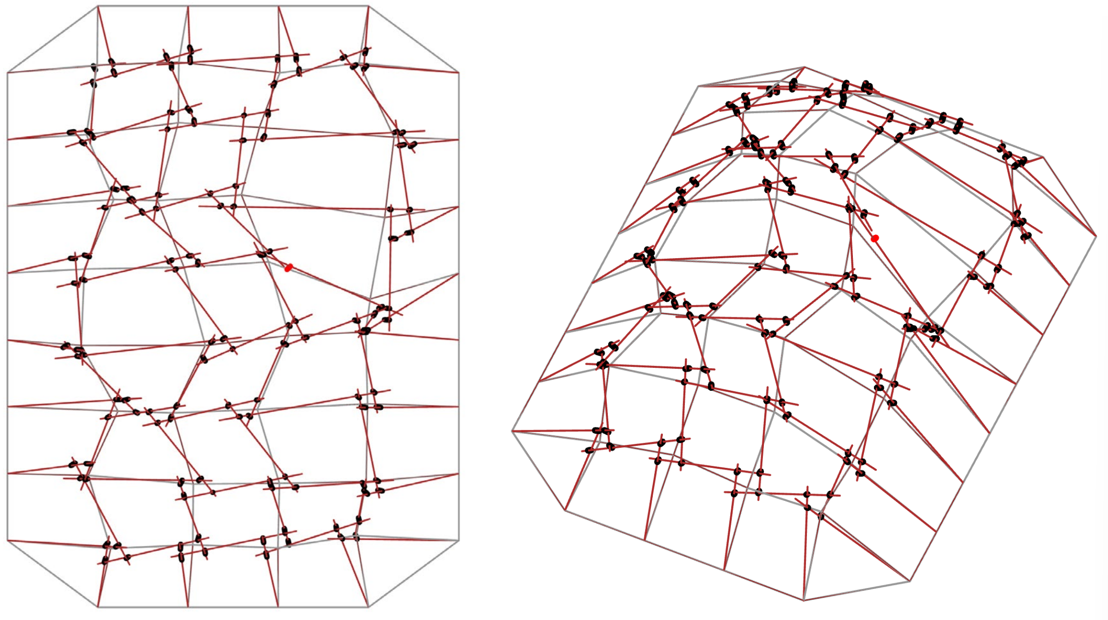

Figure 6: Form-finding results in top view (left) and 3d perspective (right); The origin network(in grey) and the reciprocal network(dark red) and joints(black);

3.4 Modelling and Physical Mock-up

In order to validate our work, we developed a detailed model and constructed a mock-up to further test construction viability. The modelling was done using Revit.

A parametric Revit family of the timber member was constructed with three levels of detail (LOD). Shown in Fig. 7, LOD-1 model mirrors that from the form-finding model, with members represented as lines, and connection joint as vectors. LOD-2 model takes member cross-section dimension and connection sizes into account and is modelled in 3D. LOD-3 model is constructed with full-scale construction in mind – details such as nuts and bolts are added.

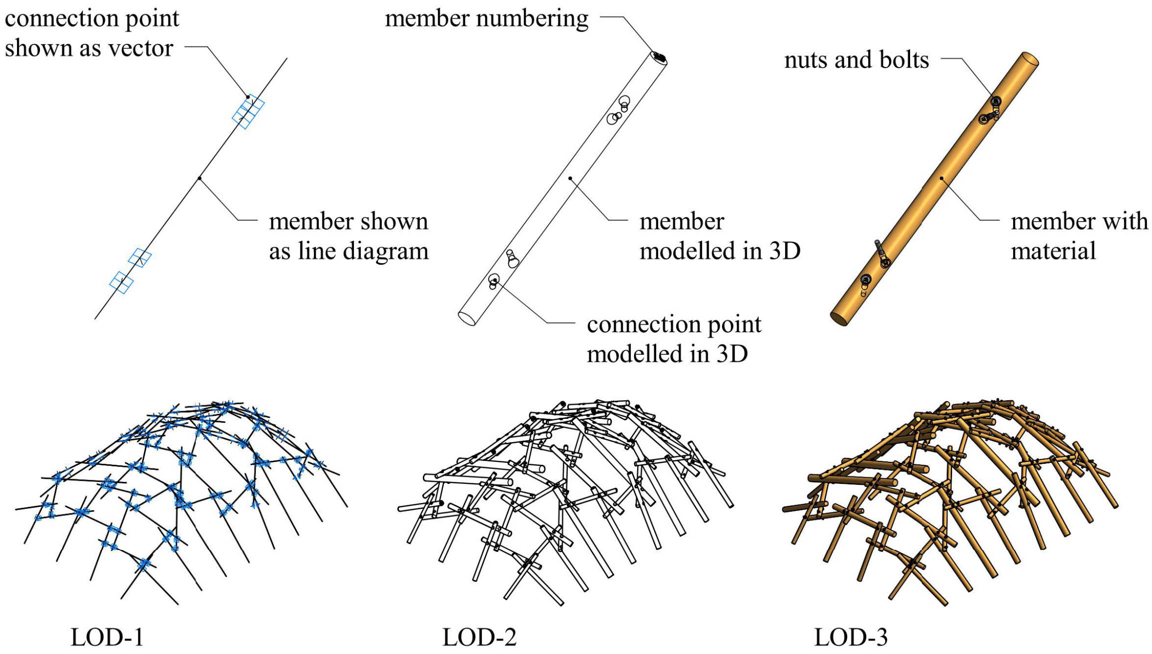

Figure 7: Revit family constructed with three LODs

The data was fed into Revit to instantiate instances of the family, rather than relying on dead geometries. *Rhino.Inside.Revit* is used transfer data from Rhino to generate Revit-native parametric models. The resulting structural members are described by the following parameters: Member numbering (N), Overall length (L), Member Radius (r), Base plane (BP), including origin point of each member and its orientation in space (v), Location of connection points on each member (tx), Orientation of each connection (a), Numbering of connecting member on each connection point (n)

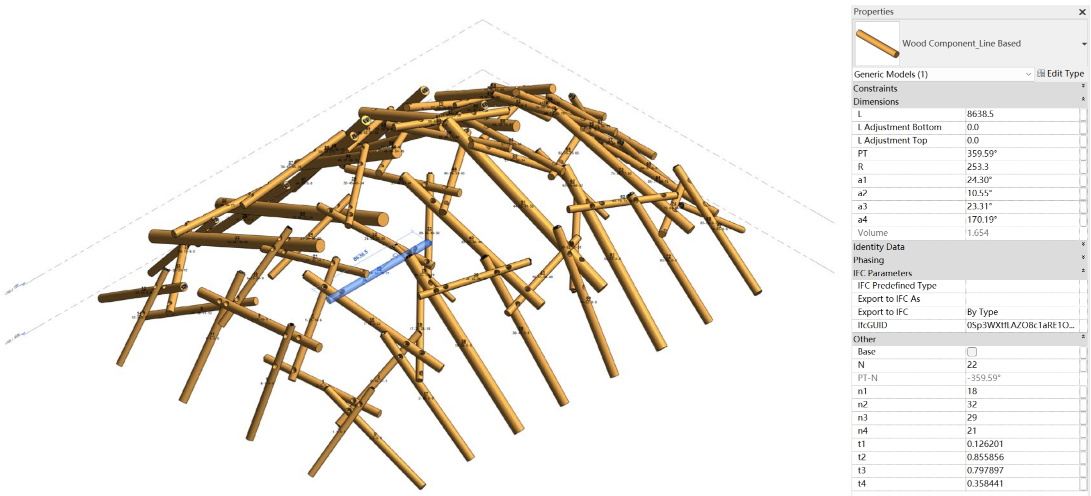

Figure 8: a) Model generated using Revit-native family; b) Parameters and associated values of timber members

A mock-up at 1:100 scale is built to validate the model and facilitated tests for construction constraints, including sequencing and connection design. This is done by 3D printing the LOD-2 model and assembled with screws. With the help of the physical model, we were able to improve the design of the connections, optimize and streamline the workflow.

The BIM model aided in visualizing the finished product during assembly. The ability to retrieve information from the BIM model and generate other forms of graphic representation is also vitally important. A plan generated from Revit with each timber member tagged with its respective numbering and the numbers of connected members, served as a guide for the assembly process. This is similar to construction documents, and we were able to develop the workflow and prepare for future work where this can be built in full-scale construction.

a) b)

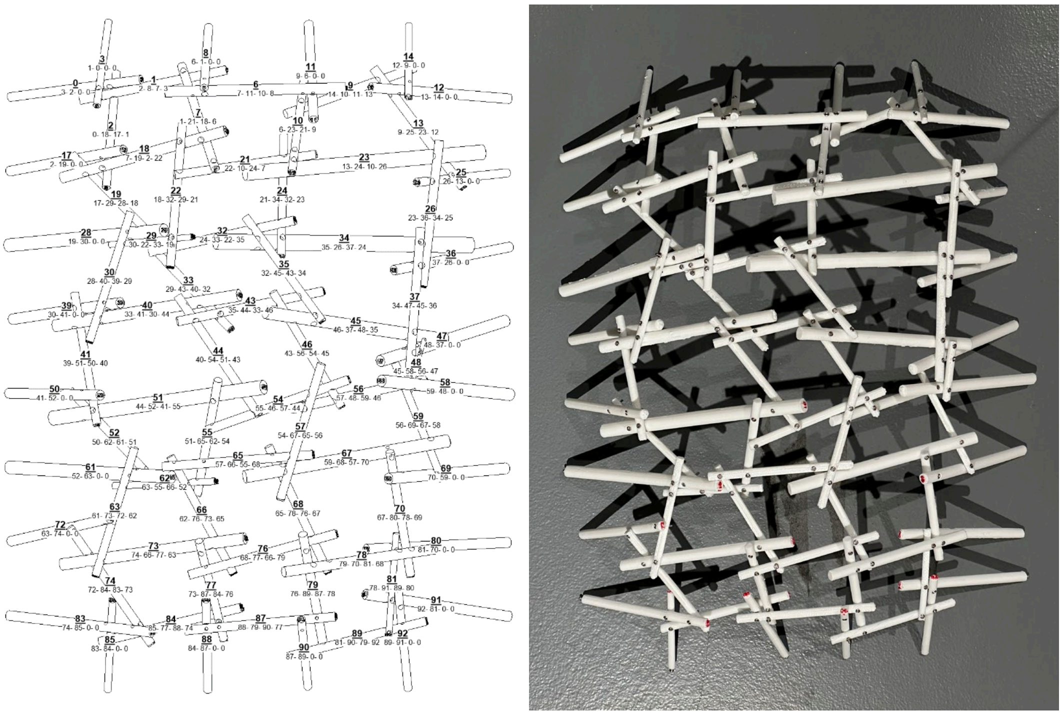

Figure 9: a) Revit floor plan, all timber members are tagged with its numbering and numberings of connected members; b) 3D printed and assembled physical model

3. Conclusion

This paper presents a multifaceted approach to timber structure reuse, comprising three integral components: a computational workflow, innovative joint design, and a seamless connection to real construction practices. The computational workflow integrates VGS tool, Kangaroo Physics, and BIM to enable real-time interactive structural design, material strength validation, geometric optimization, and detailed parametric modeling, fostering a streamlined and efficient design process.

The realization of the case study demonstrates the feasibility of the design and process, however there are several things to consider for future works:

a. The deviation of the reciprocal structure from the initial VGS model, although minimal, changes the structure and needs assessment. This can be done using FEM (Finite Element Method).

b. The form-finding process is done in two separate steps, which might create inefficiency in structural design that can be improved.

c. All members are simplified as bars with its structural strength directly related to its cross-section dimension, without considering factors such as cross-section types, irregularity, actual strength due to decay, etc.

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