Topology Optimization and Robotic Fabrication of Advanced Timber Space-Frame Structures

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Abstract This paper presents a novel method for integrated topology optimization and fabrication of advanced timber space-frame structures. The method, developed in research collaboration between ETH Zürich, Aarhus School of Architecture and Israel Institute of Technology, entails the coupling of truss-based topology optimization with digital procedures for rationalization and robotic assembly of bespoke timber members, through a procedural, cross-application workflow. Through this, a direct chaining of optimization and robotic fabrication is established, in which optimization data is driving subsequent processes solving timber joint intersections, robotically controlling member prefabrication, and spatial robotic assembly of the optimized timber structures. The implication of this concept is studied through pilot fabrication and load-testing of a full scale prototype structure.

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1 Introduction

Topology optimization (Bendsøe and Sigmund 1999) may broadly be defined as a family of procedures aimed at creating efficient structural layouts. In the form of continuum representations, this equates the redistribution of material within a Finite Element-discretized design space. In the form of truss-based representations, it equates the determining of the topological connections and cross section sizes from a pre-defined set of possible members.

In a preceding research work, continuum optimization was explored for architectural concrete structures (Dombernowsky and Søndergaard 2012; Feringa and Søndergaard 2015; see also Fig. 1). While these studies successfully indicated significant potentials for design innovation and reduction of material consumption compared to commonly found standard structures (Dombernowsky 2011), the work also found inherent complexity in translation from optimization result to construction design. Furthermore, current continuum procedures are not directly applicable to the majority of construction projects, which are realized through assembly of prefabricated semi-manufactures and components, necessitating alternative modes of optimization. These limitations can be conceptually addressed through the application of truss-based topology optimization (Søndergaard 2013). This approach enables the optimization of pre-defined member—and connection types within predetermined ranges of cross-sections, hereby facilitating the generation of optimized designs, which align closer with current building and construction practice. However, the topological complexity of the optimization results derived from such processes necessitates digital new means of pre-fabrication and assembly to become practical to full-scale building implementation. As of today, no method exists for direct realization of optimization result, in which the complex challenges in prefabrication and assembly arising from the complexity of the optimized topologies are handled in an integrated, digital process. The collaborative research presented in this paper addresses these challenges targeted at the special application area of digital manufacturing of timber structures.

2 State-of-the-Art

Recent developments within architectural robotics have presented novel procedures for digital fabrication of advanced timber structures. In the seminal experiments conducted at ETH Zürich (Gramazio and Kohler Research), integrated robotic fabrication and assembly have been demonstrated within layered assembly of timber structures (Willmann et al. 2016; Gramazio et al. 2015). This process is currently being applied for large scale production of the $80 \times 22.5 \text{ m}$ Arc-Tech-Lab roof structure under construction at the ETH Hönggerberg university campus (Apolinarska et al. 2016). Furthermore, recent experiments at the ICD Stuttgart (Knippers and Menges 2013) have demonstrated full-scale fabrication of plated timber structures in combination with manual assembly through robotic CNC-milling of bespoke elements for the Research Pavilion 2011 while long-threaded developments at the EPFL Lausanne are investigating digital structural design and fabrication of new timber structures (Weinand 2009).

Most recently, research was undertaken at ETH Zürich to explore the potential of robotic assembly of single-joint spatial structures in combination with application of fast-curing, 2-component chemical binder (Helm et al. 2016). The collaborative work presented in this paper builds on this development, while process parameters have been extended to enable the realization of topology optimized structures.

3 Optimization of Timber Structures

The structure fabricated within the current study is essentially a rationalization of a result of a topology and sizing optimization procedure. We rely on well-established formulations from the field of structural optimization, where the purpose is to find the optimal structural layout of a truss (locations of existing members) as well as the optimal cross-section areas. Such layouts have been investigated since the early 20th century stemming from Michell's classical work on least-weight grid-like continua (Michell 1904).
3.1 Implementation of Truss Optimization Using Optimality Criteria Approach

The current implementation uses the so-called “ground structure” approach (Dorn et al. 1964), where for example the design domain is discretized using a fixed set of nodal points, which are then connected by a set of potential truss bars. The only requirement in setting the ground structure is that it should be able to transfer the loads to the points of supports without forming a mechanism. Then, the objective of topology and sizing optimization is to determine the optimal topology and cross-section areas of all potential bars, including eliminating unnecessary bars by assigning them a zero cross-section area. In its most basic form, the topology optimization procedure aims at “finding the stiffest truss”. This can be stated as follows: find the structural topology and cross-section areas, so that stiffness is maximized (i.e. external work is minimized), subject to an upper limit on the volume of material used, and provided that structural equilibrium can be satisfied. The corresponding mathematical statement is:

$$
\min_{\mathbf{u}} \ f^T \mathbf{u} \\
\text{s.t.: } \mathbf{K}(\mathbf{a})\mathbf{u} = \mathbf{f} \\
\sum_{i=1}^{\text{NBARS}} a_i l_i - V \leq 0 \\
a_i \geq 0 \quad i = 1, \ldots, \text{NBARS}
$$

Here \(\mathbf{a}\) is a vector of non-negative cross-section areas; \(\mathbf{f}\) is the external load vector; \(\mathbf{u}\) is the displacements vector; \(\mathbf{K}\) is the stiffness matrix, depending on \(\mathbf{a}\); \(l_i\) represents the length of the \(i\)-th member; and \(V\) is an upper limit on the volume of the structure. The solution is found by an optimality criteria approach where the over-stressed cross-section areas are gradually increased while the under-stressed ones are decreased.

This implementation was applied in the development of prototype designs for the purpose of testing rationalization and fabrication methods (Fig. 2). The prototype design was reached by optimization from 1711 possible connections in an irregular, trapezoid ground structure with 5×5×5 subdivisions in the XYZ directions. The configuration was fully supported on three nodes at points (1,1,1; 1,5,1 and 5,1,1) and eccentrically loaded with 5 kN single point load at (3,2,5). Optimized for a minimization of compliance under a volume constraint of 0.14 m³, the processes resulted in a geometrically complex 34 bar structure.

![Fig. 2 Optimization result of a 4-point supported single-load configuration (left). Early result of the prototype optimization (right)](image)

4 Geometry Rationalization

The optimization procedure described in the previous sections accounts for the structural load-capacity of the topological configuration, and the dimensioning of member cross-sections. However, the output does not solve the geometrical intersection of members at node levels, which must be processed in a secondary step. To accommodate for this, a rationalization procedure is developed and implemented in GhPython (Fig. 3). The objective of this procedure is to, given any topological structure, solve the necessary cutting sequence and orientation for bars in each

![Fig. 3 Workflow diagram of the rationalization procedure](image)
node, based on the limitations of the robotically controlled sawing process. The outcome is a discrete list of revised bar geometries, which avoid in-node overlaps, while (a) ensuring structural continuity from load-points to points of support, and (b) minimizing the number of necessary intersections while maximizing the contact surface area at member joints.

Members are discretized into ranges of pre-determined cross-section dimensions, and joints rationalized according to the member cross-section dimensions included in the joint: joints containing members of only one dimension type are trimmed against a shared plane derived from the bi-sector of the center axis of the intersecting members. For joints containing members of several dimension types, largest dimension types are trimmed per bisector as previously described, while smaller dimension types are trimmed against the cross-section profiles of larger members. The result of this operation is that lower level bars will share a surface only with one higher level member, leading to simplified joining faces in this situation.

5 Assembly Procedure

A predominant challenge for robotic fabrication of topology optimized space-frames is the auto-generation of valid assembly motion sequences, which must determine the chronological order of member insertion while avoiding collision with the structure under construction. Addressing this challenge an assembly processor is developed, which computes the assembly sequence and the respective trajectories directly from the node geometries, hereby avoiding simultaneously in-node collision at joint level and global collision at the structural level (Fig. 4).

This is conducted in an operation, in which members and nodes are sorted according to their distance to the robot base, and the bar with the smallest angle relative to the base-plane is selected. Once the first valid bar is found, insertion trajectories are computed by the sum vector of the normals of the contact faces of neighboring members within the same joint, defining collision avoidance as any trajectory which is $>90^\circ$ to any normals of the neighboring contact faces. If collision is found, and cannot be solved through incremental search for alternative trajectories in the trajectory solution space, a combinatorial search is performed for the insertion sequence with least collisions; the obstacle member is retracted and validity is re-checked after every insertion of a new node.

For every insertion operation, a connectivity check is performed at the end-node of each inserted bar member (opposite of the joint node). If found, the connecting bar will be inserted ensuring, where possible, a build-up through triangulation, which help to ensure physical stability during assembly (Fig. 5).

6 Robotic Operations

The fabrication setup at ETH Zürich consisted of a KR 150 L110-2 KUKA robot on a 7 m linear axis (Gramazio et al. 2015) and a Mafell Erika 85 circular table saw. A custom positioning table for material feeding was added to the saw. The robot is equipped with a custom parallel gripper, which is capable of holding the beams stiff enough during the cutting process. Within the robotic process, the following steps were repeated for every beam: first, a wooden beam was gripped, and then positioned in 5 axes for cutting. Then, the positioning and cutting procedures were then repeated for all cutting planes. Finally, the robot could reach the final assembly position, where multiple beams can be prepared for gluing. Each step of the geometric constraints, the robotic movement and the assembly is explained in more detail in the following paragraphs.
6.1 Geometric Constraints

The idea of the cutting operations was to perform every cut with a vertical sawblade, while the robot could perform all complex geometric orientations. The orientations can be computed through a transformation matrix, which aligns the trimming plane vertically, while keeping on of the edges of the beam horizontal (Fig. 6).

This approach allows for a wide range of possible cutting angles (Fig. 7, left). The positioning angle (in the XY plane) depends on the specific length of each beam, the distance to the tool and the saw's maximal pulling distance. The cut angle (in the vertical plane) depends on the size of the gripper and parts of the end effector, which could cause collisions. A threshold angle of 60° was identified for the current setup.

Fig. 6 Vertical cutting orientation

Fig. 7 Maximum angles (left), and assembly surface (right)

Building on previous research (NRP-66 research projects, 2012–17), joints where connected using a fast-curing, two-component adhesive with curing times of 5–10 s (Zock et al. 2014). Each connecting face was perforated to allow for the adhesive to permeate deeper into the structure, hereby increasing resistance to tensile stress. Due to the high viscosity of the adhesive, gaps between connecting faces were sealed with tape during injection, to avoid leakage during the short-term curing. This approach allowed for accommodating tolerances between 2–10 mm, while ensuring strong connections.

6.2 Robotic Movement

A number of challenges were encountered in the programming of the toolpaths for robotic movements. The geometric operations and toolpath data was computed in python. For the simulation and post-processing the software HAL was used.

For angles beyond the threshold angle in Sect. 6.1, a regripping procedure was created. During this procedure, the robot places the beam on the table vertically and regrips it afterwards at a 90° angle. Due to safety reasons, beams were rotated horizontally in a safety-plane above the sawblade. Therefore, the robots a6 joint had to perform most of the movements. The rotational limits were easily reached. This issue was solved with using joint-movements to a custom unwinding position between each of the cuts, where the joint of the 6th axis can rotate in interpolated movements to a zero value. This created some additional movements, but provided a safe position for the motion-planning. It helped in avoiding collisions between very long beams and the robot during the cutting and positioning. Custom positioning of the robot base was used to allow the robotic rotations of the beams, which outer corners reached beyond the linear axis (Fig. 8).

For the positioning of the robot base three cases needed to be considered. Ideally, the base moves along a position normal to the current target plane (a). This works only for rotations along the maximal offset domain of the robot. Therefore repositioning of the base can be anticipated and performed during a safe position as the unwinding position (b). Inward rotations can be performed with the maximum offset depending of the reach of the robot (c). Therefore a pattern for all base positions had to be calculated in advance for all toolpath targets.

Fig. 8 Custom robot base positioning
6.3 Assembly Trajectories

For the assembly motion planning a slightly curved reference surface was created, slightly hovering over the planned structure. The assembly direction planes derived from the assembly processor described in Chap. 6 were then pulled in the normal direction on the surface. This allowed for an easy control of the trajectories since the upper paths are projected above the structure, whereas the lower paths remain in ideal safe regions around the structure. Figure 9 shows the final prototype, which was constructed using the above described processes.

7 Analysis and Load-Test

The fabricated timber truss was finally tested under point loading in order to validate the effectiveness of the overall design and fabrication process (Fig. 10, left).

Since the performance of timber structures is determined by the capacity of the joints, a key question was the structural capacity of the glued connections. In the numerical simulations, both in MATLAB (within the optimization procedure) as well as in RSTAB, very small displacements were predicted under a load of 5 kN. Furthermore, the difference in displacement between the optimized design (with variable cross-sections) and the fabricated design (with three bar types only) was under 10%. At the moment of writing, load-testing went to 13.6 kN, but failed to proceed to collapse due to rupture of the connecting metal braces (Fig. 10, right). While this limits the measurement of the actual stiffness of the structure, it nevertheless indicates that joints—despite geometrical complexity and variability of gluing conditions—perform overall within expected range and that the prototype indeed is very stiff due to its optimized configuration.

8 Conclusions and Outlook

This paper has presented a process that facilitates integrated optimization, production rationalization, robotic fabrication and assembly of topology optimized space-frame structures. The method discussed presents a solution for the production of spatial structures with a high concentration of bars at individual nodes, the implication of this is demonstrated through optimization, fabrication and load-testing of a full scale structure. Analysis and tests show general consistency between predicted capacities in optimization, the analysis of the rationalized geometry and the performance during physical testing.

While the presented work demonstrates the feasibility of the proposed process, a number of challenges were identified for further work. The high level of complexity of all steps of the described process necessitates either fully automated or highly automated construction processes to remain feasible in full scale architectural applications. This implies in particular (a) that custom adaptive/feedback-based processes are needed in the future for handling un-modeled material effects (in particular gravitational sagging of the structure during assembly and tolerances stemming from member warping during cutting) and (b) therefore the development of novel, fully integrated design and fabrication workflows/tools are required. Finally, automation of the sealing process as presented is challenged by the high degree of joint complexity. While manually solvable, robotic automation would be key to improving the industrial applicability of the process.
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