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Design to fabrication method of thin shell structures based on a friction-fit connection system

Bojan Tepavčević*, Vesna Stojaković, Dejan Mitov, Ivana Bajšanski, Marko Jovanović

Department of Architecture, Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovica 6, 21000 Novi Sad, Serbia

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ABSTRACT

The use of production systems based on CNC manufactured integral joinery has been increasing in many design fields including architecture, construction and industrial design. In many cases, such production systems are based on connectors that utilize interlocking mechanisms between components for assembly, sustained only by friction. Assembly systems based on friction-fit connections are low-cost, easy to manufacture and can be flat packed, shipped for construction and assembled with no special tools, fasteners or adhesives.

In this paper, we propose a design to fabrication method based on a 2D tool path CNC production system with the friction-fit connection assembly logic that can be easily manufactured and assembled. The presented method provides extended groundwork for architectural design exploration based on tessellation procedures. It can be used for the design of discrete thin shells and applied to different scenarios in architecture. The method combines construction and manufacturing constraints, along with architectural and aesthetic requirements, in order to achieve a visually balanced pattern of panels and connectors. Due to this, parametric design of construction details with multi-criteria design optimization was used. The design to fabrication method proposed was tested on two models with different form generation approaches, size and scale illustrating that the method can successfully fulfil all necessary constraints.

1. Introduction

Digital tools bring diverse design strategies to architecture, resulting in the emerging complexity of building forms. One of the most important issues in designing and manufacturing of such objects is the feasibility of realization, which pertains to a streamlined and automated construction and manufacturing process. Moreover, construction-aware and fabrication-aware design processes are important for efficient construction of buildings and structures of greater complexity [1,2]. Such design approaches incorporate construction and material properties, as well as constraints imposed by the cost-efficiency of the fabrication technology during the early design phase.

In the past decade, many digital tools have been developed to incorporate different construction and material constraints, expanding versatility in digital tectonic shapes and design innovation through digital fabrication. Material properties and behaviors can be embedded into digital form-finding methods, resulting in design and explorations of thin shell structures in a diverse range of materials [3]. While vaulted structures are usually considered to be manufactured from stone, masonry blocks, or tiles, the novel form-finding and manufacturing tools extended the design possibilities to light-weight materials, including plywood. Structurally informed shell designs in plywood have been used to explore differing goals, including variable-volume and mass solutions [4], advanced manufacturing with industrial robots [5–7], as well as connection and assembly strategies [8–10].

However, current design approaches to fabrication of complex 3D shapes are often based on fabrication tools and technologies that cannot provide satisfactory results in terms of fabrication time, cost, scale, and quality.

One of the possible solutions for the construction and manufacturing of low-cost, digitally fabricated structures is based on utilization of a friction-fit connection assembly system. The reasons for recent increase in interest within the design research community into the friction-fit connection system lie in the fact that it enables rapid assembly and disassembly of structures. Interlocking friction-fit structures do not require any special tools or fasteners in the assembly process and they are able to transfer the loads and to be held together purely through friction between integral attachments. In the recycling process, after the exploitation period of wooden friction-fit structures has ended, there is no problem separating different materials, as may occur with glue or metal connectors.

The friction-fit system has been proven to be efficient in the creation

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* Corresponding author.
E-mail address: tepavcevicb@uns.ac.rs (B. Tepavčević).

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of high-quality and low-cost housing. The YourHOUSE low-cost housing design project conducted by MIT's Design Lab demonstrates the efficiency of this approach such that all pavilion elements can be CNC cut, flat packed, shipped for construction, and assembled without skilled workers and with no special tools [11]. The efficiency of the friction-fit assembly system has also been verified through other projects, including the "Instant house" which was fabricated and assembled in 90 h from 984 CNC manufactured plywood elements [12], and "House for New Orleans" that consists of 5000 elements, including historical ornamentation [13]. Successful friction-fit housing design projects have proven that interlocking the friction-fit system with mono-material assembly has the potential to impact design where visual aesthetics, along with design customization and variation, are important [14].

The friction-fit connection relies on interlocking elements with a tight connection. The interlocking system in the assembly process of the shell and spatial structures is used with different design and fabrication strategies, including reciprocal frame structures with notches [15–17] and folded plate components [18–20]. In some projects, the interlocking connection on a freeform plywood thin shell has been achieved [6,7], but such structures require a 5 axis CNC manufacturing process, as well as mechanical fasteners or adhesives in the assembly process. In other projects, friction-fit connectors designed from flat sheet panels and 2D tool paths for CNC were used to design complex wall structures or pavilions [21–23], but not for the free form thin shell structures. While friction-fit system have been proven to be an efficient for fabricating low cost, high quality housing, wall structures and pavilions, it has not been examined as a design to fabrication strategy for free form thin shell structures.

In this paper, we propose a design to fabrication approach based on the friction-fit connection system for free form thin shells. The described approach considers construction and tessellation logic of discrete shells integrally. It is aimed to achieve visually balanced panel and connector patterns. Such design of wooden shells may be used for canopies in public spaces, or as an economical formwork for vaulted masonry construction.

The aim of this paper is to propose a design to fabrication method of a free-form thin shell plywood structure based on the friction-fit assembly system that consists of components manufactured only from 2D tool paths for CNC cutting. The fabrication-aware design process proposed in this paper, which deals with components constrained to 2D geometries for cutting and 3D assembly is a low-cost, rapid and easy manufacturing production system that can be set up on site with small CNC cutting machines, delivered by a small truck, with information supplied from a portable computer [12]. Moreover, architectural requirements for creating tessellated discrete components pertain to visual, contextual and functional requirements and they are embedded in the design process.

2. Methods

The design to fabrication approach presented in this paper is based on implementation of modified cross-lap joinery technique, in which the two members are joined by removing material from each at the point of intersection. Discrete thin shell structures described in this paper consist of triangular panel elements and connectors that are in mutually perpendicular planes. This kind of integrated joinery system enables connection of elements based on friction-fit assembly, without additional fasteners or adhesives.

The design to fabrication method for creating such discrete freeform shells is divided into three phases:

i) The first phase implies geometry generation and design optimization. It includes the design of a thin shell, the tessellation design process based on triangular meshes and multi-objective design optimization. In this paper, we present two design approaches: free form and form-found with different topologies, demonstrating possibility of implementation in different design scenarios. The Rhinoceros3D software [24] was used to design the freeform shell, and its plug-in RhinoVault [25] was used to design the structurally informed design solutions. The EvoluteToolsPRO [26] plug-in for Rhinoceros3D was used in design tessellation and nonlinear optimization process.
ii) The second phase refers to the design of construction details for connectors and panels. In this phase, the final shape of each connector and panel with notches for friction-fit connection are generated. Construction details presented in this phase are based on the modified cross-lap joinery technique. Panels and connectors are modeled with Grasshopper [27], a graphical algorithm editor for Rhinoceros3D.
iii) The last phase covers manufacturing and assembly process. In this phase, Grasshopper and the RhinoNest plug-in [28] were used for tagging elements and designing 2D tool paths for CNC cutting.

The design to fabrication method proposed in this paper was tested on two models with different form generation, size and scale. For the construction of test models, plywood was chosen as a low cost, sustainable, visually appealing and easy to fabricate material, which also works well under tension and compression.

3. Geometry generation and design optimization

The method for the design of the discrete thin shells presented in this paper is based on a top-down design approach, where overall shape was generated first.

The design to fabrication approach presented in this paper was tested on two shells, Model 1 and Model 2 (Fig. 1) of different complexities, topologies and design approaches. Model 1 (Fig. 1a) is a freeform egg-shaped shell, designed with common NURBS modeling tools. Model 2 (Fig. 1b) is a form-found shell with a more complex shape and topology compared to Model 1. Model 2 was designed through a structurally informed design process using the RhinoVault tool.

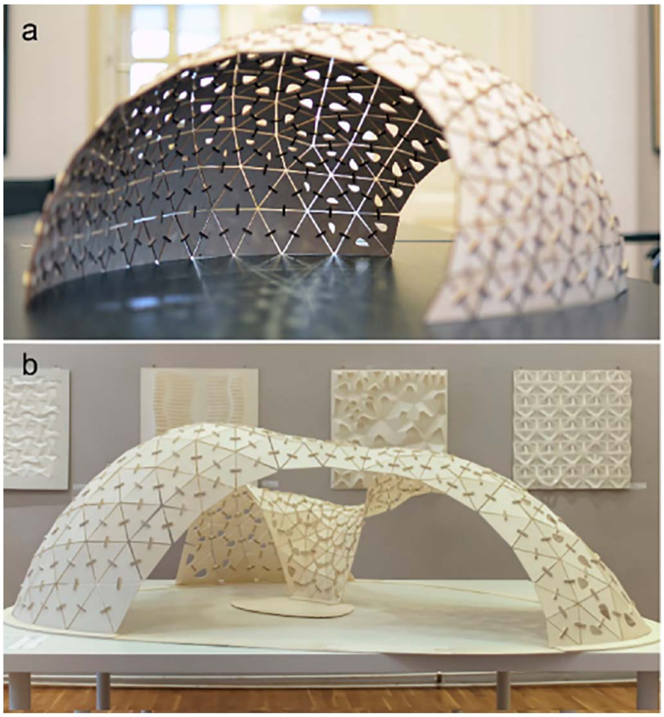

Fig. 1. Fabricated thin shell models: a) Egg-shaped shell model- Model 1, structurally-informed shell- Model 2.