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Published in:
Creativity in Structural Design

Published: 01/01/2018

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Interlocking Particle Structures: Design and Fabrication of a Medium Scale Demonstrator

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Abstract
This paper describes the design, fabrication and assembly process of a medium scale demonstrator that was developed in the framework of the authors’ research on Interlocking Particle Structures (IPS). The demonstrator not only served as proof of concept, but also as an exhibition booth during the 2017 Aalto Festival in Espoo, Finland. In addition to insights from the design, fabrication and assembly process, the paper also presents a FEA study that sheds light on the structural performance of individual IPS joints, as well as IPS as a structural system. The demonstrator in question (see fig. 1) is based on a configuration with an initially orthogonal distribution of panels in space. It is composed of six square birch plywood panels with an edge length of 145 cm and a thickness of 27 mm.

Fig. 1: The demonstrator served as an exhibition booth during the Aalto Festival 2017
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Due to the demonstrator’s underlying geometric principle, there are only three ways of assembling it. Each of the three ways requires the assembly of two clusters of three panels, which are then put together. In addition to these basic geometric constraints, the elastic deformation of the panels during the assembly presented a further challenge. The paper presents potential design modifications that address these and other issues. The internal forces in the panels are visualized by the above-mentioned FEA study.
Moreover, the results of this study indicate that early expectations regarding the structural performance of IPS were justified.

**Keywords**: assembly and material driven design, digital fabrication, tectonic space, material systems, macro-particle structures, interlocking plate structures

1. Introduction

This paper describes the design, fabrication and assembly process of a medium scale demonstrator that is based on the authors’ research on Interlocking Particle Structures (IPS). This research aims to explore the basic principles and qualities as well as potential applications of IPS in the fields of architecture and design. In the context of this research, the notion of IPS respectively refers to aggregates and porous agglomerates of interlocking plate-shaped elements. Moreover, they can also be described as particle systems with structural qualities, whereupon the term structural refers to load-bearing, ordering and space-generating capacities. As such, research on IPS can be seen as an attempt to combine the generative behavior of particle systems with the tectonic exploration of material systems. It is based on the hypothesis that the controlled and informed distribution of material in space supports the emergence of multifunctional material systems, meaning systems, which on top of their structural capacities possess other performative qualities as well [1]. In addition, IPS and the underlying principles of topological interlocking are of relevance with regard to the increasing importance of circular economies and related questions of simple assembly and disassembly of building components. As mentioned in a previous publication on IPS, the assembly principle itself is not new. It can be found in toys, furniture and other applications. Over the past few years, it also has increasingly been applied and studied in academic design studio [2] and research projects [3, 4, 5]. Whereas practically all of these cases pursue a surface or envelope focused approach, the here presented research puts its focus on spatial configurations.

2. Design Process and Geometrical Background

The demonstrator is composed of six square birch plywood panels with an edge length of 145 cm and a thickness of 27 mm. Its design is based on an orthogonal spatial array of initially 18 panels. Whereas all panels have the same dimensions, they form three different groups, each of which is either aligned with the xy-, xz- or the yz-plane. The individual panels of these three groups intersect with each other. The intersection depth corresponds to approximately one fifth of the panels’ edge length. The initially orthogonal alignment is then transformed by applying three consecutive rotations of 15° about the x-, y- and z-axis of the panels’ local coordinate systems (see fig. 02). From this transformed configuration, a group of six panels was selected for the demonstrator. The selected panels form an assembly that appears to be ring-shaped, at least from a select number of angles of vision. However, due to the underlying geometrical order, a theoretically unlimited number of additional panels could be added in all three axes of this structure.

![Fig. 02](image)

*Fig. 02*: The initially orthogonal alignment of the panels is transformed by applying three consecutive rotations of 15° about the x-, y- and z-axis of their local coordinate systems
In principle, the demonstrator is a scaled-up version of a previous IPS study. On a smaller scale, basics of the interlocking mechanism were already explored and fabrication processes established. With the bigger scale, new issues are brought to the forefront, like the handling of the size and weight of the panels during assembly, or the stability and deformations of the configuration under self-weight. These issues were at the center of interest in the here presented research phase.

3. Fabrication and Assembly

The angled slots and their fabrication played an important role for the assembly and stability of the demonstrator, especially with regard to the depth of interlocking of two panels. CNC milling procedures generally employ cylindrical cutting bits, which consequently results in chamfered corners. This is problematic, as the final interlocked position of two panels cannot be determined in a precise manner. Ideally, two panels would be interlocked in such a way, that they have one common planar contact surface. In a previous study with smaller panels, this was achieved through T-shaped cuts. In the case of the demonstrator, the milling of the slots and the panels’ outlines was carried out in two passes. The first pass was executed with a rough milling tool with a diameter of 19.68 mm. The second pass was only applied to the pre-cut slots and carried out with a milling tool of 10 mm diameter, following the two longitudinal edges of the first incision, and surpassing its length by approximately 5 mm. The milling paths were created with SURFCAM 2015 R2, Build 221. Whereas the angles of the slots could be manufactured relatively effortless, other configurations with lower angles would require a different and more laborious milling set-up. One challenge regarding the width of the slots is the discrepancy between the panels’ actual and nominal thickness.

In later stages of the assembly process, the low fabrication tolerance turned out to be challenging. The slots were partly too tight for the assembly process. It was hard to fully interlock the panels, due to deformations caused by the panels’ self-weight. But even more due to the need of sliding in the panels fully in-line with the cutting direction, which turned out to be a challenge due to the size and self-weight of the panels and the limited height of the exhibition space. As a final design and fabrication step, in order to avoid denting and to provide for a better load transfer, three panel corners, the resting points, were cut off with a virtual plane, parallel to the ground plane.

Despite its simplicity, the underlying geometric principle implies constraints regarding the assembly sequence of the demonstrator and all other configurations based on this principle. There are only three different assembly sequences possible. Each of the three ways requires the assembly of two clusters of three panels, which are then put together. In addition to these geometry related constraints, the construction location of the demonstrator presented additional challenges. One panel has an approximate weight of 40 kg. Hence, the overall weight of the structure is approximately 240 kg and a cluster of three panels has a weight of about 120 kg. Due to the indoor situation and the relatively low ceiling height, it was not possible to employ mechanical tools like cranes. In order to stabilize the semi-assembled structure, it was temporarily attached to adjacent columns with lashing belts. No additional scaffolding was required.

One possible conclusion could be that a lower fabrication tolerance makes assembly easier. On the other hand, using additional tools for assembly, like for example lashing belts, might allow for less precision and better performance. Whereas a higher fabrication tolerance might be disadvantageous for the stability of a single connection, it might make it easier to assemble configurations in which one panel is connected with several other ones, and where these multiple connections provide for a better overall stability.

4. Structural Behavior and Performance

As mentioned earlier, the demonstrator served as proof of concept and as an exhibition booth. Its underlying panel configuration does not necessarily represent one that would be used in a building application. Despite this, the demonstrator provides some clues regarding the structural capacity of other configurations of IPS.

The FEA study primarily aims at gaining a better understanding of the connections, which consist of two incisions, one in each of the interlocking plywood panels. In the FEA model, each incision was
defined as a line hinge with three out of six degrees of freedom. Thus, in the direction of the respective joint plane, which is to a large extent orthogonal to the longitudinal contact surface, an $N_x$ (axial force in $x$), a $V_y$ (lateral force in $y$) and a $M_z$ (bending moment around $z$) transfer are possible; the $V_z$ (lateral force in $z$) and the $M_y$ (bending moment around $y$) and $M_x$ (torsion moment around $x$), however, are freely moveable or freely rotatable without force transfer.

The illustration of the main internal forces under dead load (see fig. 3) clearly shows the maximum and minimum bending moments in the panel direction (meaning orthogonal to the panel plane) at the end of each incision. Simply put, each incision acts with two outer contact surfaces on the intermediate plate and a maximum possible lever arm in-between those and thus creates a clamping leverage effect.

![Illustration of the main internal forces under dead load](image)

**Fig. 3:** Illustration of the main internal forces under dead load

Location and situation specific incision lengths and opposing angular orientation of the incisions, as well as increasing the number of incisions to at least three per plate, could thereby improve the stability of the overall system. In addition, the respective single length of each lever arm of the rather vertically oriented plate $a_v$ and the rather horizontally oriented plate $a_h$ can be activated as a common length $a_v + a_h$ by respectively adding frontally embedded screw connections, so that $V_z$ can also be used at the plate edge. This doubles the lever arm, or rather the force couple is halved, and thus reduces the decisive effects of the bending moments on the plate.

5. Conclusions and Outlook

The ongoing research on IPS shows that contemporary industrial wood products are opening up new possibilities in construction due to their dimensions and improved structural capacity. Despite its relatively moderate size, the demonstrator possesses a number of spatial and tectonic qualities that are
commonly not associated with timber construction. The flexibility of the connections provides for a formal richness and variety that requires additional architectural and engineering research.

One of the topics that the demonstrator brings up is the question of precision in the fabrication and its relation to the structural behavior of the overall configuration. With rising complexity of an IPS configuration, it is expected that structural redundancy will occur and that variations in the sliding direction will introduce geometric constraints, resulting in a global geometric interlocking that overcomes local weaknesses. In addition to the precision of the cuts, the depth of interlocking has a direct impact on the structural performance as well. The bigger the cut, the bigger the resulting lever arm.

A currently ongoing project, a temporary roof structure on the campus of Aalto University in Otaniemi, will benefit from the here presented insights and findings. As a potential answer to the above-described constraints regarding the cutting of the slots, water jet cutting will be tested. The results of recent load testing experiments, carried out by Professor Gerhard Fink and postdoctoral researcher Chrysl Aranha at Aalto University, will provide further insights on the structural performance of IPS. These results will be published in a separate paper in the near future.

Potential applications of IPS include self-supporting and structural facades as well as reusable construction systems for pavilions and other purposes. It remains to be seen if a pure wood-to-wood connection will be sufficient for such large-scale configurations and applications of IPS. In addition to strengthening the connection, semi-standardized steel parts could also be advantageous regarding the disassembly and reuse of IPS. Obviously, the downside of such an approach would be the loss of the tectonic and conceptual simplicity.

Acknowledgements

The authors would like to express their gratitude to Hannu Paajanen, Jari Simanainen, Ashish Mohite, Zeynep Bacinoğlu, Fahimeh Fotouhi, Yoon Han, Kane Borg, Gerhard Fink and Chrysl Aranha.

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