Transferring the concept of interlocking puzzles to construction joints

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Abstract

Construction joints often demand a large quantity and diversity of materials for their connections. These connection materials are often in sight, while they are often not intended to be in sight. This paper contains an overview of existing joint construction techniques and applications, and introduces a method wherein connection materials are no longer necessary to apply; it makes a technology transfer from mechanical interlocking puzzles to construction joints. The connection method of interlocking puzzles can make a useful contribution in designing smooth construction joints wherein the overflow of materials flows smoothly and wherein connection materials become superfluous. By doing so, the aesthetic value of buildings can no longer be affected by connection materials. In addition, the method might lead to a more efficient use of material and to an increased building speed. In the paper, various mechanical puzzles are discussed in order to be able to select the best suitable options for construction and to display the added value of the new method.

1. Introduction

Construction joints often demand a large quantity and diversity of materials for their connections. These connection materials are often in sight, while they are often not intended to be in sight. In this introduction, existing connection methods are discussed in order to provide a general overview of methods used in the building industry, and benefits and drawbacks of these methods are discussed in order to reveal where improvements are desired.

In the thesis ‘Architecture in space structures’ by Mick Eekhout, a method is introduced wherein a solution is found for joining multiple elements coming from multiple directions, it is called the The Nodus joint. The connection materials are well hidden, but consist of many small elements.

The company Novum Structures presents and works with various structures wherein the connection material is positioned within hollow beams, so that they are not visible and cannot affect the architectural image. Connections in these systems are all bolted. A hole is made on top of these beams, through which the bolts can be applied. A well-known structure by Novum Structures is the Mero-structure.

An important drawback of these systems is that the beams require being hollow. The system has limited material species that fulfill the system requirements; this excludes many kinds of construction materials, which results in limited material options that are applicable.

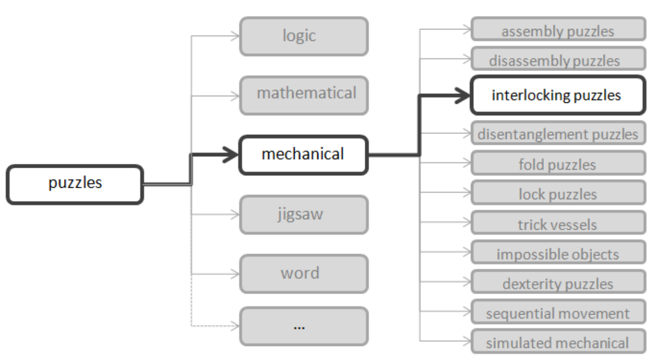
As displayed with the figures below, an existing option is to hide the connection materials, but an interlocking joint is desired. This paper introduces a method wherein connection materials in construction joints are no longer necessary; it makes a technology transfer from mechanical interlocking puzzles to construction joints. Applying the connection method of mechanical interlocking puzzles in construction joints might improve three factors; it might lead to a more efficient use of material, to an increased building speed, and it might be considered an aesthetical improvement.

Figure 1 Joint with connection material

Figure 2 Desired joint without connection material

Because of the presumed additional value of the puzzle technique, the focus in this paper is on mechanical puzzles; ‘Mechanical puzzles are hand-held objects that must be manipulated to achieve a specific goal’ (1). The manipulation of these objects is interesting since several mechanical puzzles appear to be small examples of how to create a joint without the use of fastenings or connection material, as can be seen later on in this paper.

An important observation in the wide variety of mechanical puzzles is the difference between 2D puzzles that are solvable in a single elevation, and 3D puzzles in which multiple dimensions have to be considered. In various 3D puzzles it is required to sequentially place certain elements –individually or in combination- in



their final position to be able to solve the puzzle; when this is done correctly, the elements are locked. These puzzles entail a subcategory in the category of mechanical puzzles named the interlocking puzzles. These puzzles contain valuable information for a transfer to construction joints, because a strong and stable joint is created without the use of fastenings and connection material. It is for this reason that this paper focuses on the past developments and applications of interlocking puzzles, and future challenges for their use in construction joints are discussed.

2. Puzzles

Within the category of interlocking puzzles, various assembly methods and connection materials can be distinguished. Focusing only on the sliding assembly method, burr puzzles are an extensively researched example. These puzzles derive their name from the similar look of the first model to the burr seed. The puzzles can be built up out of an n amount of pieces. ‘Once a burr puzzle is assembled by slipping in the last puzzle piece, no other pieces can be taken out unless this key piece is moved first. Since the key piece locks the entire 3D model, the whole geometric structure of the 3D puzzle can remain stable without glue, screw, nail or other connection material’ (2).

2.1 Past developments

2.1.1 Puzzles

The first known burr puzzle is traced back to 1733, where it appears in a Spanish book by Pablo Minguet E. Irol (3). It appears in several catalogues all over Europe in the years after (4).

It is in 1899 that Scientific American published a puzzle designed by Wilhelm Segerblom, the three piece burr. ‘All three pieces are identical. There exist only one solution since the pieces and their mirror images are identical. To assemble, all three pieces have to be slid together in a diagonal movement; it is not possible to put two pieces together and then slide the third one in’ (4).

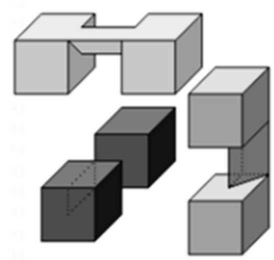


Figure 4 Burr puzzle **(4)**

Originally published in 1928, the book ‘Puzzles in Wood’ by E.M. Wyatt presents over forty unique puzzles with locked links and burr puzzles included. ‘In the book a version of the three piece burr is described that requires a piece which can be rotated to make room to slide the other two pieces together.’ (4) (5).

Wyatt wrote ‘Wonders in Wood’ that was originally published in 1946 which contains the Wood Knot which is a three piece cross (6), simple six piece burrs, and a number of other Burr puzzles (7).

In 1978, 1988 and 1994 an American mathematician and systems analyst named Bill Cutler publishes articles about the six piece burr in which the mathematical properties are analyzed (8) (9) (10).

In 1994 the original three piece burr has been tried to improve again by J. Slocum by the addition of a triangular section to improve stability. However, the center is not filled completely (4).

In 1997 an online version of Stewart Coffin’s book ‘The Puzzling World of Polyhedral Dissections’ appeared when the interest in the book was greater than the available hard copies and publishers were not interested in reprinting the book. The book shows various burr puzzles of different levels [11].

Over the years, many persons have contributed in expanding the collection of burr puzzles by submitting their designs. This has resulted in an extremely large collection and diversity of the existing burr puzzles. This collection is not included in this paper, since the value of the technique is more important than individual examples. In the next part this will be clarified.

2.1.2. Designing and analyzing puzzles with computer programs

The use of computers enables the creation of more complex puzzles. Already in the 1980s software is written by Bill Cutler for analyzing 6-piece burrs. The BURR6 program tests how many assemblies are possible with the six individual pieces and each of these assemblies are tried to be disassembled by using rectilinear movements [12]. The input of this program is assumed to be similar to the online free to use version of IBM Research where a program allows persons to design their own burr puzzle [4].

The use of computers has led to more complex designs and to the classification of burr puzzles. The scale in which the puzzles can be classified is ranging from 1 to 12 so far, depending on the amount of moves it takes to take the first piece out. The highest known manmade burr puzzle is of level 9 while the computer program can easily make puzzles with a higher complexity. However, only one level 12 burr puzzle has been created so far [4].

The highest known manmade burr puzzle is made by Peter Marineau[4]; it concerns six individual pieces. The first puzzle piece can be removed after nine moves, the second piece after three more moves and after that the other four pieces can be removed by a single move. This is described as a level 9.3.1.1.1.1. puzzle.

It is important to note that the more complex the puzzle is, the more movements are required to disassemble the puzzle.

The programs ‘Puzzle Solver 3D’ and ‘BurrTools’ have been developed in the following years wherein the possibilities of assembly, analysis and animation are expanded [13].

2.2 Existing transfers

A transfer of the interlocking puzzles is made for cutlery; the “Tableware Tripod” is made of an interlocking knife, fork and spoon. The principle of interlocking is used in this transfer to present the cutlery in a unique way [14].

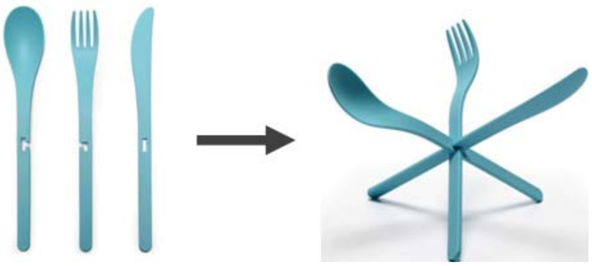


Figure 5 Tableware Tripod **[14]**

Rinus Roelofs used the Leonardo Grid construction system to make construction based on simple line shaped elements, like rods or beams. Each element in this system has four connection points, two at or near the ends and the other two somewhere in the middle at a certain distance from each other, the so called: endpoints and interior points. The endpoints in this system can only be connected to midpoints and vice versa. An example of a dome structure is shown in figure 6 and a drawing of the structure in figure 7 [16].

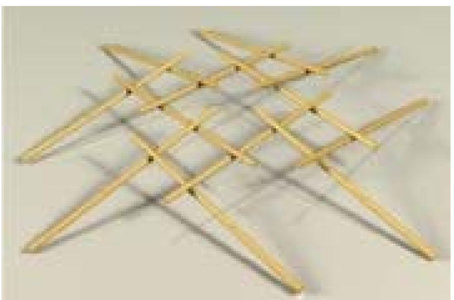


Figure 6 Dome structure

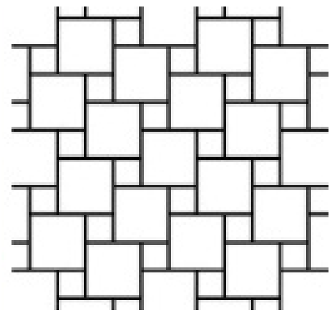


Figure 7 Leonardo Grid, Graph

An approximation of a transfer is found in Japanese joinery where a multiple of joints - which are made entirely out of wood- is used for constructions. The book ‘The art of Japanese joinery’ by Kiyosi Seike displays an overview of Japanese joints containing interlocking joints concerning splicing and connection joints. The ‘Sao-tsugi’ shows similarities to the interlocking puzzles. ‘This model exists out of a gooseneck mortise and tenon to join its members firmly. A very long rodlike half or tenon is driven through the post, into a female joint on the other side of the post. Once the male and female halves of the lapped rod tenon are in place, two keys are driven into the joint -on either sides of the tenon- to firmly lock it’ [15]. The latter action of locking the joint with keys makes this joint aberrant from the intended transfer, since the keys can be categorized as connection material or fastenings. Therefore, this example is not a pure transfer of the mechanical interlocking puzzles. In the next part, the requirements for a pure transfer are discussed.

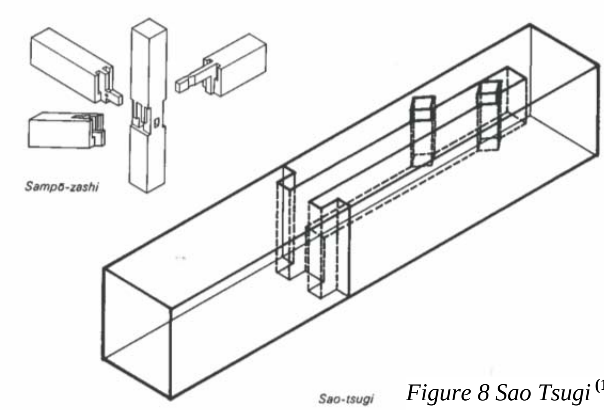


Figure 8 Sao Tsugi **[15]**

3. Design Requirements

When transferring the puzzles to construction joints, two perspectives can be distinguished. Joints can be analyzed from a puzzle perspective and from the perspective of the actual application in constructions. Different requirements can be derived from these approaches; for a successful transfer all these requirements need to be met.

3.1 Requirements from the puzzle perspective

It is inevitable that designs will need to be arranged on a grid [5]. Similar sizes and distances in the x, y and z directions are required, since for example the x-length of one piece requires fitting a y-length of another piece. In other words, the slots must all be of similar size in order to fit one another.

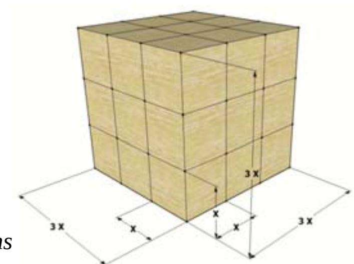


Figure 9 Size cube with use of modular dimensions

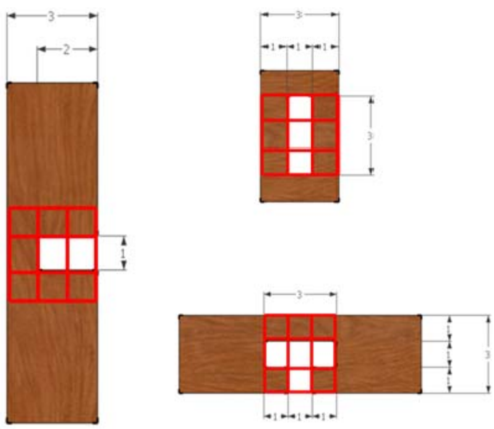


Figure 10 Similar slot sizes

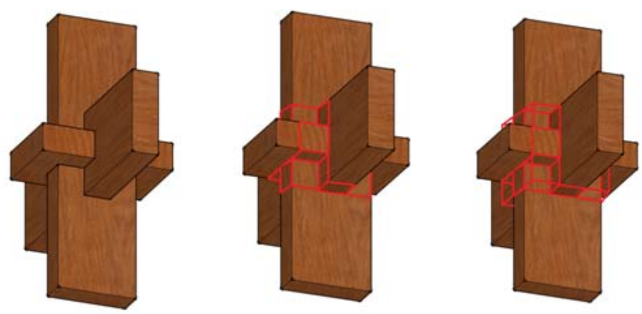


Figure 11 Similar sizes / Size cube applied in joint

3.2 Requirement from the application perspective

The function of a joint is to transfer forces from (mostly) upper construction parts -like columns and beams- through the joint into lower construction parts, so that the forces eventually reach the foundation. In order to transfer the forces in a joint, it is important that the forces per unit of area are smaller than the maximum loading capacity of the material used. Otherwise, the material and eventually the construction will succumb. This means that the areas of the supporting elements require a certain minimum size to be able to transfer the forces, and need to be symmetrically loaded. Thus, in order to construct as slim as possible, it is preferred that all the supporting surfaces in the joint are maximally involved in the transmission of forces and will be symmetrically loaded. These factors need to be taken into account in the design of the joints.

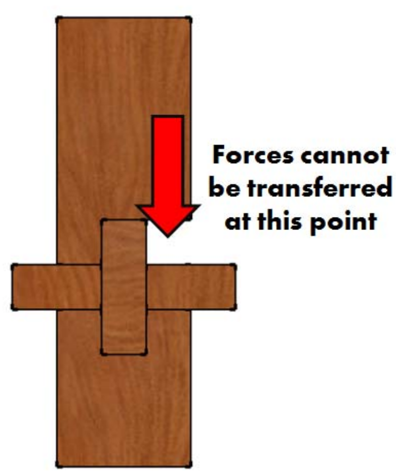


Figure 12 Undesired asymmetrical loading

3.3 Application in the built environment

An example of the application of interlocking puzzles in the built environment is shown in figure 13. The applied connection method of the interlocking puzzle is a relatively easy connection. The assembly of the construction is fast in comparison with the traditional mounting methods, since no additional materials are required for the connection. The higher the level and thus the amount of moves, the better the joint is fixed and secured, since it will take multiple moves in a predefined sequence to unlock the joint.

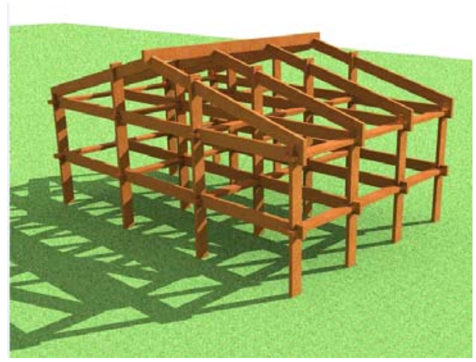


Figure 13 Construction with interlocking joints

3.4 Designing with the help of software

For the design of one interlocking joint it might be considered superfluous to use computer software, but when it is desired to design an entire building with only interlocking joints it might be useful to use computer software. Since already existing software is able to analyze puzzles on their disassembly steps in certain directions, it might not be difficult to expand the possibilities of this software with an option of designing two joints –for example the both ends of a beam- in which the key piece has to be moved in similar predetermined direction after which both joints will be locked; the key piece in this case is the beam itself. This will lead to having a structured approach of joints so that a standardization of joints will be achieved and the entire construction of a building can be erected with using only interlocking joints.

4. Conclusions

Based on the literature study the transfer of interlocking puzzles to construction joints is not yet applied in practice. Some similarities can be found in construction joints in Japanese joinery, but the key pieces in Japanese joinery concern additional materials in order to lock a joint.

The study shows that a technology transfer of interlocking puzzles to construction joints can be realized without the use of additional locking material, since burr puzzles display a method to lock a joint without additional material. The key piece in a burr puzzle can require movement in multiple directions or a movement combined with another piece; this firmly locks a joint.

The study notes that the technology transfer from puzzles to construction joints requires more than enlarging the pieces of the puzzle to construction elements, since the transfer of forces might create asymmetrical loading. This has to be taken into account when a joint is designed.

Furthermore, the research points out that when a design might be considered too complex, computer software can support the designer in designing stable construction joints.

In conclusion, the transfer to a interlocking joint will reduce the connection materials and increase the esthetic values, by simplifying the joints.

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