Towards a Digitally Fabricated Disassemble-able Building System

A CNC fabricated T-Slot Joint

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Growing dissemination of digital fabrication technologies coupled with a renewed interest in wood as a construction material have led to a resurgence of research into integral wood joints. Recent research on digitally fabricated wood joints has focused primarily on robotic or on CNC router produced snap-fit or tab-and-slot joints. These types of joints have several problems in sheathing to structure connections. The present paper reports on research into design and fabrication of T-slot joints that allow hidden back-face connections which are disassemble-able. It is part of an ongoing research whose aim is to develop disassemble-able and mass customizable construction system of partition walls for building renovation.

Keywords: *Wood Joints, Digital Fabrication, Wood, Design for Disassembly*

INTRODUCTION

Towards the end of XX century, there was a significant increase in engineered wood products, such as CLT (Cross Laminated Timber) in the form of panels, LVL (Laminated Veneer Lumber) for structural battens, just to name a few. This spur in wood products is linked with growing environmental concerns and wood particular properties as a renewable material that combines structural performance with some efficiency as insulation (Krötsch and Huß, 2016). There has also been a growing awareness of the need to reduce construction impacts on the environment at the energy level, resource consumption and waste generation, which has promoted strategies such as Design for Disassembly (DfD). Instead of focusing on energy efficiency in building operation, this strategy aims to respond to the growing weight of embodied energy in the materials, the construction process but also on the sequential renovation cycles over the building lifetime. It prioritizes reuse of building systems, components and materials and, at a lower hierarchical level, on recycling and down-cycling. It can be considered a subset of a model of environmental sustainable construction and requires understanding the building as set of layers with different service lives, as it was proposed by Brand (1994). Crowther (2009) identified a comprehensive set of principles for designing buildings or construction systems that are disassemble-able. They can be summarized as: (1) reversibility of assemblies and subassemblies into basic materials, (2) avoiding chemical connections between different materials, (3) minimize number and types of different components and connectors, (4) use lightweight recyclable or recycled materials, (5) prefabricate subassemblies, (6) increase interchangeability, (7) use construction technologies that are compatible with standard building practice and common tools, (8) increase serviceability, (9) document the construction process. Consequently, the fundamental aspect of disassemble-able systems is the nature of the interfaces between materials, building components and systems. Traditional wood joinery has developed throughout the centuries, particularly in Japan, highly sophisticated geometrical interlocks with disassembly potential. However, industrialization has led to wide replacement of these techniques by mass-produced fasteners. Digital fabrication presents an opportunity to rethink the use of integral mechanical joining techniques (Robeller et al., 2014). As Hosey (2015) has demonstrated, digital design and fabrication tools can have an important part in enabling design and production of building systems or hole buildings that achieve these principles, particularly through the use of digitally fabricated joinery. These production methods can accommodate local geometrical variability without incurring into significant production overheads, a fundamental enabler of mass customization.

Wood Joints in Cost-Effective Digitally Fabricated Building Systems

Digital fabrication tools like CNC routers or robotic arms are becoming widespread both because of reducing costs and of initiatives like Fab Lab or the Global Village Construction Set (Naboni and Paoletti, 2015). Three axis CNC milling machines have spurred an interest in construction with flat wood panels, such as plywood, oriented strand board (OSB) or medium density fiberboard (MDF), which are cheap, standard and readily available materials with known properties and more dimensionally stable and homogeneous than raw wood. The same reasoning has led a number of authors to research the innovation potential of using digital design and fabrication tools on customization of wood products for cost effective construction, such as Sass's Instant House (2006) or the WikiHouse (Parvin, 2013), or the our previous work with partition walls for renovation of old buildings (Brandao et al., 2016). They are composed of digitally fabricated components cut of flat panels with integrated wood-wood joinery that relies on geometric features and friction-fit joints for transference of stresses and connection of parts. Yet, for the connection of the sheathing to the structure friction-fit joints, also known as tab and slot joints, present some limitations, as they don't constrain the sheathing in the perpendicular axis to the plane. While this is desirable from them point of view of disassembly and assembly, warping of the panels produced by variations of moisture and temperature might cause connection problems. Furthermore, the joints are visible from the outside, which although it might be considered a design feature, can be aesthetically undesirable, particularly in interior walls. While adding extra layers to the wall is a possibility, for interior walls this is undesirable because it increases costs, wall thickness and reduces the disassemble-ability of the system. These frame and panel systems align with some design principles of DfD and are apt for mass customization strategies. Yet all parts are assembled on site thereby shifting the complexity from the fabrication stage to the assembly stage. Furthermore, while customization at the building element level allows the production of a larger array of forms, it reduces future adaptability. Following a parametric modular approach, with parametrically defined prefabricated component assemblies, provides a balance between customization and adaptability requirements. Elsayed followed that approach in his Low Cost Housing (2017). A combination of snap-fit joints with tab-and-slot joints is used to produce modular components. Snap-fit joint are easy to assemble and disassemble, address the warping problem and constrain the sheathing but as these joints protrude the surface of the panel, they increase the exposure of the joint and further complicate personalization of interior and exterior surfaces by requiring that the finishes project beyond the joint. Thus this paper focuses on material level connections that make the component subassembly. It is desirable that there is the least number of visible joints, for aesthetic reasons but also because they increase sound transmis-

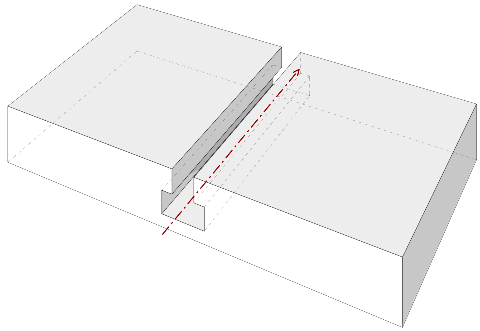
Figure 1
T-slot groove for profiles

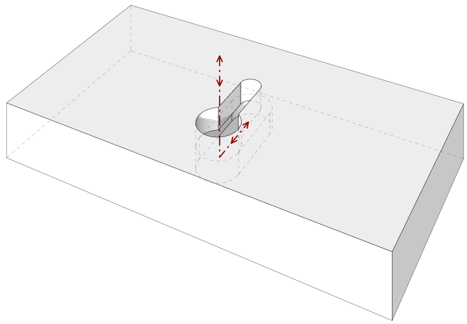
Figure 2
Keyhole slot

sion and tolerance problems. On the other hand, it is important that these connections are reversible for two sets of requirements: (1) to allow changes and maintenance during the system service life; and (2) to allow material reuse when the components are no longer useful for their original purpose. Hence it is useful to consider two types of reversible connections. Type I joints can be disassembled at any moment in the system service life while the latter type, Type II is only disassembled at the fabrication or deconstruction stages. The latter has lower tolerances and better overall performance while the first type trades structural performance for ease of assembly on site. The types of joints attainable with a given fabrication or construction process dictate the possible material assemblies and consequently the form of a construction system and its expressiveness. This article reports our findings on possible alternatives for the design of the joint and for their fabrication with a 3 axis CNC Router. Several options are prototyped, and their mechanical behavior is analyzed using Finite Element Analysis. Based on these findings we propose a possible partition wall construction system that meets the previously mentioned design principles.

METHODS

To overcome these issues, this research focuses on developing back-face integral joints that constrain Z-axis of the sheathing but allow its disassembly, without access to the back-face, by vertically or horizontally shifting the panel. There have been two main routes of research in wood joints using digital fabrication, one that explores the flexibility of robots and another that focuses on lower cost 2D CNC processes. Both lines of research have focused on joints produced with straight tools, ball head or flat head bits. Most recent research on panel to panel connections has focused on edgewise connections using robotic fabricated dovetail joinery. We explore the T-slot router bit to produce negative cuts on the board with a 3 axis CNC router (Figure 3.1). T-slot cutters are inexpensive tools commonly used for cutting grooves in MDF panels for metal profiles or keyhole slots for screws (Figure 1 and 2). The former slots are cut with full immersion milling starting and ending on opposing sides of the board, whereas the latter requires symmetrical exit and milling strategies, a combination of a boring operation with a full immersion milling. These types of slots are not useful for wood-wood joints produced with a 3 axis CNC, as these do not allow machining both sides of the board.





T-SLOT JOINT DESIGN

Designing joints for a t-slot bit requires careful consideration of the tool path and defining an exit strategy. The tool overhang and the height of the cutting edges, on the neck and head of tool, are two important dimensions that determine the design of the joint (Figure 3.1). A T-slot joint is composed of

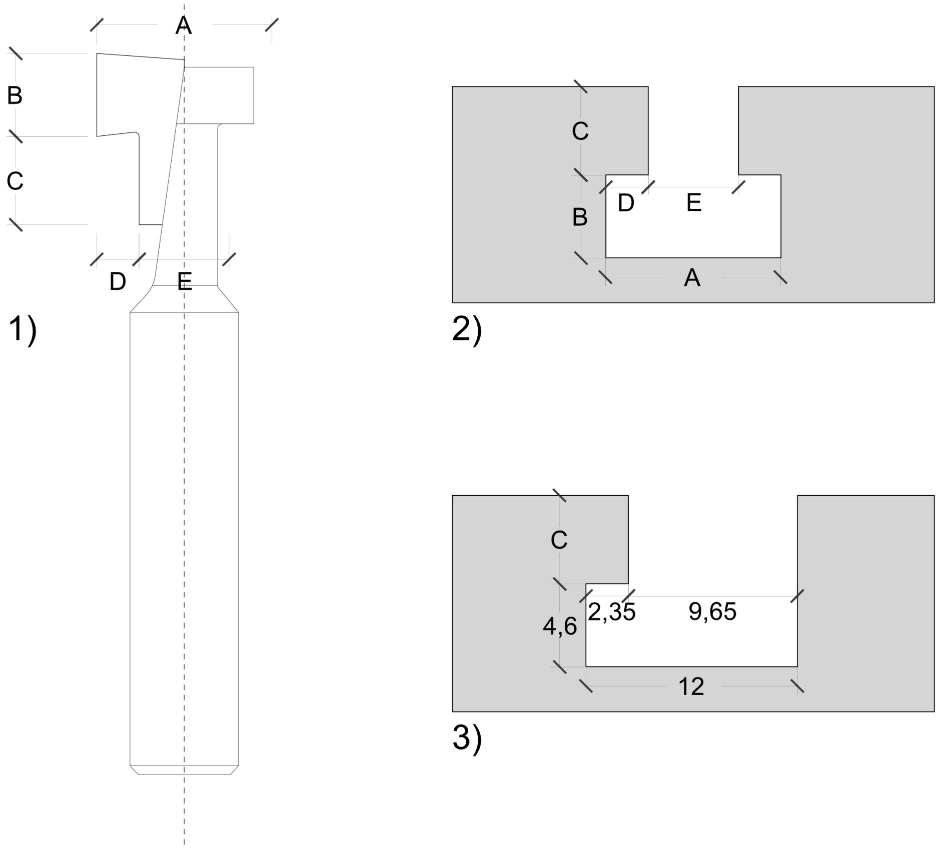
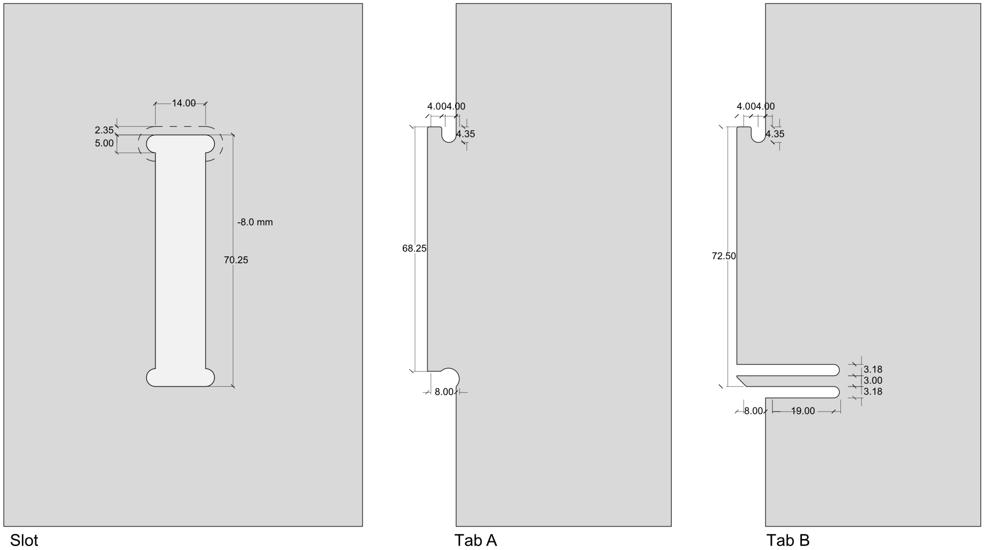


Figure 3
1) T-slot bit parts: (A) Head diameter 9,7mm (B) Head height 4,6mm (C) Neck height 4,9mm (D) Overhang 2,35mm (E) Neck diameter 5mm; 2) Typical T-slot groove: (A) Thickness of the tab (B) Height of the head (C) Mating feature height (C+B) Depth of the cut (D) Mating feature overhang (E) Neck width; 3) Modified T-slot groove for flatbed CNC

female and male parts: a slot with two overhangs and a grooved tab (Figure 3.2). To connect the parts a sliding movement parallel to the slot length is required. Frequently, a flat end mill is used for routing a groove prior to using the T-slot bit. We further explore the combined use of the two bits to produce asymmetrical slots with only one overhang (Figure 3.3), thus enabling the production of the mating feature of the structure to the sheathing on the flat-bed CNC. A 6mm flat-end mill is used to carve a pocket or a groove on the sheathing with the thickness of the structure minus the overhang, then the T-slot bit is used to create the mating feature. The overhang is limited to the difference in radii between the neck and head of the t-slot tool. The height of the mating (C in Figure 3.3) feature is determined by the depth of the pocket with an upper limit on the overall flute height, 9,5mm with our tool. The mating tab is grooved at the required distance from the edge with a 4mm flat-end mill. Several variations of

Figure 4
Type I T-Slot Joint: Vertical Slot and two variations of tab design



the joint have been designed and prototyped, they can be separated according to the types of disassembly required that have been previously defined: Type I and Type II. Joints of the first type (Figure 4) are demountable while the system is completely assembled, thus the panels are limited to small horizontal or vertical movements for detachment of the structure, using tolerance gaps between panels. The T-slot bit is used to create an overhang along the top edge of a vertical or horizontal slot. A mating hook is created on the top of a tab on the structural element. As this joint is meant to be assembled and disassembled without visual guidance while holding the panel against a wall, a larger tolerance is needed. Consequently, the sheathing contribution to the overall structural performance of the wall is significantly reduced.

An alternative design with a cantilever was explored to stiffen the connection. To dimension the cantilever, first an overall design was defined using rough approximations. Care was taken to reduce the length of the cantilever to the minimum size possible, as it reduces the resistance of the structure. Then the force required to bend the cantilever 2,5mm was determined, using the BASF (2007) design guidelines for snap-fit joints, and the thickness of the cantilever beam adjusted to a range of adequate values. There are some differences on how the snap-fit joint works and where the force is applied. Nonetheless both the general formulas or the improved formulas for the beam deflection still apply. Then several versions of the joint where prototyped to test the assumptions and fine tune the required level of force for the assembly. A 3mm thickness was found to be adequate for easier assembly, requiring 0.14 KN of force. The dimension of the slots was adjusted to act as a limiter to the bending of the cantilever.

A possible Type II joint is simply a full or half panel length slot, nonetheless this type of joint creates a continuous fragility line along the length of the joint.

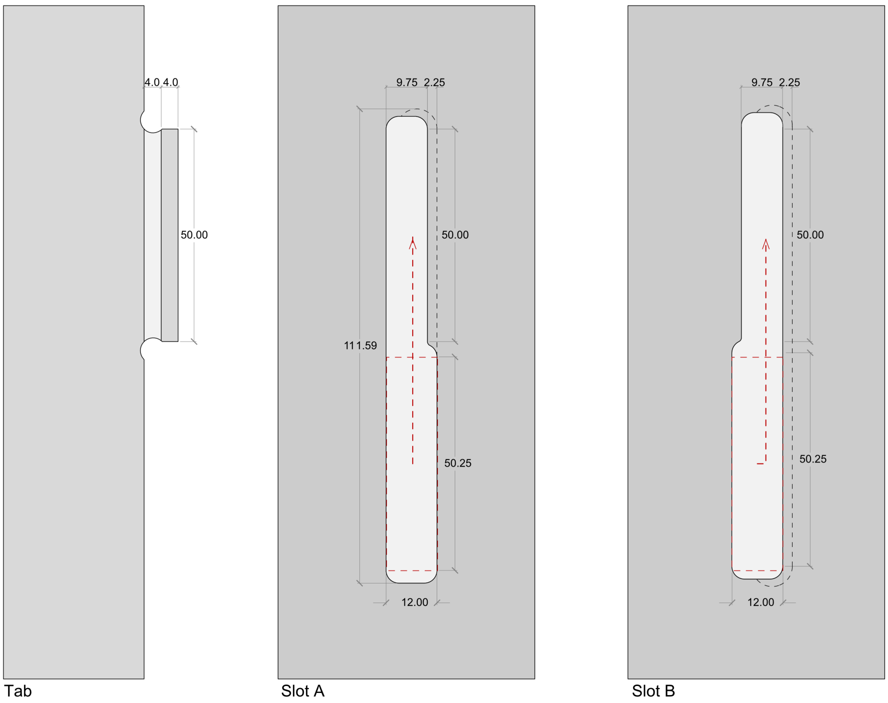


Figure 5
Type I T-Slot Joint: Vertical Slot and two variations of tab design

Another possibility is creating discontinuous connection points (Figure 5). This requires that the slot includes and entry area with the thickness of the structure. While the number of assembly movements increases, less effort is required to assemble the parts. Two alternative designs for the slot were evaluated, Slot A and Slot B, the first being easier to assemble and the latter trading easy assembly by improved structural resistance of the overhang.

T-SLOT JOINT FABRICATION

Several prototypes of the joints were produced to test the design assumptions and the assembly sequences. We have selected eucalyptus plywood as a test material, because it is locally produced from trees harvested in local forests - eucalyptus globulus. These boards are available in a range of thicknesses: 9, 12, 15, 18, 22 mm. We have selected plywood with 12mm nominal thickness, a good compromise for structural and sheathing uses, with 7 plies and an overall thickness tolerance of ±0,3mm. Our prototypes were produced in an Ouplan 3-axis router equipped with: a Solid tungsten carbide router with a radius of 6mm, operated at a feed rate of 32mm per second and a rotational speed of 14,000 revolutions per minute; a T-Slot router with steel body and brazed tungsten carbide teeth operated at a feed rate of 15 millimeters per second and a rotational speed of 18,000 revolutions per minute. Variations of +0,4mm on the Z-depth of the cut were found to occur and were attributed to warping of the panels and flatness of the CNC bed. These variations can impact the assembly of the joint as the height of the overhang is determined by the plunge of the T-slot bit. To overcome these differences, other than flattening the table, a reduction in 0,4mm of the distance of the groove to the edge of the tab was found sufficient.

SIMULATION

Eucalyptus plywood has a density ranging from 900-950 kg/m3 and is classified as C2 for interior uses in wet environments. The manufacturer reported values for Modulus of Elasticity (MOE) in longitudinal and transversal directions are 8118MPa and 6234 MPa respectively, and bending strength values are 73,49 MPa and 78,69MPa, in the longitudinal and transversal directions. Consequently the degree of anisotropy is 1,25:1, similar to values reported by Lopes (2004) although presenting lower values for MOE. For the propose of preliminary design development, the material was simulated as isotropic taking the lower values for MOE and bending strength. Using the Finite Element Software Ansys, a t-slot joint wall element was numerically simulated. Eucalyptus Plywood was simulated as perfectly elastic. Linear brick 5-nodes elements with full integration (Solid 185) were used for the mesh. The mesh was refined in the contact areas. The model was constrained on the top face of the stud. Two symmetry axes were defined on the base of the model and on the right side, thus simulating the typical distance stud to stud and a possible distance of joint to joint over the same stud. Two models were tested, a glued version and another were contacts are defined. The interfaces between the panels and the structure were modeled by surface to surface contact elements defined by the coincident nodes of the meshes. For the contacts, a friction coefficient of μ = 0,3 (Gorst et al., 2003) was considered for the tangential behaviour and normal was defined as hard contact. Behavior of contact surface is enforced by standard contact algorithm - Augmented Lagrange. In the contact model the final deflection was 8,3mm for a failure load of 5100N applied along the mid-span of the panel, with the failure occurring at the joint (Figure 6). While in the elastic model the same load caused a 4 mm deflection at mid-span and a maximum stress of 49,75N on the support.

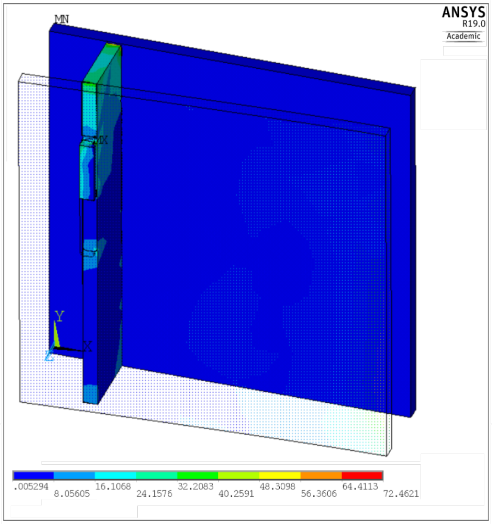


Figure 6
FEM Simulation of wall section with applied linear load on the right edge of the front panel. The image shows Von Mises stress

A PARTITION WALL CONSTRUCTION SYSTEM

The T-slot joints were used in the development of a construction system for interior partition walls, composed of plywood structure and sheathing and insulation cork board (ICB) infill. All parts were fabricated with the same tools used to prototype the T-slot joints. The system is constituted by prefabricated composite components of plywood and ICB with standard connections on all sides of the component. Thus, all components are interchangeable and reusable in different arrangements or in other contexts. As the components are parametrically defined, new components can be generated to complement parts that have been taken of existing walls to be installed in new configurations in the same space or in other locations. As there is only one way to connect the components the instruction set for users to assemble the system is small and simple to communi-

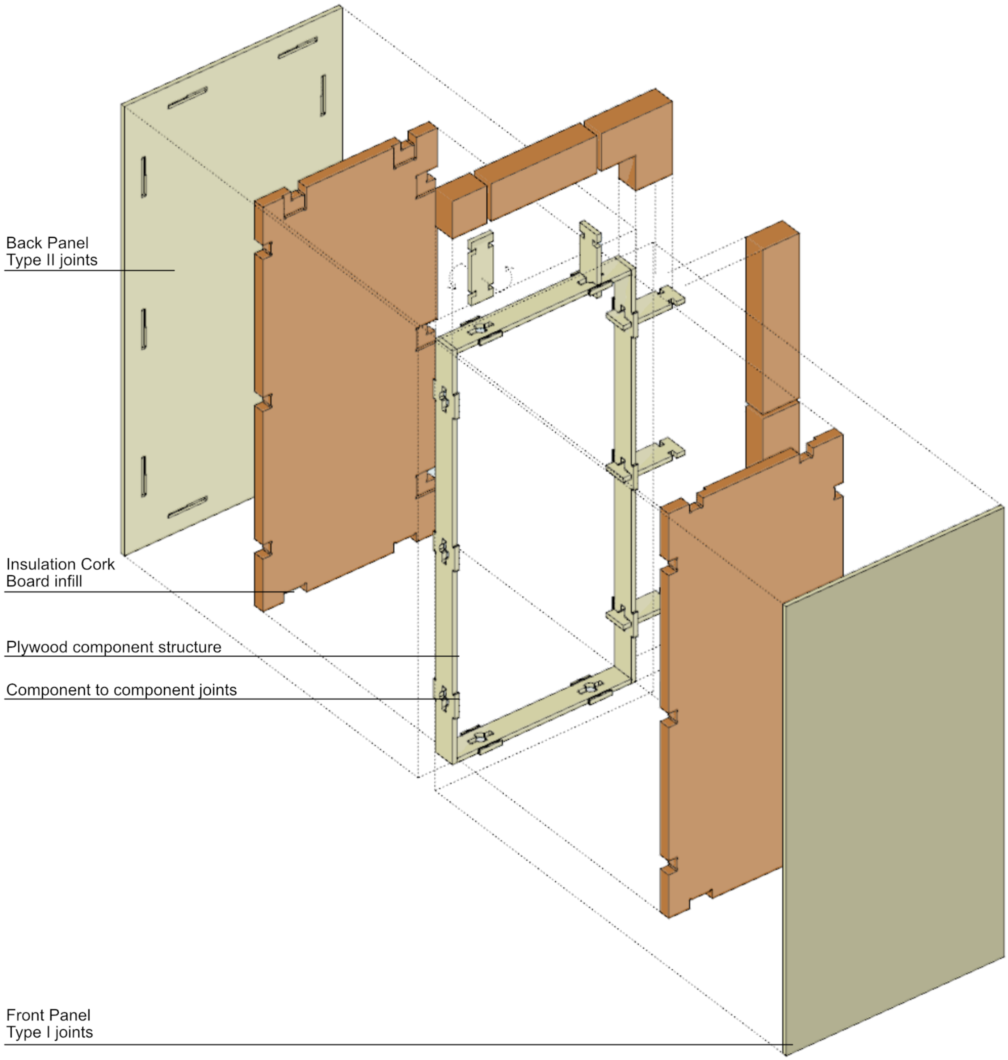


Figure 7
A wall modular composite component

cate. There is also a small number of different types of components for onsite assembly, as the only variation between components is their size. The assembly of the components is performed on the factory as in Figure 7. Front and back panels use different types of joints to allow access to the inside of the component during the assembly process and after the wall is built. Furthermore, the detail of component to component connection is reversible while the wall is assembled, which means the wall can be locally disassembled. The maximum size of the components is 1200x600mm, which corresponds to a weight of 21,9kg . A prototype of the proposed system was fabricated and assembled (Figure 8).

Figure 8
A wall section

DISCUSSION

This paper presented an ongoing research on the development of disassemble-able joints with the aim of developing a disassemble-able and mass customizable construction system of partition walls for building renovation. While the T-slot joints discussed in this article where developed for plywood and to be used in partition walls, we foresee that they can have a wider application both in other types of panellized materials with different thicknesses or connecting different building elements. They are an alternative to gluing materials to produce composite assemblies. The advantages are the possibility of decomposing a complex assembly of different materials into single material parts, thus increasing the recyclability, modularity and serviceability of the product. These last two aspects determine the degree to which a product can be repaired and thus have its life cycle extended. Another facet of modularity is that it opens the possibility for customization, both on the side of the producer or the user. Identified disadvantages are increased material use, because of the added structure and the waste in the fabrication process, more energy spent on producing the parts. Also, the dimensions of some of the features of the T-slot joint are tool dependent and consequently will not scale across materials with larger thicknesses. The simulations that were performed did not include the cork infill, which will have an impact on the distribution of loads to the back panel, possibility reducing the loads on the joint. Three point flexural test will be necessary to confirm the results of the simulations, but these results already indicate that the T-Slot joint is the assembly weakest point. To test the behavior of whole wall system, an impact test with a 50kg soft body, as specified in ETAG 03, is required. T-Slot joints open the possibility of digitally fabricating disassemble able composite components without visible joints. Furthering the objective of developing a digitally fabricated disassemble-able building system for building renovation. Furthermore, 3 axis CNC routers are more widely available than robotic arms, making the T-slot joints a more accessible alternative than dovetails for cost-effective digital construction. Nevertheless, Type I joints presented some limitations when applied to the wall system, particularly in local disassembly / assembly of specific panels. Helping tools are required for the task. Their performance was not tested or simulated but it is expected to provide little contribution to the structural performance of the system.

FUTURE WORK

The present article provided some insights into the design and fabrication of T-slot joints in plywood and their application in a construction system of partition walls that can be user assembled. While the simulations that where performed provide some understanding of their performance, further mechanical tests are necessary to fully evaluate them. Also, there is still room for design improvement, particularly in the length of the joint and the distance between them.

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