The image shows a close-up, angled view of a light-colored plywood structure. The structure is composed of several parallel horizontal strips connected by a series of interlocking joints. Each joint consists of a rectangular hole in one strip that fits over a corresponding rectangular protrusion in the adjacent strip. The joints are arranged in a regular, repeating pattern across the entire structure. The lighting is bright, highlighting the texture of the wood and the precision of the CNC milling.

SHAPING CNC-CUT PLYWOOD STRUCTURES

Design principles for CNC-milled panel wood connections in a safe spanning structure

Master thesis
Leonard Vischer
July 2015

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MASTER THESIS

Design principles for CNC-cut panel wood connections in a safe spanning structure

Author:

Leonard Vischer
4190505

Mentors:

dr. ing. Tillmann Klein,	dept AE+T, building constructions
ir. Pieter Stoutjesdijk,	dept AE+T, integration and coordination of building structures
ir. Andrew Borgart,	dept AE+T, structural behavior of buildings

In coordination with:

dr. ing. Marcel Bilow,	dept AE+T, product development
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Committee representative:

Dr. Ivan Nevzgodin,	dept AE+T, Heritage and cultural value
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Version:

May 2015

Delft University of Technology
Faculty of Architecture and the Build Environment
Department of Building Technology

01.West.110
Julianalaan 134
2628BL Delft
The Netherlands

ABSTRACT

Summary

Fab-Labs are small-scale production facilities that utilize one or a small amount of machines that can produce freeform computer aided designs. The main potential of these facilities is the inherent autonomy in respect to other building construction systems. The flexibility owed to the machine enables the Fab Lab to produce a wide variety of products: a majority of the building parts can be produced from one manufacturing system with one base material. In this thesis the structural aspect of a building system that is based on CNC milling as manufacturing process in combination with plywood as material is researched. The research restricts to these two components of the system and excludes interference of other products or systems as to identify the principle problems and subsequent solution directions.

As logistic and economic criteria dominate the overall building construction system of a Fab Lab system, for the load bearing structure the finite plywood panel dimensions and absence of adhesive bonding or doweling jointing methods form the normative problem. The inherent structural elements exclusively contain slotted joints, which cause significant discontinuities in respect to stress fluency within the structural elements.

Due to lack of precedents and available empirical data on this topic, any load bearing structure design needs validation by extensive testing of physical models, which is amplified by the mechanical complexity and heterogeneity of the material. Physical testing consumes time and resources, so a mathematical method to approximate an adequate design could save a significant amount of iterations of physical model testing.

This thesis proposes a mathematical method that can be used to design and assess spanning structures. This method covers three fundamental criteria that are imposed by both structural engineering principles and the mentioned fabrication process.

1. Joints that are inherent to the structure are optimized in terms of structural efficiency primarily, and other aspects to lesser extent.
2. Structures are safe in compliance to requirements and definitions imposed by Eurocode norms for building structures. Safe structures possess a ductile failure mechanism causing them to collapse in a preferable manner.
3. Structures remain within deformation and strength boundaries in compliance to the Eurocode norms.

The proposed design method consists of three steps:

1. An optimization process for joint shaping that is assessed by Finite Element Analysis in combination with auxiliary stress calculation methods in cases where FEA methods are inaccurate.
2. A numerical analysis method to define the participation of all joints and components respectively within the structural system, and to identify the failure mechanism.
3. A method to manipulate the behavior of joints and components within the system in order to achieve the preferred failure mechanism. The joints can be altered in terms of shape exclusively.

By application of this method, adequate design for simple spanning structures can be approximated. Despite the high potential of CNC-milling in combination with plywood in terms of material efficiency of load bearing structures, the inherent substantial labor intensity of the structural design process is a significant trade-off for a construction system that owes its potential to a typical high degree of flexibility. If the designer chooses to apply CNC-cut plywood structures within a modular building system, it should be considered the starting principle of the design, which would require all other building components to adapt.

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PART I

INTRODUCTION TO THE TOPIC: DESIGN ASPECTS OF CNC-CUT PANEL WOOD STRUCTURES



1

RELEVANCE

In the wake of the internet revolution, there has been a shift within the organization of the relation between the corporate world and costumers. Internet brought costumers in direct contact with anyone that offers a service or product, examples are sectors like hospitality (AirBNB), transport (Blablacar), fast food (thuisafgehaald.nl), taxi service (Uber) and car rental (Snappcar). These platforms offer direct access, eliminating the burden of active branding and networking for starting entrepreneurs.

This phenomenon also affects the maker industry. With the emergence of Fab Fac's – highly flexible small scale production facilities that are configured to produce small batch or one-off products – costumers can produce their own designs. This cuts short the traditional production system which involves extensive market research, design firms, product testing and certification, serial or mass production, long distance transport and retail.

Fab Facs are most commonly small enterprises with a 3D printer or CNC machine that offer their services through internet platforms such as '3D hubs' that are connecting customers and producers in the same manner as companies like AirBNB, with addition of data exchange options for down- and uploading design drawings.

The democratization of manufacturing resulting in a direct factory to customer relation, and low cost machinery are the raison d'être for Fab Facs. Mass production will always be cheaper than one-off manufacturing, so products that do not require individualization will remain within the domain of mass producing industry. Every day products like scissors, building insulation, tools are examples.

One of the virtues of Fab Facs is the ability to produce mass-customized designs. Mass customization is to make, unique products that are tailored to meet specific form and or function requirements by automatic manipulation of a parametric design algorithm. This principle combines the merits of mass production – cheap and little labor per unit – and customized production – high user quality and efficiency.

One of the ways to utilize a Fab Fac within housing context is by managing a modular system. Within this system a structure is built up from components that are interexchangeable. The interface is universal so that if a new functionality is needed just the component needs to be adjusted.

The main potential of Fab Facs is that they can be operated by a small crew and rely on one system to be able to make an unlimited amount of products. The more a building system relies on external products like screws or other mass produced products, the more effort is needed to adjust the system to the properties of these products.

2

TECHNOLOGY ANALYSIS

2.1 Introduction to Panel wood

Panel material types

A variety of panel materials can be milled with a CNC milling machine. The most common wood panel products are Particleboard, oriented strandboard (OSB), medium density fiberboard (MDF), and multiplex. Each of these materials has a distinctive base material, cohesive and production process. The suitability of these materials for structural purposes lies in their base material. The quality ranges from plywood, which is made from laminated wood veneers, to MDF, which consists of sawdust bonded by a cohesive which amounts to about half of the weight of the material.

This research focuses on structural implications of CNC-milling panel material technology, so the selection of the panel material will be defined by its structural suitability. Cost, weight and sustainability properties are considered secondary criteria only. The most suitable of panel materials can be deduced from a material strength and elasticity comparison. An important principle is that the performance of timber structures predominantly depends on the efficiency of the connections (Aicher, Garrecht, & Reinhardt, 2014). Usually the critical normative criterion for timber structures is the resistance against deformation, as opposed to resistance against collapse. This means that due to the soft nature of wood, structural elements like a beam will exceed deflection limits well before they break. Connections typically have concentrated stresses and thus larger local deformations and peak stresses. Plywood has about double the strength and rigidity of that of the other panel materials.

It can be concluded that cost and Modulus of Elasticity properties have a linear correlation. With an increase in material use, cost and stiffness increase with an equal rate, but due to comparable densities between the panel materials, weight increases as well. E.g. a structure of MDF has a comparable cost and stiffness at double the material use of that of a birch plywood structure. The MDF structure is however twice as heavy, resulting in an increased material need. The fact that Eurocodes allow plywood a more advantageous safety factor than other panel wood materials magnifies this effect. [Eurocode 5]. Though other panel materials may be suitable in other circumstances, this research will concentrate on birch plywood as it structurally the most effective material.

Plywood

Plywood is a panel wood family an Engineered Wood Product. The panels are laminated plies of wood veneer that is obtained by rotary-peeling stems of softwood or hardwood trees. The buildup consists of an odd number of plies of which

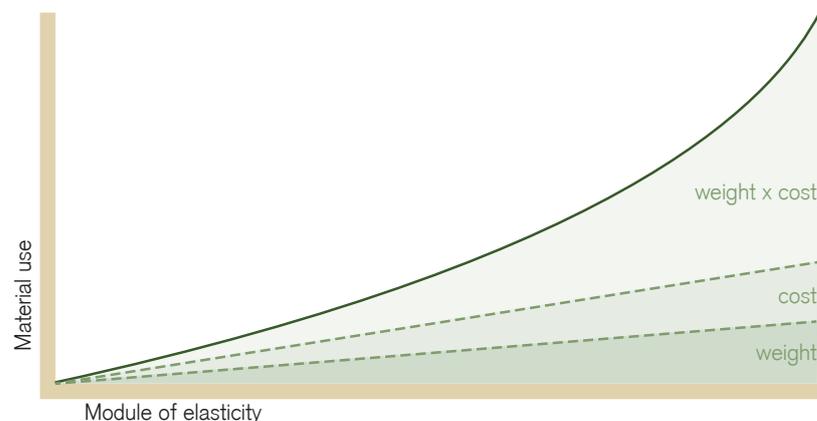


Fig1. The relation between the rigidity (module of elasticity) and material use of a structure in respect to cost and weight. At a linear increase of required rigidity, an exponential increase of material use (cost x weight) is required when cost and module of elasticity have a linear relation.

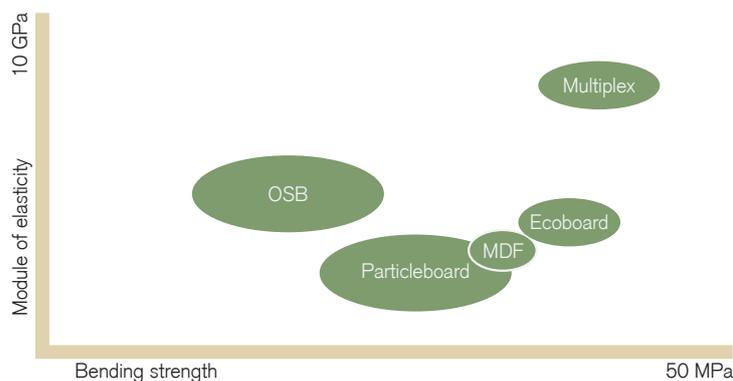
the grain direction is alternately orientated 90° and 0°. The back and front face plies have the same grain orientation so the panel will not bend. It was first produced around 1900, and has become an essential material in wood construction, due to three major advantages in respect to standard timber products:

The cross laminated veneer sheets have a positive effect on the structural quality of the material. Firstly, timber has one strong axis: along the fiber, both perpendicular axes are significantly weaker when loaded. The cross lamination of plies add a second strong axis to the material, which ensures a high shape stability and distribution of stresses through the material. Problems due to shrinking, splitting and lag are strongly reduced. "Plywood panels have significant bending strength both along the panel and across the panel, and the differences in strength and stiffness along the panel length versus across the panel are much smaller than those differences in solid wood. Plywood also has excellent dimensional stability along its length and across its width. Unlike most panels fabricated from particles, it undergoes minimal irreversible thickness swelling if wetted. The alternating grain direction of its layers makes plywood resistant to splitting, allowing fasteners to be placed very near the edges of a panel. ("Wood handbook : [electronic resource] wood as an engineering material," 2010)

Secondly, it improves the homogeneity. Due to the layering, the statistic distribution of material faults that are inherent to timber products is more preferable. The faults – like knots - occur only throughout the thickness of a single ply, rather than through the whole section, as is the case with solid timber. The European construction norms validate this property by allowing plywood a more preferable material safety factor than other timber products. Furthermore, cross-laminated veneers

The sheets of veneer are pressed into panels that can span several meters in length and width. Timber products are typically one dimensional beams due to the dimensions of the stem, surfaces like floors are created by boarding. Panel products are planar and strongly reduced material use and labor when creating surfaces. The main applications are underlayment of flooring, bracing of roofs and walls and it is used as a construction element in box and I-beams. (Larsen & Enjily, 2009).

This research mainly focuses on plywood, as the stresses in the material are not solely aligned in one direction, especially in proximity of joints, where local stresses are expected to be critical. Plywood has the best distribution properties of these scattering stresses due to its transverse layers.



Strength vs. stiffness of panel materials (Wood Handbook)

Fig 2. Relation between module of elasticity and bending strength for different panel wood materials.

General mechanical properties

To be able to design with plywood as a structural material, understanding the complex mechanical behavior of wood in general is necessary. Wood is an ancient building material that has gotten competition from other structural materials in the last centuries, but is still much used because of its lightweight, low price and easy processing. It is a versatile but complex building material, and the mechanical behavior is defined by the structures on microscopic level.

The stem is build up from wood cells. The cells are oriented in the direction of the trees' growth and are around 0,03 mm wide and around 3 mm long, depending on the wood species. As the tree grows, the stem widens: the cells multiply in lateral direction. The structural directional terms tangential, radial and longitudinal originate from the multiplication directions from the cells. Tangential means that the ring widens, radial means that the ring thickens. The cells are in direction aligned with the vertical stem axis, this is called the longitudinal direction. When sawn to timber – including plywood – these directional characteristics remain. The cells form long pores that transport liquids from the roots upwards and are called fibers. When dried, they form microscopic hollow tubes that are the main structural component of the material.

This is the underlying structure for wood to be a so-called anisotropic material, which means that it works differently in various directions. In its strong axis – along the longitudinal fiber orientation – it is slightly stronger in tension than it is in compression. When applying pressure on the fiber direction, the hollow cells compact in a permanent way, called plastic behavior. Tension causes elastic deformation, it strains, but returns to its original shape when stress is released. Wood is weakest when loaded perpendicular to the fiber orientation – either in tension or compression – independent on the wood species this is a significant factor. For example, yield compression strength for birch, is 56,3 MPa parallel to the grain (longitudinal) and 6,7 MPa perpendicular (tangential or radial) to the grain direction ("Wood handbook : [electronic resource] wood as an engineering material," 2010). Shear strength in plane of the fiber direction is relatively low, due to the phenomenon that fibers will 'roll' over each other.

In comparison to steel (210 GPa) and concrete (30 GPa), wood is a soft material. Birch timber has an elasticity modulus of 13,9 GPa. This fact makes wood structures vulnerable to deformation under stress. This is next to resistance against collapse one of the two main structural criteria in the Eurocode (Nederlands Normalisatie-Instituut, 2002).

	f_c MPa	f_t MPa	$E_{c,t}$ MPa
X	27,2*	39,2*	9148*
Y	24,8*	35,8*	8352*
Z	6,7***	6,3***	1110**

	f_v MPa	v	G MPa
XY	9,5*	0,22**	620*
XZ	2,67*	0,44**	206*
YZ	2,34*	0,44**	183*

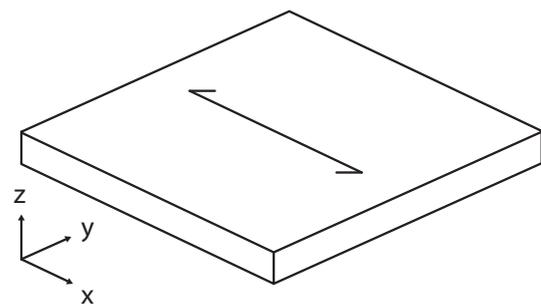


Fig 3. Mechanical properties for 18mm finnish plywood. x-axis is the grain orientation of the face layer.

Relevant mechanical properties

In the context of this research the following aspects are of significance.

1. Plywood has a high degree of linear elastic behavior, which is equal for tension and pressure loading in plane of the panel. Short before reaching maximum tensile or compression strength, the material shows viscoelastic behavior, meaning that rigidity decreases due to partial plastic behavior. In fig 4 this effect can be noted in the slight curve at the end of the elastic zone.
2. When the maximum tension strength is reached, the material fails in brittle fashion. This means that after small strain the material fails immediately and completely. A sudden decrease of strength is witnessed. Plywood fails in a ductile manner when the ultimate compression strength is reached, which means that a large plastic deformation takes place before absolute fracture. Within this plastic deformation, the material is able to absorb an additional amount of energy.
3. The compression strength of plywood is smaller than the tensile strength. In the longitudinal (x) axis of the panel this is 27,2 N/mm² and 39,2 N/mm² respectively.
4. Due to the odd number of layers the longitudinal axis of a panel has larger strength and elastic rigidity properties than in the transversal (y) axis. This means that the strength of pieces that are cut out of the panel depends on the orientation relative to the panel.

Other aspects

When designing wood structures multiple aspects need to be taken into account. Moisture content of wood can vary due to external influences. With changes in moisture content mechanical and dimension properties will change. When wood dries, it shrinks, which could cause cracks due to tension stresses perpendicular to the grain. It also becomes stronger and more rigid. Due to the cross lamination of veneers, plywood is more resistant to this effect than other timber products. Moisture content of around 10% is normal for plywood.

Plastic deformations as creep - the permanent deflection of a spanning structure due to long term stress and lag; the permanent deformation of the material around bolts are plastic behavior. Hazards like fire and fungi are not elaborated upon within this research.

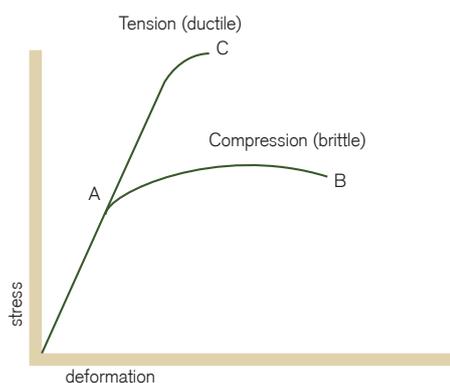


Fig 4. Mechanical behavior of plywood in compression and tension loading. A: first point of compression failure.

Material strength and elasticity data

The structural data as presented in the overview of material properties are an aggregate obtained from different sources. The data on Poisson's ratio that is missing from the supplier data sheet is supplemented from a research translating the mechanical properties of wood to an equivalent material that represents plywood which uses similar elastic properties to those of UPM specific for birch plywood (Gerrard, 1987), and the data on strength perpendicular to the panel surface is obtained from the wood handbook. ("Wood handbook : [electronic resource] wood as an engineering material," 2010)

2.2 Introduction to CNC-milling

NC technology

The CNC milling process is a phenomenon within the larger digital processing technology. The first CNC (computer numerical control) machine was built in the 1950'ies, NC-processing has since developed to be a key manufacturing process across many industries. These processes provide significant production flexibility; it enables high geometrical complexity for shaping of a wide range of materials that can be processed. In the 1980'ies, NC machine vendors developed a graphical interface for programming of the machines, these systems developed into the current CAD-software (S.T. Newman, 2008).

Digital manufacturing processes can basically be divided into additive procedures such as 3D-printing, and subtractive



Fig 5. A 3-axis CNC-machine. source: google.

procedures such as laser cutting, water jet cutting and milling. The subtractive process implies that the desired final shape is reduced from a raw material unit that is usually mass-produced, like plywood panels. The material that is removed in the process is usually waste and due to processing costs, the volume of the final shape is ideally not much less than that of the initial raw material unit. When the raw material is flat, the processing is called cutting rather than machining .

The computer aided manufacturing (CAM) process contains three main steps: Computer Aided Design (CAD) of the desired product, translation of this design to operation commands for the CNC-machine, and the processing itself.

CNC-milling in the internet era

In the last decade or so, 3D manufacturing has become accessible to a wide range of people due to the significant decrease of pricing of 3D machines and a general increase in digital literacy. Customers and hobbyists can produce their designs directly by privately owned machines or through small-scale production facilities like 'FabLabs'.

The emergence of FabLabs could bring a change to the current construction sector paradigm that can be seen across different industries: a shift from mass production to mass customization. Mass production is to produce goods as cheap as possible so that nearly everyone can afford it, where mass customization aims to produce affordable goods that nearly everyone finds exactly what they want (Pine, 1993). Pieter Stoutjesdijk argues that the potential of this technology is that an efficient process could offer cheap, customized and dismountable housing. The designer controls the whole process, including design, engineering, production and assembly. By controlling a system (like a complete house construction kit) that uses a single highly flexible machine, the 'middleman can be cut,' resulting in a more efficient process.

This implies that the whole process is centered on the digital process and the potentials and limitations of a single machine, and any dependence on other systems would water down the efficiency. For the application of a mass customization process in the construction world, it is important that as many aspects are integrated in the design, like assembly, structural considerations and logistics.



Fig 6. Various high speed steel router bits. source: google..

The customization of a project is controlled by manipulation of various predefined parameters and the success of the system is defined by how well the different aspects of the construction are integrated.

This research focuses on a specific CNC machine to limit the amount of parameters, also considering the design part of this study.

Process

The manufacturing process can be divided into three steps: the design phase, post processing where the design is translated into a set of operations for the machine, and the actual manufacturing.

Design process.

With a construction system that is based on mass customization and uses an CNC-milling machine, a difference is that all operations throughout the process need to be incorporated into the design. A construction kit type building needs to fit perfectly and any errors cannot be easily fixed. Design errors can be costly in terms of material and time waste because little further processing of the work pieces is desired after production by the CNC-machine. All the components of the product need to be final and perfect.

Design considerations include process limitations such as assembly, tooling freedom or tool palette; these impose guidelines for the design. Within these boundaries a high shape freedom remains. Efficiency is achieved by optimizing aspects like processing time and material use. Using the wrong tools or tooling approach for a process can achieve the same end product quality with a reduced economic efficiency.

The design can be drafted in any 3D-drawing program that can export standardized CAD/CAM file formats.

Post processing

The design is a drawing in CAD-format that needs translation to a language that the CNC machine understands. The translation of these two or three-dimensional design drawings to the manufacturing software of the machine - telling it how to process the material step by step – is called post processing, and comes in the form of CAD/CAM-software applications. The role of these applications has shifted from merely data translation to optimization of the production process. With these tools the designer gains control over the exact operations the machine, assisted by algorithms that optimize parts of the process (S.T. Newman, 2008).

The versatility of the NC machines has increased, as well as the complexity of the information fed into the machines. Currently there are many different types of CNC machines with a variety of properties and functions and a variety of 3D modeling software. An example is VisualCAD, a plugin that drives the VisualCAM post processing application. In this application the designer can choose the routers bits that are used, enter the material and dimensions of the work piece and set the way surfaces are finished.

After importing a 3D design with .stl .iges, .step format, from 3D drawing applications, the post processing application translates the chosen or calculated toolpaths – the path that the router travels over the workpiece - into 'G-code.' This is a code telling the machine what to do, step by step. The code consists of an action description followed by coordinates. The description is a 'G' followed by a number that indicates the type of action. For example, G01 is a linear interpolation, the coordinates mark the path on which this action should happen. Complex curves (G06.1), rapid positioning of the router to start a new path (G00) are other examples. Machine-specific actions like swapping routers are indicated by an 'M', followed by a two-digit number. The multiplicity of different actions that the machine is able to do allows a fine optimization of how the work piece is produced.

Post processing gives the operator control over how the machine processes the workpiece: the cutting and surfacing speed and the finishing quality and type. In some projects with developing surfaces, the surface is roughed by wider routers that can remove more material per sweep, and then finished by finer routers that increase resolution.

Post-processing consists of the following steps: firstly, the end machine is selected, with its specific properties and abilities. After that, the raw materials dimensions and orientation are adjusted to the machine coordinate system. Next, the materials of the objects and tools are selected, so the post-processing application can automatically determine the rotation and cutting speed of the router. The machinist then manually selects the machining actions per part of the work piece. The post-processor then generates the complete toolpath and translates it to G-code. The machinist can check his input by simulating the machining actions in a virtual display. This allows errors to be detected easily. When the machinist is satisfied, the G-code can be exported to a .nc-file and fed into the machine.

The manual input concerns the machinist to consider issues as grain direction, cutting speed and direction, choice of cutters and finishing quality. Older systems require more intensive manual labor: for example, the machinist needs to define which lines are handled in which way, like the axis or the tangent of the router needs to follow the outside, inside, middle of the drawn line.

Other post-processing applications can optimize economic use of base material. A nesting application uses an algorithm to fit as many pieces as possible within one base sheet, reducing waste.

Manufacturing process:

The following aspects of CNC-cutting are to be considered when designing:

A CNC-machine with gantry usually has tooling freedom in x, y and z-axis. Because the tool is always above the panel, milling the bottom side of the panel is impossible. This freedom is referred to as 2,5D milling.

Other than lasercutting or waterjet cutting, CNC-milling uses a rotary tool bit that removes material by blades on the outside of the cylindrical tool. At an increased router bit diameter, the blade on the outside of the tool gains speed, and more material can be removed resulting in faster cutting speeds. A router bit of 16 mm in diameter can move at 4m per minute and cut the full depth of an 18mm thick panel where a 5mm diameter moves at 0,5m/minute at a maximum depth of 3 mm per pass.

The router bits are round which means an internal corner is rounded off. If an internal corner is necessary, and the material needs to be removed because another part needs to fit, this is solved by cutting away material from the side, called a dog bone.

The work piece has to be fastened to the table to prevent movement. Some machines have a vacuum system that pulls an air permeable panel (spoil board) to the table, as well as the panel from which the work piece is cut. This is a soft surface that allows the router bit to cut through the work piece and a little bit into the panel. MDF is often used. The suction clamping strength is relative to the surface area of the work piece: the larger the part, the larger the clamping force. Small parts can move when being cut due to the force of the router and the small surface area. These parts can remain attached to the main panel by small 'bridges' that are manually cut later when the panel is finished.

The machine operates within a virtual coordinate system that is aligned with the actual space in which is milled. Before the milling process can be started, the machinist needs to make sure that the machine is setup exactly as the configuration condensed in the G-code assumes, basically, the origin and orientation of the machines coordinate system and that implemented in the G-code need to be aligned. To reset the base plane of the table to zero, it is often done to take off a thin layer of the top layer of the spoilboard by milling. Also all the tools that will be used in the production need to be in the right slot as programmed. Because there could be a slight offset between virtual and actual coordination

system, a margin of 20mm around the sides of the panel should be used.

Potentials

The possibility to translate mathematically described lines and curves to paths that can be exactly produced by stepper motors that can precisely position the spindle on point in a 2D plane, offers the ability to cut or route wood in high-resolution and complex shapes. Some construction projects, like the UK-based Wikihouse project, use this principle by making parts that fit perfectly together as in a construction kit. It needs bolts and screws just to secure the parts, not so necessarily for load transmission.

The fact that a machine can be equipped with a series of tools, makes ownership of an assortment of power tools obsolete: one machine can have the function of many different woodworking tools, making the technology available for lower skilled workers.

Limitations

There are some things that can't be done with a CNC-milling machine, these limitations have to be considered when designing. Firstly, since most of the labor is shifted to the design and planning phase, the design needs to be checked within a virtual environment. Failures in the design that are only discovered after production are costly, because the process for all affected part usually has to be done over from the start. Components that have faults usually are waste.

The CNC machines cannot produce full 3D parts, because the router bit can't mill from the bottom upwards, the z-axis is limited to cutting from the top downwards. With standard CNC machines, no angular cuts in relation to the top surface are possible. If components are designed to fit into each other in a corner, this can only be done orthogonally. The driver of the router 'thinks' in two-dimensional planes. The three-dimensional shape is built up from layering these planes.

Because in subtractive production methods material is cut away, the waste of high quality material is inherent to the process. Optimization tools for the maximum use of plates exist, but still a part of every panel is wasted, directly influencing the efficiency of the spanning structure.

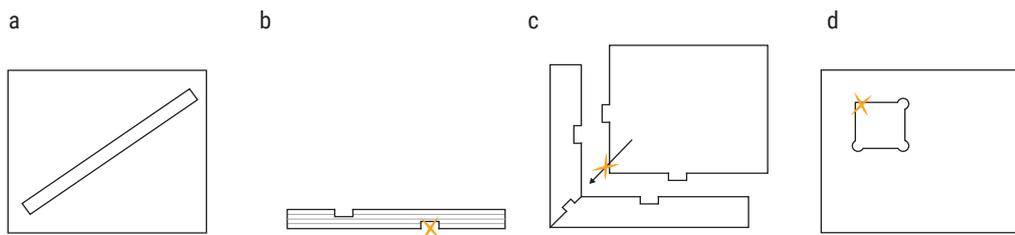


Fig 8. Limitations of the design and fabrication process. a: the panels need to be used economically, material waste is a significant economic factor. b: 2,5D milling. work pieces cannot be reached from the bottom up and cannot be flipped due to unprecise alignment with the machines' virtual working space. c: the assembly strategy needs to be implemented into the design. d: overcut notches remove extra material where a 90° corner is needed. the cylindrical router bits cannot cut sharp corners.

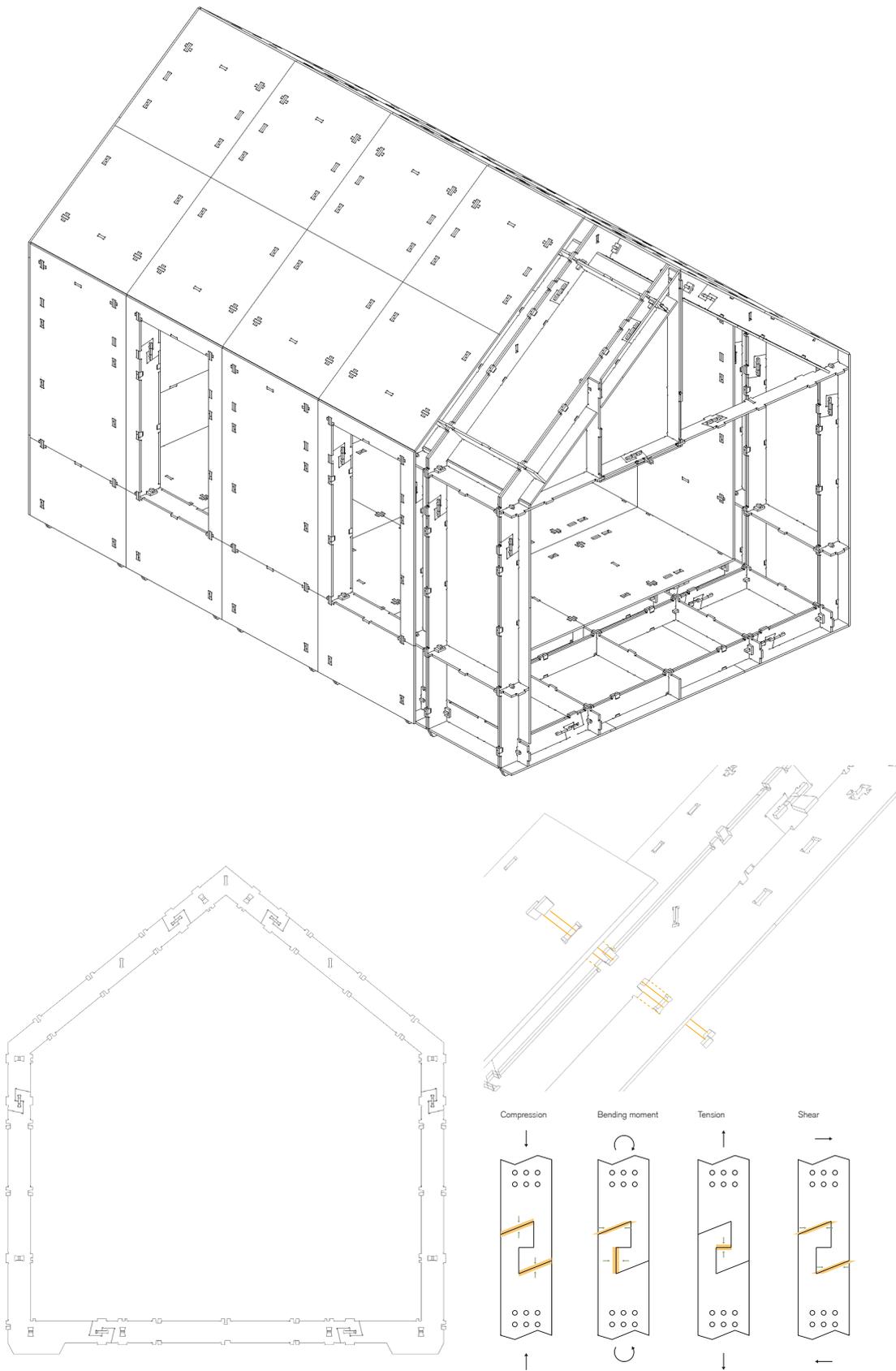


Fig 9 (top). Isometric of the Wikihouse.

Fig 10 (left). Projection of the main structural frame.

Fig 11 (right top). Jointing mechanism of the frame and cover panels. Wedges are hammered into slots.

Fig 12 (right bottom). The versatile 'S-joint' is capable of resisting all load types through compression area's (orange).

2.3 Precedent analysis

Two examples of buildings from structural CNC-cut components are compared. The open source construction kit 'Wiki-house' designed by Alistair Parvin and the modular and customizable Music Pavilion in Huis ter Heide, Netherlands, both rely heavily on the CNC-cutting of plywood as the encompassing construction principle.

These projects are categorized by system principle, structural principle, economy, material usage and complexity of assembly.

2.3.1 Wikihouse

Concept

The Wikihouse-project is an online platform for the sharing of housing construction sets. Driven by the motto "architecture for people by people," this concept aims to democratize the construction practice by granting the broad public access to cheap, easy to build designs that can be CNC-milled by a local NC machine (Glancy, 2014). Wikihouse founder Alistair Parvin formulates his goal as: "The aim is to allow anyone to design, download, and 'print' CNC-milled houses and components, which can be assembled with minimal skill or training." The designs are based on plywood sheets, but in the future designs should be based on locally available materials.

Construction principles

That low skilled labour and low dependency on third party items such as tools or screws are the main principles of this Wikihouse version can be derived from the design instructions. The designers' manual drafted by Parvins firm 00 Architects (2013) that is aimed at voluntary design contributors to the website platform suggests the components of a design to be fool proof. It also limits the tool palette to wedge spun joints that can be made with a mullet that is cut from plywood as well

These principles are the formative factors for a building type. One of the designs on the website is the 'Wikihouse v3.0.' The concept of the house states the following prerequisites:

- The whole building can be constructed using exclusively a CNC milling machine and plywood panels.
- Building components are exploited in a structurally efficient manner: the amount of material that does not contribute to the load-bearing system is reduced.

The Wikihouse is 3,60m wide, with a nock height of 4,25m. The layout is based on a 1,2 x 1,2 m grid, with a symmetry axis through the heart of the house. The length of the house can in principle expand to infinity on this axis.

A double layered frame following the outline of the cross section is the primary structural element of the Wikihouse. The five corners are rigid angles, cut from a panel. The necessary joints are integrated in the middle straight parts and are alternating between the layers to maintain stability. The beam is 200 mm in height and supports roof, facades and floor. Secondary beams are mounted between the ring-beams. Sheathing panels are fastened onto nocks on the in and outside of the beam and provide both structural stability of the façade and seem to form flanges, adding to the structural performance of the cross sectional frame.

Secondary beams traverse the primary trusses at steps of 900mm, The orthogonal frame is clad with panels that provide stability and interior finishing simultaneously. All components are connected using peg in slot joints where a peg is hammered into a tapered space cut out of a member. The tapered shape of the pegs constitutes a structural tension in the joint, increasing rigidity of the connection.

The consequence of confining to this type of connection is that all joints need to be accessible from the outside. The outer sheathing of the Wikihouse is installed in the last construction step. All designs can be edited in Sketchup, and the components are arranged and fitted in virtual plywood sheet by a plugin, so that it just needs to be sent to a machine nearby.

Structural:

The main structural component is the frame along the perimeter of the cross section of the house. This is a double frame with skipped joints to increase stability. The main Joint is the omnipotent S-joint as is depicted in the figure. This joint can resist tensile, compressive normal forces as well as bending moments and shear forces. The joint is used on different locations where joints can be applied that are more specifically designed for the type of load on that location. The frame uses the roof bracing on some points as rigid element. The small amount of connections between frame and bracing strongly limits the effect of this measure. All joints use peg in slot connections that are friction fit. The peg-in-slot joints designed so that the peg can be applied in any way, the builder cannot do it wrong.

The sheets with construction elements are not efficiently nested so a large percentage of material is wasted. Also the amount of elements is relatively high, which complicates assembly.

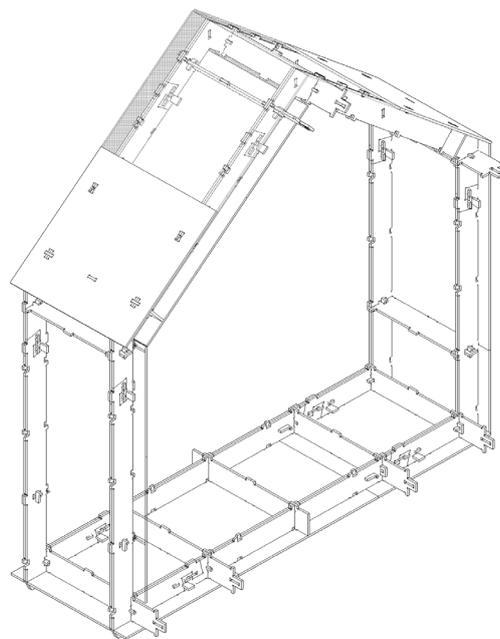
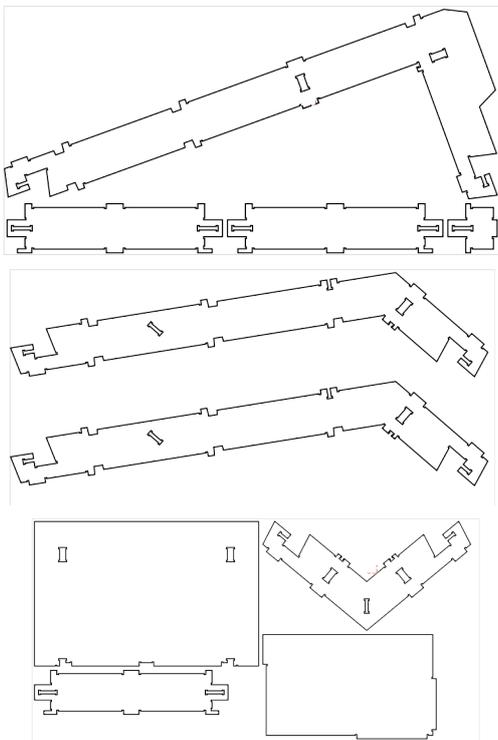


Fig 13 (left). Three panel cutting drawings as downloaded from the Wikihouse platform. The amount of waste is relatively high.

Fig 14 (right). Isometric of various structural parts of the Wikihouse.

2.3.2 Music pavilion

Concept

The Music Pavilion in Huis ter Heide is a single room building constructed with strong modular characteristics. The key principles to the design are of logistic and economic considerations. The amount of different elements is kept to a limit, while maximizing repetition. There is only one floor element type and two wall types. The modular approach is found in the principle that panel cut-outs are first assembled into components that are designed to be handled with two builders. In a next step these components are assembled to form the final structure. The panel cutouts that form a component are optimized so that they can fit in one panel. This organization of panels reduces logistical complexity. The extra step of prefabricating components is also a logistical consideration.

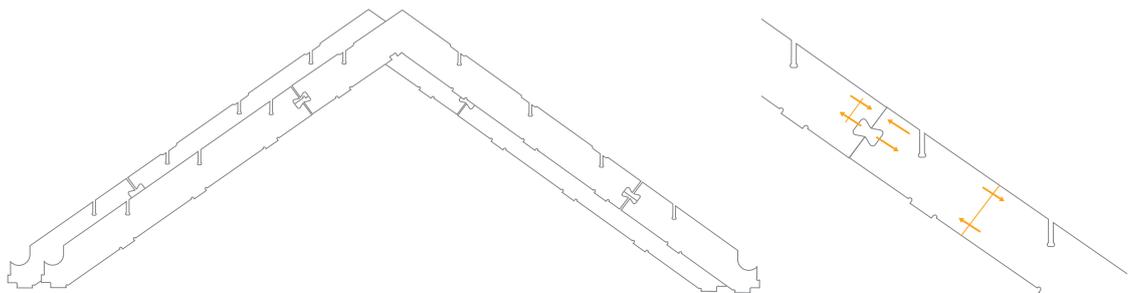
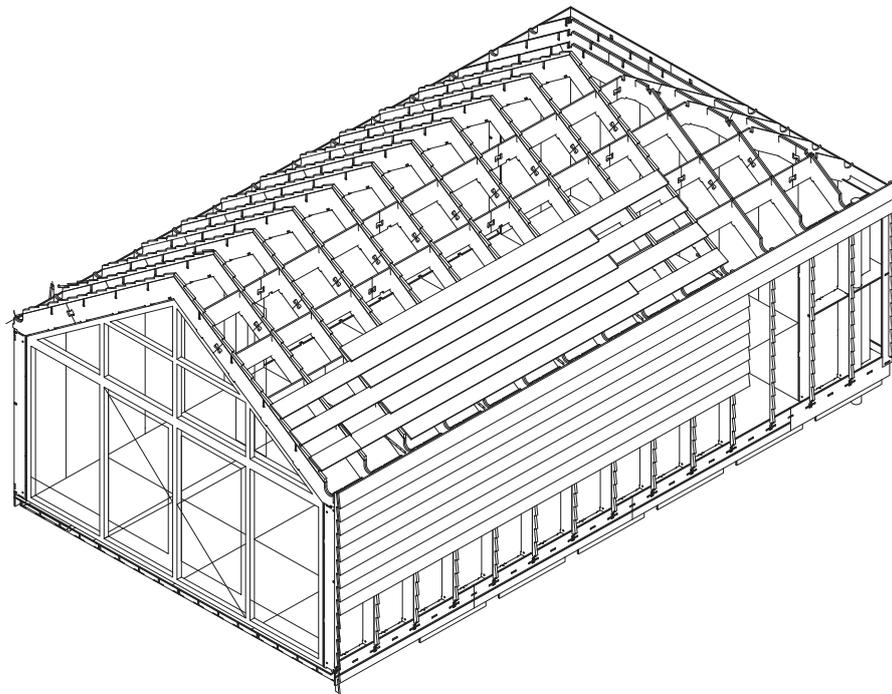


Fig 15 (top) . Isometric of the music pavilion in Huis ter Heide

Fig 16 (bottom left). roof truss structure: a double layered vertical truss with alternating seams.

Fig 17 (bottom right). Detail of the butterfly joint in the roof truss. The effective structural section is decreased at the joints' location forming a local weakness.

Wall Block
Isometric and elevations

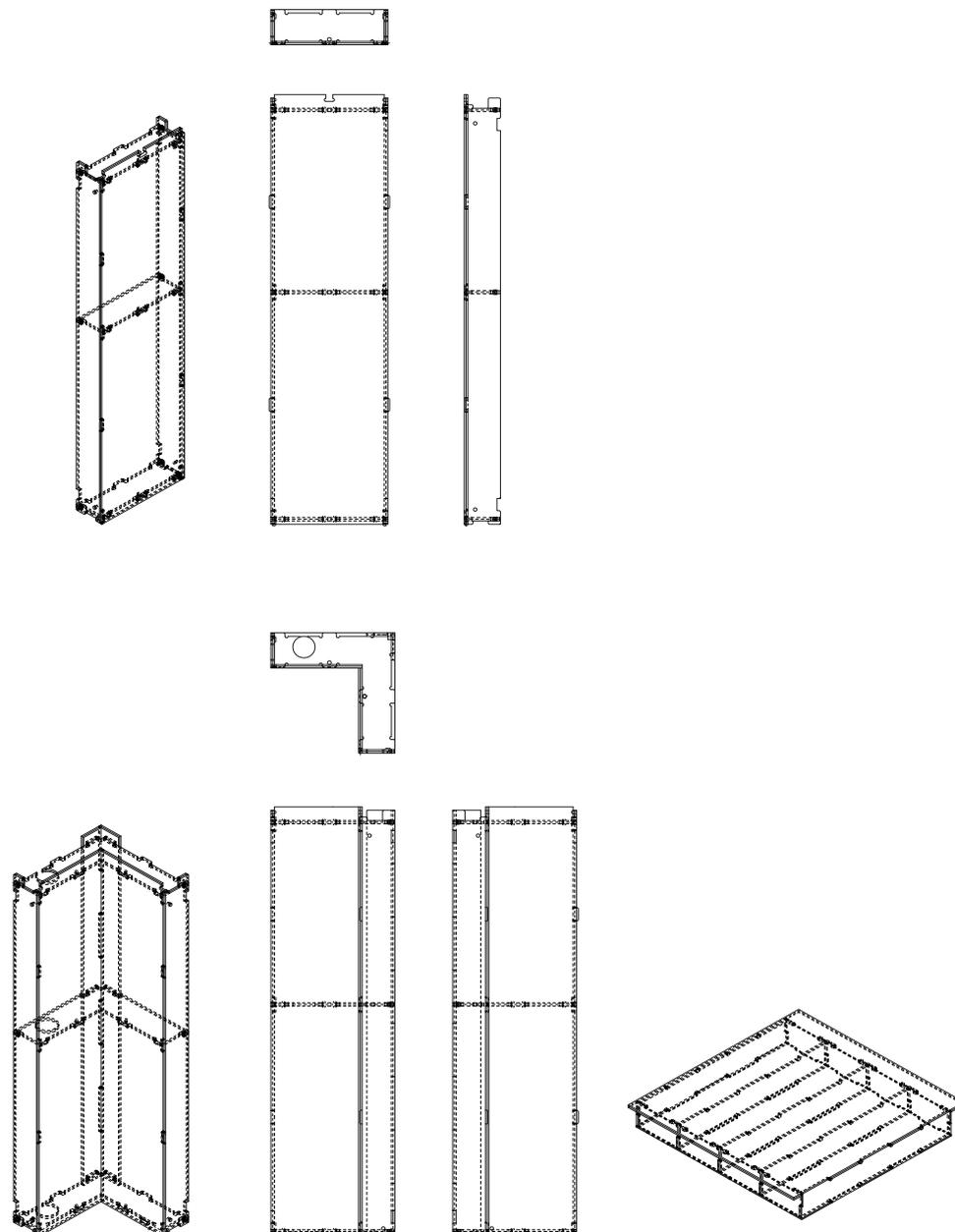


Fig 18. various prefab elements that are used in the music pavilion. Respectively a wall module, a wall corner module and a floor module. The layout of these modules is based on efficient panel cutout shapes.

Structural principles

The whole building is drawn up from CNC-cut elements, with exception of bolts that secure the wall elements, foundation beams, and a cable that resist lateral splash forces that result from the roof structure. The v-shaped roof beam is designed to be a rigid beam that is hinge supported on the wall elements. As the span is 4,8 m and the used panel size has a length of 2,440m seams are inherent, the beam consists of two layers of vertically orientated panels with alternately shifted joints to provide rigidity. The panels are butt-jointed in the seam and are joined by a third butterfly shaped connector. This is to make assembly of the beams easier because the elements do not have to interlock, which would require the elements to be shifted into each other in lateral direction. The trade-off is that introducing a third element – the butterfly connector – results in increased deformation. In addition, this connector forms the conveyance of tension forces. Because the location of the connector is in the middle of the beam height, the effective cross sectional moment of inertia decreases drastically. This consequence is partly solved by the double layered cross section. The cross section lacks flanges and has little material in compression and tension zones.

2.3.3 conclusions

The buildings show the potential of CNC-cutting plywood as a system, especially in the field of modular construction systems. Almost all of the components can be produced with one versatile CNC-milling machine. The essential criteria that define the effectiveness of this approach are logistics, material efficiency and assembly strategy. The precedent buildings show underdeveloped experience in the field of structural design. As CNC-cutting plywood is also the chosen method to produce structural elements, there are no precedents, empirical data or guidelines that address structural design using this system. The apparent structural design problems of these precedents are the spanning structures that involve seams and inherent joints. These joints can only convey forces through compression surfaces, resulting in local weaknesses of the overall structure.

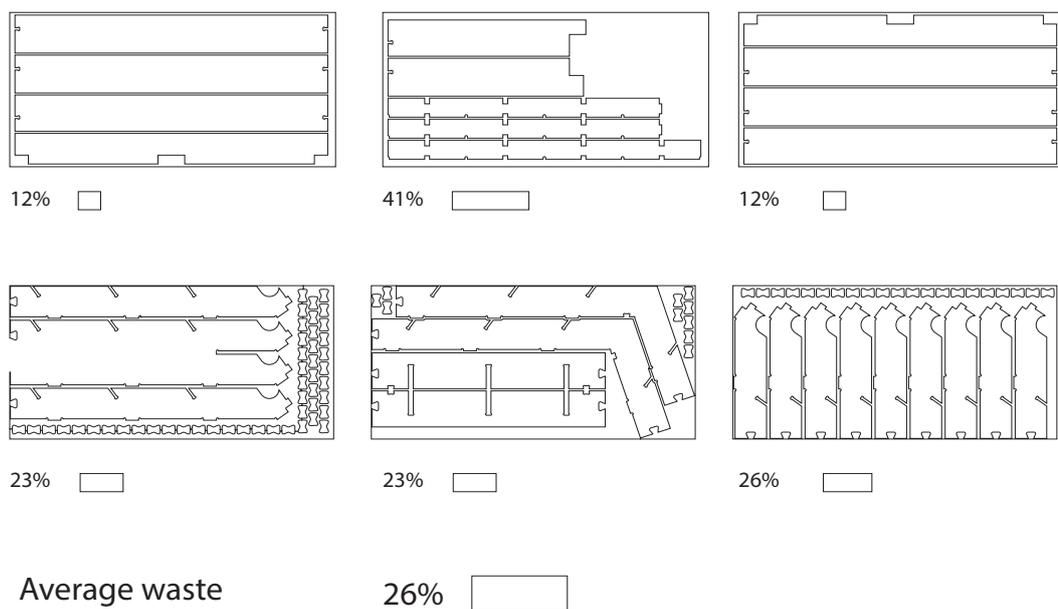


Fig 19. Various panel cutting layouts of the music pavilion. Waste reduction is a driving principle.

2.3.4 Japanese joining

Japanese joinery is a class of woodworking that has highly evolved over time. A wide range of influences has resulted in a wide variety of joints over time. Due to the many forests in Japan, wood was virtually the only viable construction material as opposed to the West or China where masonry and stone were abundant as well, but the Japanese culture has its influence on the forms of joints as well. The tree had spiritual meaning, carpentry was an honorable job and the structure of a building had to be perfect structurally as well as esthetically.

The structural design followed a system of proportionality and derived its measurements from objects of everyday use, like furniture or mats. The typical Oriental sweeping hip-and-gable roofs with large eaves are a technique to disguise the natural deflections inherent to wood construction. Radial raftering in the corners of the eaves was a structural improvement. This geometry posed further complexity to the structure, members crossing from any direction required structural and esthetical sound joining.

The carpenters used saw, ax and hammer and chisel. To limit deformations they had to deliver perfectly fitting joints, of which mortise and tenon were most used.

Criteria like member dimensions, economic factors, material behavior and strength, earthquake absorption, a specific toolset and strict esthetic requirements are the formative principles of the vocabulary of Japanese joinery. The single instrument to resolve all requirements was shape.

The most commonly used tools are saw, hammer and chisel, so all cutting lines are straight. They make use of full section wood so 3D connections are common and are used to have parts locking exactly into each other. The Japanese use no metal doweling and to increase rigidity, the joints are very precise.

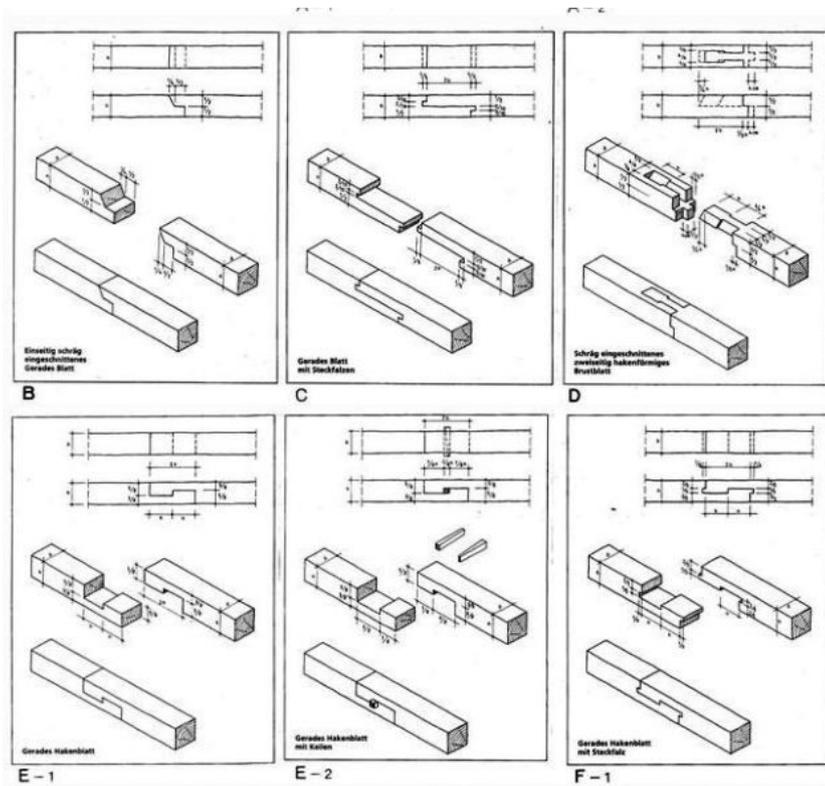


Fig 20. Various japanese joint designs. The joints fit precisely because little connector solutions were available.

2.4 Introduction to structural design of wood buildings

History of wood connections

Since the end of the ice age around 60.000 years ago, men have been using wood as a structural material. In those days just as tent frames and brushwood huts. In the following centuries the wooden structures have evolved step by step, new tools and methods leading to new construction principles, with the CNC-milling machine as one of the latest developments. In this chapter the evolution of wood connections is summarized.

One of the first jointing techniques used the natural shape of wooden members – like forks and hooks – to fit the construction. Bent wooden parts are also used as consoles. The application of rope-like material made joints possible that are not confined to the shape of found wood parts. The cross bond could cross-connect any wooden parts together. The material used ranged from plant material to yak hide. With the application of wedges and pegs, connections could more or less be made rigid, and locked into place. By driving a wedge between parts, the parts are put under internal tension and conjoin in the structure. In some cases a harder wood type – like oak – is used to fasten softer wood elements to strengthen this principle. Pegs were soon to be forced through the middle of wooden elements, which was the basis for both nails and dowels. These joints use solely mass-produced nails, which were cut by metal tools.

Eurocodes

A structure is normally designed based on experience of an engineer in a certain material and is assessed by computer modeling and control formulas that are based on a large pool of empirical data. The structural designs are approved if they comply with construction norms. In Europe the norms are called the Eurocodes. If the integrity of a structural design cannot be proved by calculations based on the formulas, further evidence needs to be delivered. This can be in the form of physical tests among others

Safe structures

A structural element can collapse in two ways: ductile or brittle. The first results in a deformation due to increased loss of elastic rigidity. Brittle failure of a material is when a part completely fractures after a relatively small strain. All structures are preferably designed to fail in a manner that the structure gives a warning before collapse. When a brittle joint fails, all capacity is instantly lost. When a joint fails in ductile mode, the loss of capacity happens gradually, along with a deformation. As the joint weakens, a redistribution of stresses in the whole structure can take place. (Nederlands Normalisatie-Instituut, 1994). Timber and steel dowel joints are therefore required to fail through a double plastic hinge, keeping wood as a brittle material intact.

3

RESEARCH DEFINITION

3.1 Problem statement

The most efficient way of utilizing a Fab Fac production facility is to keep the design principles close to the fabrication process. The primary potential of a Fab Fac is automated production of a digital design that is easy to modify and thus able to create a wide variety of products without the need of a large design effort. A modular building construction system would be a logical method based on this principle, due to the partitioning of the building into components that can be modified individually without influencing other parts of the building.

To preserve the autonomy and flexibility of the Fab Fac production system it is best to limit the dependency on industrially produced third party products like bolts or steel profiles as much as possible because it will require the Fab Fac design to adapt to their properties. The less compromises have to be made, the easier the design is managed, reducing the design effort.

This principle implies that the ideal load bearing structure design is composed solely from joints that are cut from the panel and do not require connectors. As CNC cutting panels is a 2D freeform operation, shape is the only instrument to manipulate effectiveness of connections.

No adhesion between the panels is possible so all joints in the load bearing structure are based on conveyance of forces through compression surface areas. Tension joints can also convey forces through these compression areas by creating an interlocking shape. Other than for example steel or concrete, an aggregate CNC-cut panel wood structure does not have a fluent distribution of stresses through parts of the structure, but conveys internal stresses through a multitude of these compression surface areas, where these stresses are concentrated. This complicates structural design of such structures.

The limited dimensions of the panels pose the main problem. Length and width define the reach of a panel, any spanning structure that is larger than the length of a panel unavoidably has seams where forces between panels need to be conveyed. These seams are normally an obstruction of the flow of forces that concentrate around the compression areas of a joint. The surface area of these compression surfaces is limited by the thickness of the panel in one dimension. If two panels intersect perpendicular to each other, the maximum surface area is the panel thickness squared. These relatively small areas convey a large part of the internal forces and subsequent stress concentrations are assumed to be normative in terms of deformations and maximum strength of the structure.

The many connections make an assembled structural component relatively complex for structural design. All joints interact within the system and because every joint influences the stress distribution within the structure due to their viscoelastic behavior, such a structure has a high degree of non-linear behavior. This makes prediction and analysis of the design a difficult task.

The construction norms require structures to be safe through implementation of a ductile failure mechanism. This means that the performances of all of the joints in an aggregate structure need to be controlled. The typical low E-modulus of panel materials and initial movement in loaded seams due to fabrication tolerances forms a significant challenge in respect to deformation requirements by the Eurocodes.

3.2 Research goals

The aim of this thesis is to provide the designer and operator of a Fab Fac facility bearing on how to tackle the issue of structural design as part of their product. The reader learns the relevant aspects of structural design in relation to material properties and production process, how to approach structural engineering with this process and give insight in the possibilities and limitations of this way of construction.

3.3 Research questions

What implications does the production process of CNC-milling technology in combination with panel wood provide for structural design?

Sub-questions

What is an efficient load bearing structure?

What is effective design for a safe load bearing structure?

What is an efficient design for a CNC-cut plywood roof structure?

What criteria follow from production process and material choice?

What are critical joints in a CNC-cut plywood load bearing structure?

What is an effective method for structural design of CNC-cut plywood load bearing structures?

What effect has structural design of CNC-cut plywood load bearing structures on a modular design system?

3.4 Scope

The construction system of CNC-cutting plywood involves a broad range of criteria, including material efficiency, assembly strategies, logistics and architecture. This research will exclusively focus on the aspect of structural design within this building system and other criteria will only be involved as a side note without extensive scientific backing. The topic of CNC-cut plywood structure design is reduced to essential aspects that involve this technology and principles of structural design as a discipline.

3.5 Methodology

Design can be described as a process of emergence and discovery resulting from the definition of the constraints, their relationships, and the design problem (Kilian, 2006). There is little information on hand about shape-oriented design of compression contact area-joints for wooden spanning structures, so it is essential to map the constraints and their relations to each other and the whole structure. In this research aspects like machining limitations, material behavior, structural engineering principles and optimization processes conjoin.

As all these aspects are to be explored, they are analyzed individually and are tested in a design where they interact. This is a spanning structure design that covers all these areas.

The research is conducted through research by design in order to fix a large amount of parameters. A case study is conducted that involves a production facility and a design assignment. The design of the building generates a set of criteria for the design of the structure, which can be duly assessed.

A method for structural optimization of joint shapes is proposed.

A mathematical approach for design of spanning structures is proposed

A method for validation by physical testing is proposed

These methods are assessed by the design assignment following from the case study.

PART II

CASE STUDY: BUILDING THE TU DELFT P.O.-LAB



4

OBJECT DESIGN: P.O.-LAB

4.1 Architectural Concept

The design of a building that houses a course for master students of the architecture faculty, to be called 'PO-Lab' forms the basis of the research. It shall be build on the parking area outside the faculty, elevated one story above terrain so little parking spaces will be lost. It houses the buckylab course is a course where students are challenged to realize their technical designs into mockups. This is a hands-on course with a lot of handicraft and creative energy. The pragmatic and industrial spirit of the course is translated into a simple but effective cross section of the building.

The design is based on passive lighting and ventilation systems shaping the cross section of the building. The building is an extrusion of that cross section to give it a simplistic and pragmatic character. The grid is based on a new layout for the underlying parking spaces, a grid of 2,7m squared. The shed roof is inclined at 15°.

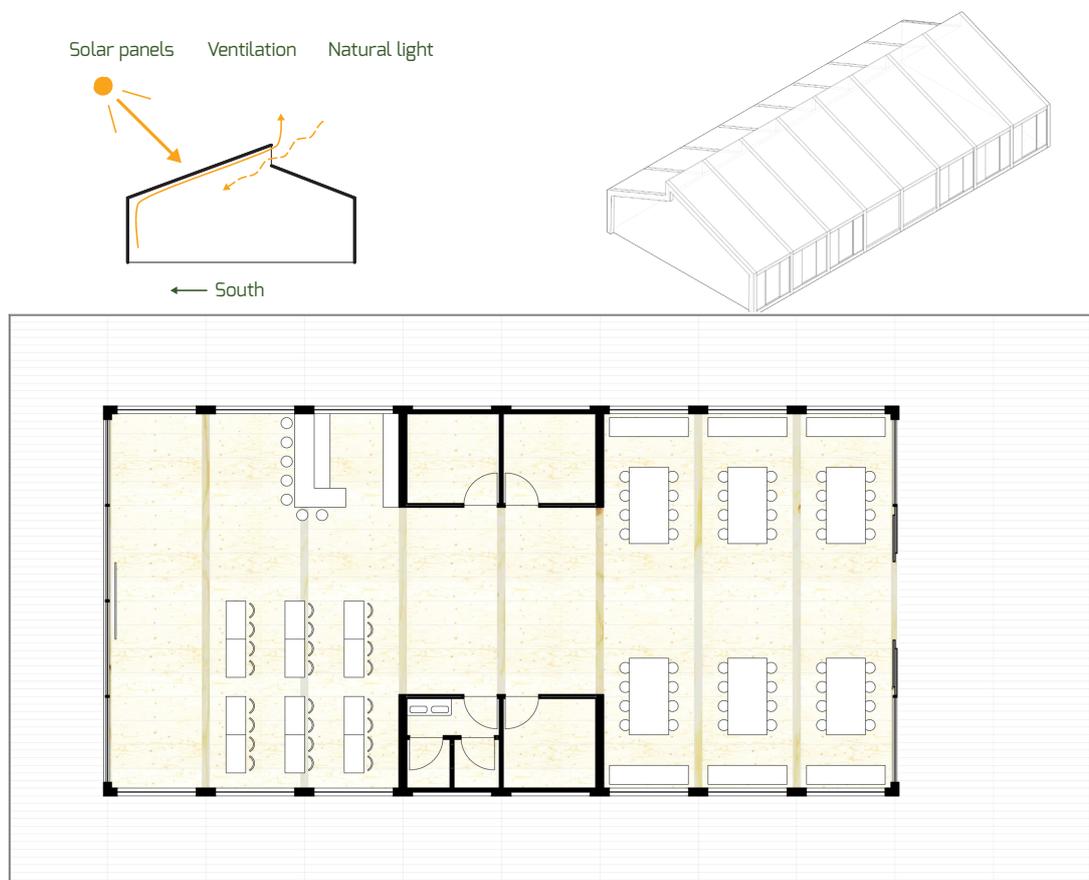


Fig 21 (top left). The cross section shape is based on passive building design principles

Fig 22 (top right). Isometric of the P.O. lab.

Fig 23. (bottom). The floor plan of the P.O.-lab. The right section for machine operation and construction is divided from the left section class room and bar by two stability cores that house toilets and storage space.

4.2 Properties of the manufacturing facility

A Fab Lab in Delft is designated as the production facility of the structure. Its hardware is a CNC-milling machine with x,y,z axis freedom and a vacuum clamping system.

Sales value of a 18mm birch plywood panel at 1220 x 2440 mm is EUR 72,-, which is EUR 24,19 per m². Machining prices vary per tool:

Router bits: 16mm / 4,0 meter per minute / 0,50 EURO per meter

4,675mm / 0,5 meter per minute / 24,00 EURO per meter (sweeps max 3mm depth)

The machining tolerance is defined at $\pm 0,05$ mm.

The used material is birch plywood is exclusively applied indoors. The thickness tolerance for 18 mm thick sheets is between 17,1 and 18,1 mm. Mechanical data are related to the data obtained from the 5 percentile weakest panels that were tested, as published in the Handbook of Finnish plywood (2007).

4.3 Structural requirements.

This research follows the Eurocode norms. Eurocode 0 and 1 are used for calculating the loading on the load bearing structure. Eurocode 5 is used for material specific requirements and joint design.

Eurocode 5 states that a construction needs to have resistance in serviceability and ultimate limit states.

Serviceability limit state for a roof structure: max deformation = $1/250 \cdot L$

The applied loading:

Permanent loading: self weight.

Variable loading: heaviest of snow or persons

Safety factors for loads: $P \cdot 1,2$ and $Q \cdot 1,5$ in ultimate limit state

Safety factors for loads: $P \cdot 1,35$ in serviceability limit state

Safety factors for material: plywood = 1,2

Safety factors for connections: 1,2

The Eurocode prescribes that structures are safe by design of a ductile failure mechanism. This is calculated by the Johanson formulas for doweled joints. A safe structure collapses after two different parts have failed, and an additional structural capacity between these failure moments is present. This means that when the joint fails, it should be able to maintain functional but at a far lower flexural rigidity so the stresses can be redistributed through other parts of the structure. Fig 24b shows the mechanical behavior of a safe structure. Plywood has ductile properties when loaded in compression and thus has the potential of safe joint design.

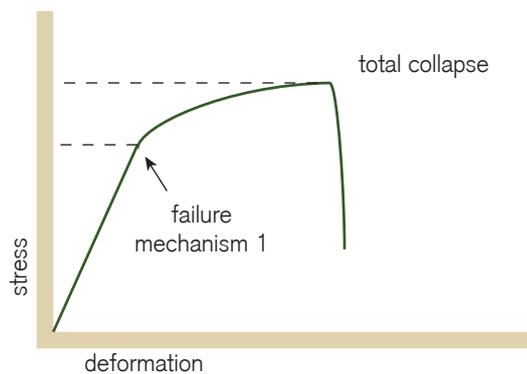
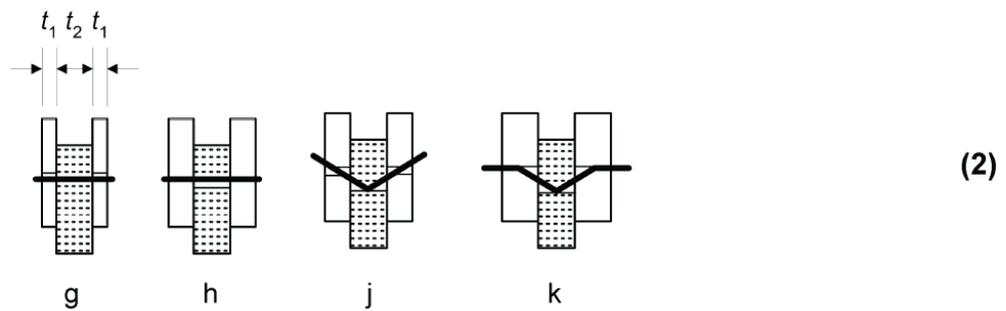
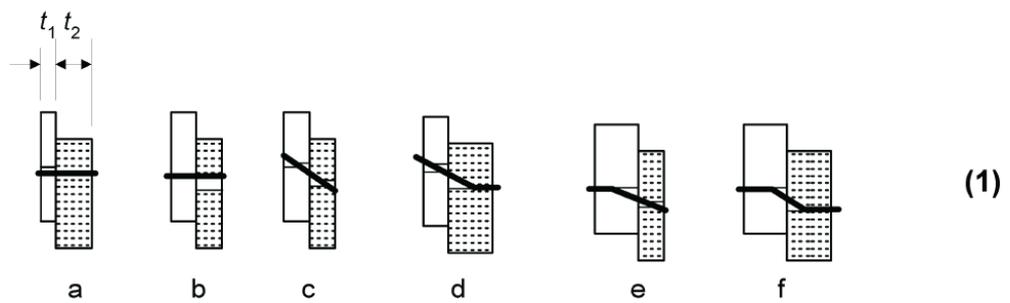


Fig. 24a. failure types of bolted wood joints as depicted in Eurocode 5 (wood construction). EC5 requires that joints fail like type 'f' and 'k' because the structure fails through two plastic hinges in the bolt. this is a ductile failure mechanism. in all other types a brittle wooden element fails, causing the structure to be unsafe.
 Fig. 24b. Failure mechanism of a safe structure

5

SPANNING STRUCTURE DESIGN

5.1 Spanning structure types

Introduction

To determine the optimal structure principle for the P.O.-lab, a top down approach will be followed, where providing stability to the whole structure and spanning the floor are the starting points. Three truss types with each its specific structural principle are structurally analyzed and designed to be built with 2440 mm x 1220 mm panels, milled by CNC machine. From these variants, proper details should follow.

In this research, three truss principles are designed within the boundaries of the technologies considering CNC-milling of wood panel material. This approach is used to explore the aspects that follow specifically from building with panels. The different structural principles from each truss type will spawn different challenges within the CNC-milling aspect. As each truss type relies on specific connections and load bearing principles, the offered solution confined to CNC milling wood panel limitations could prove the structure principle either more or less viable.

In this chapter, the advantages and challenges of each truss type within the context of stability, strength as well as CNC milling technology and material properties are explored. In a first stage, the main mechanical diagram of each truss type is determined. Then, the trusses are designed following a principal mechanical approach considering the panel dimensions and favorable joint locations. The trusses are structurally compared in a two dimensional structural model consisting of strictly beams, supports, hinges and rigid connections. The results show the difference in magnitude of bending moments and shear forces, which imply the challenges for each truss type. The designs are elaborated so that a functional mockup can be constructed strictly based on CNC cutting of plywood panels, to find the bottleneck of the system.

Firstly the optimal mechanical configuration is defined, after that, a model is analyzed with realistic loading.

Considerations from a structural engineering point of view.

Loading of the structure

The loading on the structure as well as the structure properties are approximated in this phase, and relevant parts of the Eurocode norms are applied. These are the following:

The Eurocode principle is to validate the integrity of structures by their performance in certain limit states. For this research the Ultimate Limit state (maximum resistance before collapse), and Serviceability State (maximum resistance before structural functioning, comfort and aesthetical requirements are lost) are applicable (Nederlands Normalisatie-Instituut, 2002).

Use of reduction factors for loads as well as mechanical strength in a single load case.

To keep control over the research, the mechanical diagrams are strongly simplified.

The truss members are considered as a homogeneous element (all parts are welded), disregarding the many connections that construction with this technology implies. Mechanical hinges are considered as pure hinges, where they are likely to act as spring hinges in practice.

Stability

The essential properties of a structure are strength, stability and rigidity. With the typical shape, an uninterrupted extrusion of a barn shape, there is a single extruded cross section. Along with the span of 11,4 m the stability concept

is a main factor for design of the trusses.

Horizontal forces, mainly wind load, need to be in equilibrium with the support reactions. In the direction parallel to the structure axis, the stability can be provided by the façade elements that form a diaphragm, transforming moments resulting from horizontal loads to axial forces that are conveyed to the foundation. Wind loads perpendicular to the structure axis can be taken by the head façade elements. These act as diaphragms, but due to the distance they are apart from each other, more stability measures along the long side need to be taken. Designing the trusses so that they singularly or in combination with other elements provide stability within their plane would solve this.

The types are mainly distinguished concerning the locations of hinges and rigid elements. An assumption about the supporting frame is made that it can provide its own stability.

References

Three hinged roof structures

The three-hinged truss has similarities to some truss types that are used in older and more recent buildings. A relevant example is the rafter roof structure, where the elements that support the roof span from cam to the truss foot. Roof cladding is mounted on beams spanning the rafters. The rafters have a homogeneous section throughout the beams' length, and thus a limited moment capacity.

Larger roof structures applying this principle are the steekspant and Dutch truss. A modern steekspant is a simple setup of truss legs hinged together in the cam and placed on the wall. The splash forces are taken care of by a kapbalk that also supports the attic floor. In larger roof structures, a horizontal beam is added to form an extra support to the truss legs which tend to deflect due to the large span. This beam, the hanenbalk is mounted to the makelaar which is hung from the cam. These structures are called Dutch trusses.

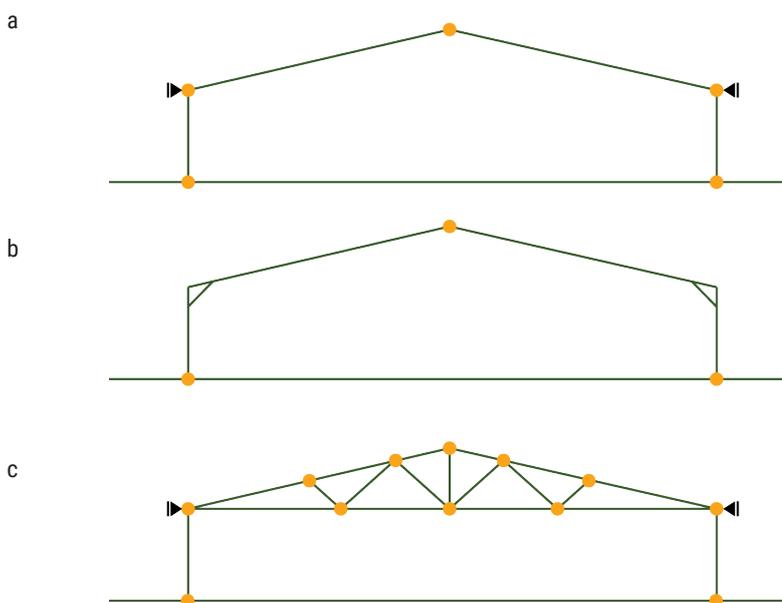


Fig 25. Mechanical diagrams of three optional load bearing structure designs. a. 5-hinged structure. b. 3-hinged structure with rigid corners. c. king post truss variant

The spijkerspant is aimed at fast wooden frame construction: the members are joined by spijkerplaten. The relative simplicity of this type means that the forces are fully conveyed through the jointing elements.

Conclusion: stabile in own plane. Earlier steekspant nokverbindingen are tooth in groove to avoid lateral shearing of the truss legs. These had to be very precise to make them strong enough.

The so-called hinge roof uses the same principle. It consists of two opposite prefabricated roof parts that are joined together by hinge in the cam and are transported as flat package. The element is hoisted onto the roof where it is opened and slid over the exterior wall. On the inside a beam is mounted that falls together with a wall plate, to convey the shear forces to the attic floor. This roofing can be fabricated and requires relatively little effort to install.

Truss type 1: Five hinges with additional stability measures

Truss type 1 is mechanically hinged in every corner. The concept is to divide the truss into the exclusively straight elements to avoid moments in corners and limiting the length for handling purposes. The truss is hinge supported to avoid unfavorable bending moments.

The consequence of this configuration is that both stability within the trusses' own plane, nor provisions against the splash effect are provided. Both should be solved by measures lateral to the truss: bracing or diaphragms that connect the truss to designated secondary stability elements like a head façade or stability core.

This is thus not stabile in its own plane. This system depends on a diaphragm provided by the roofing plane that conveys horizontal forces from the trusses to designated stability measures, such as the head facades or stability cores.

Advantages:

The absence of rigid corners and bracing of the trusses leads to mostly axial forces within the spanning members in the wind load case. Mostly the side façades take a bending moment from wind loading.

Another advantage is that the maximum length of the parts of the truss is limited; the longest member measures half the span. This is advantageous for construction purposes when considering weight, and handling properties. Also for the shorter lengths, a smaller number of panels is necessary, so the amount of joints between these panels is limited.

The bending moments occur within linear, simple shaped members, as opposed to corners or complex shapes. The potential of this feature is that the bending moments can be controlled easier.

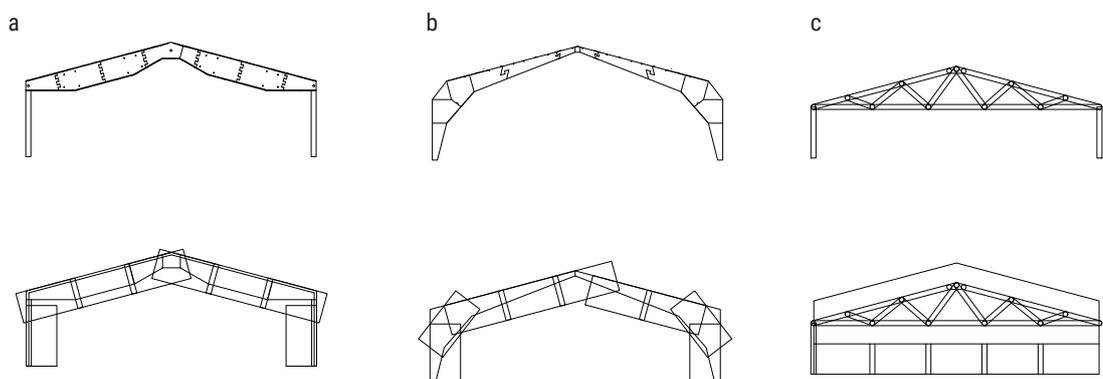


Fig 26. layout of the spanning structures. distribution of seams based on panel dimensions of 2,4m x 1,2m.

Challenges:

The trade-off is the full dependency on braces or diaphragms provided by secondary elements. This system requires a diaphragm roof that contributes to the main structural system, and should comply with its strict requirements set by construction norms.

It also has a relatively large bending moment as it consists of beams that are hinge supported at each end. It does not profit from a favorable moment distribution that a beam on more supports typically has.

Due to the large amount of mechanical hinges – five – a more extensive structural displacement is expected. This forms a difficulty at achieving the Serviceability limit state requirements that requires a maximum displacement of the structure. This depends strongly on the effectiveness or rigidity of the roof diaphragm and stability elements. If the in-plane stability measures are too far apart from each other, the cam sinks and the gutter corners are translated to the outside.

Design:

The large bending moments in the two spanning beams are the formative principle of this truss. The length of one beam, from hinge to hinge, is around 6 meters, or 3 panel lengths. The cross section of the beam is a box shape, including two web panels, and flanges on top and bottom. As the moment is largest in the middle of the beam, the largest stresses are in the flanges. The middle flange panels are at the moment peak, to keep the weak, axial connections between the flange panels under the lowest possible stresses. The section between the webs, is located at the exact middle of the beam, where shear forces are lowest. The tapered shape of the beam is to conserve room height, although allowing a high beam section profile at the peak moment location.

Truss type 2: Three hinged truss

Type 2 is a variant on the commonly known three-hinged truss, consisting of two L-shaped elements.

The principle of a three-hinged frame is based on two mechanical principles; hinge support in the cam, where the two elements lean together and opposite forces cross each other out; and the truss legs are hinge-supported to avoid unwanted moments in the ground support (Janse & Rijksdienst voor de Monumentenzorg, 1989).

The line of the truss ideally follows the inversed deformation line, to form a parabola (Quist, 2002).

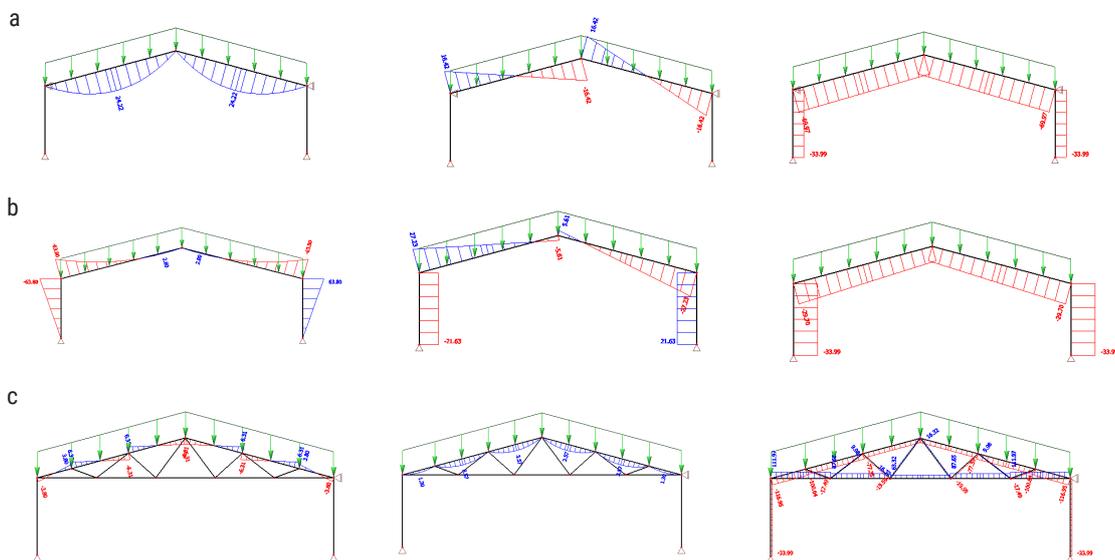


Fig 27. Resulting bending moments, shear forces and normal forces for structure type 1, 2 and 3.

In the case of a 'knee-truss' with the corners at the gutter are rigid and take by far most of the bending moments resulting from vertical and horizontal loads. This structural principle is stable in its own plane, and requires bracing in lateral direction, like the other truss types.

These trusses are commonly seen in farm or horse-riding structures, which require a large span and select wood for its oxidation and acid resistance. The cross section of the elements is usually solid glulam in a rectangle, increasing in section height to its thickest section in the corner to resist the largest moment. In the corner, two glulam beams are finger jointed.

Advantages

One of the main feats of the three hinged truss principle is that it provides stability in its plane, without need of secondary stability elements. A stability core is not necessary when applying this principle. This has its merits in construction phase as well, resulting in a more extensive freedom of building order. The typical high rigidity of this truss also has positive effect on the displacement requirements.

Challenges

The truss has by far the largest bending moments in comparison to the other truss types. This moment is even larger in a wind load and vertical load combination, in the truss leg opposite to the wind direction gets double loading. The bending moment peak is located in the corner of the leg, where typically the biggest cross section is. The difficulty is to transfer forces through this corner, as a corner cannot be made with a planar element, there is a continuity problem that needs to be solved.

The knee elements measure half of the span plus the height of the façade, which makes them relatively large elements. Taken into account that a certain amount of material needs to be accumulated in the corner, the legs can be considered as relatively heavy and difficult to handle. As the bending moments expand on almost the whole length of the elements, the conveyance of tension, compression and shear stresses are interrupted by a larger amount of joints between panels with a potential loss of rigidity as consequence. The typical knee truss is a homogeneous beam; a knee truss constructed from a multitude of different panels makes concessions in this aspect.

design

the large bending moment in the corner requires a significant sectional moment of inertia. In the design, the most favorable setup is to have the inevitable connections between panels as far away from the peak moment as possible. The middle of the panel is located at the peak in the corner, the distribution of the other panels is organized from this panel on. The critical corner section requires a significant sectional surface area, by joining panels laterally; a more or less solid section is created. As the whole leg is loaded with a bending moment, flanges are attached to the top and bottom of the beams for extra bending resistance.

	Bending moment				Normal force		Shear force		Hinge shear force	
	Mmax (kNm)	relative	Iy necessary (•10 ⁴ mm ⁴)	HEB comparison	Nmax (kN)	relative	Vmax (kN)	relative	Vmax (kN)	relative
	24,2	0,60	52000	HE400B	70,0	0,60	16,4	0,60	16,4	0,14
	63,8	1,00	479000	HE900B	34,0	0,29	27,2	1,00	5,61	0,05
	3,58	0,06	N/A	N/A	117	1,00	6,31	0,23	117	1,00

Fig 29. Table of forces in each spanning structure. At 'HEB comparison' the required cross section dimensions are listed. e.g. HEB 400 is a steel profile cross section materialized in wood to fulfill rigidity requirements by Eurocode.

Truss 3: king post truss variant

This truss type is found in many bridges and heavy civil engineering structures and is typically constructed in steel or iron. In older buildings with large spaces this truss can be found as well, executed in timber.

Advantages:

The principle of the truss type to induce axial loading in favor of internal bending moments results in this case in very low bending moments as well, compared to the other truss types. The beams that support the roof can be considered as hinged on two supports, formed by the bracing elements. The bending moments are small because of the short span. Another advantage is that the truss can be designed for the maximum element lengths as provided by the plywood panel size limitations, reducing the interruptions of beams. The axial loading of elements prevents the use of members that can resist bending moments, these are typically difficult to construct.

Challenges

The consequence of this type is the size. It has to be constructed as a single element spanning the full distance. It is a large, clumsy and heavy piece that will be difficult to assemble and put in place. Due to the eleven hinges, potential difficulties with serviceability limit state can occur. Each connection should allow rotational freedom and this has consequences for the rigidity of the whole structure.

Like Truss 1, this structure is dependent on secondary stability measures like a stability core and a diaphragm roof. Typical are problems with lateral torsional buckling, due to unfavorable torsional section. It needs bracing in lateral direction.

Design:

Properties: Based on king post truss. To limit the amount of hinges, the truss is based on maximum length members.

They elements can be 2440mm long, excluding any overlap space required by the connections.

Axially loaded members, critical joint is the axial load connection,

Design of timber truss bridges is similar to that of roof trusses. The length of the truss panel is determined by economical spacing of support beams, minimum number of joints and commercial availability of timber lengths (I & Linville, 2012). (Construction & Linville, 2012)

For the design of truss #3 this means that based on a maximum panel length of 2440 mm with subtraction of 2•5mm milling margin and approximately 2•200 mm joint overlap, the members have a maximum length of 2030mm. The second criterion is to reduce the amount of joints, as that is the critical issue in deformation.

Lateral forces tend to be greater on truss bridges, bracing is usually required to provide stability to the trusses (I & Linville, 2012). A bracing measure to prevent lateral torsional deformation may be necessary.

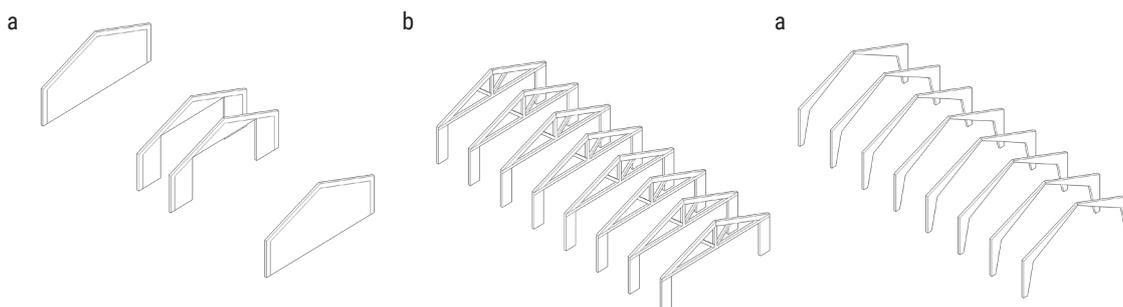


Fig 30. Isometric of stability measures for each spanning type. a: Type 1 needs additional stability measures like extra walls. Type 2 and 3 provide their own stability.

PART III

DESIGN AND OPTIMIZATION METHODS FOR CNC-CUT PLYWOOD STRUCTURES



6

DESIGN AND ASSESSMENT METHOD

6.1 Introduction and goals

The goal of this research is to inform a Fab Fac designer and engineer on how to design and assess a spanning structure, as well as defining the vocabulary of designing with CNC-cut plywood and exploring the weaknesses of that process. In order to design a load bearing structure that behaves as is desired, the structural engineer needs to know how to operate the various parameters that influence this behavior. The aggregate structures rely on a multitude of compression joints, connecting various panel cutouts. Due to the complexity of such structural components, the amount of criteria needs to be reduced until the design is mathematically predictable, and the most essential structural design approach can be defined. After this is covered, secondary criteria like material usage and simplicity of assembly could be optimized.

The primary aim is to define the design method for structural components such that it fulfills three requirements:

The structure contains efficient joints

The structure is safe

The structure remains within deformation boundaries

Efficient joints are considered to possess a shape that has optimal strength and deformation properties within the context of their function. Joint efficiency is a relative criterion, which is obtained by shape optimization.

A safe structure is designed to collapse in a controlled manner. A part of the structure collapses through a ductile failure mechanism, which causes a deformation that allows redistribution of stresses before a second fatal mechanism is activated. This implies that a certain joint is designated and designed to be the weakest link. It is an absolute criterion that is assessed through the structural performance of the aggregate structure as a whole. A safe structure either is or is not achieved.

A structure remains within deformation boundaries if the lateral deformation does not exceed a certain percentage of the span. This research limits to the initial deformation through settling of the joints and deformation relative to cross sectional rigidity of the structural component within its elastic zone. This is an absolute criterion, which either is or is not achieved.

In this research a spanning structure will be designed and assessed through these three criteria. It is designed to contain the critical aspects of the CNC-cut plywood production process: seams that require joints with various functions. Through this design method the mathematical approach is defined, to be able to design other structures by theoretical approximation. Physical validation of such designs will always be required.

6.2 Theoretical and practical analysis approach

Structures from isotropic materials with homogeneous shapes – like bolted steel beams – can be calculated without a lot of effort, due to their linear deformation behavior under increased loading. The anisotropic properties of plywood and multitude of connections cause a complex behavior. Therefore validation of mathematical design methods is needed. Each theoretical approach needs to be assessed by physical testing.

6.3 Research method

The three criteria are refined in individual researches. This will be done in the following steps:

1. the most suitable of the three possible spanning structures will be selected for further elaboration. As the spanning structures are dependent on a wide range of connections, the structure will be simplified to an element that can be assessed in the three criteria as stated above.
2. The various joint types that occur in this structure are described and optimized. The optimization criteria are primarily structural. A shape finding process that can be applied to every joint type is proposed.
3. The brittle and ductile failure modes of each optimized joint are identified as well as the shape parameters that define resistance of each parameter. In other words, how a shape can be modified to make a preferred failure mechanism the weakest. In this way, the true strength and failure mechanism of each individual joint can be controlled by manipulation of dimensions.
4. A beam is designed based on the results of the former two outcomes. These methods are assessed by a series of bending tests that verify joint rigidity, strength and the failure mechanism of the structural component.

7

OPTIMIZATION OF INDIVIDUAL JOINTS

7.1 Joint types

Connections

The different truss types rely on various connection principles specific to limitations of CNC-milling and the panel material. As this is mainly about elongation of an element by joining elements with a limited length and joining panels under an angle, these connections can be categorized into the following:

Axial loading

In-plane jointing

Overlap jointing

Angular jointing

Rotational loading

Rigid connections

Hinged connections

The joints between the panels are the weakest links in the load bearing structure. To gain a high strength of the spanning structure, optimization of these joints is important. Each of the trusses relies on a different set of joints, each with a variety of properties. The quality of these joints lies in mechanical properties as well as aspects like manufacturing speed and ease of assembly.

In this chapter, some joint types are refined and tested for these criteria. The optimized joints are applied into the respective trusses and define their ultimate strength.

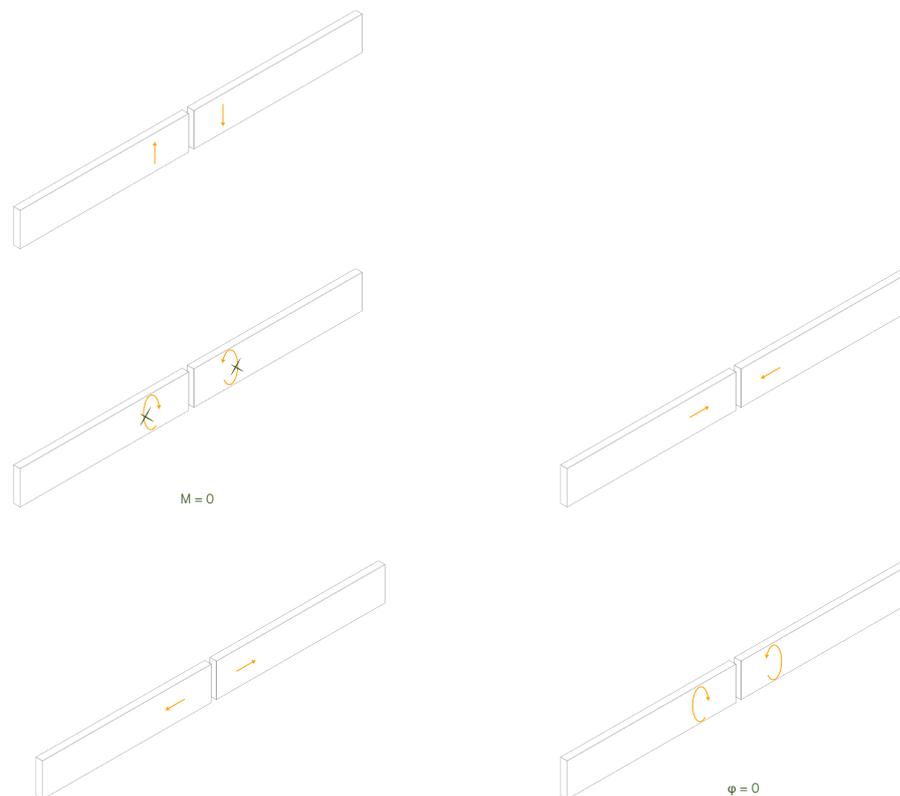


Fig 31. Overview of different joints that can occur within a structure. Types are shear joints, hinge joints, tension joints, compression joints, rigid joints.

7.2 Design, Optimization and Assessment methods

7.2.1 FEM optimization

FEM Modeling and results

Goal

The optimization is strictly one of finding the best performing shape. To find this optimal shape, it is best to have a fast design-to-assessment procedure. This research uses finite element analysis of shapes that are drawn up in CAD software.

This technique is used to compare and optimize distinctive joint types. As structural performance is the main criterion, the desired outputs of the model are mainly stresses and displacements, which are compared to specific material properties.

The panel material is almost exclusively loaded and shaped in two axes, which means that the loading and/or shaping in the third axis – e.g. along the thickness of a sheet – is uniform. A 2D-modeling system of the samples is therefore found most suitable.

The following principles lay at the basis of this model:

Element type.

The 'plane 82' element type is commonly used for 2D geometry analysis. The Ansys manual by SAS-IP (2012) says that this 8-node element type "provides more accurate results for mixed (quadrilateral-triangular) automatic meshes and can tolerate irregular shapes without much loss of accuracy. The ... elements have compatible displacement shapes and are well suited to model curved boundaries." The joint variants that are modeled will have a refined mesh at local stress concentrations, and curved boundaries due to the circular router bits.

Material properties

18 mm birch plywood is the material that is used in the theoretic part of this research. Due to material availability, the physical testing is done with samples of another material. The variant analysis and optimization is a research based on relative, therefore representative strengths are irrelevant in the form-finding stage of the research. In this respect, the material is modeled with linear elastic behavior, which simplifies comparison between variants. In later stage where the absolute strength of connections in particular and structures as a whole is important, a more accurate plastic-elastic behavior is modeled.

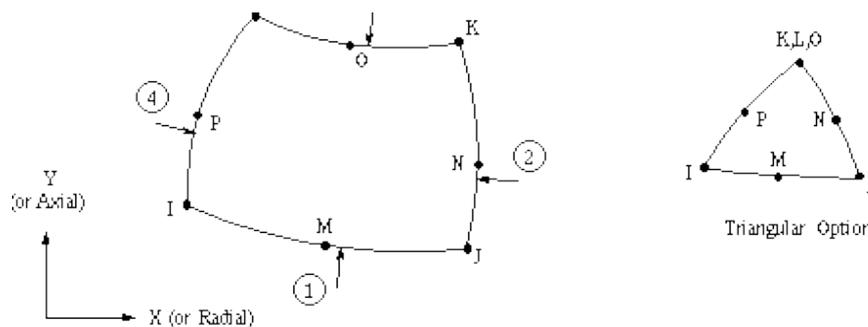


Fig 32. schematic representation of the 'plane 82' element type. The element is twodimensional and either quadrical or triangular with nodes in corner pnts and midpoints for enhanced accuracy. source: Ansys manual

Constraining

For each variant a suitable constraining method is defined. Where the connection is a cut-out-piece of a larger part, the constraints are modeled as rigid supports along the perimeter lines, as little displacement is possible.

Meshing

The element mesh structure is refined at locations where concentrated stresses occur. A higher density of nodes improves accuracy. This research uses the Ansys meshing tool that automatically refines the mesh at locations with complex geometry, with a consequence that meshes differ from sample to sample. The effect on the output is assumed to be negligible if the compared models have an element size where stresses are not changing significantly anymore when the mesh is further refined.

Output display

Samples are loaded in plane, from any combination of two axis of the orthotropic material. Because anisotropy of the material, both compression and tension stresses on each axis are required, rather than just the maximum stress which is the case with i.e. steel modeling. Shear stresses and local displacements caused by the joint configuration are the other criteria. The output values are derived from the graphic result data display from Ansys.

In every node, the displacements and stresses from one part of an element are transferred to another element. The larger the element is, the more the local stresses are averaged. At locations of peak stresses, this can result in skewed and unrepresentative values. An own test concluded that a refinement of the mesh at local peak stresses at the material edge gives significantly increasing stresses at every refinement step, until an asymptote value is reached where values do not change at refinement increments. However this value is very local – double value increase within the millimeter can occur - is considered the representative value. Whether this indeed improves the accuracy is deducted from the physical testing.

For the sake of comparison, this representative value needs to be reached by fine meshing.

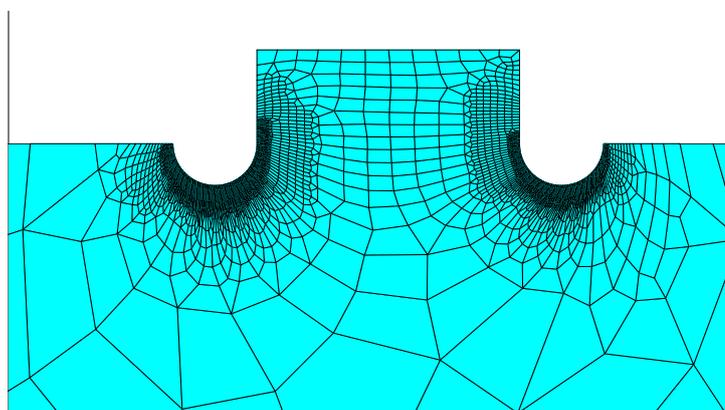


Fig 33. Meshing structure of a notch joint. The elements are refined near the objects boundaries, where peak stresses occur.

Method

A proposed method to find and optimize suitable shapes for the different joint types consists of the following steps:

1. Principle definition
2. Problem statements
3. Sketch variants
4. Reasoning assessment
5. Hand calculation
6. FEM-model calculation
7. Prediction of physical test
8. Physical testing and analysis

In the next paragraph the types of structural assessment methods are described. An example of the optimization of a joint is described in paragraph 9.2.

9.1.1 Ansys finite element modeling

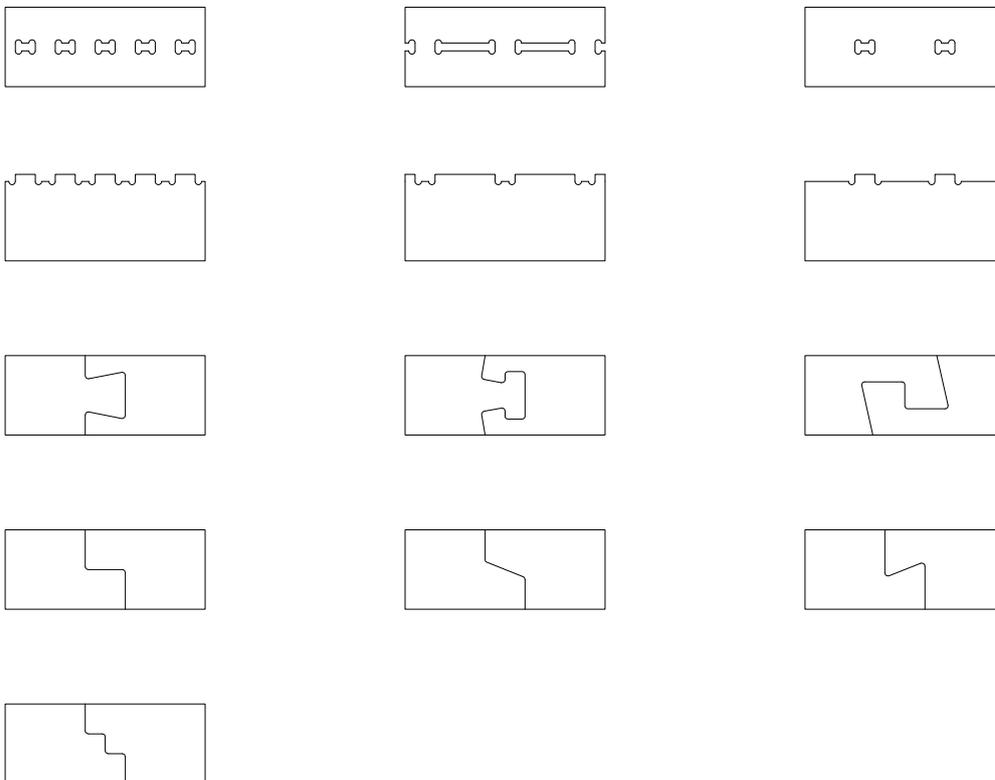


Fig 34. Various sketch variants for respectively perpendicular shear, tension and planar shear joints.

In a research on FEM-analysis of timber and concrete joints, the difficulties of timber modeling due to orthotropic behavior are described as follows:

"In spite of the problems related with the definition of the elastic properties of timber, the most significant difficulties are caused by the modeling of the elastic-plastic strain behaviour. Each one of the orthotropic directions has mechanical properties that are different from the other and in each direction the behaviour is also different in tension and in compression. Under compression the behavior of timber is relatively plastic and can thus be reasonably approximated by an elastic-plastic law with hardening. On the other hand, on tension the behaviour is rather brittle and the maximum stresses are low, in the direction perpendicular to the fibers, but high in the direction parallel to the grain. For tension stresses, an elastic-plastic model is not representative for the actual behaviour of the material" (A.M.P.G. Dias, 2007).

Tests show that the elastic behavior of birch plywood is extremely linear in both tensile and compression modes, until a certain stress level is reached. The test shows some viscoelastic behavior short before fracture. This implies that linear elastic modeling is possible to a certain extent.

This means the object needs to be modeled with transverse isotropy of wood, assuming identical properties in radial and tangential directions.

The most frequently used failure criterion for anisotropic brittle materials is the maximum normal stress criterion, which states that the material will fail when any one of the stresses in the principal material directions exceeds the material strength in that direction (J.J. del Coz Díaz & Hernández, 2013).

7.2.2 Stress hot spots

Hot spots problem

Finite element analysis is a fast method to compare different variants, however the stress outputs do not display absolute strength. In some circumstances the mathematical model shows output data that is not representative for actual material behavior. In some FE models very intense stress concentrations occur in very small areas, these are referred to as hot spot stresses. In practice, these stresses are distributed more evenly due to viscoelastic behavior or the material that will flow locally under high stress. Maximum stresses are significantly lower.

These distortions of mathematical models are caused by boundary conditions in the model. This is basically a rapid

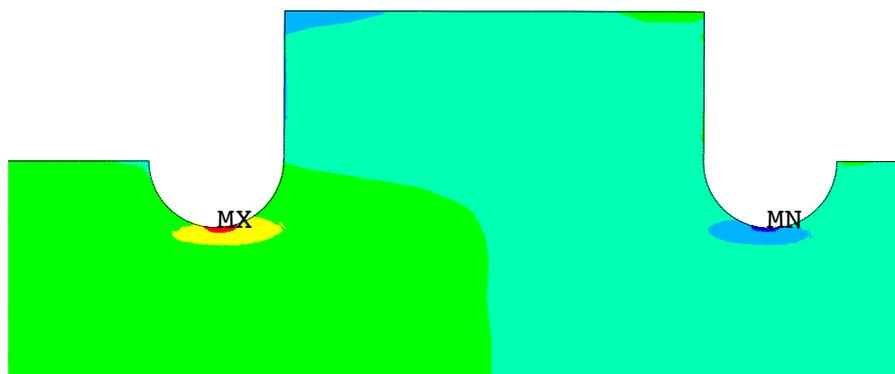


Fig 35. Output display for the nock joint with maximum (tension) and minimum (compression) stresses.

change of geometry or load. For example, when a point load is put on a surface, the surface area of the point is zero. The stress in the material at that location is therefore the force divided by zero surface area: infinitely high, distorting the output when set to maximum stress. This phenomenon also occurs at edges of the modeled piece that form a geographic discontinuity, like a notch in a loaded panel.

A variant of a connection between web and flange is taken to illustrate this phenomenon. The piece has overcut notches under the compression-loaded tabs. These tabs transfer shear forces between the flange and the web of an aggregate beam. In the model the tab is loaded with a stress of 39,2 N/mm².

As these FE models are not representative, engineers can apply St. Venant's principle: "... the difference between the effects of two different but statically equivalent loads becomes very small at sufficiently large distances from load" (Love, 1927), meaning that at a small distance from the boundary condition, the stresses normalize. The stresses are not as high as represented in the FEM-model, but there still is a concentration that could be significant for the structural assessment of a piece. The true effects of such hot spots are derived by interpretation. Different methods can be applied to approximate the true stress values. In this research different theoretical methods are compared to results from physical testing on a machine.

This effect is limited to boundary conditions. The displacements and stresses that occur away from these boundary conditions are not distorted by stress hot spots and are considered valid.

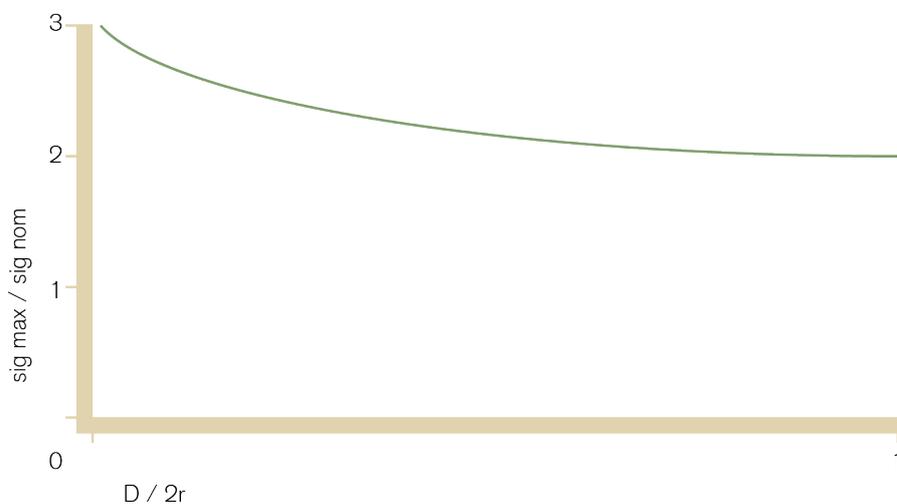


Fig 36. Relation between stress concentration factor and hole-panel height ratio. Peak stresses can be approximated by this formula that assumes the maximum stress concentration to be 3 times the nominal stress (at $D/2r=0$)

7.2.3 Stress concentration factors

The representative value of peak stresses can be approximated by using stress concentration factors. This is the factor between the nominal stress in a plate and the peak stress at the discontinuity of the plate, such as directly under an overcut notch. The concentration factor (K_t) is defined by a relation between the geometry of the notch and the height of the plate.

Some generalized formulas describe this factor based on common loading cases and anisotropic material behavior (Young & Budynas, 2002). In these formulas the concentration factor at infinitely low ratio ($D/r = 1$) between plate height (D) and notch radius (r) is 2. If the ratio is infinitely high, the peak stress is three times the nominal stress. The specific material properties, geometry of the researched joints and load type deviate from these formulas and should be derived from a physical test specifically designed for these joints. An optical stress-strain analysis can measure the strains on the surface of the joint, thus giving the local stresses. The specific function for CNC-cut joint can be described if samples when different plate height – notch diameter ratios are tested. The standard formulas do however give insight in the parameters that define the peak stress. This can be used for influencing the behavior of the connections.

Hot spot stresses are also a common facet in the area of welded steel structures. A weld between two perpendicular plates is modeled as a 45-degree fillet that has sharp angles at junctions with the plates, thus causing singularity in the FE-model. The actual peak stress is approximated by using data from the FE-model. Two increment points on a line that represents stress intensity on a cross section of the plate are extrapolated to a third point at the border where the hot spot is. The extrapolated line is a simplification of an otherwise exponentially increasing line.

Photoelastic analysis is a third method of measuring stress. A hard transparent resin with similar viscoelastic properties of plywood is placed on top of a lamp and a polarized sheet. The light waves align with the principal stress vectors, showing rings that represent these principal stresses. This method shows the relative intensity of stresses throughout the object, and the location of the largest stress can easily be identified.

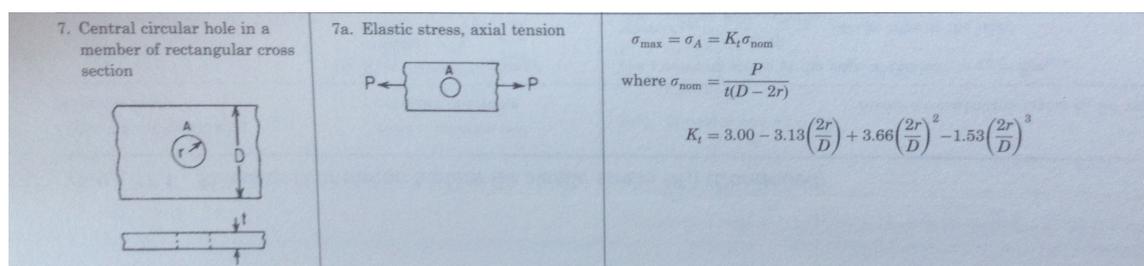


Fig 37. Diagram and formula for definition of stress concentration factors for panels with a hole. source: Roark's formula's for stress and strain

7.3 Optimization example: sleeve tension joint.

Principle

Panels can be milled to halfway the depth when using the so-called 2.5th dimension: the z-axis. This principle allows panels that are loaded in tension and joined in the same plane to overlap and convey forces over a larger area. Spreading the stresses is assumed to be more advantageous than introducing them through a small contact area.

The surfaces are milled so that both panels have a hook and a depression that lock into each other. Per 'hook' a part of the forces is introduced, the series of hooks introduce the forces gradually into the next panel. Due to the milling precision of $\pm 0,05\text{mm}$, the connection should fit perfectly resulting in little displacement necessary to fully activate the joint.

Specific difficulties

A. Shear loading and failure mode

The panels will be loaded in shear in the plane parallel to the ply lamination, the weak plane. This means shear stresses act laterally on the fibers of the plane, which causes the 'rolling' effect. When reaching the strength limit, the connection will fail due to brittle failure instead of the more preferable ductile failure where a deformation takes place before collapse, warning the users inside the building.

B. Decreased panel length

The larger the length of the overlap, the shorter the maximum length of the elements can be, but the overlap needs to have some length to be able to sufficiently convey the forces.

C. Undesirable internal bending moment

The shape of the connection causes an asymmetric flow of forces through each of the panel ends, resulting in an internal bending moment. This moment causes the panel ends to bend away from each other, decreasing contact area and weakening the connection. The moments occur mostly in the thinnest part that is most eccentric from the normal line.

D. Panel geometry

one sided milling of the panels costs the element one plane of symmetry. The consequence is that the panels with this particular connection need to be fitted into each other, before being fitted into other elements of an aggregate beam.

E. Very thin panel cross sections

Removing material in order to create the hook and depressions results in thin cross sections locally. Guiding forces through these thin parts is risky.

Sketch variants

1. stress strength – shear strength relation

the overlap of the panel ends can be decreased to the limit when both the contact surface of the 'hook' – loaded on compression, and the section surface area of the hook – loaded on shear, are configured optimally. Compression stress is limited at $27,2 \text{ N/mm}^2$, maximum shear stress in this particular plane is $2,34 \text{ N/mm}^2$. The ratio compression surface area versus shear stress area would be $11,6 : 1$ following this logic.

Sketch design

In sketch variant 1 this ratio is applied to the hook width and height dimensions, measuring 20 mm and 3 mm respectively. Each panel end has four hook-and-depression elements, locking into a counter panel end.

Sketch variant 2 introduces rounded router bits, decreasing the apparent undesirable effect of sharp angles. For this process both an internally and externally rounded router bit is used. A plunge roundover bit can have a rounding down to 3mm radius. The same applies for a ball nose bit.

In a 2D – FEM analysis a force of 27,2 N/mm² is applied to the end of the beam, as a benchmark for 100% material capacity use. The element is put under maximum stress so the output values can be assessed in relation to maximum cross section capacity. The joint is modeled as a homogeneous so that contact zones are bonded. This effect eliminates sliding of the contact zones.

Assessment

Internal moments due to asymmetric loading cause a bending motion of the outer parts of the joint ends. In the first variant, shear stresses concentrate in internal corners. These stresses peak at 26 N/mm² which is around 9 times the yield strength for shear. Also tension stresses in the y-plane measuring up to 38 N/mm² are found at these places, this is exceeding the yield strength with a factor 6. Both failure modes are brittle.

The stress flow acts different than predicted. A high concentration of shear stresses is located at the corner

2. Securing the panel ends from bending

Measures in the form of a bolt through the overlap or a clamp over the joint could prevent the ends from moving outwards, as explained above.

Sketch Design

The sketch variant includes four hooks and depressions. In a FEM-model the two panel ends hook into each other and are supported on one end and a tensile line force is applied on the other. The two components are modeled with contact elements so the influence of rotation due to the bending moment can be researched.

3. Inclined hooks

As a solution to the critical shear stresses, an inclination of the hooks could cause a more preferable distribution of stresses. The inclination can be made by using an angled milling tool or by making a jagged slope with small intervals, like stairs. The first option has a resulting force outward to the connection that is undesirable, as described at problem C. The jagged slope could be favorable due to the fact that stress vectors are not diverted and that the router does not have to be changed.

The sketch design includes four hooks and depressions as to compare it with the other variants.

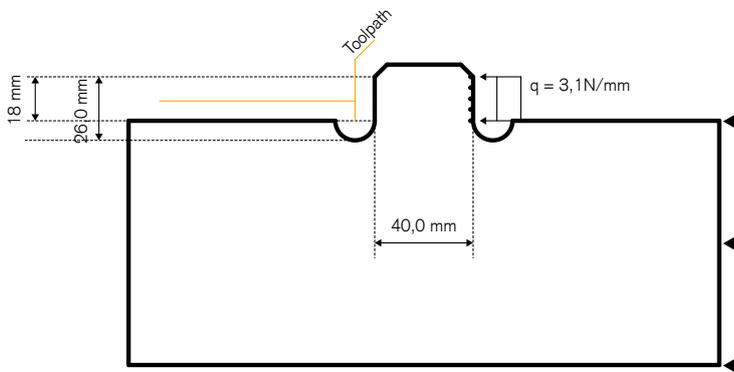
Special attention needs to be given to the fact that the panel ends are brittle due to the thin sheet inherent to the connection. The logistic plan should include this risk, mostly because of the cost of breaking.

To test this type of connection, variants are designed and tested to shear strength, size of overlap, influence of inclined ribs (trapezium-shaped) on shear strength, and need for measures against swaying out of the tabs.

Perpendicular Shear joint

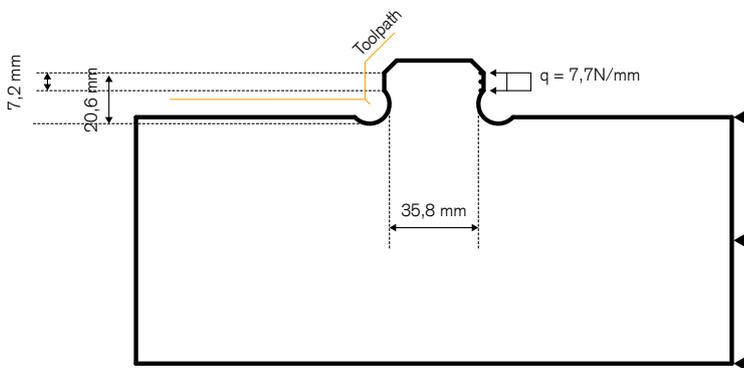
The dog bone-problem, due to the inability of milling straight angles when CNC-milling knows different solutions. One is the actual dog bone. In this method the router follows a line that is a T-junction: an extension of one of the lines. The second way is to make an Y-junction, where the router follows a path at 135° on either of the paths. To analyze which one of the two is the more favorable in structural applications, they are compared at stress resistance and displacement when put under the same force: 1kN. Both samples are 18mm thick, the tooth is 18mm + a guiding part of 5mm high.

a



U_x	• 0,121 mm • 0,114 mm • 0,104 mm • 0,091 mm • 0,073 mm
$U_{x,avg}$	0,101 mm
$S_{1,max}$	13,6 N/mm ²
$S_{3,max}$	5,54 N/mm ²

b



U_x	• 0,127 mm • 0,121 mm • 0,105 mm
$U_{x,avg}$	0,127 mm
$S_{1,max}$	11,8 N/mm ²
$S_{3,max}$	8,95 N/mm ²

Fig 38. comparison of notch joints with straight undercut notch (a) and inclined undercut notch (b). FE-analysis shows that a has lower displacement (high flexural rigidity) but has higher maximum compression and tension stresses.

8

METHODS FOR SAFE STRUCTURAL DESIGN

8.1 Goals

The effect of all joints on the whole structure needs to be defined. A shear joint is tested in a 4-point bending test and the results are translated to a method for the design of a safe structure.

8.2 Bending test

8.2.1 A physical test is designed to compare theoretical predictions with the actual behavior of a spanning structure. The following assumptions need verification:

accuracy of the Finite element analysis in terms of stresses and displacements

accuracy of the stress concentration factor calculation

validity of failure mode design.

8.2.2 Bending test method

Physical testing has been done on a machine that monitors load and deformation. The supports are steel tubes welded on a frame, which function as roller hinge supports. The span between these supports is 1000mm. Bending tests are often done with a two-point load applied on the topside of the test object, which causes the length between the loads to be loaded with purely bending moment. The distance between the point loads is 300 mm.

The data output of the machine is force in relation to displacement.



Fig 39. 4-point bending experiment setup.

8.3 Design of the test object

The test should measure behavior of individual joints and behavior of joints in relation to the whole structure. The designed beam should represent the spanning structure. As an example the design approach for the perpendicular shear joint connecting web and flange of an H-beam is tested. The jagged joint of 50mm tab and 50mm notch is tested in particular.

The beam height is 125mm, flange width is 200mm, the material thickness is 18 mm.

Test: behavior and strength of a notch-in-slot shear joint.

A 50mm-50mm notched web-flange joint cut with a 16mm router bit. desired data: rigidity of the connection (displacement per increased unit of force, rigidity EA in N/mm²), maximum strength (force in notch at fracture, F in kN), failure mechanism. Also the effect of the joint being either in tension or compression zone is researched.

Two T-shaped beam with a single cross section are tested in a four point bending test. One beam with the flange on the top side (compression) and one with the flange on the bottom side (tension). To measure the effect on one notch without other ones contaminating the test, a flange is connected to a joint on either end of the beam. The activation of the flange as structural component is done through these joints only. The joints are located near the supports to increase their participation in the forces of the beam.

Each of these beams has a counterpart that has the same cross section but without the flanges. These four beams are called 1A (flange on top), 1B (no flange), 2A (flange on bottom) and 2B (no flange).

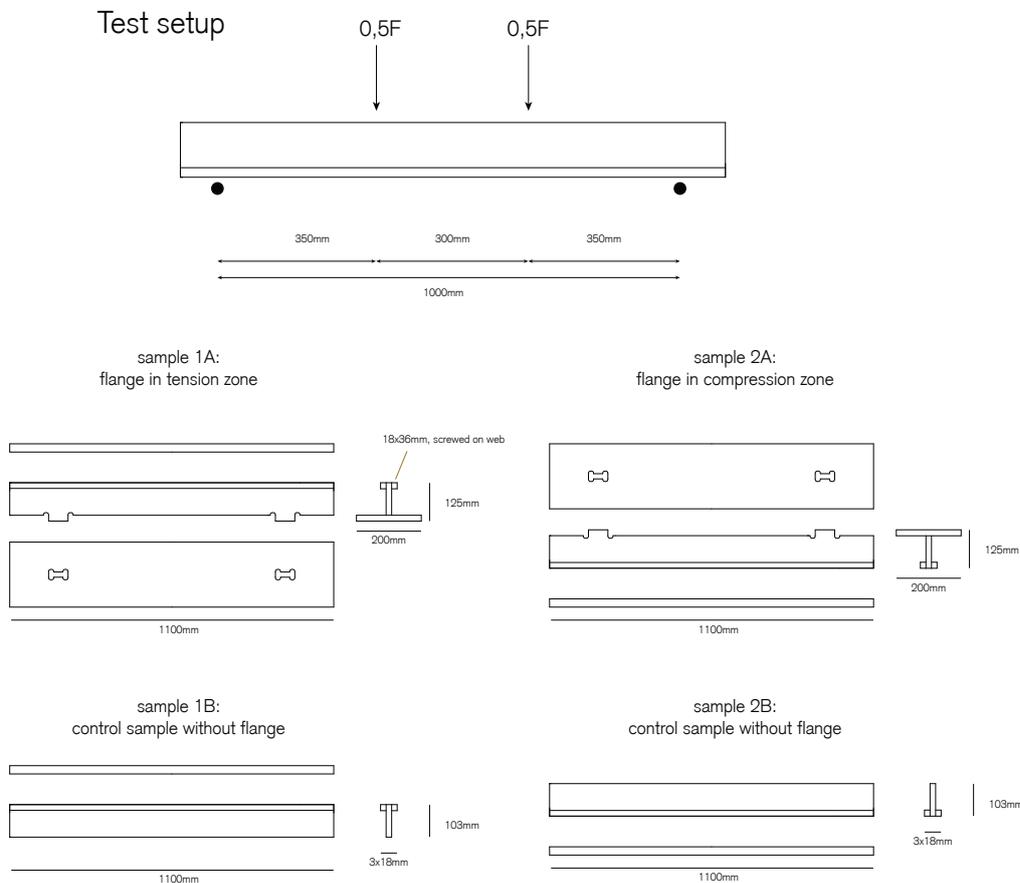


Fig 40. theoretical 4-point bending experiment setup. Mechanical behavior of samples 1A (bottom flange) and 2A (top flange) are compared. 1B and 2B are reference samples without a flange.

Bending test results:

The results are derived from the force-displacement diagram. By comparing EI-values of the models with and without flanges, the participation of the flange in the system and thus its rigidity and strength can be determined. The rigidity of the system is expressed in EI. The theoretical rigidity is determined by geometrical moment of inertia of the cross section (I) and E-module of the material (E). The bracketed numbers in the results correspond to the numbered events in the force-displacements diagrams above.

1A:

Theoretical rigidity: $I = 13,1 \cdot 10^6 \text{ mm}^4$ $E = 8352 \text{ N/mm}^2$ (parts are aligned to y-axis of panel) $EI = 109 \cdot 10^9 \text{ Nmm}^2$

Displacement range in elastic zone: 7,5-25 mm

Force range in elastic zone: 0,2-16,9 kN

Measured average rigidity in elastic zone: $EI = 20,4 \cdot 10^9 \text{ Nmm}^2$

Factor theoretical / measured rigidity: 5,3

Failure mechanism: shear failure of nock (2) and tensile failure in web (3).

Load at failure: 16,9 kN

Bending moment at failure: 2,96 kNm

The compression stress at the contact area of the nock at fracture as calculated: $34,0 \text{ N/mm}^2$. This is compared with the Numerical analysis of the same joint. At a line load on the nock of $39,2 \text{ N/mm}^2$, the average shear stress is between $12,8$ and 16 N/mm^2 , and the displacement is $1,0 \text{ mm}$ consisting from $0,70 \text{ mm}$ in the nock and $0,30 \text{ mm}$ in the slot. This translates to approximately 12 N/mm^2 at a line load of $34,0 \text{ N/mm}^2$. The factory data on claims $9,5 \text{ N/mm}^2$ shear strength, this is a deviation of approximately 20%.

1B:

Theoretical rigidity: $I = 4,70 \cdot 10^6 \text{ mm}^4$ $E = 8352 \text{ N/mm}^2$ $EI = 39,0 \cdot 10^9 \text{ Nmm}^2$

Displacement range in elastic zone: 6,5-19 mm

Force range in elastic zone: 0,3- 8,5 kN

Measured average rigidity in elastic zone: $EI = 14,1 \cdot 10^9 \text{ Nmm}^2$

Factor theoretical / measured rigidity: 2,8

Failure mechanism: tension failure of web (5)

Load at failure: 8,5 kN

Bending moment at failure: 1,49 kNm

2A:

Theoretical rigidity: $I = 13,1 \cdot 10^6 \text{ mm}^4$ $E = 8352 \text{ N/mm}^2$ $EI = 109 \cdot 10^9 \text{ Nmm}^2$

Displacement range in elastic zone: 5,5-25 mm

Force range in elastic zone: 0,25 – 14,0 kN

Measured average rigidity in elastic zone: $EI = 20,4 \cdot 10^9 \text{ Nmm}^2$

Factor theoretical / measured rigidity: 5,3

Failure mechanism: tension failure of web and consequently shear fracture of nock (7) and tensile failure in web (8).

Load at failure: 16,9 kN

Bending moment at failure: 2,96 kNm

2B:

Theoretical rigidity: $I = 4,70 \cdot 10^6 \text{ mm}^4$ $E = 8352 \text{ N/mm}^2$ $EI = 39,0 \cdot 10^9 \text{ Nmm}^2$

Displacement range in elastic zone: 7 - 23 mm

Force range in elastic zone: 0,5 - 9,1 kN

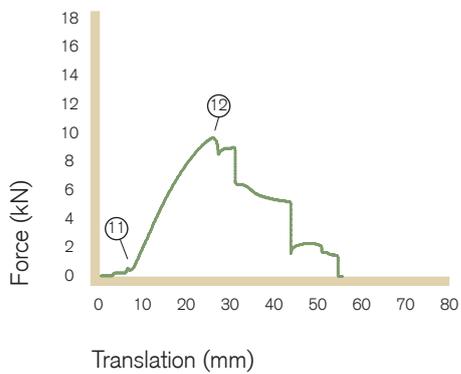
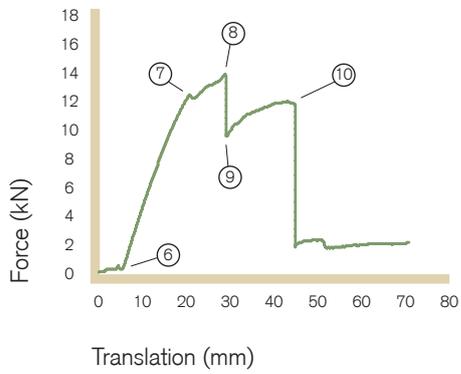
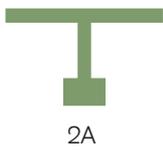
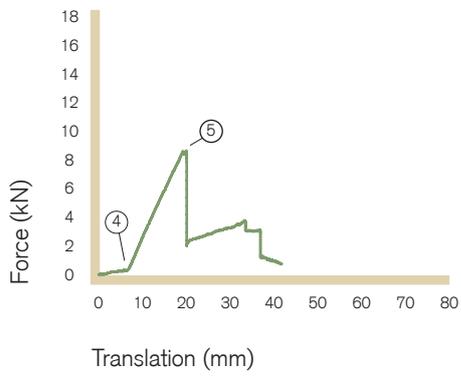
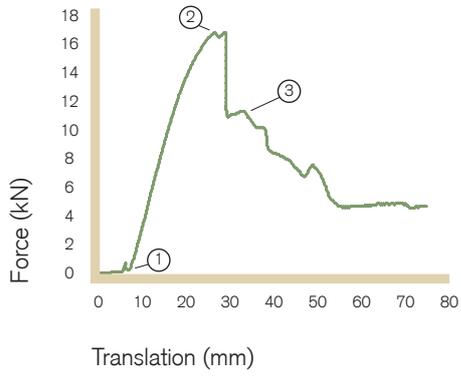


Fig 41. force - displacement diagrams of the test samples. Inclination rate is the flexural rigidity of the beam, steeper is more rigid. Sample 2A shows ductile failure mechanism behavior.

Measured average rigidity in elastic zone: $EI=14,1 \cdot 10^9 \text{ Nmm}^2$

Factor theoretical / measured rigidity: 3,3

Failure mechanism: compression failure of web (12)

Load at failure: 9,1 kN

Bending moment at failure: 1,59 kNm

Conclusions:

1. The rigidity of the theoretical and measured model without flange (1B) differs by a factor of 2,8. This is caused by either difference between factory data and the actual elasticity properties, loss of elastic rigidity of the beam through screwed joints or a combination of both. Because either are constants and are consequently applied throughout the test ensures that the test still useful in relative terms. FEM analysis of two joints showed that reducing the E-modulus within a joint by a factor 3 does not influence the magnitude of tension by more than 10%. The differences between samples with and without flanges in respect to the theoretical rigidity – 2,8 and 5,3 – can be attributed to the fact that the flange is not part of the continuous cross section, but merely a stiffener attached between two points of the flange. From the difference in rigidity between 1A ($EI=20,4 \cdot 10^9 \text{ Nmm}^2$) and 1B ($EI=14,1 \cdot 10^9 \text{ Nmm}^2$) can be derived that the flange attributes significantly to the overall rigidity, even when just two nocks contribute. In this case the EI increases by 45%. Also difference in strength is significantly improved: comparing maximum strength of 1A ($F=16,9 \text{ kN}$ at fracture) and 1B ($F= 8,5 \text{ kN}$ at fracture) shows an increase of 99%.

2. Sample 1B shows perfectly linear elastic behavior, the diagram shows a straight line between (4) and (5), where samples 1A, 2A and 2B show an increasing reduction of rigidity when closing the point of fracture, as can be concluded from the slight curve in the elastic zone. This can be noted from the lines between (1) and (2) respectively (6) and (7). For sample 2B, between (11) and (12), this effect can be attributed to the instable positioning of the load and subsequent wrinkling of the web. For samples 1A and 2A this effect is caused by viscoelastic behavior due to stress concentrations around the flange joints. This effect is advantageous, as the weakest joints will take less stress when nearing their moment of fracture than other participating joints at the same deformation rate.

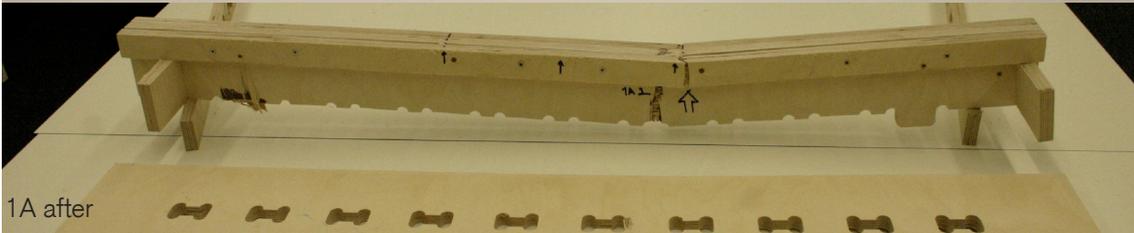
3. Samples 1A and 2A have exact equal flexural rigidity; both have an EI of $20,4 \cdot 10^9 \text{ Nmm}^2$, implying predictable behavior of the connections, however this needs more testing to determine the actual coefficient of variation.

4. The diagram of sample 2A shows a seemingly safe failure behavior. After the first fracture at 14 kN (7) the resistance against bending remains, however at a larger deformation rate, until a second failure moment is reached at 15,5 kN (8). The first failure mechanism is shearing of the nock, which happens gradually. As the compression zone in the web relaxes relative to the flange joint, the latter is increasingly stressed until fracture of a second mechanism: the tension zone of the web beneath one point load tears but the two slats on either side remain intact (8). This can be derived from the fact that there is instant loss of strength between (8) and (9), implying brittle failure in the tensile zone. It can be concluded that the compression zone remained functional because after resettling at (9), the beam could still resist a force up to 12 kN until a third mechanism failed (10). This strength has not been achieved by samples 1B or 2B, so this additional capacity can be attributed to the flange. The capacity to resist the increase of the bending moment after the first failure defines a safe structure.

5. Sample 1A also fails through nock shear (2), but at a higher load (17,2 kN) than 2A (13,8 kN). The abrupt decrease of the system strength after (2) suggests brittle failure. Contrary to the nock of 2A, this is not a safe failure mechanism. However sample 1A and 2A theoretically have the same mechanical behavior, as is also confirmed by their similar EI-values, their failure mechanisms are very different. This is due to the fact that the compression zone of the web fractures first with a plastic deformation as result. The lateral deformation of the top of the web and the top flange are



1A before



1A after



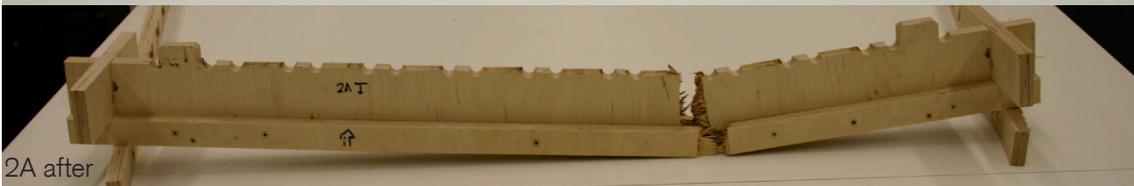
1B before



1B after



2A before



2A after



2B before



2B after

equal due to the nocks. The lateral deformation of the web directly causes an increase in stress in the top nocks, which compensate for this loss of elastic rigidity and draw proportionally more stress causing a higher deformation rate. This effect is evident at the line between (7) and (8). The bottom of the web in 1A is loaded in tension. The tensile strength of birch plywood is 31% higher than the compression strength; in the case of 1A this caused the nock to be the first failure mechanism of the two, in contrast to 2A where the web is weakest in respect to the top nock.

The inaccuracy of the test method can involve the following aspects:

- a. The quality of the nocks varies. A local failure weakens the nock of sample 2A, which causes it to fracture well before the other nocks. The coefficient of variability of the nock quality needs to be determined by a series of tests of these individual shapes to confirm or exclude this effect. The identical behavior in the elastic zone of 1A and 2A suggests similar qualities of the nocks.
- b. The flange-web connection of sample 1A is in close proximity of the support as opposed to that of 2A, which is at the top. The shear stresses concentrate around the supports and can affect the flow of forces near the connection. This effect can be analyzed in a similar test that is supported in a more symmetric way: i.e. near the normal line.

6. The second failure mechanism is typically in the same zone as the first failure mechanism. If for example a joint in the compression zone of a beam fails, this part relaxes and loses participation in the whole system. As a result the normal line of the beam moves away from this location and down to the tension zone. This change in the cross sectional moment of inertia causes an increase of stress in the remaining joints in the compression zone. This is a preferable effect because different joints work together as failure mechanism.

7. The bending tests with the results of 1A and 2A in particular show that the preferred location of the first failure mechanism is in the compression zone, consisting of both flange-web connection fracture and plastic deformation of the compression zone of the web simultaneously, while preserving additional resistance capacity against bending moments. A cross section with both top and bottom flange should be designed in such a way that the first failure mechanism is the compression zone of the web because of its large deformation capacity. The second failure mechanisms should be the top nock to allow the beam to plastically deform. The width of the nock limits its deformation capacity. The extent of resultant deformation in the plastic-elastic zone in both weakest joints defines the extra moment capacity after the first failure mechanism.

8.3 Analysis of failure modes of an aggregate construction

An H-beam is constructed from multiple panel components that are connected by several types of joints. Each component and each joint has their distinctive elastic rigidity, strength properties and inherent failure mechanisms. In order to designate certain parts of the beam to be the weakest link, the behavior and participation of all components and joints need to be known. Based on that knowledge, certain elements can be manipulated to achieve the desired strength and elastic rigidity to form the desired failure mechanism.

This analysis is exclusively valid if linear elastic behavior of the aggregate structure is assured. The particular effect of any non-linear behavior like settling of joint seams or plastic deformations cannot be extracted from the bending tests and requires complex non-linear FE-modeling.

The joints and components need to be modeled in linear elastic structural engineering software with the following input and desired output:

Input:

Panel components: 1D or 2D with moment of inertia and elasticity module: EI in Nmm^2 .

Joints: non-dimensional with a spring constant: k in mm/N .

Fig 42 (left page) before and after photo's of the test samples.

first failure mechanism

second failure mechanism

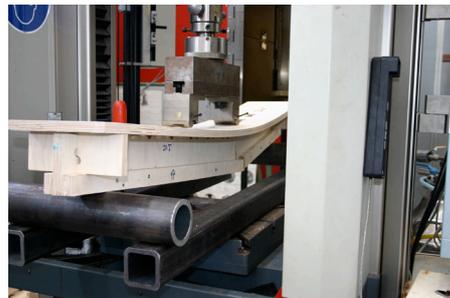
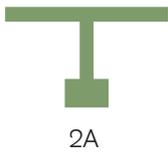
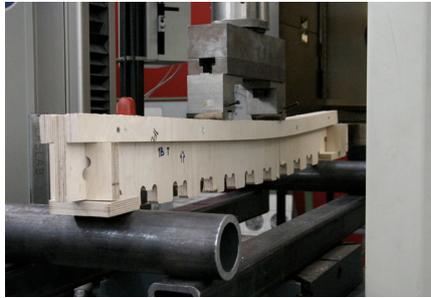
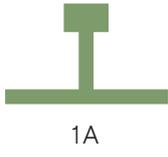


Fig 43. Failure mechanisms of the test samples. Sample 1A and 2A collapsed in a sequence of failure modes.

0F	flange	number:	loading type: coord. system						
variant:									
50 50 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	41	39,2	0,96					
fc,x	N/mm2	43	27,2	0,63	24,7962791				
ft,y	N/mm2	18	35,8	1,99					
fc,y	N/mm2	36	24,8	0,69					
fv,xy	N/mm2	12,5	9,5	0,76					
ux,interval	mm (avg)	0,29							
ux,tot	mm								
0W	web	number:	loading type: coord. system						
variant:									
50 50 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	109	39,2	0,36					
fc,x	N/mm2	117	27,2	0,23	9,11316239				
ft,y	N/mm2	98	35,8	0,37					
fc,y	N/mm2	68	24,8	0,36					
fv,xy	N/mm2	25	9,5	0,38					
ux,interval	mm (avg)	0,71							
ux,tot	mm								
1F	flange	number:	loading type: coord. system						
variant:									
60 40 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	45	39,2	0,87					
fc,x	N/mm2	46	27,2	0,59	23,1791304				
ft,y	N/mm2	23	35,8	1,56					
fc,y	N/mm2	40	24,8	0,62					
fv,xy	N/mm2	12,9	9,5	0,74					
ux,interval	mm (avg)	0,31							
ux,tot	mm								
1W	web	number:	loading type: coord. system						
variant:									
60 40 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	104	39,2	0,38					
fc,x	N/mm2	98	27,2	0,28	10,88				
ft,y	N/mm2	76	35,8	0,47					
fc,y	N/mm2	44	24,8	0,56					
fv,xy	N/mm2	22	9,5	0,43					
ux,interval	mm (avg)	0,35							
ux,tot	mm								
2F	flange	number:	loading type: coord. system						
variant:									
40 60 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	40	39,2	0,98					
fc,x	N/mm2	42	27,2	0,65	25,3866667				
ft,y	N/mm2	20	35,8	1,79					
fc,y	N/mm2	34	24,8	0,73					
fv,xy	N/mm2	11,8	9,5	0,81					
ux,interval	mm (avg)								
ux,tot	mm								
2W	web	number:	loading type: coord. system						
variant:									
40 60 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	130	39,2	0,30					
fc,x	N/mm2	128	27,2	0,21	8,33				
ft,y	N/mm2	110	35,8	0,33					
fc,y	N/mm2	88	24,8	0,28					
fv,xy	N/mm2	31,7	9,5	0,30					
ux,interval	mm (avg)	0,5							
ux,tot	mm								
3W	web	number:	loading type: coord. system						
variant:									
70 40 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	95	39,2	0,41					
fc,x	N/mm2	85	27,2	0,32	12,544				
ft,y	N/mm2	69	35,8	0,52					
fc,y	N/mm2	40	24,8	0,62					
fv,xy	N/mm2	19,5	9,5	0,49					
ux,interval	mm (avg)	0,35							
ux,tot	mm								
4W	web	number:	loading type: coord. system						
variant:									
80 40 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	89	39,2	0,44					
fc,x	N/mm2	79	27,2	0,34	13,4967089				
ft,y	N/mm2	55,6	35,8	0,64					
fc,y	N/mm2	25	24,8	0,99					
fv,xy	N/mm2	18,5	9,5	0,51					
ux,interval	mm (avg)								
ux,tot	mm								
5W	web	number:	loading type: coord. system						
variant:									
90 40 notched		0	fc,x	XY					
failure mode:	max value	yield strengtl UC	equivalent yield strength at failure of critical loading type						
ft,x	N/mm2	87	39,2	0,45					
fc,x	N/mm2	74	27,2	0,37	14,4086486				
ft,y	N/mm2	66	35,8	0,54					
fc,y	N/mm2	29	24,8	0,86					
fv,xy	N/mm2	17,3	9,5	0,55					
ux,interval	mm (avg)								
ux,tot	mm								
Optimization of nock distribution with of nock total width					strength	surfaces/m	N/mm/m		
40	76	8,3	13,2	109,2					
50	86	9,7	11,6	112,8					
60	96	10,9	10,4	113,5					
70	106	12,5	9,4	117,9					
80	116	13,5	8,6	116,4					
90	126	14,4	7,9	114,3					

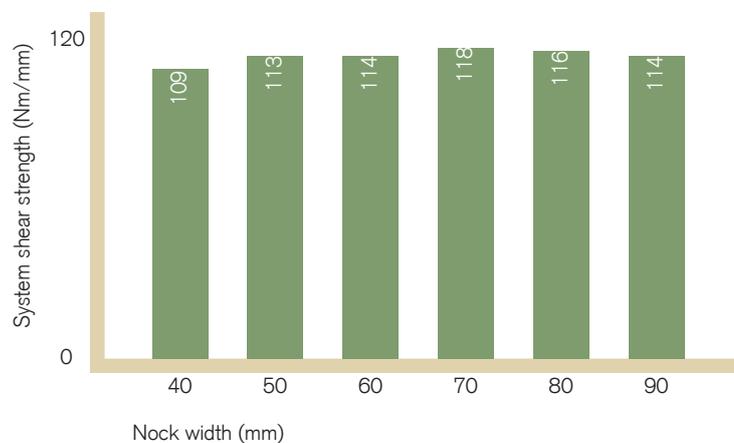


Fig 44 (top). Experiment with different nock-slot joint configurations. Wider nocks and slots are stronger, but a smaller amount can be used per meter resulting in a larger load per joint at a constant loading of the beam per meter.
 Fig 45. (bottom). Relation of nock/slot width and system strength after normalization for amount of joints per meter. The optimum lies near a nock/slot width of 70 mm, though differences are small. This indicates that secondary criteria that define joint distance can be the leading principle without loss of structural integrity.

Output: force conveyance of all joints and maximum stress in panels.

The output loads on all joints need to be compared with the strengths of all failure mechanisms, the joint with the largest load relative to their strength forms the failure mechanism.

10.4 Manipulation of structural properties of joints and panel components

The different elements of the structure – joints and panel components – need to be configured in a manner that the right order of fracture events happens. The rigidity of these components together defines the mechanism of the whole structure: i.e. how the forces flow through the structural element and the magnitude of forces flowing through the various joints and cutout components. The respective failure modes and ultimate strength of these various elements define the order of failure events: the failure mechanism of the beam.

Therefore all the joints and cutout panels need to be configured in a way that the desired failure mechanism is achieved. This can be done by manipulation of the strength and rigidity properties of those components; this manipulation can only be done by altering the shape of the different components. The method of

An overview of different possible changes of shape per joint or component, the corresponding structural effect on these joints and components and assessment method is given in the next paragraph.

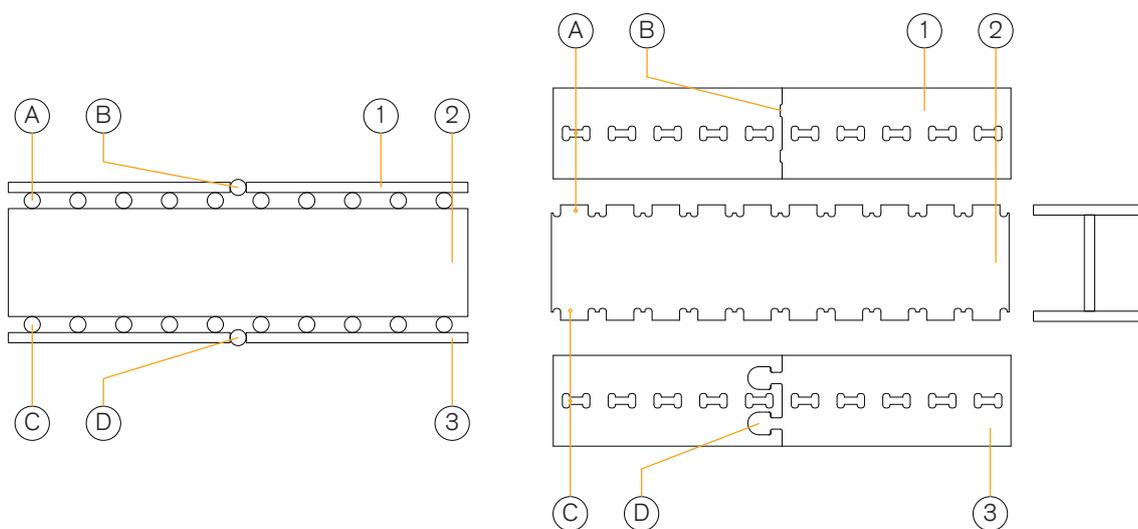


Fig 46. Schematic and projection of an H-beam with seams. The letters indicate joint types (zero-dimensional rigidity properties), the numbers indicate panel types (1 or 2 dimensional rigidity properties)

Example of a beam analysis.

A sample beam has an H-shaped cross section with flanges and a web. The flanges have a seam in the middle and are connected with a joint that has been selected from the joint library. The inherent strengths and rigidity can be analyzed as follows:

All joints and panel cutouts are numbered and individually analyzed based on the magnitude of force they convey. The elements are:

- A: 90° shear joint, connecting web and top flange.
- B: Compression butt joint connecting top flange panels
- C: 90° shear joint, connecting web and bottom flange.
- D: Tension joint, connecting bottom flange panels
- 1: top flange panel
- 2: web panel
- 3: bottom flange panel

As an example the shear joint A is explained.

The shear joint consists of a nock on the web and a slot in the flange.

Possible failure modes:

- Nock shear failure (ductile)
- Nock tensile failure in overcut notch (brittle)
- Nock compression failure in overcut notch (ductile)
- Slot transverse tear of flange (brittle)
- Slot compression failure of contact zone (ductile)

Shape aspects of the shear joint:

1. Nock thickness:

The increase of the thickness of the nock – and thus the whole web – is directly proportional to the increase of strength and elastic rigidity. This means that the failure mode cannot be changed by this modification. Because the whole web becomes thicker, this can only be used to change structural properties in relation to the flanges.

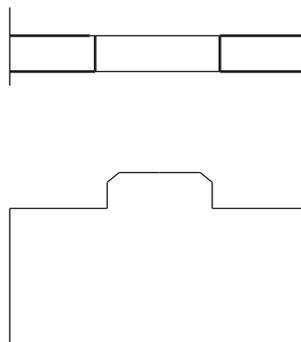
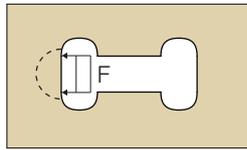


Fig 47. schematic projection of a nock-slot joint.

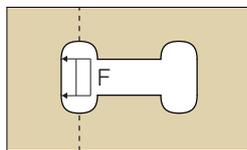
Failure mechanism: compression punch



Tools:

1. Slot distance
2. Flange thickness
3. notch aspect ratio (oval)
4. notch diameter
5. Slot width
6. amount of slots

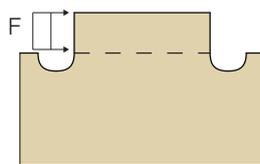
Failure mechanism: lateral tear to flange edge



Tools:

1. Flange width
2. Flange thickness
3. notch aspect ratio (oval)
4. notch diameter
5. Slot width
6. amount of slots

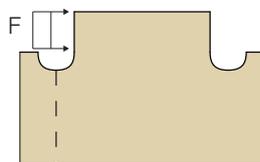
Failure mechanism: shear



Tools:

1. Web height
2. notch depth
3. notch aspect ratio
4. notch diameter
5. panel thickness
6. amount of nocks

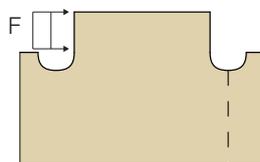
Failure mechanism: tension in notch



Tools:

1. Web height
2. notch depth
3. notch aspect ratio
4. notch diameter
5. panel thickness
6. amount of nocks

Failure mechanism: compression in notch



Tools:

1. Web height
2. notch depth
3. notch aspect ratio
4. notch diameter
5. panel thickness
6. amount of nocks

2. Nock width

An increase of the nock width at a constant action force from the flange will decrease the shear stresses and stresses at the overcut notches. However, when the nocks are made wider, the amount of nocks per meter decreases as well, resulting in larger loads per nock. The function for this effect is one with a maximum strength: a nock of 70mm wide has the lowest relative stresses and is considered optimal.

3. Overcut notch diameter

at a fixed web height an increase of the overcut notch diameter – by using a larger router bit for example – the peak stress reduces relative to the nominal stress. Due to the cut depth, the elastic rigidity of the joint will also decrease. At a web height of 200mm the Kt-factors for a 5mm router bit and a 16 mm router bit are respectively 2,92 and 2,77. This difference is small compared to the difference in loss of rigidity. This is based on a generic formula.

4. Amount of nocks

By changing the density of nocks the force distribution over the nocks changes as well.

5. notch aspect ratio

By giving the notches an oval shape with the large radius at the peak stress location, the stress intensity decreases. Ovals require complex shape descriptions – splines – which are difficult to process with a CNC-milling machine. This effect can be calculated with stress concentration factors.

6. flange width

By changing the flange width, the nominal stress in the flange decreases, effectively reducing stress in the overcut notch and increasing flange rigidity. This effect can be calculated with stress concentration factor formulae.

7. flange thickness

increasing flange thickness will proportionally increase all other structural aspects of the flange slot. It will however influence the nock because the introduction of force is higher and will require a higher nock.

Calculations:

The calculations of the resistance of the different failure modes can be calculated as follows:

Elastic rigidity of the nock and slot can be derived from a FE-model by measuring displacement of the contact zone and divide it by the action force. Displacements of either part of the two connected elements can be added.

Shear stress in the nock can be derived from a FE-model, by averaging the shear stress on the shear line.

Tensile and compression stresses in the overcut notches of the nock can be analyzed by stress concentration factor formulas. The already present stresses from web bending need to be added to this stress.

Fig 48 (left page). Possible failure mechanisms for nock-slot joints. The failure mechanism defines the maximum strength of a joint for the loading that is specific to the joint type. For each failure mechanism is indicated what the palette of shape modification options is, which manipulate the strength and flexural rigidity properties of the joints.

9

DESIGN SUGGESTIONS

8.1 Suggested structural design process

Structural design of a spanning structure can be organized as follows:

1. Definition of structural starting principles

External loads, load introduction and the span of the beam are defined. The inherent maximum deflection and required bending moment resistance can be derived from the Eurocodes. These form the criteria for the cross section and joints of the beam.

2. Structural system predesign

Sketch the construction in accordance to the global structural systems and include the panel elements and seams based on the maximum dimensions of the used panel. Place the seams in structurally preferable locations. Draw the joints into the structure based on additional external criteria such as is required by compatibility with other elements. An example is the girders that are supported by the nocks of an H-beam.

3. Selecting joints from database.

The Fab Fac designer manages a library where iterations of joint types can accumulate. The information sheets of these joint types contain the rigidity, strength and failure mode of the joint as well as secondary aspects like required router bits, milling time and other relevant information. The selected joints can be further optimized for the distinct purpose and requirements in the beam by the optimization method proposed in chapter 9. The optimized iteration of the joint is to be stored in the library.

4. Analysis of the failure mechanism of the beam.

The elastic rigidity properties of 0D joints and 1D or 2D panel components are modeled in structural statics analysis software. The stresses in panels and forces in joints can be derived from the output data and are compared to the actual strengths of the failure modes of joints and panel components, which indicates the failure mechanism of the beam and magnitude of over- or undercapacity of the joints and panels.

5. Reconfiguration of the failure mechanism of the beam.

The desired failure mechanism of the beam is defined. The shape of the critical joints is manipulated in a manner that the joints get the desired elastic rigidity, strength and failure mode using the methods proposed in chapter 10. The adjusted system of joints and panels are modeled in further iterations until the desired failure mechanism of the beam and structural requirements in terms of strength and deflection are achieved.

6. Testing of the structural system.

A sufficient amount of beam samples is produced and assembled and proofed with a 4-point bending test.

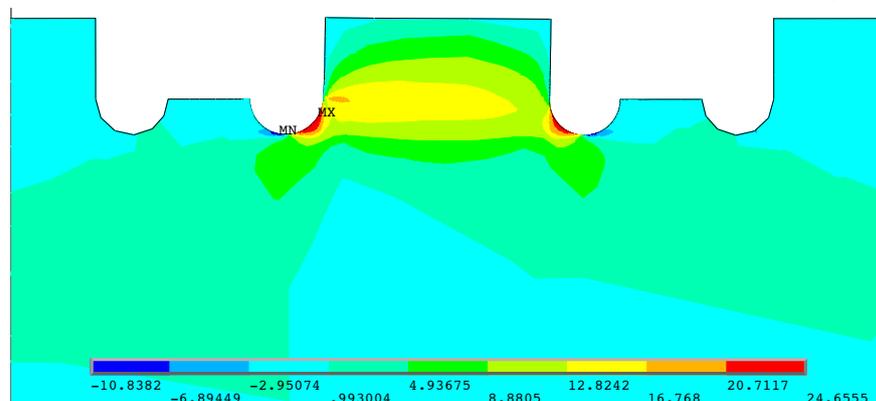
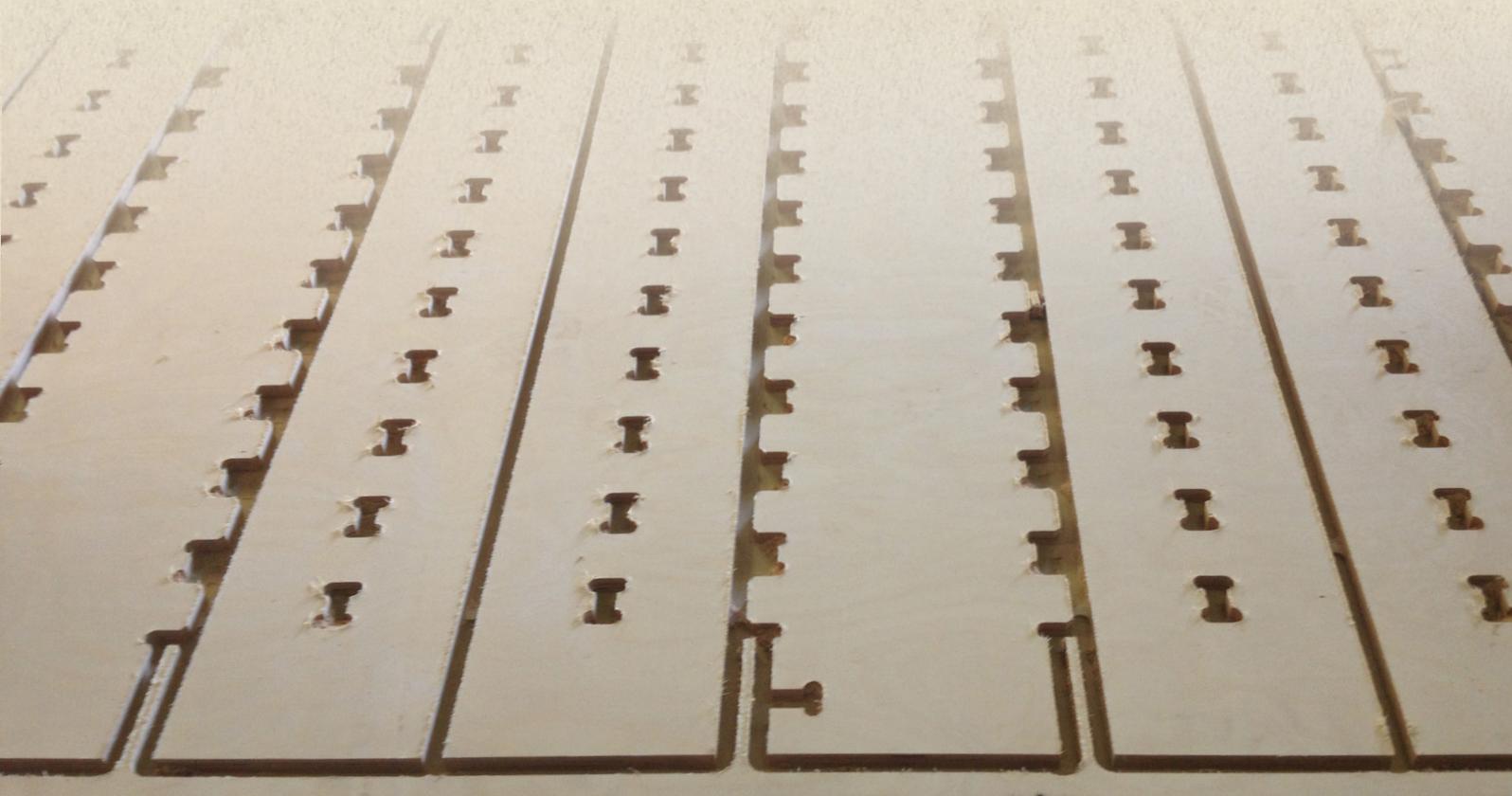


Fig 49. FEM output of a nock joint displaying shear stress. Local peak stresses need to be ignored due to mathematical inaccuracies in the model that do not represent actual behavior. This joint has shear stress of 13 - 16 N/mm². Compared to the material shear strength of 9 N/mm² it is loaded over its capacity at a modeled load of 40 N/mm² on the contact zone

PART IV

CONCLUSIONS AND SUG- GESTIONS FOR FURTHER RE- SEARCH



10 CONCLUSIONS

10.1 Research conclusions

In comparison to other structural systems that can be calculated by using standard formulae and standardized methods, construction systems that depend on compression contact surfaces like CNC-cut plywood structures tend to be subject to highly irregular mechanical behavior. To be able to calculate strength and elastic rigidity of a structure design, the cooperation of all joints need to be defined. It is essential to know at what load the designed structural element breaks.

In the case of a new structural design first a design needs to be calculated as accurately as possible so the amount of iterations of physical proofing can be reduced. When designing a structure, the engineer needs to know the mechanical behavior of joints and be able to control these by manipulating their shape. The effect of these manipulations can be assessed by methods like concentration factor calculation FEM-analysis and physical testing. Managing proportionality between joints and failure mechanisms is essential to design a safe structure.

A CNC-cut plywood structure has very complex and specific properties. The design of one requires specialized structural engineering skills, a relatively large investment in engineering and investment in physical proofing of the design. Because this type of structural system is new, it is necessary to gain experience before it can be intensively applied.

A beam should always be tested because there are no norms or guidelines to design a structure. To design a good system, a combination of theoretical approximation and physical validation is needed. The more accurate the theoretical approximation method is, the less iterations in physical testing is needed. It is preferred to control the design method as much as possible.

Structural cross sections that use webs and flanges, like H-beams and box-beams have advantageous rigidity and strength properties compared to other types of cross sections. Due to the ability to make efficient cross sections, the material can be economically used. The material properties of plywood are advantageous for safe structure design in the sense that it possesses ductile failure properties in compression loading.

If this structural approach is to be used within the context of a modular building system, it would be the starting principle for every design due to its inherent inertia: it takes a lot of effort to design a new structural element, or modify an existing one. The parameters that influence the variety of these spanning structures should be reduced as much as possible, for example only predefined loading cases.

The combination of CNC-milling technique and cross-laminated panel woods is a very potent system to produce efficient structural elements. However, due to the complexity of the structural system and anisotropic material properties in addition to the fact that there is little empirical data on this type of structures, the engineering aspect is particularly labor-intensive. All iterations of a structural component need extensive modeling and physical testing.

10.2 A guide for the Fab Lab engineer

This is a guide for the engineer that manages a building system that intends to exploit the shape freedom potentials of the CNC-milling process. The chances lie in the high autonomy that this principle delivers; the goal is to maximize the amount of components of the building that can be produced through the CNC-milling fabrication process.

By using design and fabrication technology based on a CNC-machine and plywood, a high degree of material efficiency can be reached e.g. compared to timber construction. The shape freedom allows the necessary joints to be optimized, and required structural safety measures (a ductile failure mechanism) to be implemented into the structural components.

The trade-off is that shape freedom inherently causes complexity within the structural design assessment process. All iterations of joint shapes require a labor-intensive assessment round including finite element modeling and result interpretation of single joints and joint compositions in a structural part. This cannot be automated and requires specialized engineering.

Because structural engineering of these types of structures requires a high amount of resources, it is advised to start by designing a standard spanning structure that can be used for a majority of the modular building designs. The structure will be designed for a specific loading type so it is essential to check if the actual load case on the modular building designs comply with the calculated loading. The dimensions of the spanning structure cannot be altered. This design should be the starting point for further research and optimization cycles.

At this point, two types of load bearing structures are possible to apply in buildings.

1. hinge supported beam structures.

This thesis shows that H-section profile or box profile designs are the most advantageous structural principle due to three aspects:

- a. Cross-sections composed from webs and flanges have inherent high moment of inertia, meaning that little material is needed to achieve high structural performance in terms of strength and rigidity.
- b. Nock-slot type of joints are effective and are safe due to viscoelastic behavior before failure which allows forces to redistribute through other joints.
- c. The combination of a web and flanges are the condition for ductile failure mechanism implementation, allowing for safe structural design.

The trade-off is that structural systems based on hinges have no in-plane stability. They need additional stability measures which are difficult to offer through the CNC-cut plywood construction technology itself. Application of steel tension cables is the most obvious solution.

2. structures with rigid corners

As an alternative to the H-section beam structures, a design that consists of rigid angles can be applied. This type consists of several vertically oriented layers of panel wood that are cut into the shape of the corner, for example at the gutter. The corners have a typically high local bending moment, usually this is the normative loading for the construction. Because flanges cannot convey forces when they are at an angle with each other, the structural cross section of these corners are rectangular. This is a rather uneconomic cross section as a large portion of the material in the cross section will not be loaded to its maximum potential.

At larger spans this type of construction is not viable as the bending moment increases exponentially where the E-modulus of the material remains constant. The material becomes less rigid relative to the loading at an increased span.

Future research should therefore be focused on structures with H-section or box-beams.

In order to develop a first prototype that is based on web-and-flange beams, it is essential that the following three aspects be researched.

- a. The avoidance of rigid angles automatically means that mechanical hinges are used instead. These hinges are required to convey significant normal and shear forces that concentrate at the joint while maintaining rotational freedom. As this type of joint is rather difficult to produce by CNC-milling technique, for example when the forces need to be conveyed in-plane, these joints may be best produced by using additional materials or products. The design criteria and an adequate assessment method need to be developed. When the construction consists of hinges, additional stability measures need to be taken. A steel cable is a good option.
- b. Shear joints in the webs of H-section or box profiles are complex aspects to model. The normal line (zero tension or compression stress) lies in the web, which means that both tension and compression stresses occur in the web. The shear joint can only convey compression stresses however, and the division between compression and tension zone is dependent on the rigidity and stress distribution of the whole system of joints. The joint system forming the beam and the shear joint are dependent on each other, causing singularity. An approach to modeling this configuration needs to be researched before a H-section beam can be calculated.
- c. Unrealistic peak stresses are inherent to FE-modeling. The different methods to interpretate FE-model output need to be refined. Stress concentration factor analysis, photoelastic analysis and other types of analysis need to be elaborated upon and be confirmed by lab experimentation.

When these aspects are covered, the web-flange beam elements can be calculated and designed as a safe structure. From this point an optimization process in terms of joint design, mathematical structural assessment, experimental structural assessment, global loadbearing structure design and implementation into the modular building system can be started.

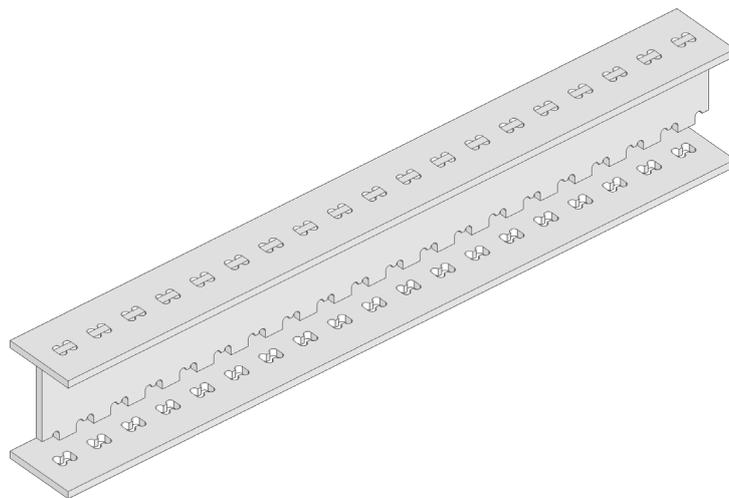


Fig 50. Beam designs consisting from webs and flanges are the optimal use for structural elements created through CNC-based construction system.

11

SUGGESTIONS FOR FURTHER RESEARCH

11.1 Suggestions for further research in respect to proposed structural design methods

The method of modeling spanning structure systems based on component rigidity needs elaboration.

The calculation method of failure modes of joints that have hot spot stresses need to be researched. Gathering data empirically with optical stress-strain analysis of sample pieces can do this. As a result formulae for different loading types can be designed.

Other types of connections also need researching. Examples are hinge support connections and seams in panels that convey shear forces.

Wood construction design involves more criteria than the ones that are treated in this research. Lag and creep are time-dependent structural criteria that need to be predicted as well. Other criteria are resistance against fire and the influence of humidity. These criteria are dependent on the function of the building and differ throughout various applications of the proposed structures.

Research on the topic of other criteria like efficient fitting of cutout shapes into the base panels so little material is lost can result in a significant increase of the overall efficiency of CNC-cutting plywood as construction principle. Also the interface of the proposed structural system with other building components needs refinement, including the effect on the structural system.

11.2 Suggestions for further research in respect to potential additional solutions

As a kickstarter for the graduation project, a creative session has been held to explore the range of solutions of building with panels. The setup was to start from general connection types, and see where the discussion would lead to, unhampered by restrictions to what the solutions could be. The central challenge was conveying forces from one panel to another, for example the tension stresses within a flange that is part of an aggregate beam.

The session yielded five ideas to be elaborated upon.

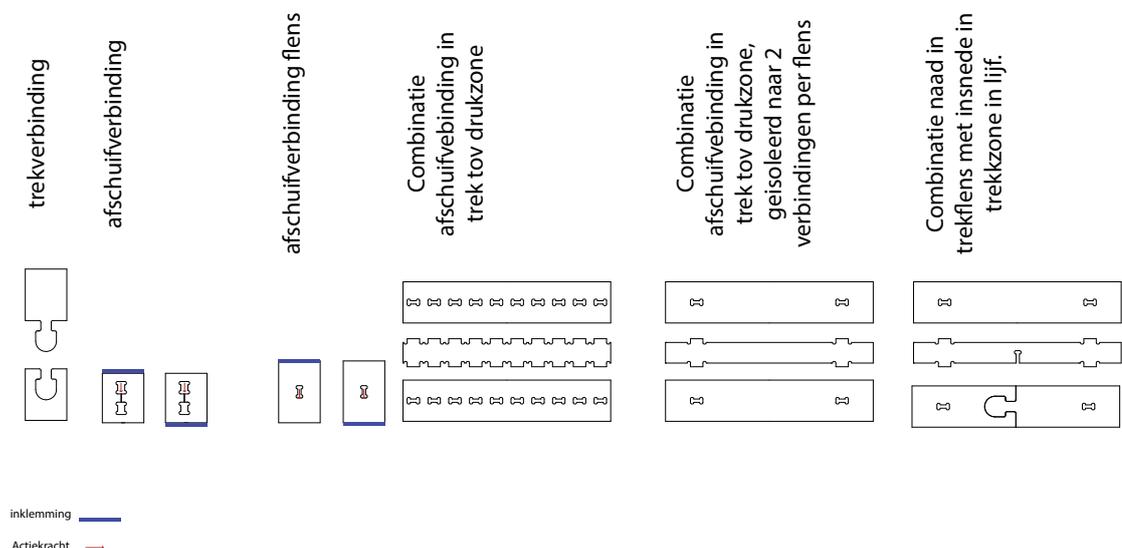


Fig 51. Various test setups of individual joints and joint combinations that are recommended to be further researched.

1. rigid connector

joining two panels that need stresses to be conveyed in the same plane has the disadvantage that cutting lines interrupt the stress vectors, especially at areas that are tension loaded. Two panels can be connected jigsaw-puzzle style, which can be done in two ways. Large parts that are either directly connected, or through an integrated third piece, a 'connector.' The first option has the smallest contact surface area strength loss, but is more difficult when handling: the large and elements need to be fitted into each other. The second option has twice the strength loss, but the large elements can be positioned easier before applying the connector. As stresses will be concentrated in the connector, deformations play an important role.

As a conclusion to this idea, both the effect of stiffness of the connector and double cut sides can be analyzed. Both force conveyance and translations are subject of interest.

2. rotation of fiber orientation.

For connections that are loaded on shear force, it would be interesting whether the 45 degree rotation of the ortholiner fiber orientation would be better for flow of stresses, and have better shear resistance properties. This could be applied at the notch in slot joints of a flange-web-connection. If this is a viable solution, the consequence would be that these elements need to be cut diagonally from the base panel at cost of useable surface area. The effect of rotating this fiber orientation cannot be assessed by FEM-software, because its input in orthogonal axis is linear. In practice, this is about brittle behavior of the material. half of the layers would have the fibers orientated parallel to the shear force vector, thus in its weak axis, leaving the other half to distribute the shear forces. At yield tension, the tooth would break instead of reaching elastic limit. Analysing brittle behavior is outside the scope of this research, so this idea will not be elaborated upon.

3. industrial standard connector

The shape freedom provided by CNC-milling could be used to perfectly fit an industrial element that is mass produced and therefore cheap and easy to come by. These components could be inserted in a customized contra-shaped gap to assist the flow of forces and easy placement. In addition to the easy mounting, measures to precisely place e.g. bolts or steel consoles can be integrated into the design. The construction element would act as a form of jig. The 'domino' is an example of this type of joining.

The standard woodworkers hard wood dowel and bulldog are examples, but because they are specifically designed for typical wood construction, their application would implicate to use the plywood structural system as a typical wood construction system. Therefore these solutions are no further researched.

The connector can be a medium of a truly bolted connection or convey forces by tight-fit. The former solution would be a typical bolted connection, where the potential of CNC-milling lies in quick-fitting the industrially produced components and tool placement. The latter solution would mean that forces are introduced outside the center of gravity of the plywood elements, and introducing internal shear stresses acting on the same plane as the material is layered: its weak shear plane due to the weak lateral fiber bonds.

4. large contact surface area

panels can be milled to halfway the depth, when using the so-called 2.5th dimension. This principle allows panels that are loaded and joined in the same plane to overlap and convey forces over a larger area. The surfaces are milled so both hook into each other through milled ridges.

The larger the length of the overlap, the shorter the maximum length of the elements can be, but the overlap needs to have some length to be able to sufficiently convey the forces, as the panels will be loaded in shear in their x-y plane, the weak plane. Due to the milling precision of $\pm 0,05\text{mm}$, the connection should fit perfectly.

To test this type of connection, variants are designed and tested to shear strength, size of overlap, influence of inclined ribs (trapezium-shaped) on shear strength, and need for measures against swaying out of the tabs.

5. prestressing elements

When structural elements with moment bearing capacity span longer distances than the length of a panel, the elements should be composed from multiple parts. The joints that connect stress elements like flanges allow the largest lateral movement, causing the joint to act as a sort of hinge. The stresses due to internal moments could theoretically be cancelled when a prestress is applied. Prestressing is commonly seen in large concrete structures such as bridges, where it is used to put the whole cross section under pressure so that the concrete doesn't have to tear before the steel reinforcement cables are activated, ultimately decreasing the total deflection and protecting the steel reinforcement with an intact cement layer.

When in this case the cross section is put under compression, the tension joints are eliminated, but the compression stresses in the top part of the section will be significantly larger.

Prestressing as a solution for CNC-milled structures could involve different existing industrial solutions such as spanning bands, packaging ties and steel cables.

To research the palette of industrial solutions, the required strength of such solutions needs to be defined. Tension joints will be needed when the beam is longer than the maximum length of a panel. For an indication, the length could be two panels long. With the assumption of normal roof loading and beam height, an internal bending moment, and consequently the tension stress in the outer fiber can be defined. The resulting required strength of the prestress element that cancels out the tension to bring the stress to zero can be calculated from there.

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