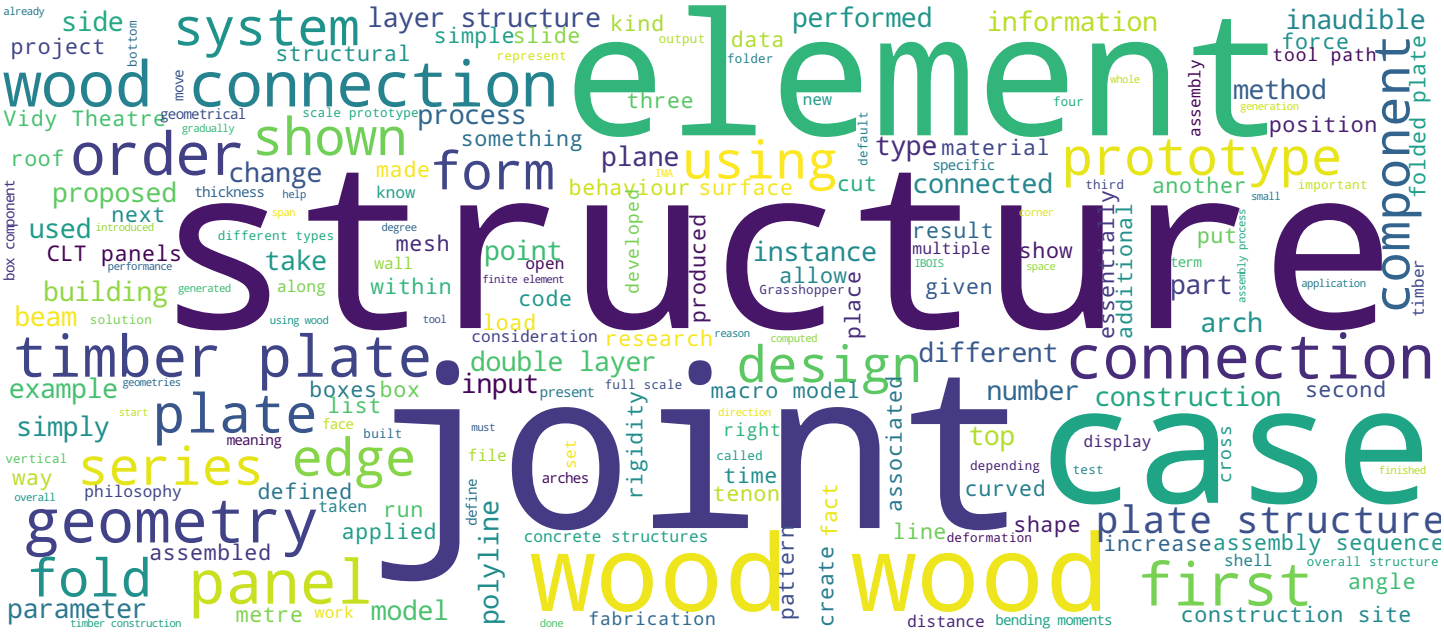


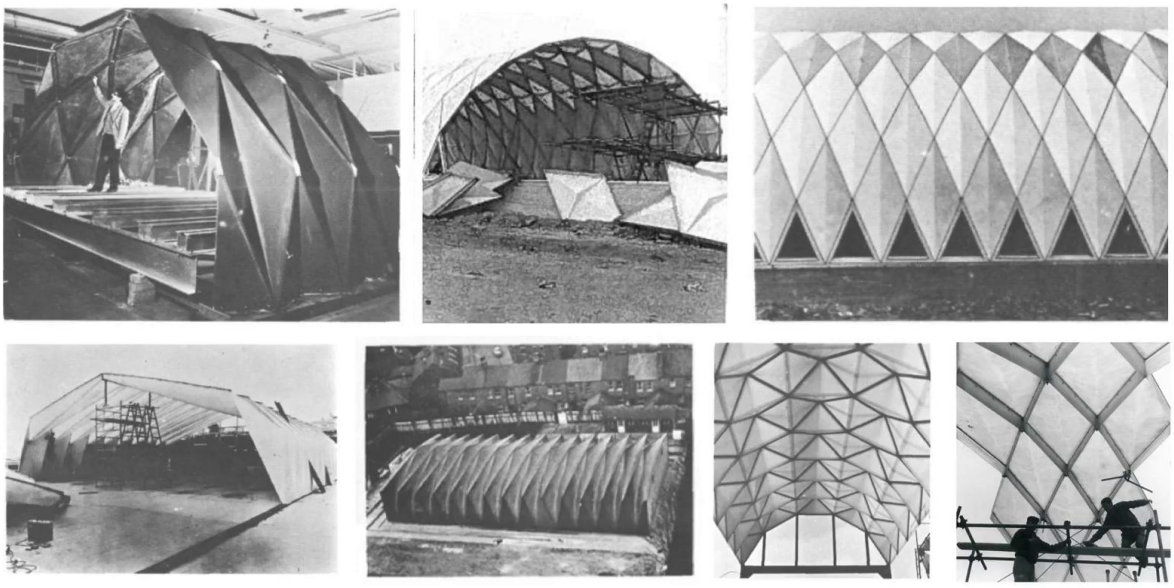
Search MOOC

Video

EPFL

Historical Examples – Folded Systems

Prof. Dr. Yves Weinand



1. Makowski, Z., 2.,3.,7. Renzo Piano Sulfur Factory 4. Temporary Accommodation for Farmworkers, CA USA, 5. Swimming Pool, Lincoln, UK 6. Huybers, P.

I would like to present a new pavilion for the Vidy Theatre at Lausanne. Of course, we have a number of historical examples regarding folded systems. Folded systems are liked for the rigidity and the lightness. But what often has not been taken into consideration in sufficient manner are the connections and the assembly process.

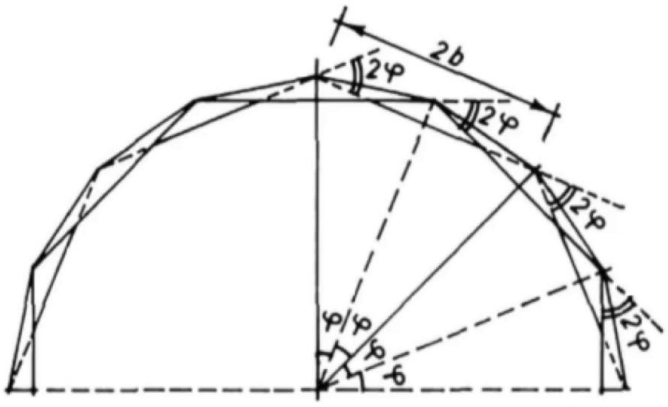
Notes

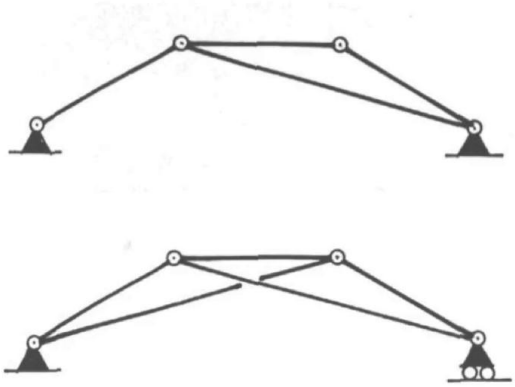
Summary

0m 04s

Historical Examples – Folded Systems

Prof. Dr. Yves Weinand





Huybers, P. *See-through Structuring - A Method of constructions for large span plastics roofs*, 1972

We understand that by introducing folds and with the depth of the fold, we increase the static height of a given system.

Notes

Summary

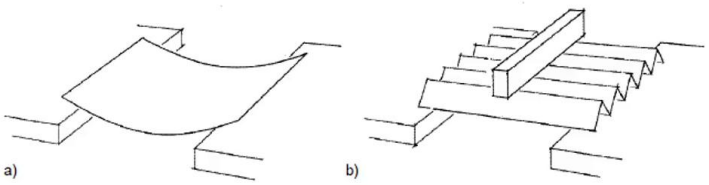
0m 29s

Historical Examples – Folded Systems

Prof. Dr. Yves Weinand

Deployable (kinematic) –
take advantage of the folds in order to enable movement

Static structures -
use structural benefits of folding for achieving higher structural stiffness at minimal expense of weight



We also vary from unfolded to folding a situation where we would like to know how these type of structures can be unfolded and how they should be folded, and what type of geometrical positions they might take.

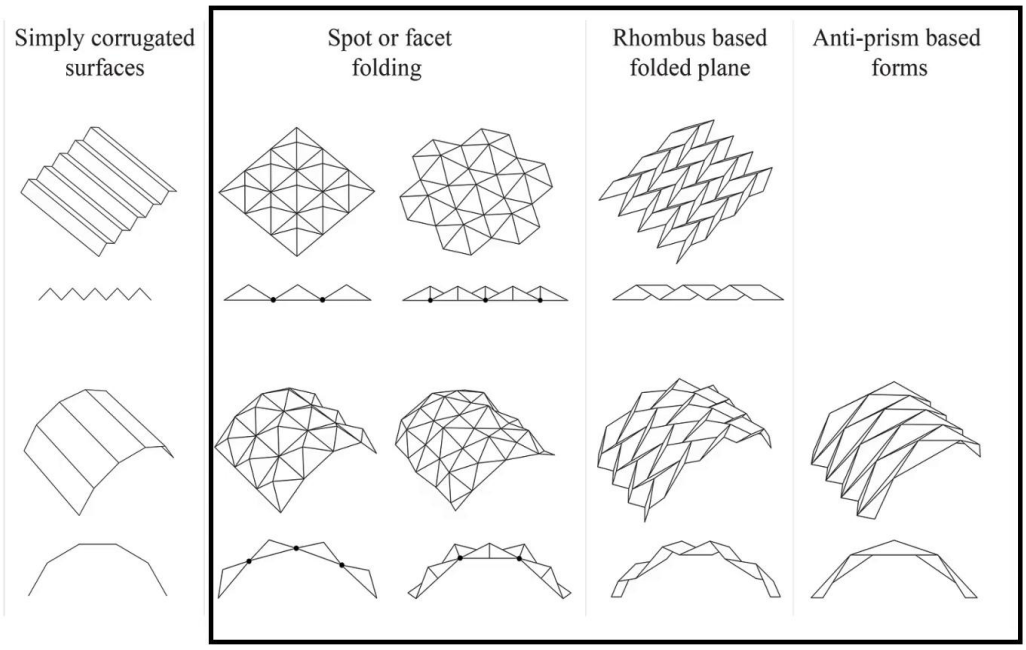
Notes

Summary

0m 39s

Historical Examples – Folded Systems

Prof. Dr. Yves Weinand



Historical examples show that we have simply corrugated surfaces. We have also spot or face folding, rhombus-based folded plane, and anti-prism-based forms. All this has been extensively discussed in [inaudible 00:01:16] thesis performed at deep work.

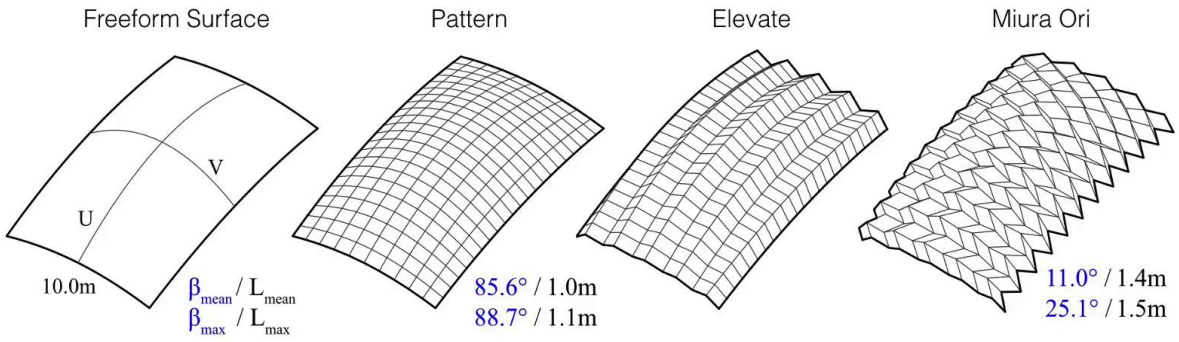
Notes

Summary

0m 59s

Origami Patterns

Prof. Dr. Yves Weinand



Robeller and Weinand, *Fabrication Aware Design of Folded Plate Structures with Double-through tenon joints*, in Robotic Fabrication in Architecture 2016

We have a look here at freeform surface, pattern, elevations, and also, it has been discussed already, Miura Ori, the folds and patterns, which can be proposed.

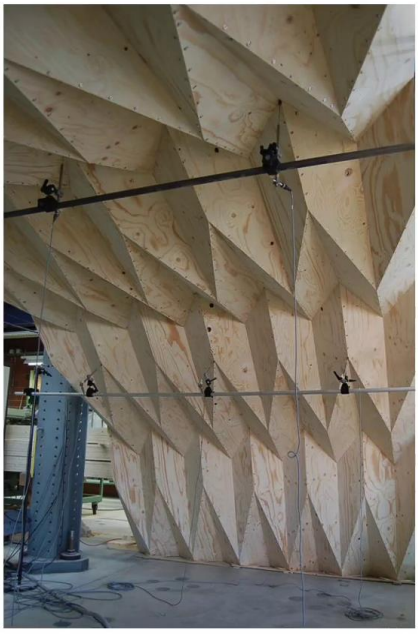
Notes

Summary

1m 18s

Origami Folded Plate Structures

Prof. Dr. Yves Weinand



We presented already the reversed fold, which was applied first at Origami structures, and then at the Chapel San.

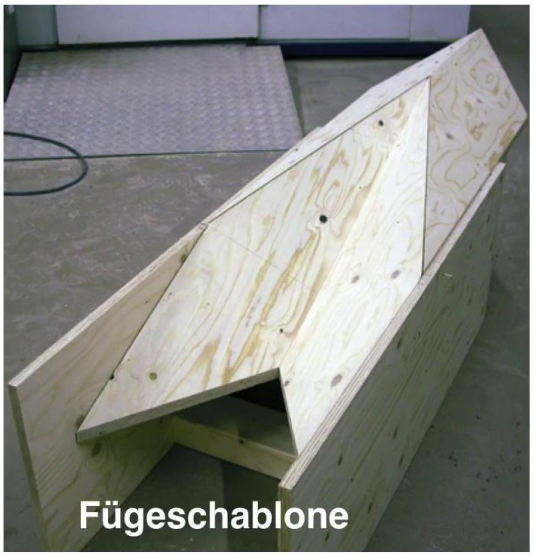
Notes

Summary

1m 31s

Origami Folded Plate Structures

Prof. Dr. Yves Weinand



In addition to the structural performance, we also see that those basic forms can help to guide the builder to in order to recognise the precise end position of each panel and the way it should be connected.

Notes

Summary

1m 40s

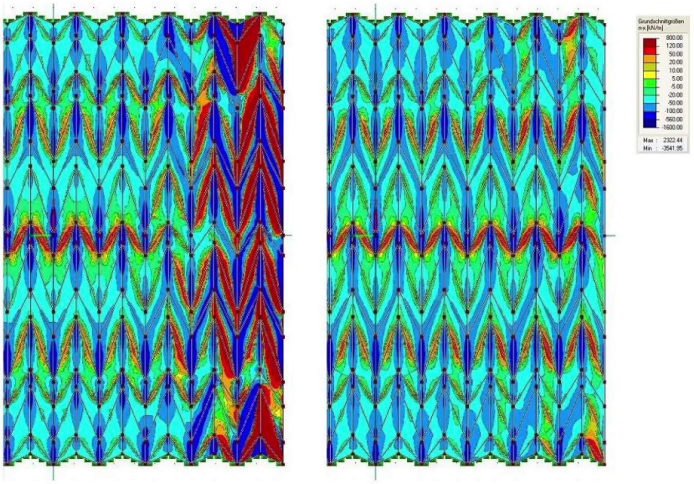
Origami Folded Plate Structures

Prof. Dr. Yves Weinand

Buri, H. *Origami Folded Plate Structures*, 2006-2010

Gelenkige Verbindungen

Starre Verbindungen



Hahn, B. *Analyse eines räumlichen Tragwerks aus Brettsperrholz*, 2009

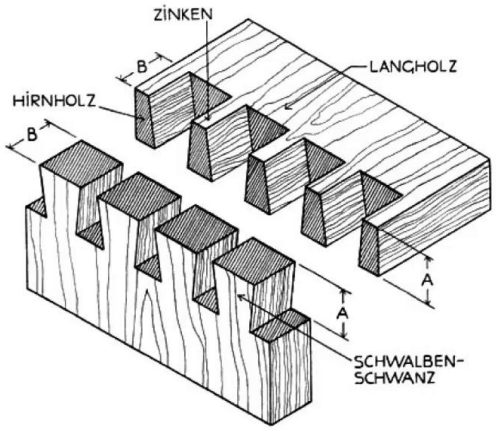
We also saw by the analyse that again, the weak points were the connections between those different panels.

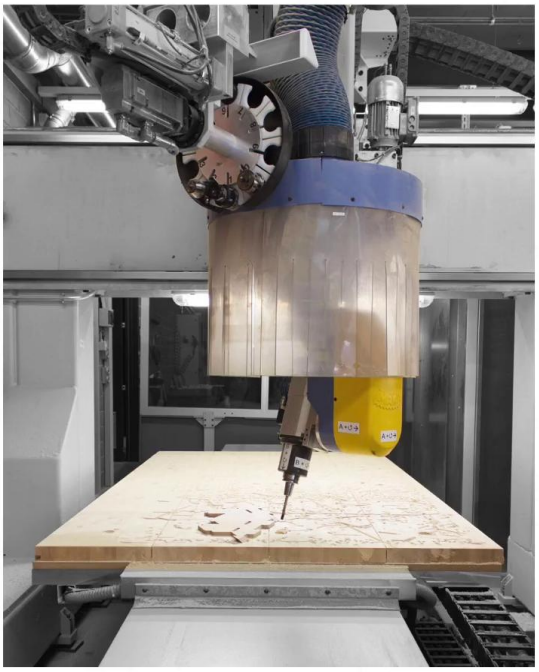
Notes

Summary

1m 59s

Introduction of Timber Joinery





Prof. Dr. Yves Weinand

In this case, you see that they were even nailed. We had to introduce timber joinery techniques as it has been exposed and inspired by vernacular wood-wood connections and transpose them to the world of automation.

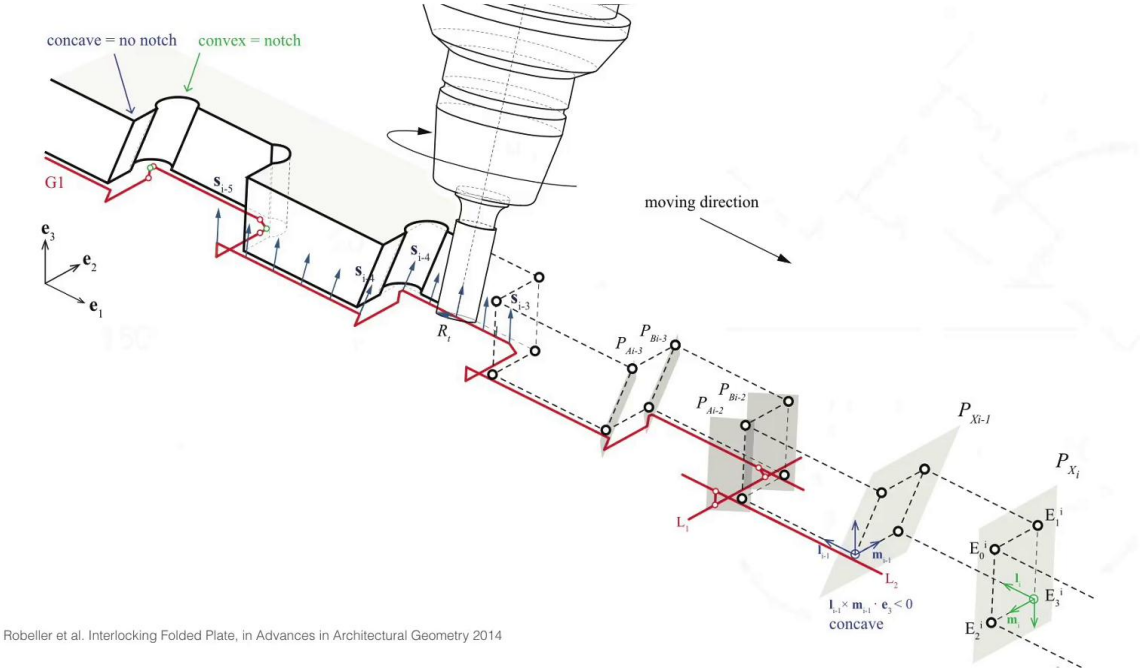
Notes

Summary

2m 07s

Fabrication of Timber Joinery

Prof. Dr. Yves Weinand



Robeller et al. Interlocking Folded Plate, in Advances in Architectural Geometry 2014

Christopher Robeller performed a thesis where a tool path would be developed, and those wood-wood connections would be cut out by a given tool path.

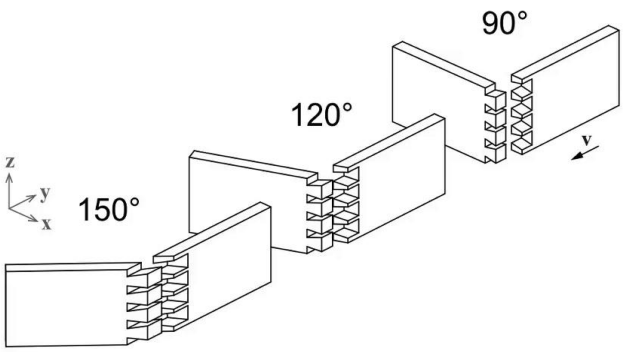
Notes

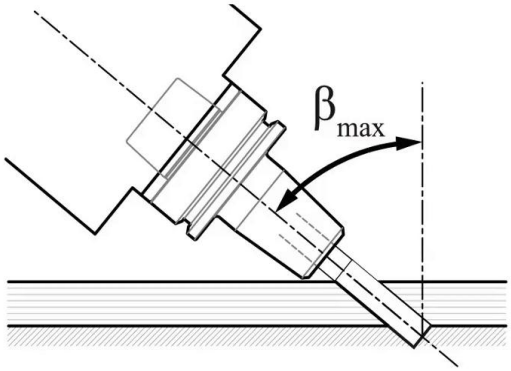
Summary

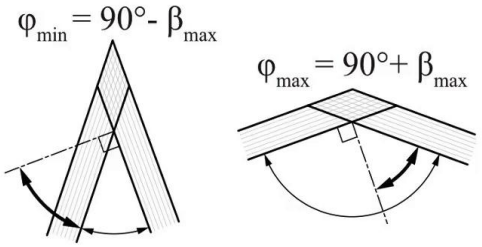
2m 26s

Fabrication of Timber Joinery

Prof. Dr. Yves Weinand







Fabrication constraints come into the process at an early stage because regarding which kind of fold or angle you have been choosing, its realisation could be difficult or even impossible.

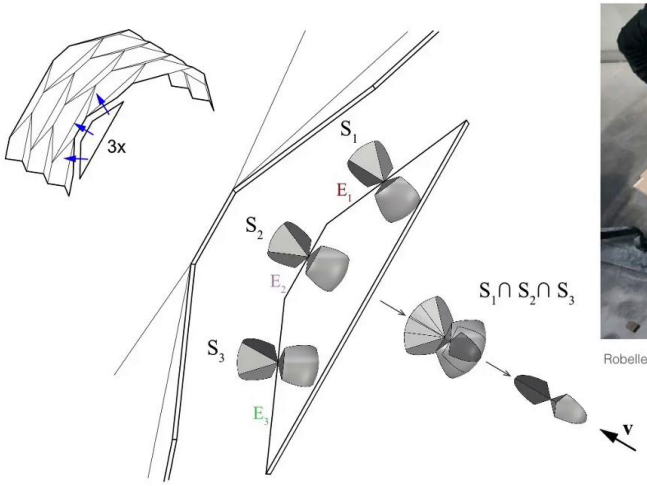
Notes

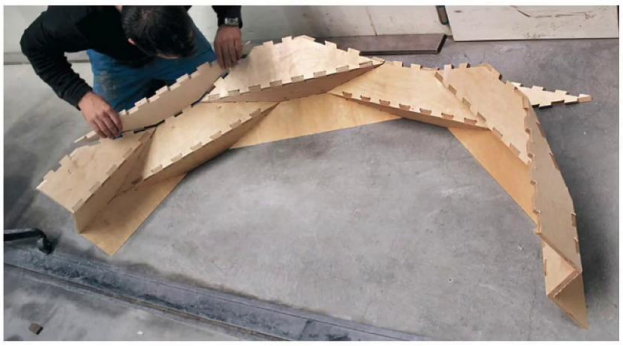
Summary

2m 39s

Assembly

Prof. Dr. Yves Weinand





Robeller et al. Interlocking Folded Plate, in Advances in Architectural Geometry 2014

Here you see its major finding, where a common insertion space of three different lines in space would define an insertion space possibly for three plates against three old plates.

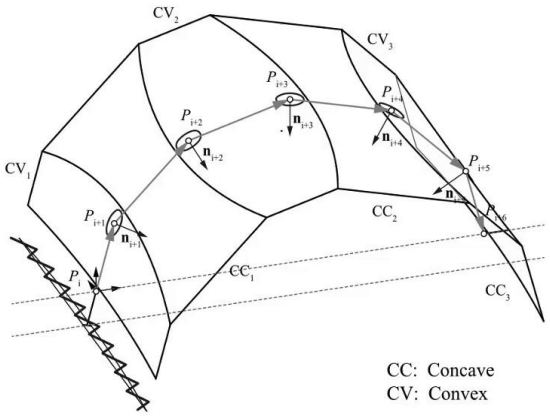
Notes

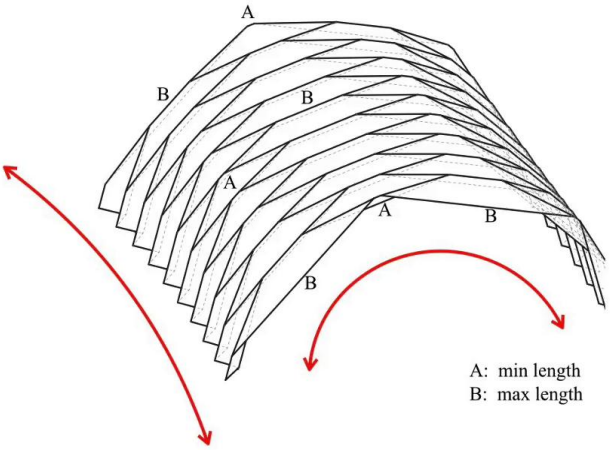
Summary

2m 56s

Double Curved Folding

Prof. Dr. Yves Weinand





More interestingly, we could even introduce longitudinal curvature. That would even increase the rigidity of the overall structure because we would not have a constant section running to the building, but by introducing a longitudinal curvature, we can increase or the rigidity of the overall structure and use limit its deformation.

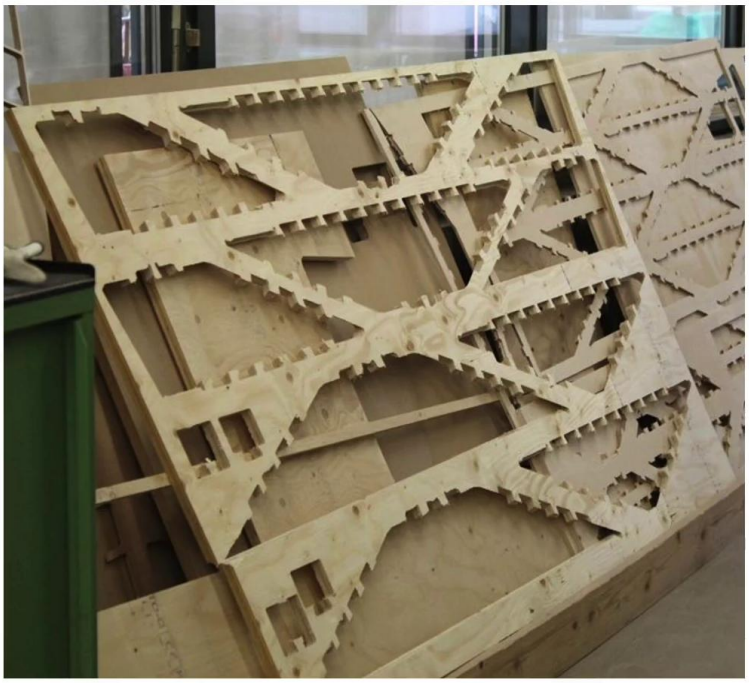
Notes

Summary

3m 13s

Fabrication

Prof. Dr. Yves Weinand



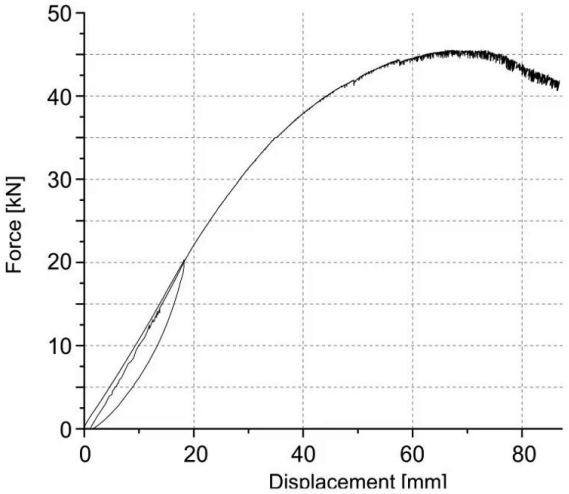
Here you can see some samples of how the automated process is first played virtually by videos, where we can check if the production can be performed properly. After having checked that, we can send those files towards the CNC cutting machine and engage in the process.

Notes

Summary

3m 42s

Structural Performance



Robeller and Weinand, Interlocking Folded Plate, in International Journal of Space Structures, 2015

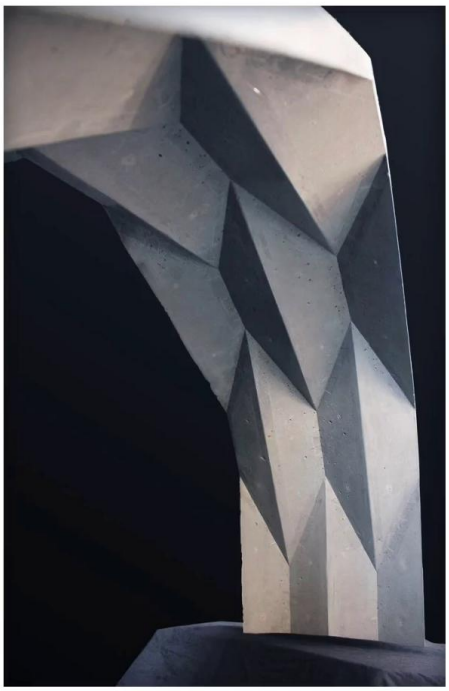
Assembly sequences are introduced, structure performs is verified.

Notes

Summary

4m 05s

Collaborations – Concrete Form-work



Prof. Dr. Yves Weinand

We even also so possibilities to transfer that technology to precast concrete structures, where we know that for freeform concrete structures, the cost of the precast is quite high, and that precast is also something which is not reused. That's one of the reasons why it's very high. One of the solutions to improve the economical aspects of freeform concrete structures could be to generate precasting out of timber panels in such an automatic manner.

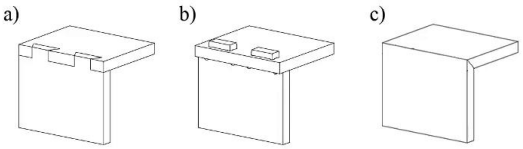
Notes

Summary

4m 12s

Joinery Testing

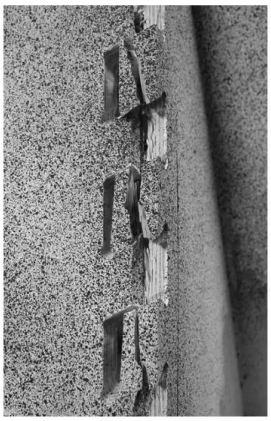
Prof. Dr. Yves Weinand

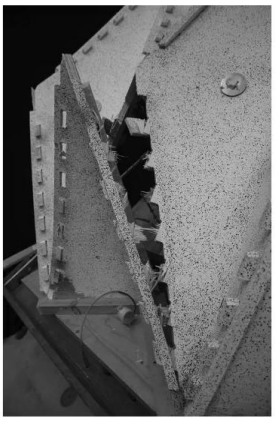


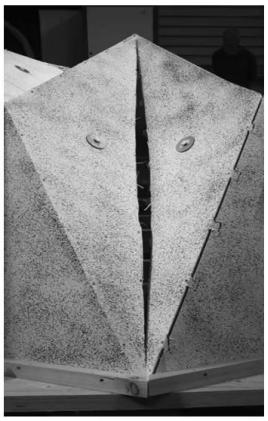
with open slots

with closed slots

Adhesively bonded connections







We showed already that the weakness happened at the fold and performed wood-wood connections along those edges.

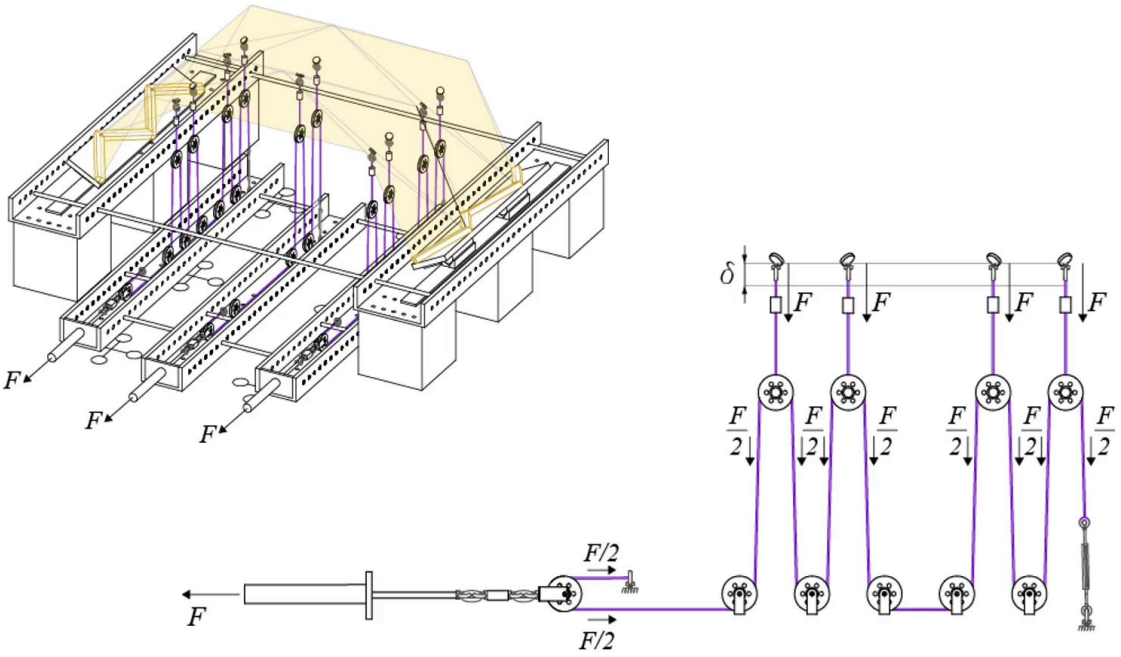
Notes

Summary

4m 52s

Joinery Testing

Prof. Dr. Yves Weinand



We also had joinery testing before we moved on to a larger scale.

Notes

Summary

5m 01s

Joinery Testing

Prof. Dr. Yves Weinand

All those sets have been performed as well by [inaudible 00:05:11].

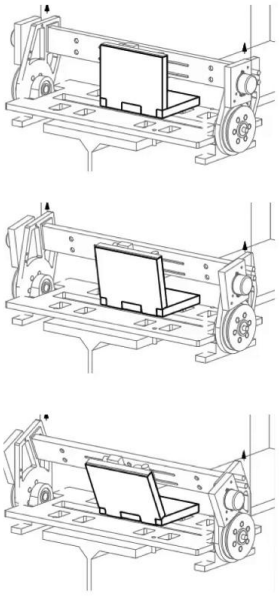
Notes

Summary

5m 08s

Structural Testing

Prof. Dr. Yves Weinand



Roche, S. Rotational Stiffness of Joints at Ridges in Folded Plate Structures, 2014

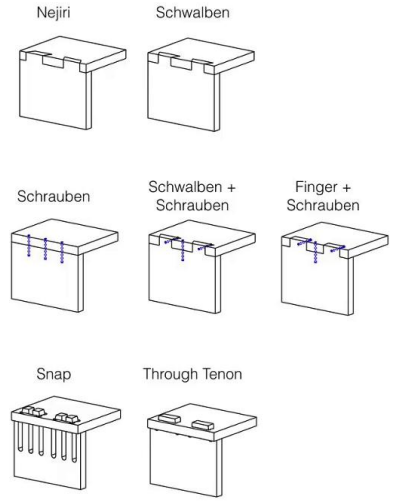
We looked at different types of wood-wood connections, which could be on the edge or which could also slide into the surface of the panel, which would give choose another architectural expression.

Notes

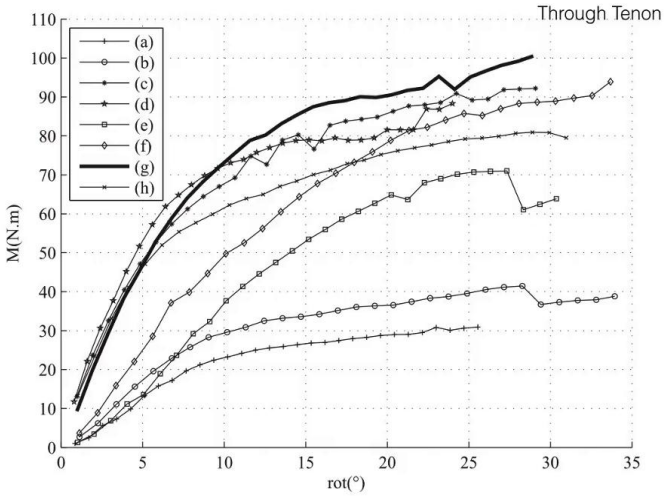
Summary

5m 13s

Prof. Dr. Yves Weinand



Roche, S. Rotational Stiffness of Joints at Ridges in Folded Plate Structures, 2014



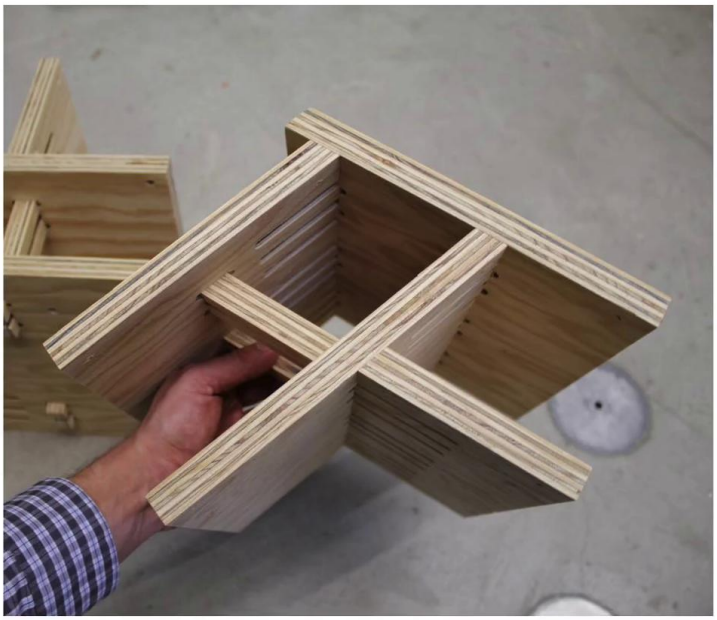
All those different types of connection have as well been analysed by Stephan Roche in his thesis, where he proposed an analytical model for wood-wood connections, which helped us to go further into that research.

Notes

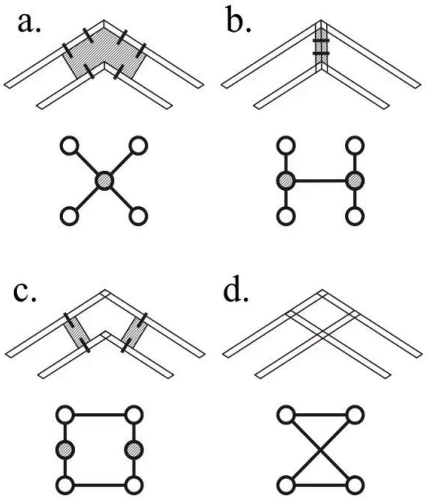
Summary

5m 27s

2-layer System



Robeller and Weinand, *Fabrication Aware Design of Folded Plate Structures with Double-through tenon joints*, in Robotic Fabrication in Architecture 2016



Prof. Dr. Yves Weinand

The philosophy of connecting different layers was also questioned because we proposed a double layer structure. But not only double layer, but both layers would cross at each edge of the structure or fold, meaning that along the fold, the double layer structures would have an increased rigidity, a because the inside layer would run through the other inside layer and touch the other side, choose having more rotational rigidity along the edge. This is shown in those block halves as you can see on the right side of that image.

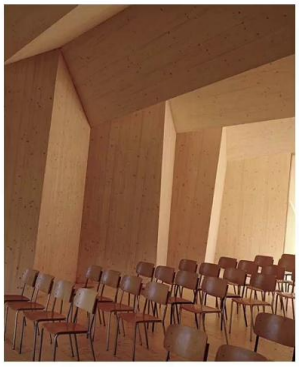
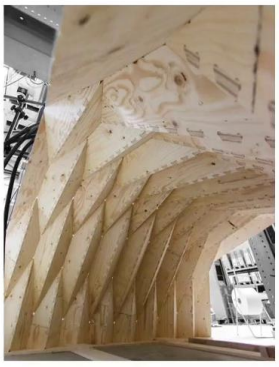
Notes

Summary

5m 44s

Sequence of the Research Lines

Prof. Dr. Yves Weinand

2006 →	2008 →	2014 →	2015
			
Einfach gekrümmt	Rahmen	Zweifach gekrümmt	Zweifach gekrümmt
Gehrung	Gehrung	Schwalbenschwanzzinken	Zapfen-/Loch
Einschichtig	Einschichtig	Einschichtig	Zweischichtig
Abwickelbar	Abwickelbar	Abwickelbar	Abwickelbar
8	39	107	152

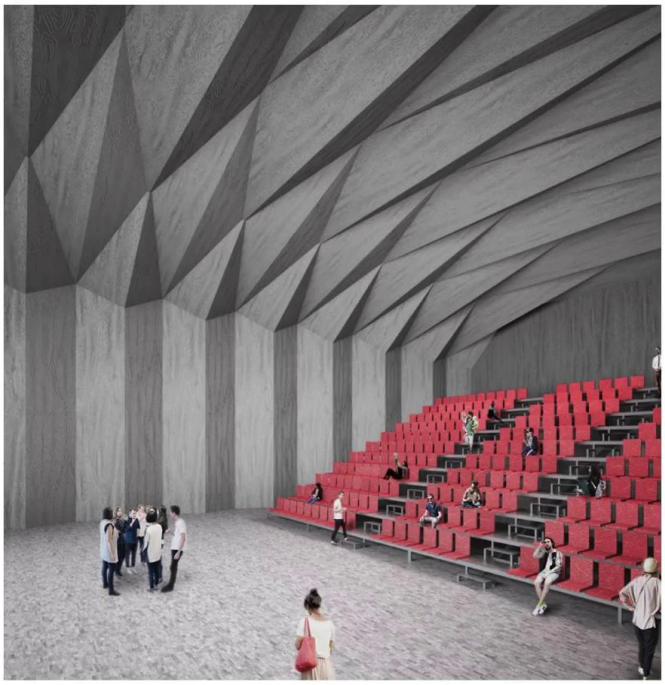
We performed several prototypes as it has been shown using wood-wood connections for a double layer structure. You can see the full evolution of the research from single plate structures to its first large-scale prototype going to wood-wood connections of folded plate structures to going on to double-folded plate structures using wood-wood connection.

Notes

Summary

6m 26s

Vidy Theater



Prof. Dr. Yves Weinand

Finally, seen here, the first full scale application at the Vidy Theatre project, which is the subject of this lesson. On the right, you see a prototype at scale 1-1, where both layers of the wall structures cross as well and touch the outside layers. Those are 40 millimetre thick panels which stand on a distance of 30 centimetre.

Notes

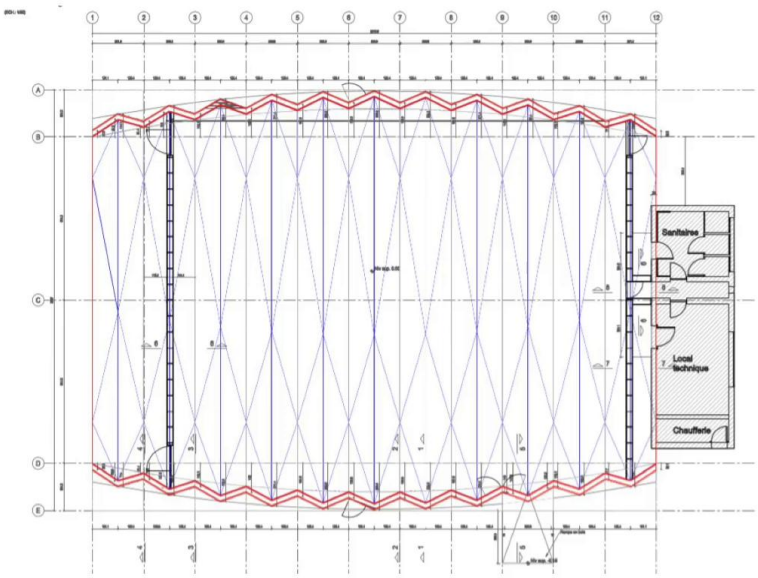
Summary

6m 55s

Vidy Theater

Prof. Dr. Yves Weinand

Grundfläche	538 m²
Spannweite	16-20 m
Platten	304
Unterschiedl. P.	152
Verb. Gesamt	456
Verb. Baustelle	44 (22)



The demand of the theatre was to have an additional presentation room of about 250-300 seats so that we generated one single space, which walls are slightly curved, and the roof is also slightly curved.

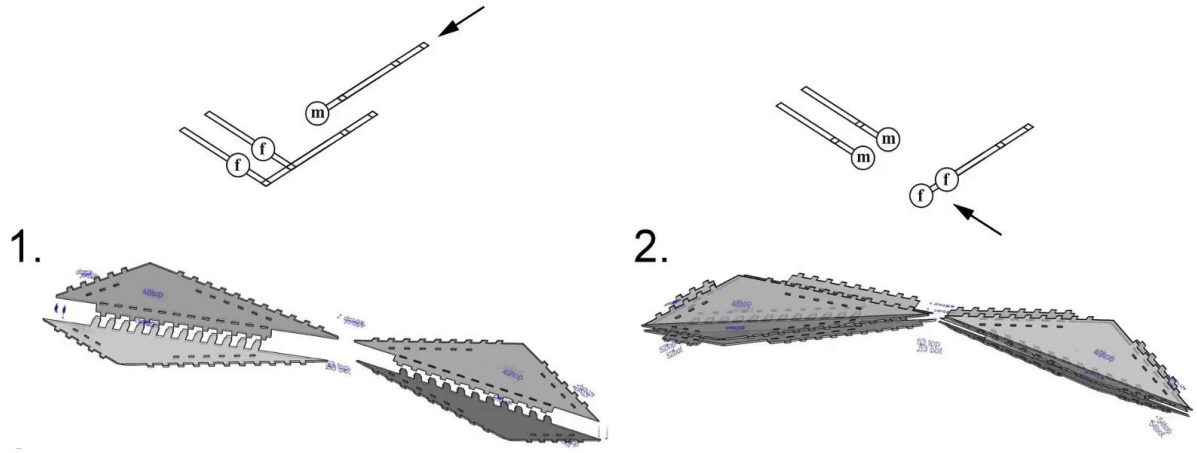
Notes

Summary

7m 24s

Vidy Theater

Prof. Dr. Yves Weinand



A parametrical model would be proposed, as you can see in here in order to fabricate all panels of the Vidy Theatre. Also, a double layer structure with a given assembly sequence was defined as you can see here. Larger panels up to 6 metre would be connected only by wood-wood connections to the next layer. Once that sandwich construction would be finished, it would have been to connected also to the next position or fold.

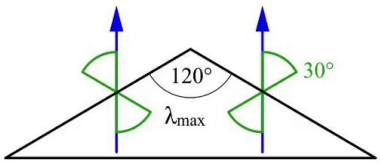
Notes

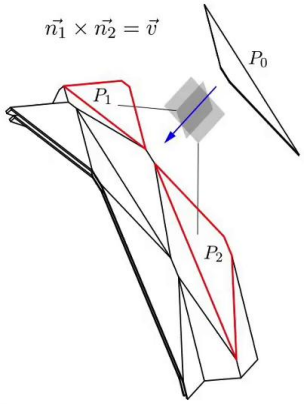
Summary

7m 43s

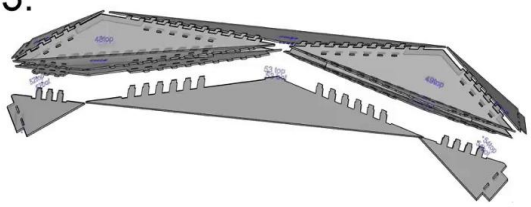
Vidy Theater

Prof. Dr. Yves Weinand

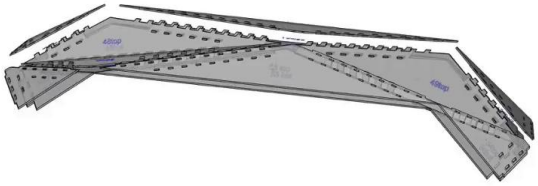




3.



4.



Here you can see the main element which carries the roof, which spans over up to 21 metre. You can see this montage sequence of those elements shown in the picture along with the insert connectors.

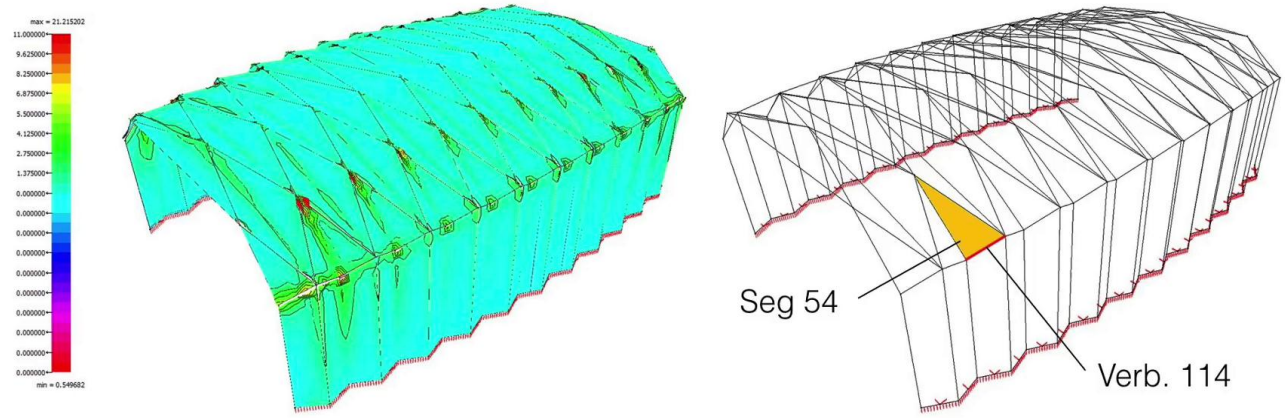
Notes

Summary

8m 17s

Vidy Theater

Prof. Dr. Yves Weinand



A mechanical analyse has been performed first for a single layer structure, where you can see that the structure itself is very rigid regardless of the fact that panels only have a thickness of 40 millimetres. We could avoid any frame structure or any beam, and it's really this double layer structure which forms what we call an envelope, which is a structural envelope, but which also is a waterproof layer and which contains insulation in between.

Notes

Summary

8m 35s

Vidy Theater

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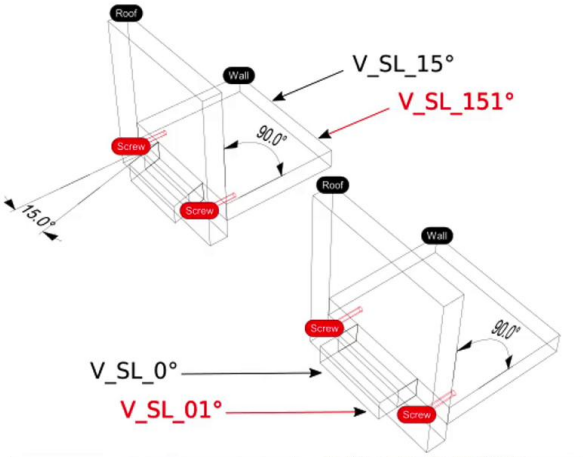
Sample geometries

- Simple Layer
- Tenon 150 mm
- Shoulders 75 mm
- Dihedral angle 90°

- Parameters tested:
  1. Material
  2. Tenon inclination
  3. Screw

- 3 materials
  1. CLT 40 mm 3 layers
  2. CLT 45 mm 5 layers
  3. Kerto Q 39 mm



Some mechanical results have also been tested locally on each panel, as you can see here, and discussions have been done for the development of additional connection details, notably between the walls and the roof, where for construction and prefabrication reasons, the company wanted to introduce another detail. That detail had been performed out of different timber-derived panels, as you can see, LVL, but also CLT panels. Notably, even LVL panels are often preferred by structural engineers for their better mechanical performance, as then CLT panels. In this case, the CLT panels for that specific connection would perform better. That was also good news because the overall price of the use panels, staying only with a three-layer structure, would drop down. Rotational stiffness is measured on this testing advice, which is largely shown in publications you can find on the IBOIS website.

Notes

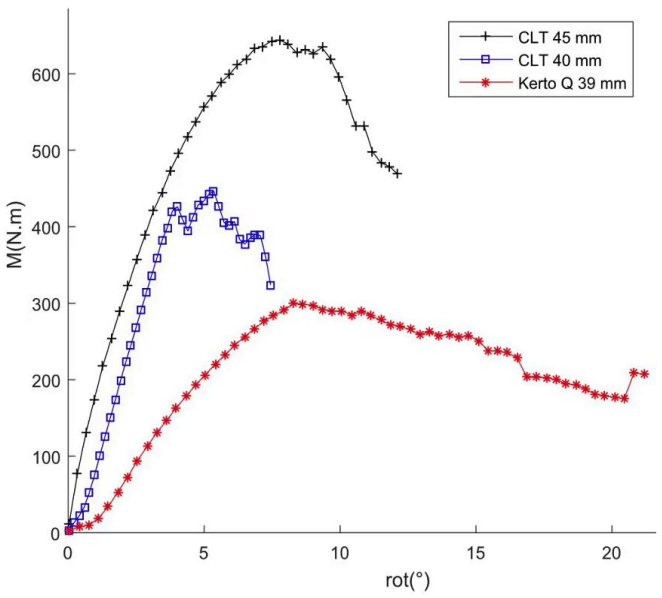
Summary

9m 09s

Vidy Theater

Why 5 layers CLT :

- Higher rotational Stiffness
- Higher Yield Moment
- Allow larger rotation than CLT 3 layers
- Utlimate moment twice higher than Kerto Q
- More homogeneous
- Rupture less brittle thanks to the layer number



We have sample generation here. We found those results for rotational stiffness very appealing for CLT panels.

Notes

Summary

10m 19s

Vidy Theater

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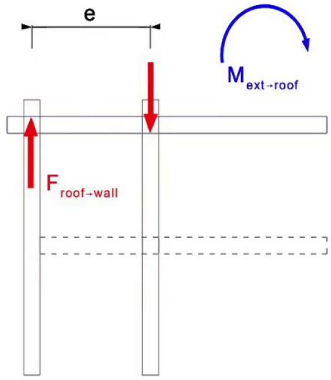
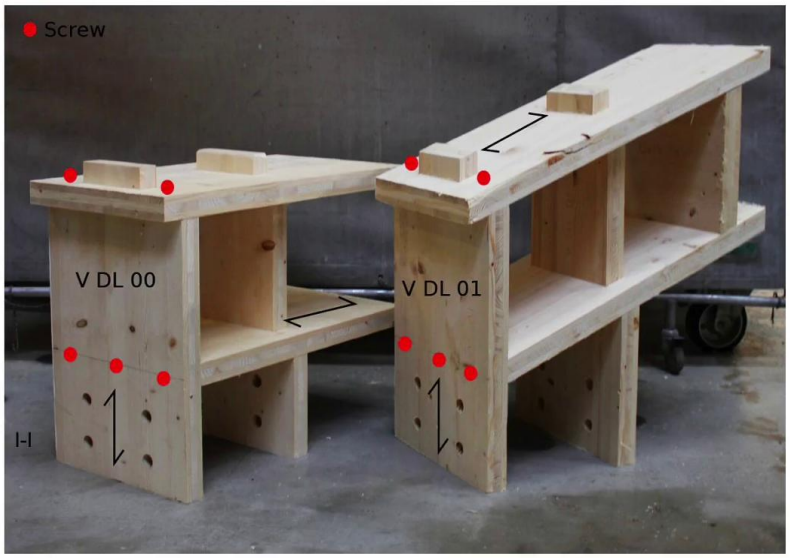


T_{Plate}	45 mm
$T_{Structure}$	300 mm



Here, you can see the test advice for the corner of the Vidy Theatre, where you have also this philosophy of intersecting of two layers, in this case, the wall layer and the roof layer and the rigidity, which is needed in there and bending moments. If you look at the overall section, we wanted to take part of the bending moments on the top edges in order to execute foundations which would be very light, and which would always no bending bone have to take.

Notes

Summary

10m 27s

Vidy Theater

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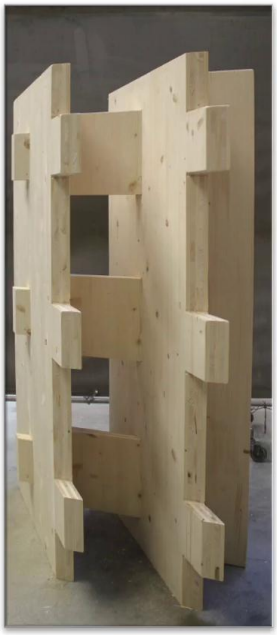
Key Points:

- CLT Panel has shown strong qualities
- Better than Kerto for rotational stiffness
- 5 layers CLT in 45 mm is the best option
- Double layer joint has a high rigidity
- Compromise between :
  - Tenon number
  - Tenon length
  - Reduced section
  - Assembly gap



Deformations was measured on the prototype and the structural results would be shown, as you can see here. A prototype would be produced also to understand better how those panels can be manipulated by hand, by machines, and how they can be connected. The accuracy of every tenon had also to be checked before we could move to the construction site.

Notes

Summary

11m 01s

Vidy Theater

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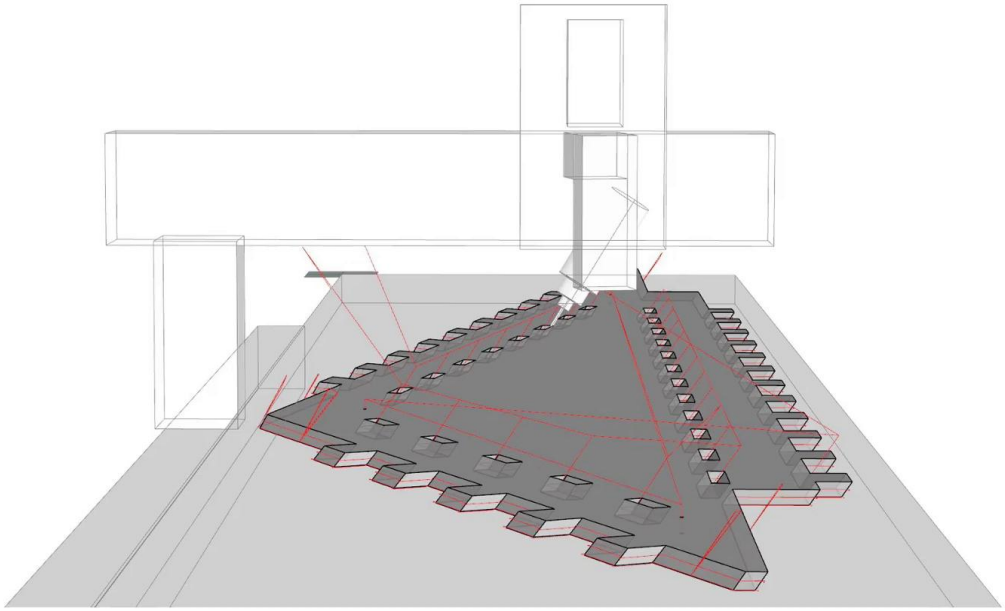

A full-scale prototype would be tested at the company [inaudible 00:11:31], where those elements were assembled and produced. We even performed a full low test. Here you see that two tonnes are positioned on one of those roof elements spanning over 21 metre, and it was increasingly interesting to see how well the structure performed under those loads. Tool path cutting.

Notes

Summary

11m 28s

Execution of main panels. Process of lifting them up. Assembling those panels into prefabricated elements, sort of sandwich composition. Even the outside cladding, the thermal insulation and other accessors would be applied at the shop before transport to the construction site in order to concentrate a maximum of operations within the workshop. On the construction site, elements where we put into place at a larger scale, and the company needed only four walking people in order to place all those elements on site. Here you see one of the major roof elements before being put into position, and specifically, the corner detail as shown and explained earlier. After several days, a third of the building had been built. This was a break for Christmas, and then the rest of the building needed an additional five days. The whole construction process was very fast, also because the finishing was already included in the prefabrication process. This is something which is very specific to timber construction, where once you have finished the foundation, you are on a dry construction site without water, and you can combine several operations even of finishing within the general montage of the building. The form of the building appears very smooth because the eye is not able to catch its form because of its double curvature, and the hardness of the fold is softened by that curvature.

Notes

Summary

12m 00s