COST Action FP1004

Final Meeting

15 April – 17 April 2015 – Lisbon, Portugal

Some Structural Design Issues of the 14-Storey Timber Framed Building "Treet" in Norway

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1. Introduction

Outline

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    ii. Stiffness connection: dowels/slotted-in steel plates
    iii. Sensitivity to stiffness of connections
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    vi. Damping properties of external walls
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1. Introduction

- Bergen, Norway
  – 14 storey timber building
- "Treet" (The tree)
  – is under construction now.
- Net area of 5830 m^2.
- 62 apartments
- Ground works: April 2014
- Timber elements: Oct. 14
- Residents: autumn 2015.
- Webcam service

Location: Bergen, Norway

The building site in Bergen

2. Design

- Trondheim 2005:
- Glulam trusses for 5 storey blocks

Design

- Prefabrication: reduce the work on site and building time

Timber frame modules

Only 4 levels

Each module / apartment complies with the passive house standard

Design:

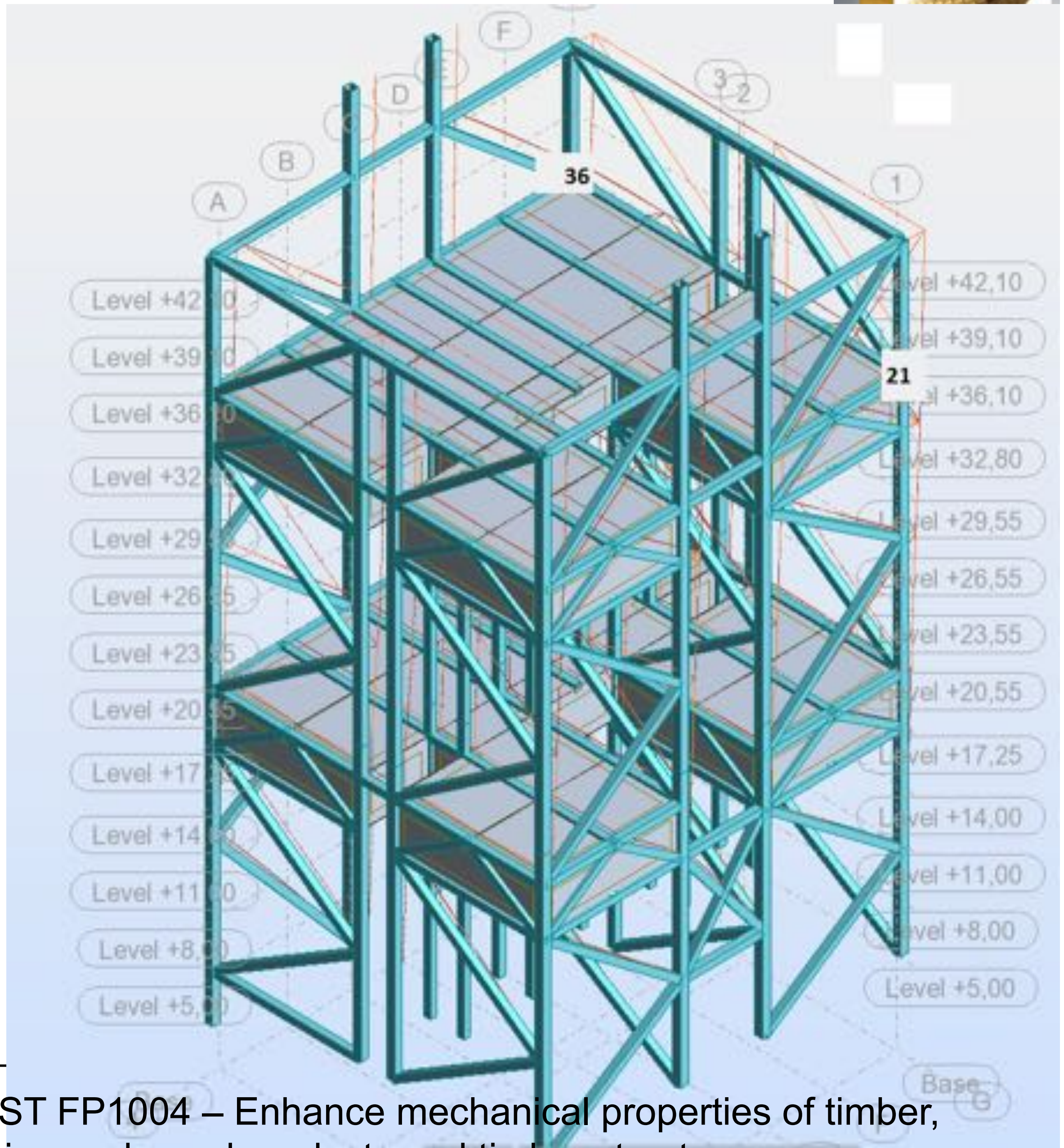
- Cabinet rack for modules
- Glulam load-carrying frame
- Facts:
  - 45 m high
  - 550 m^3 glulam
  - 385 m^3 CLT
  - The building rests on top of a concrete garage.
  - Pile foundations
  - Light weight building > tension anchorages. (936 kN max tension)
  - Drawn in Revit. 3D. BIM

Design: Typical floor plan

typisk etasjeplan

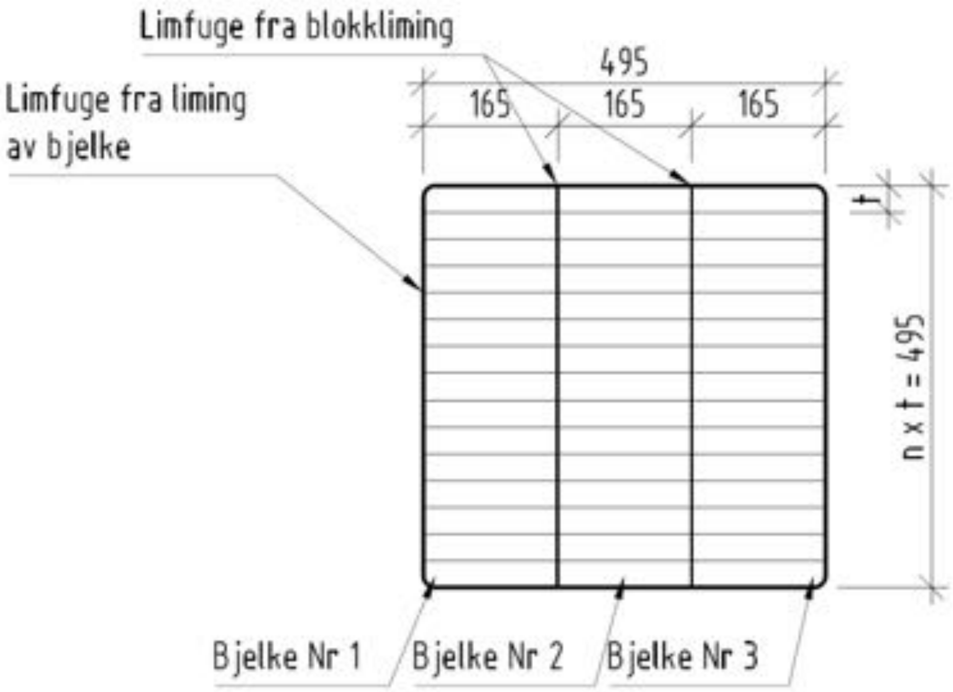
Design:

- Calculated by Robot software
- Glulam carries all vertical load
- Concrete decks serve as:
  - extra weight,
  - roof and
  - platform for modules
- Prefabricated timber frame building modules are inserted into the “cabinet rack”
- CLT is used in:
  - the staircases,
  - elevator shaft (15 storeys),
  - some inner walls and balconies
- CLT is not structurally connected to the glulam



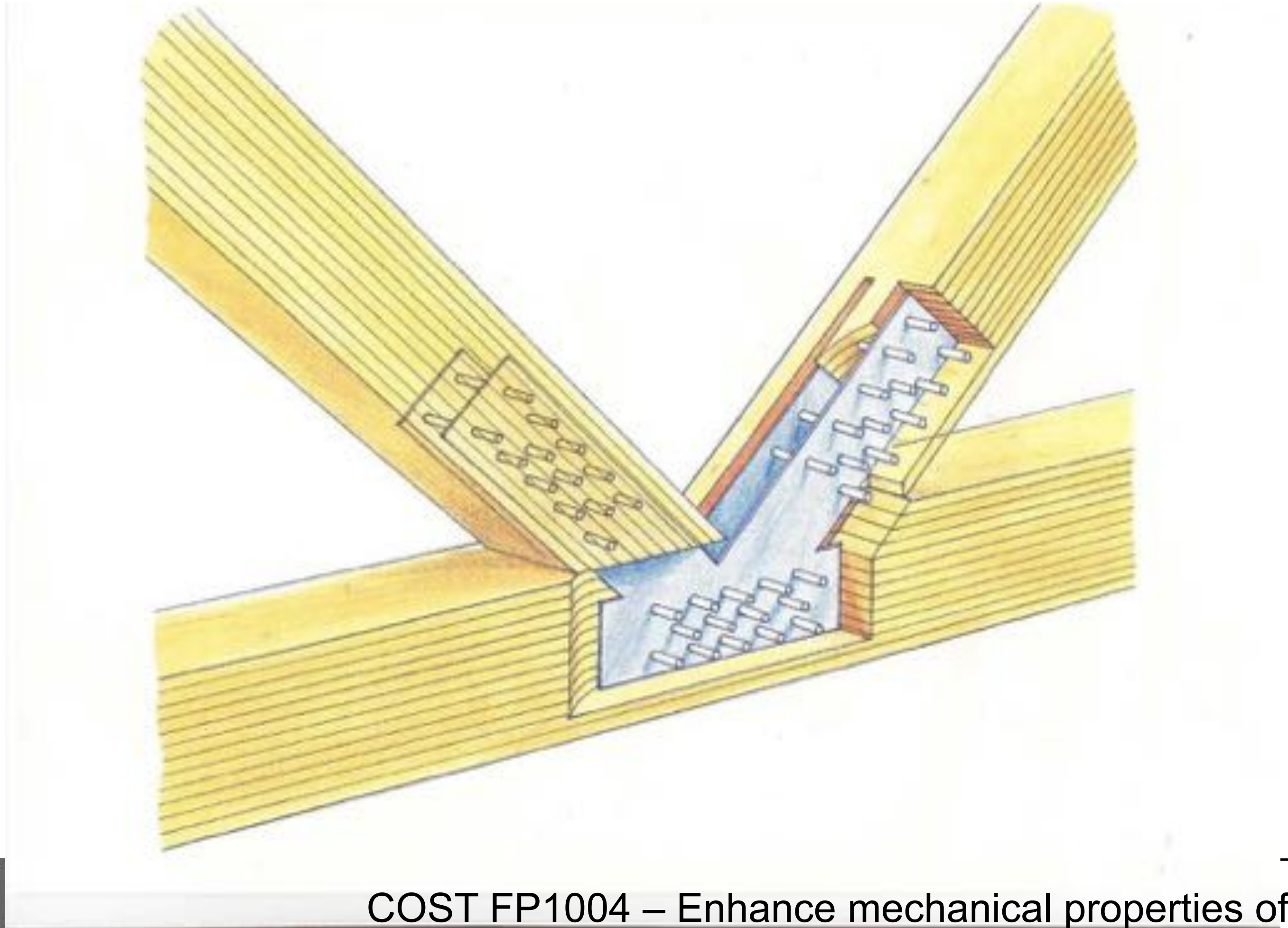
Design

- Prefabricated modules:
  - stacked up to 4 levels
  - connected to main structure at the base
- Glulam sections:
  - block glued
- Typical columns:
  - 405x650 and 495x495 mm
- Typical diagonals:
  - 405x405 mm.
- Glulam quality:
  - GL 30c and GL 30h (EN 14080)

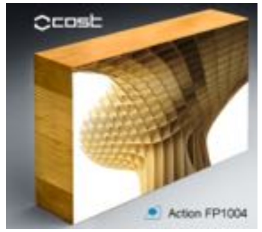


Design

- Connections: Slotted-in steel plates and dowels.

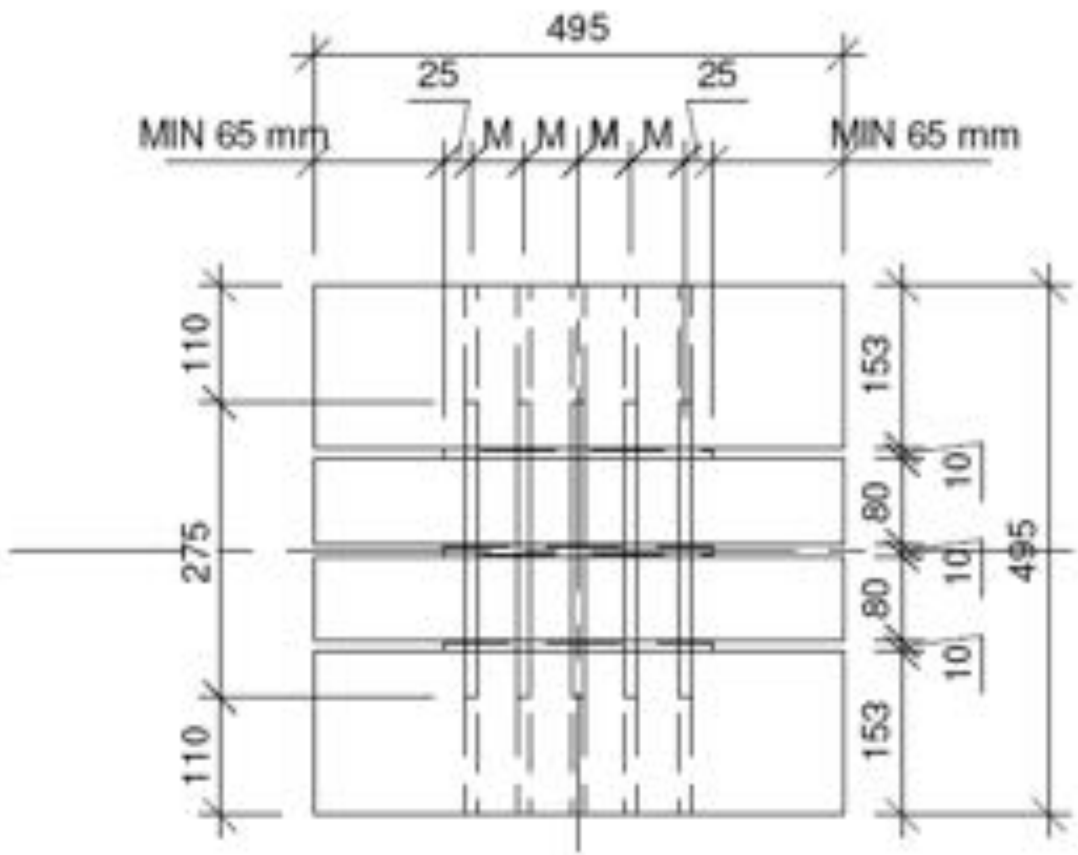


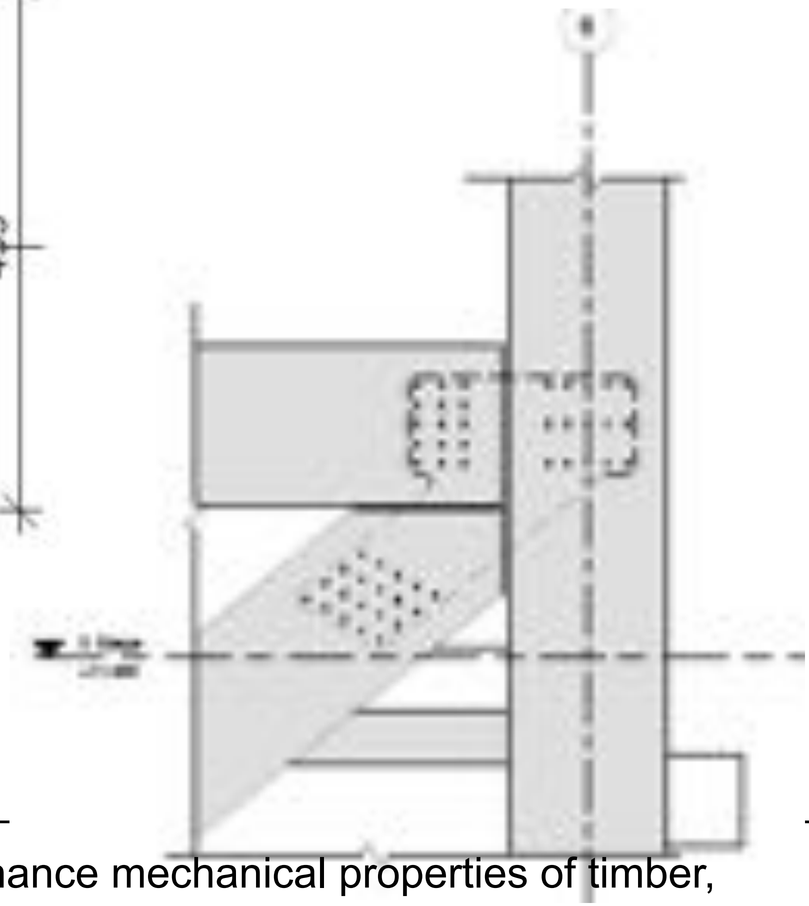
Fire design



- Timber is not pre-accepted as material for high-risers in Norway
- Norwegian regulations allow alternative materials, but documentation required
- Fire design is according to Eurocode (EN1995-1-1-2)
- Timber can burn, but the glulam is so thick that it can burn for 90 minutes without failure.
- No extra gypsum is used on the glulam.
- All steel connections are protected inside timber. It will not fail within the required fire resistance time
- In addition to improve fire safety:
  - sprinklers,
  - pressurized escape stairs and
  - painted surfaces

Fire design - connections

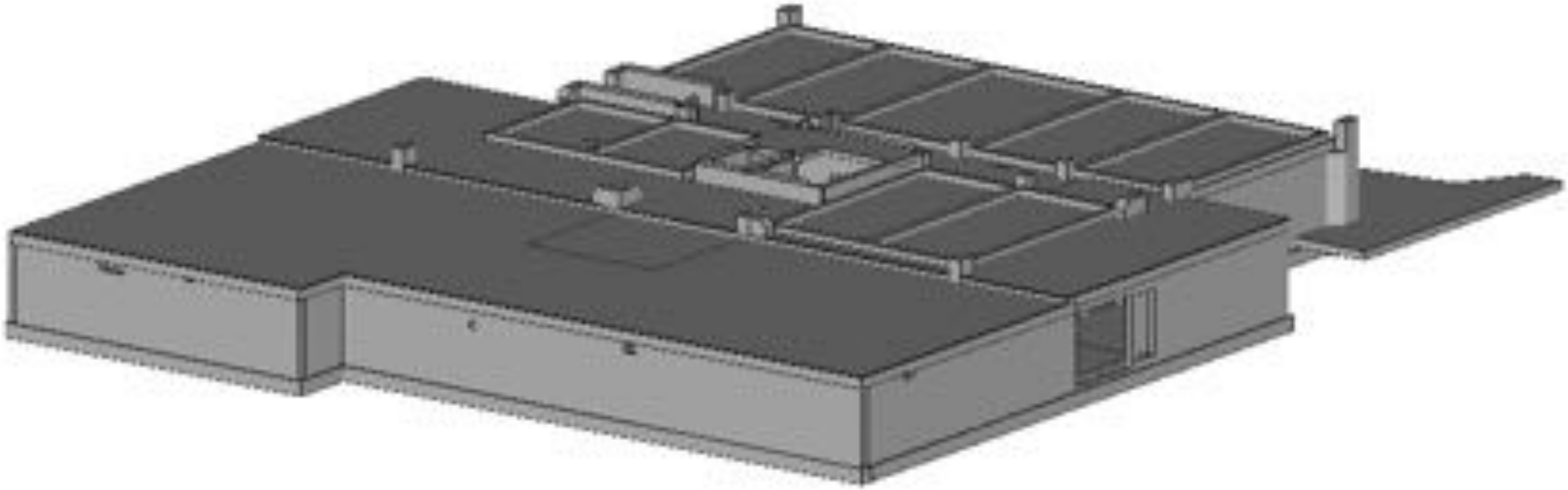




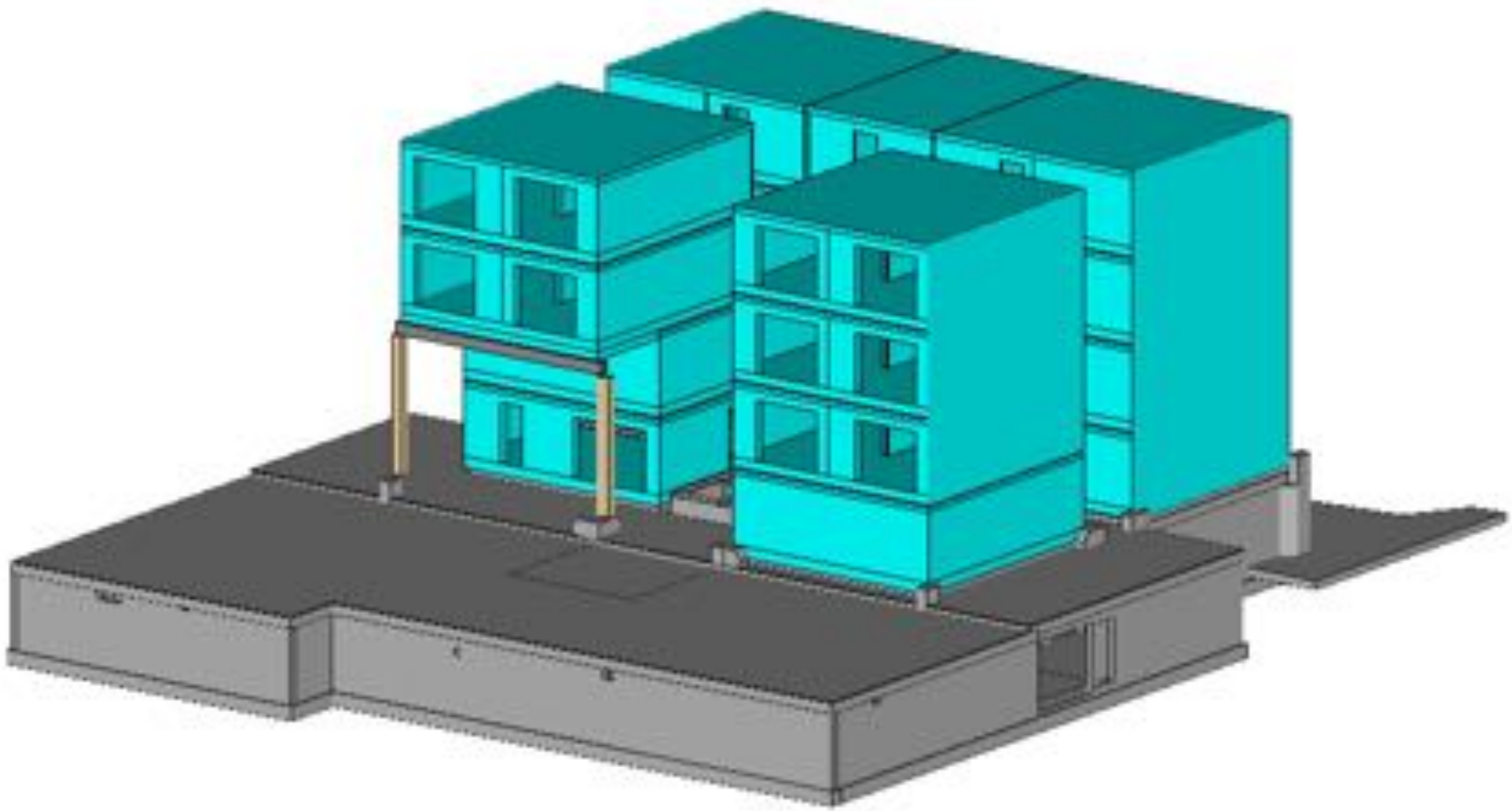
8 mm steel plates

12 mm dowels

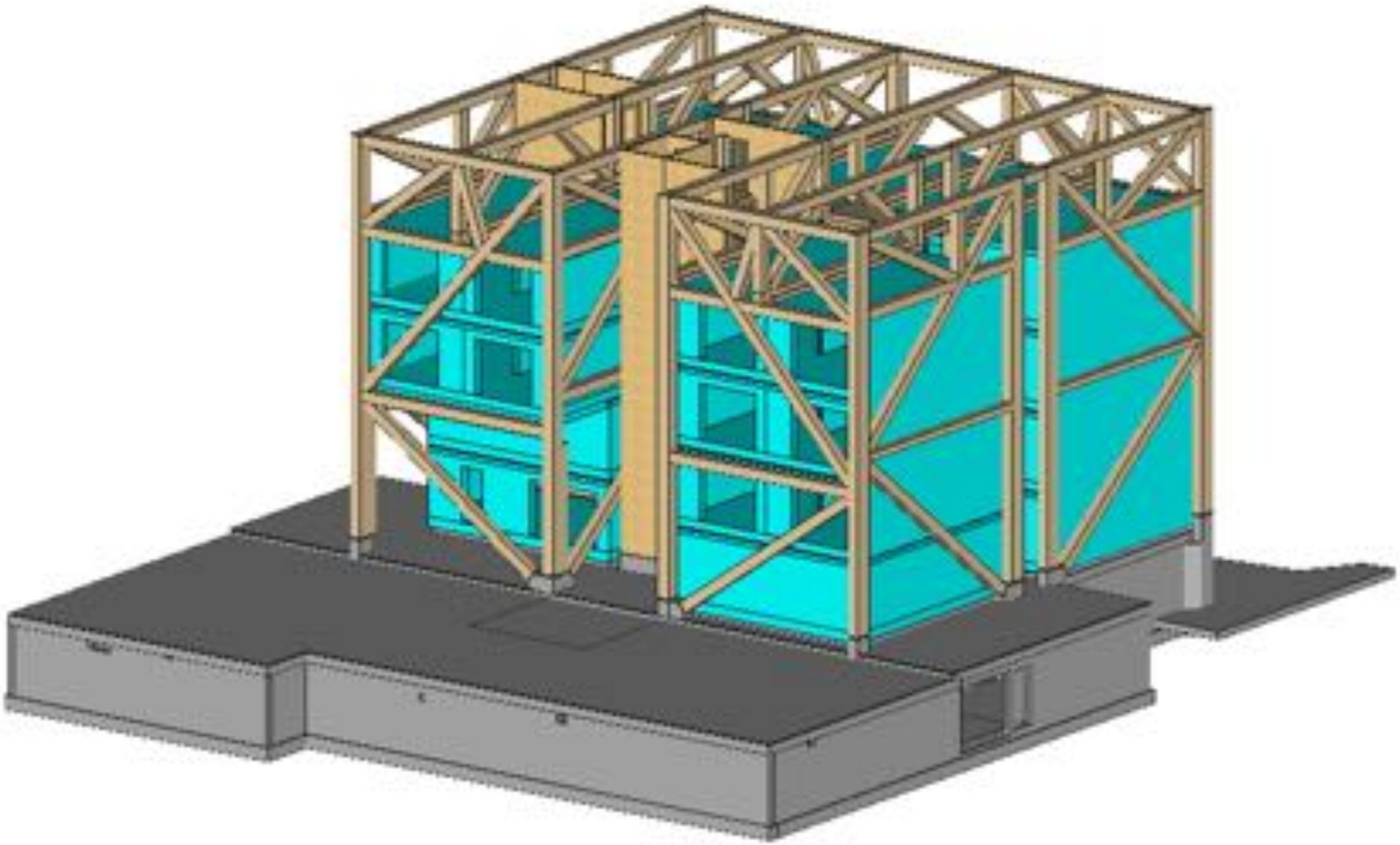
Basement - Parking



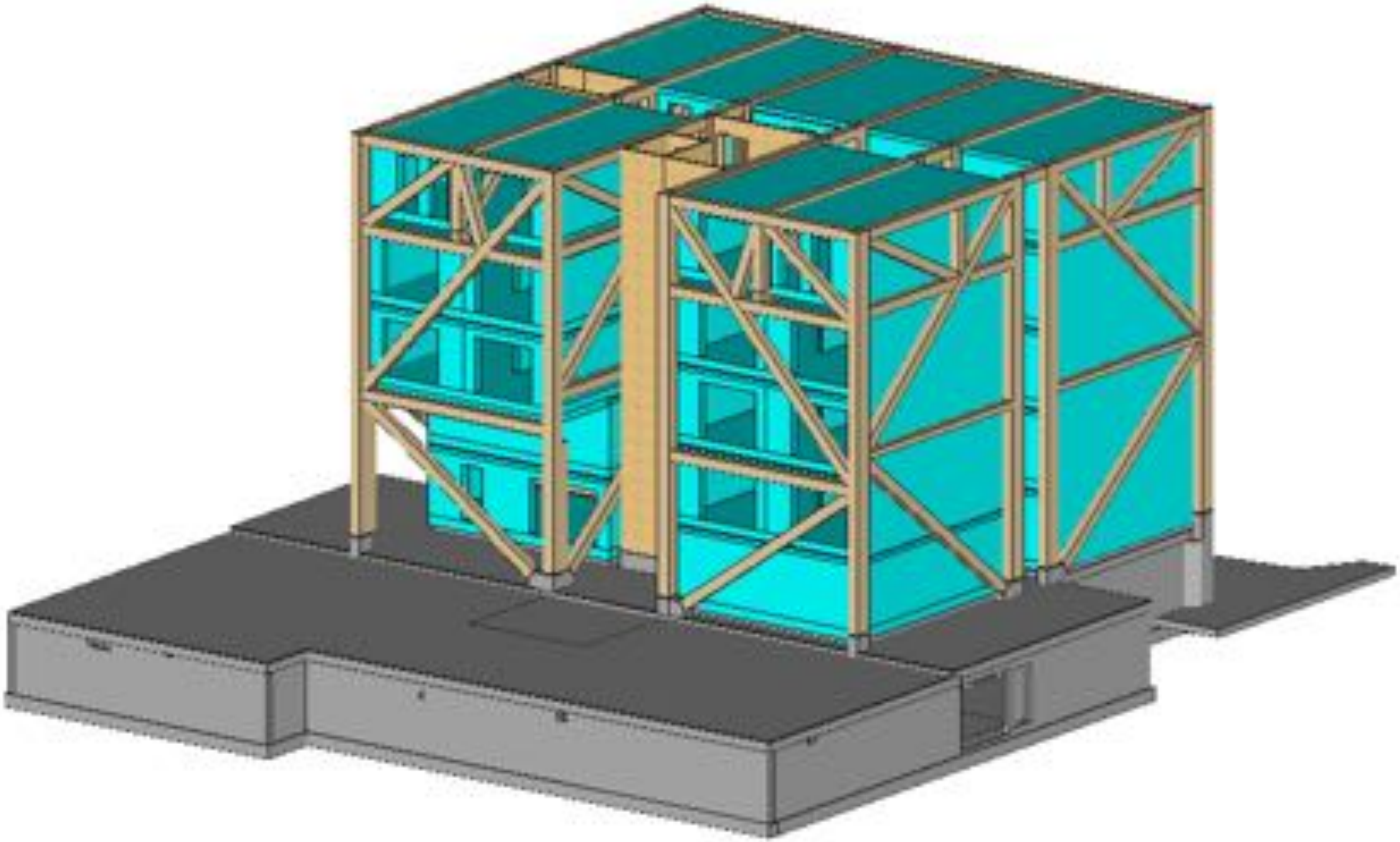
Assembly. Step by step
Prefab modules in 4 levels



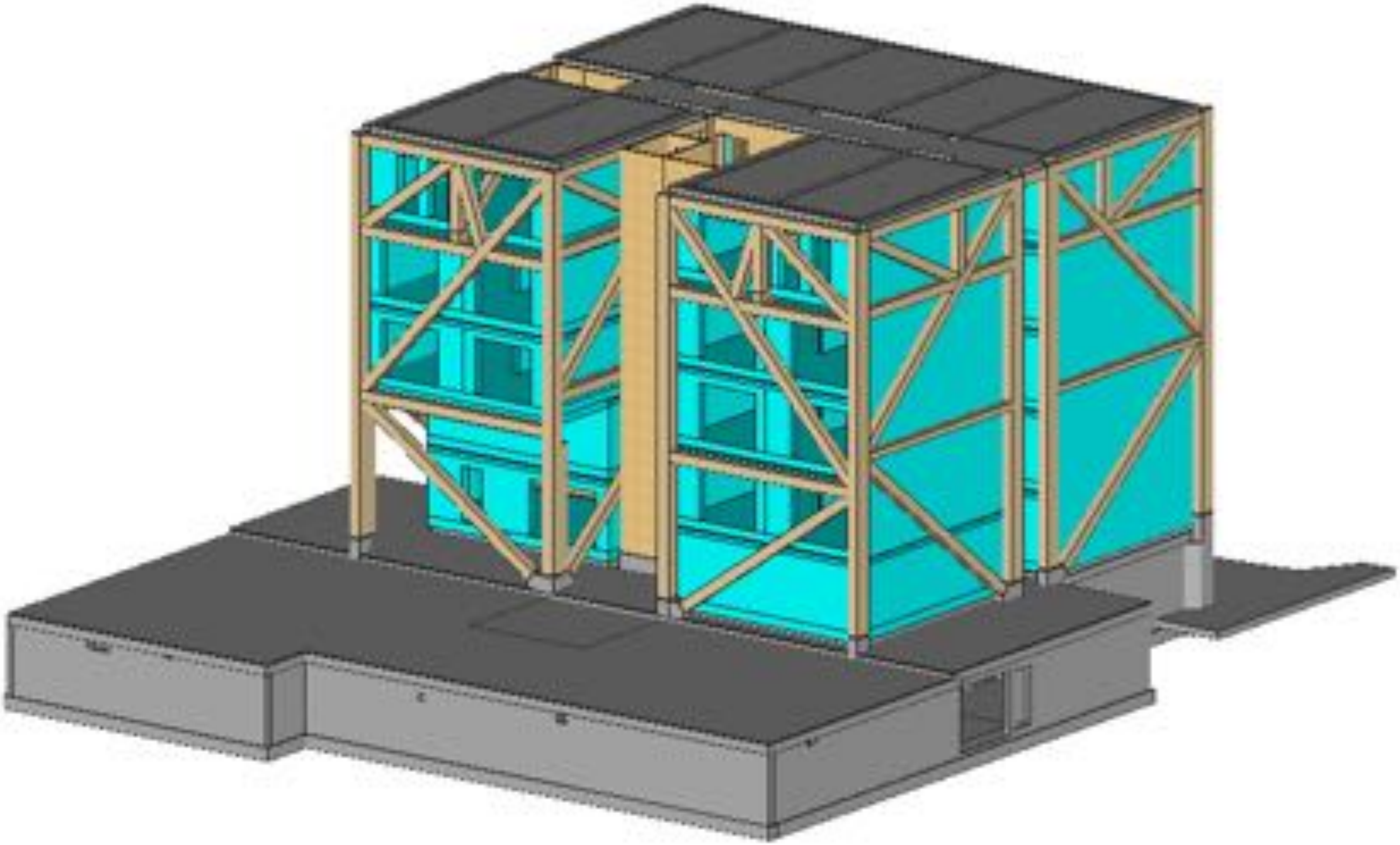
Assembly. Step by step: Glulam trusses



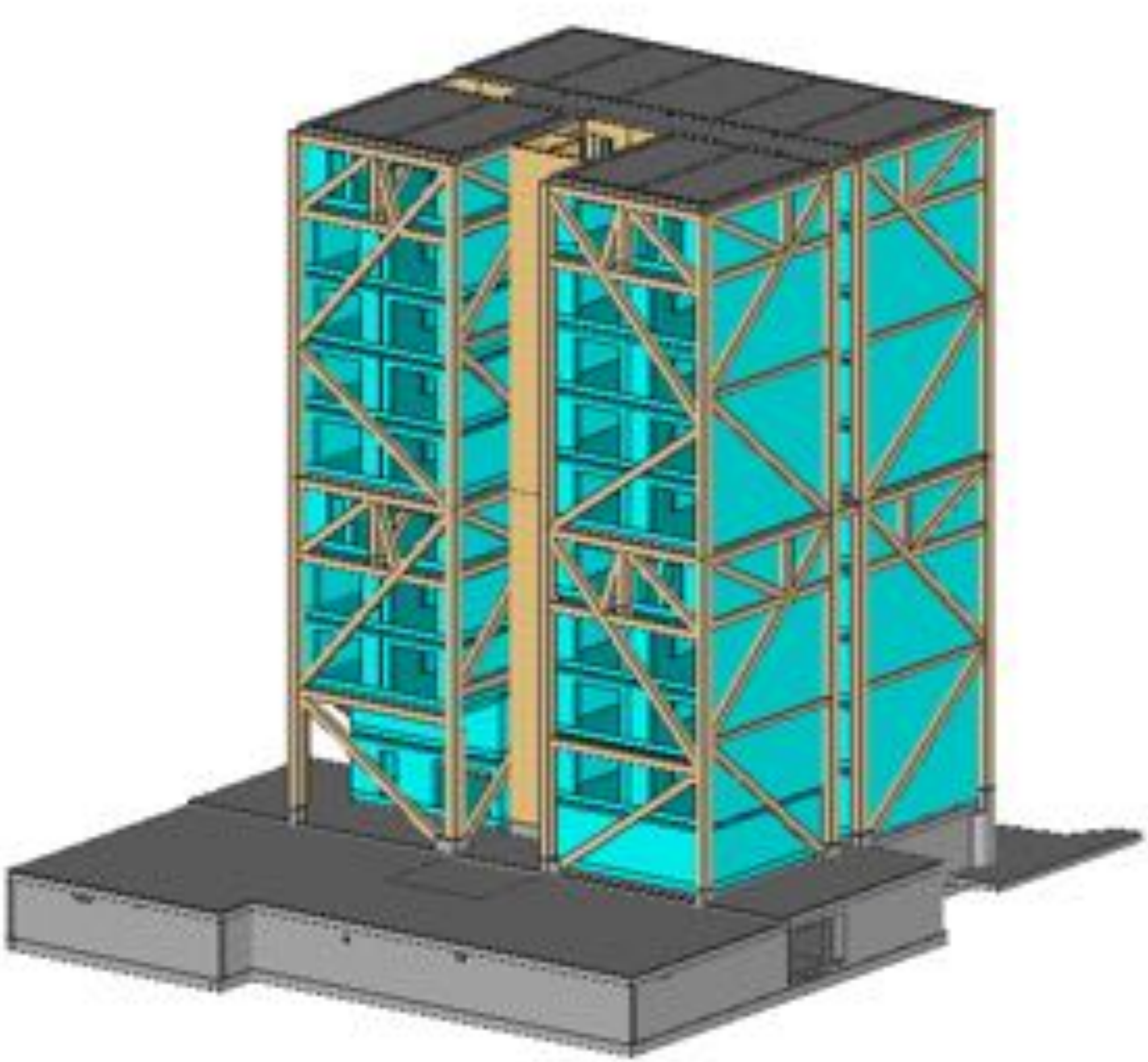
Assembly. Install level 5 modules



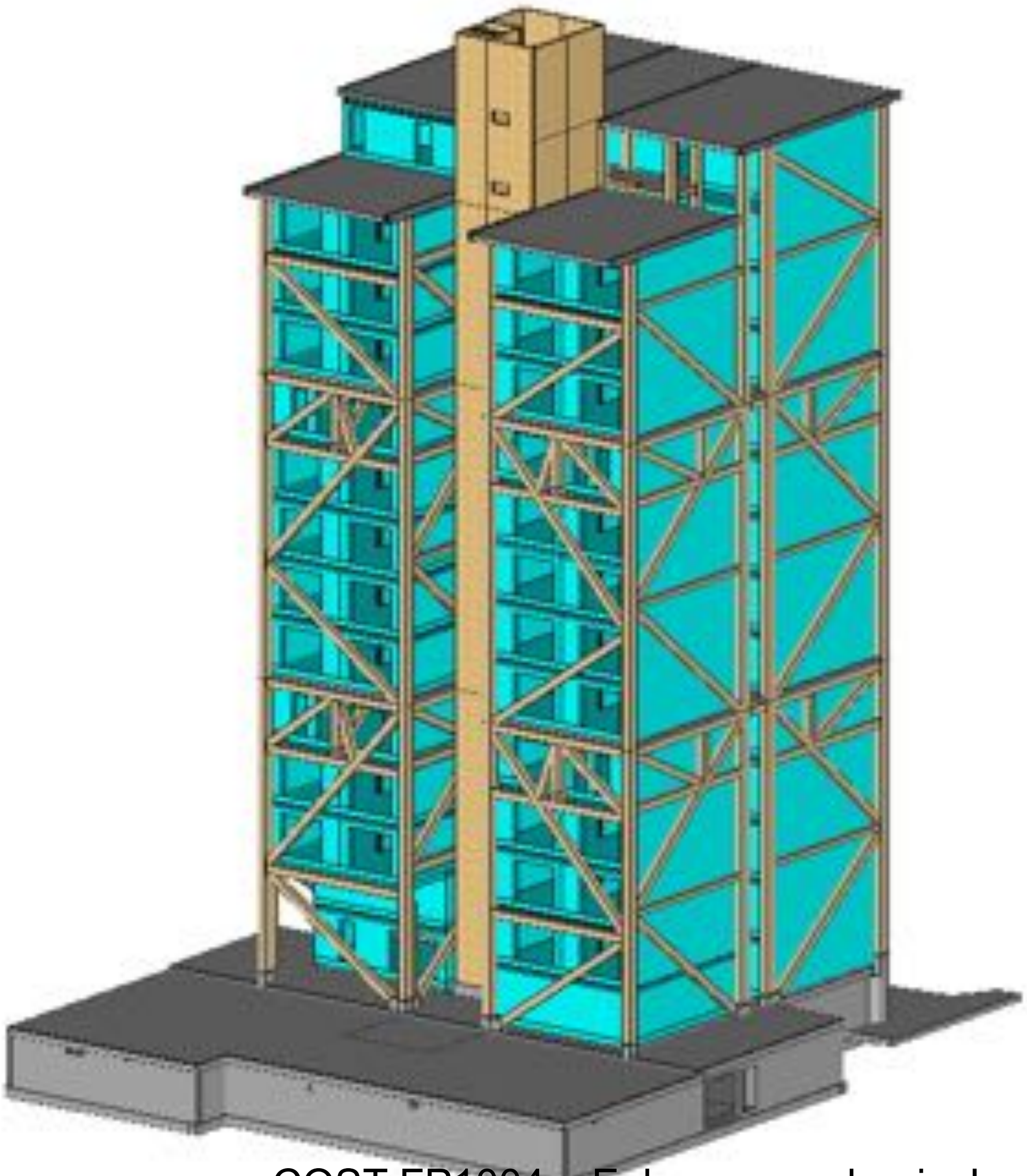
Concrete floor – new foundation



Assembly: Repeat the previous steps

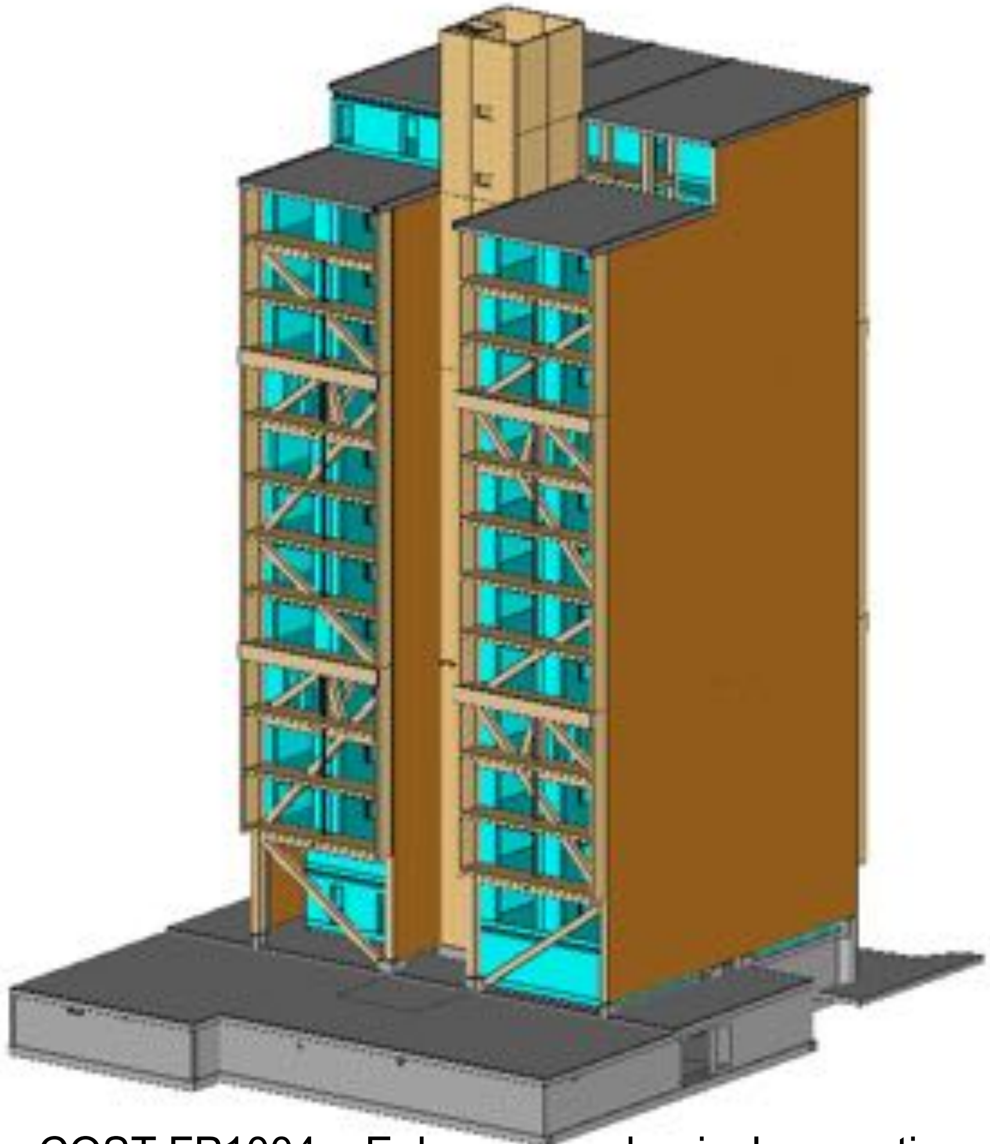


Assembly. Step by step

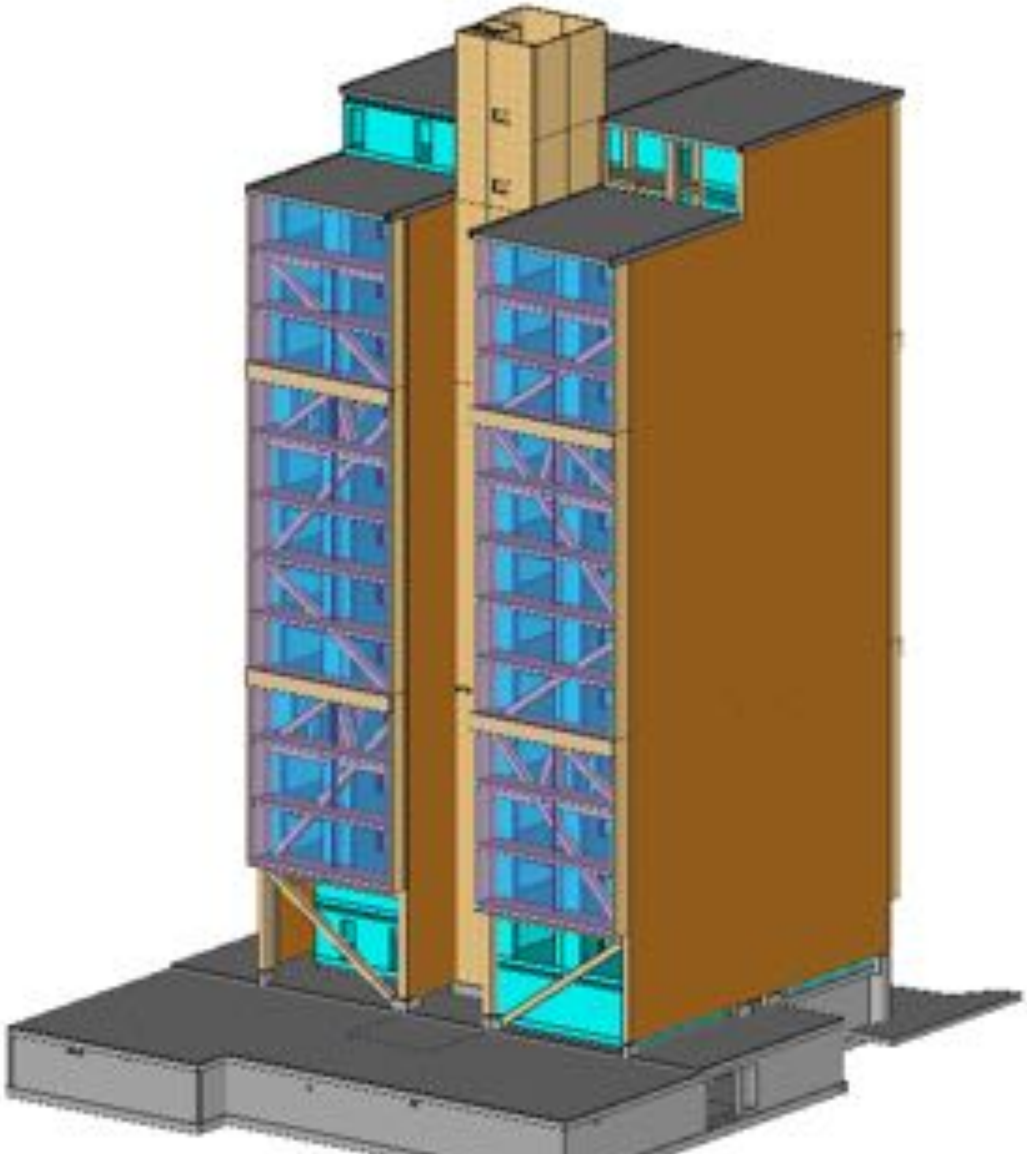


COST FP1004 – Enhance mechanical properties of timber, engineered wood products and timber structures

Weather skin: Metal sheating

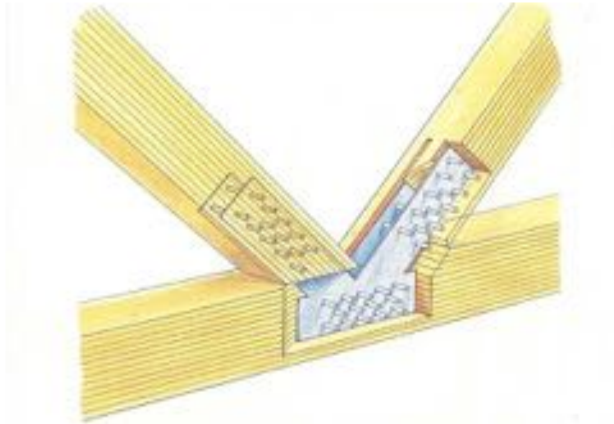


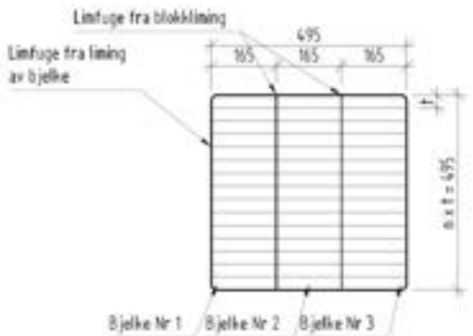
Weather skin: Glazing

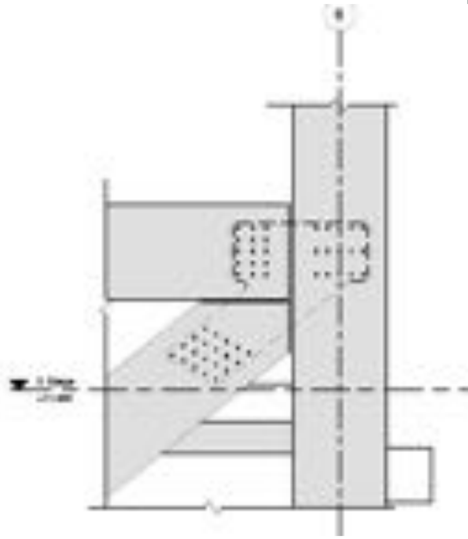


COST FP1004 – Enhance mechanical properties of timber, engineered wood products and timber structures

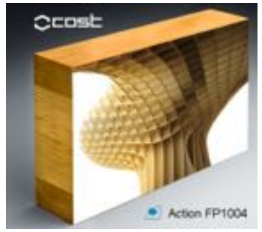
4. Glulam load-carrying frame







Tall timber buildings using trusses



- «Treet» is a relatively high building with low structural weight.

- Comparison to a similar steel truss building:

  - **Steel:** stiffness $\frac{E_s}{\rho_s} = 27$ Strength $\frac{f_y}{\rho_s} = 46$

  - **Wood:** stiffness $\frac{E_w}{\rho_w} = 30$ Strength $\frac{f_m}{\rho_w} = 70$

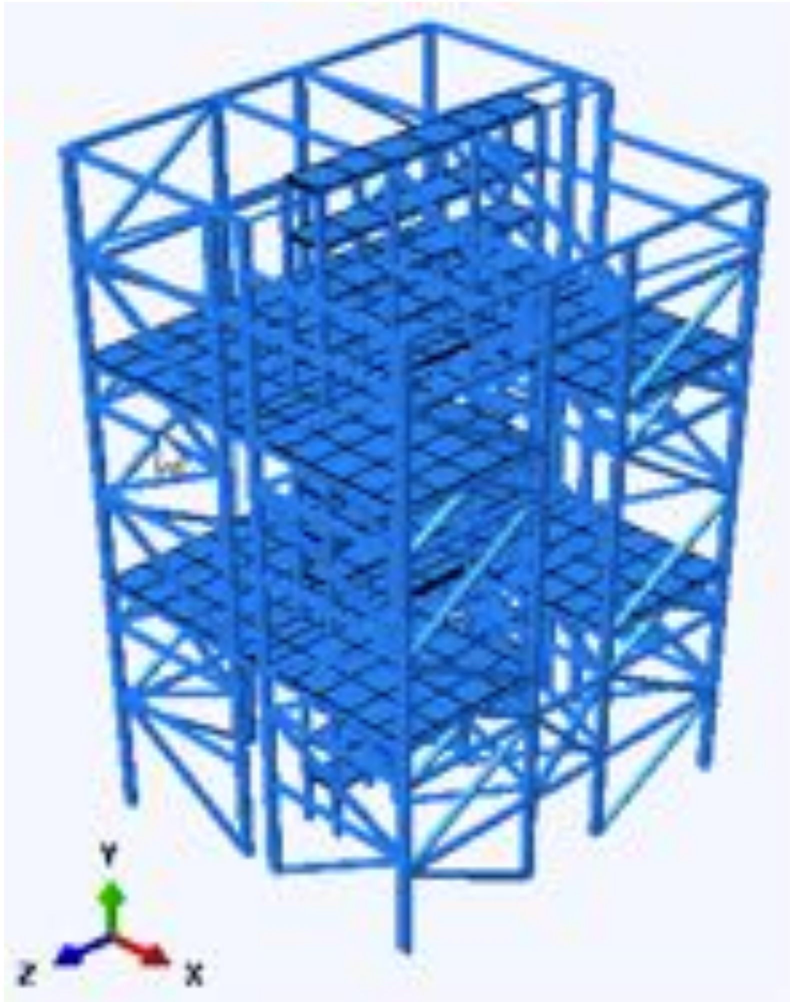
- Expectation: Steel and timber trusses behave quite similar

- Expected fundamental frequency: (simplified for steel) $f_1 \approx {}^{46}\!/_{H} \approx {}^{46}\!/_{45} \approx 1 \quad \text{Hz}$

Modelling of glulam frame

Sensitivity study (Abaqus):

- Rotational stiffness of joints:
- Pinned vs. Rigid?
  - Deformations:
    - Insignificant differences
  - Frequencies:
    - Insignificant differences
- Rotational stiffness of joints are unimportant.



Axial behaviour of connections:

- Stiffness:
  - Loading curve:10-50%

    $$K_{\mathrm{sec}} = 260 \cdot 10^3 \quad \mathrm{N/m}$$

  - Un/reloading cycle:

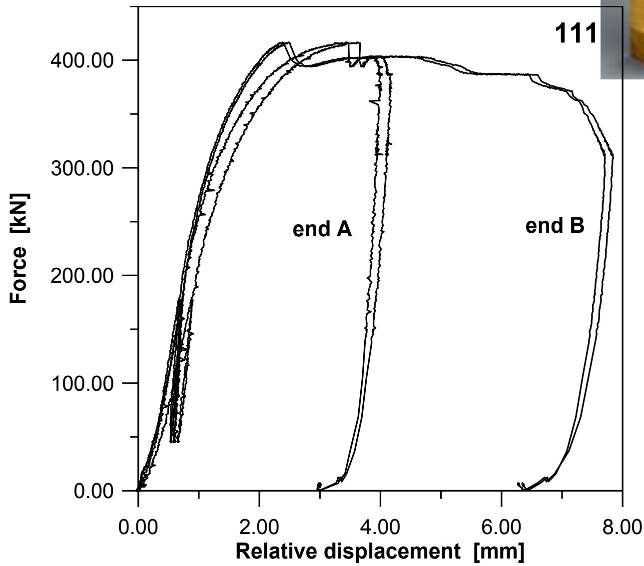
    $$K_{\mathrm{cyc}} = 780 \cdot 10^3 \quad \mathrm{N/m}$$

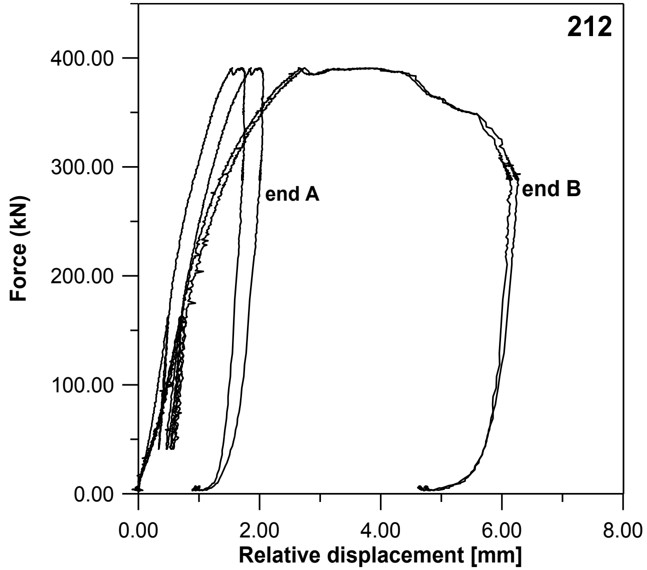
  - Eurocode 5:

    $$K_{ser} = 2\rho_{mean}^{1.5} \frac{d}{23}$$

    $$\Rightarrow 447 \cdot 10^3 \quad \mathrm{N/m}$$

- Note the unloading!



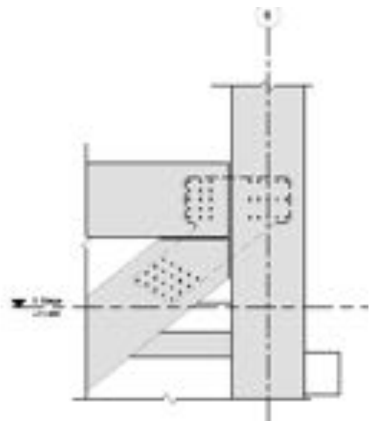


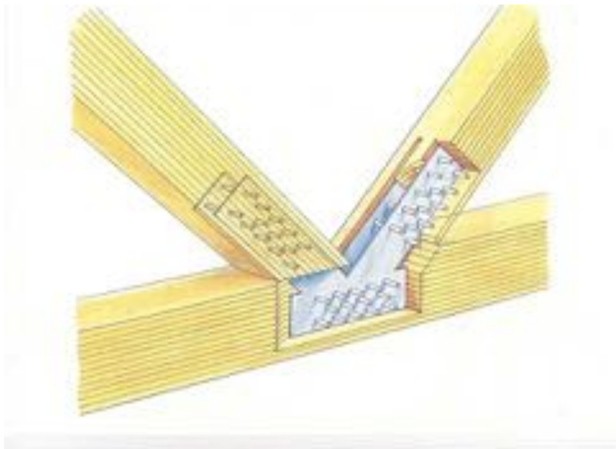
Axial stiffness of connection

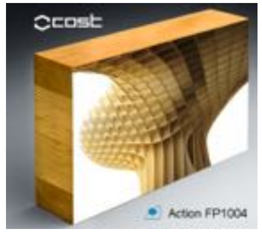
- Relative stiffness of connections: $k_{rel} := \frac{K}{AE/l_{connection}}$
  - Range in tests: $k_{rel} = 0.35 \quad (K = K_{\sec}) \quad \rightarrow \quad 1.0 \quad (K = K_{cyc})$

- Numerical simulations (Abaqus):
  - Beams and diagonals connected to vertical columns:

$$l_{element} := l_{connection}$$
$$A_{element} := k_{rel} \cdot A$$

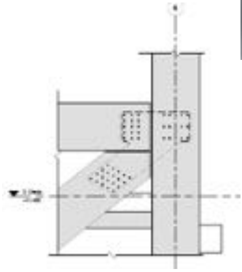




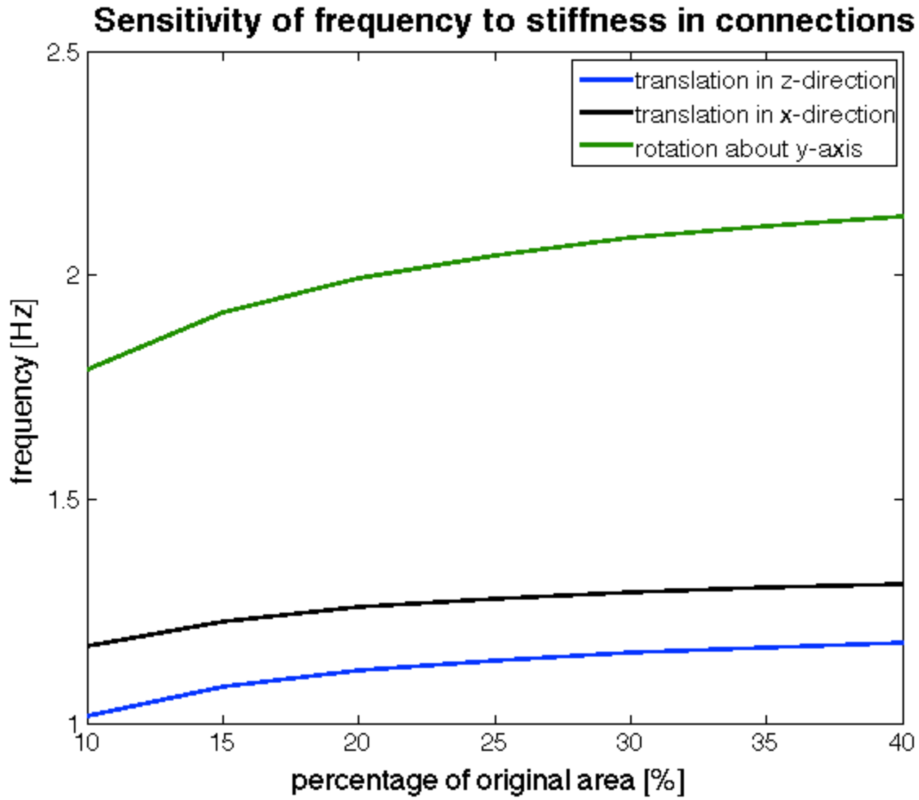


Effects of axial stiffness of connection (Abaqus)

- Relative stiffness of connections: $k_{rel} := \dfrac{A_{element}}{A_{original}}$



  - Deformations:
    - Insignificant changes
  - Mode shapes:
    - Insensitive
  - Frequencies
    - Insensitive for $k_{rel} > 0.40$
    - Decreased for $k_{rel} < 0.25$



Damping properties of glulam members

- Damping measures:

$$\xi = \delta / 2\pi = \eta / 2$$

ξ equivalent viscous damping

δ logarithmic decrement

η loss coefficient

- Sources of damping:

$$\xi = \xi_{struct} + \xi_{mat}$$

- Glulam beams:

$$\xi_{mat} = 0.005 \rightarrow 0.010 \quad \text{(increases with incresing shear)}$$

- Glulam axial strained members:

$$\xi_{mat} = 0.005$$

Structural damping properties

- Dowel connections, Reynolds et al: (single dowel):

$$\delta = 0.12 \quad \text{or} \quad \xi_{struct} = 0.019$$

- Timber floors, Labonnote et al: (incr shear) $\xi = 0.02 - 0.03$

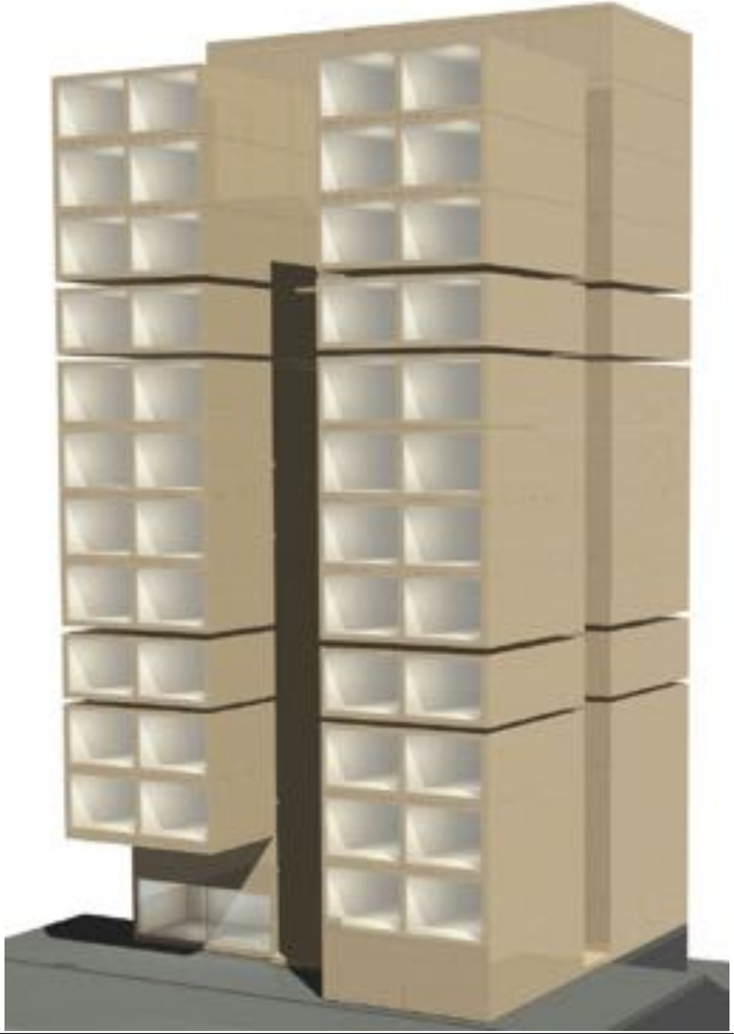
- Eurocode 5 (EN1995-1-1): $\xi = 0.01$
- Eurocode 5 (EN1995-2 Bridges): $\xi = 0.015$
- Eurocode 1: $\xi = 0.019$

- Walls: Highly interconnected!
  - Infill incl studs and battens
  - External battens and metal cladding
  - Shear deformation
- Assummed range: $\xi = 0.015 - 0.025$
- Chosen value for simulations: $\xi = 0.019$

5. Dynamic properties of residential modules

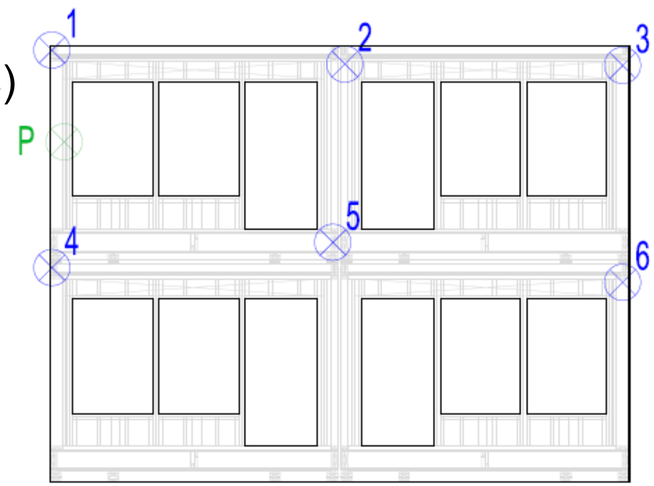
- How should the modules be fastened to the glulam frame?
- Can the dynamics of the modules cause problems?
  - Interface forces?
  - Interaction with the glulam frame?
  - Too high acellerations in apartments?

- Lack of experience and reliable knowledge about the dynamics of modules.
- Testing needed!

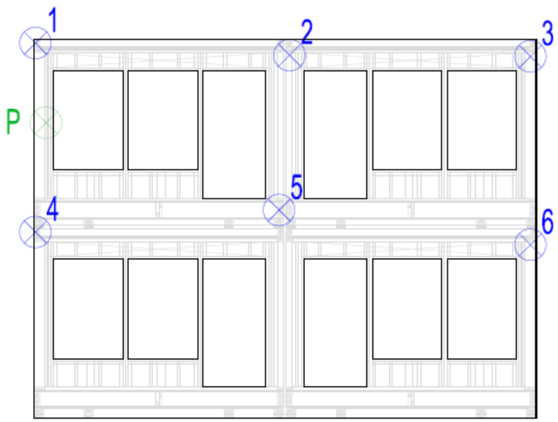


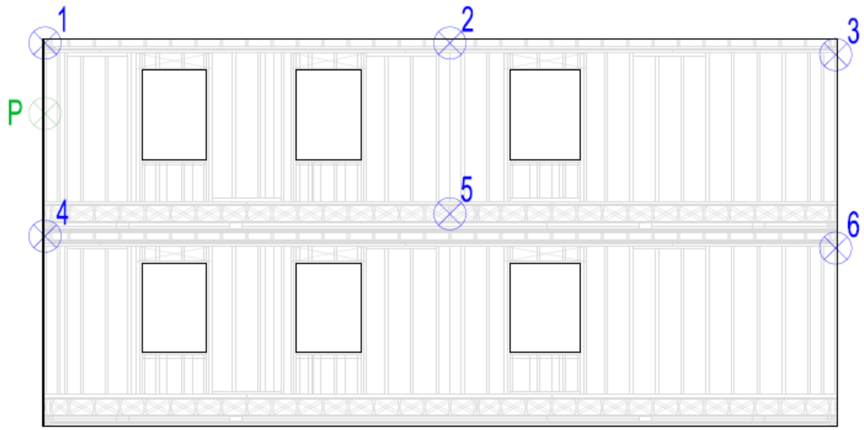
Test setup, methods and instrumentation

- Test location: Kodumaja, Tartu, Estonia, september 2012
- Performed by: NTNU (Norw. Univ. Of Science & Tech)
- Loading: Instrumented Impact Hammer
- Instrumentation: Array of 1-D accelerometers + 1 piezoel. Acc.
- Two test protocols:
  - Modal Analyses (MA)
    - Instrumented impact hammer
    - Roving hammer method (matrix of impact points)
    - 1 Piezo- accelerometers
  - System Identification (SID)
    - Matrix of accelerometers
    - Dynamic excitation by hammer

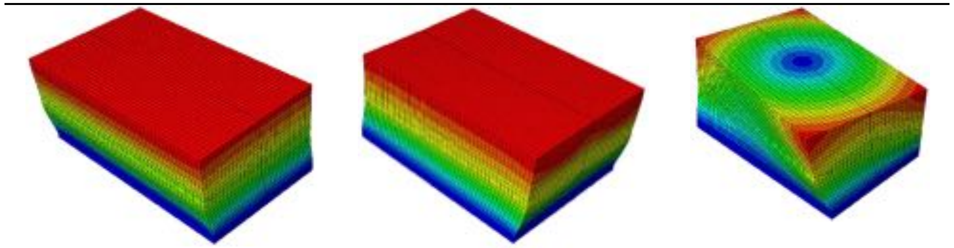


Test setup, methods and instrumentation





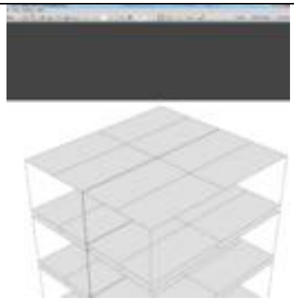
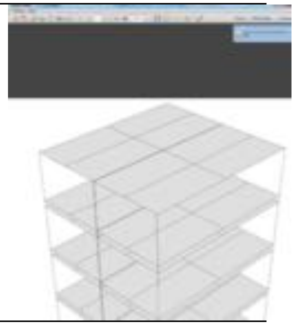
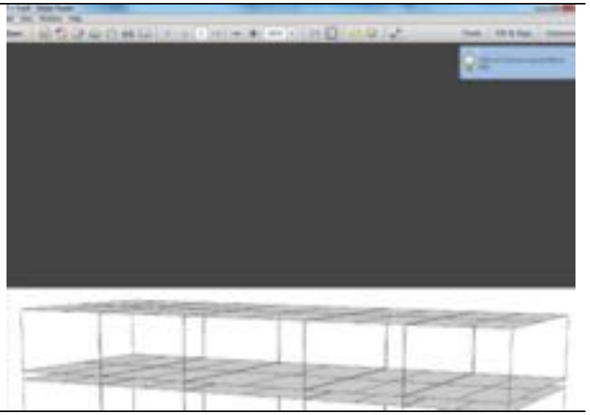
Test results

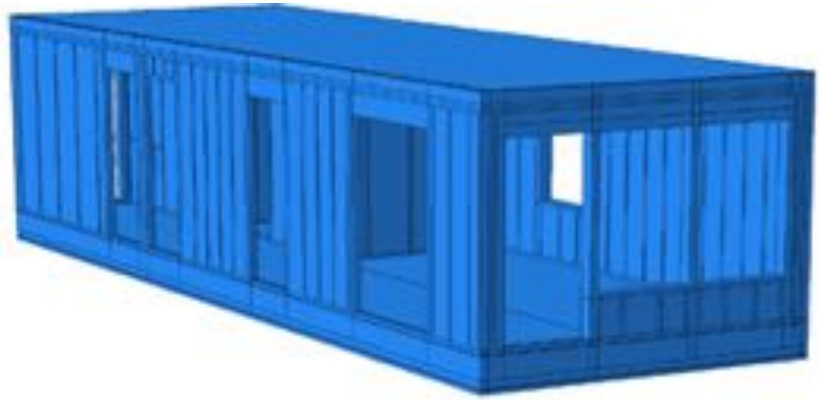


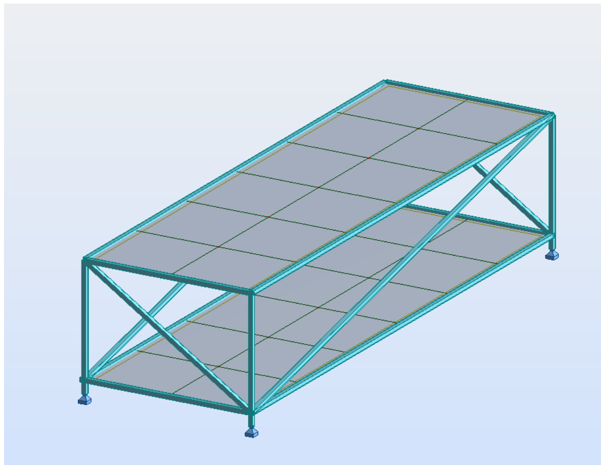
Transverse	Longitudinal	Torsional

Impact side	Mode	Protocol	Frequency Hz	Damping %
Long	Transverse	MA	5.5	3.2
		SID	4.9	3.9
	Deviation		0.6	-0.70
	Torsional	MA	10.7	3.1
		SID	10.2	3.2
	Deviation		0.5	-0.1
Short	Longitudinal	MA	9.0	6.0
		SID	8.5	6.7
	Deviation		0.5	-0.7
	Torsional	MA	10.7	2.8
		SID	10.2	3.4
	Deviation		0.5	-0.6

Numerical modelling, extrapolating the measured results: Simplified models.

1		2	
3	2 x 3 stack of modules	4	2 x 4 stack of modules
5			
6	5 x 4 stack of modules	7	



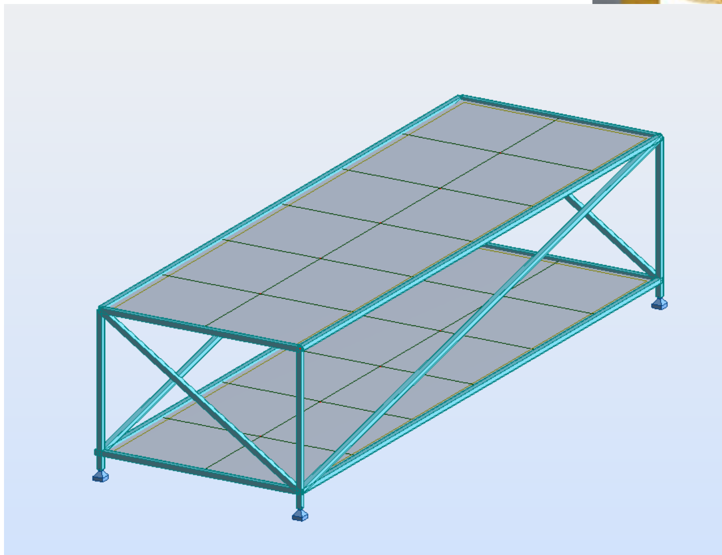


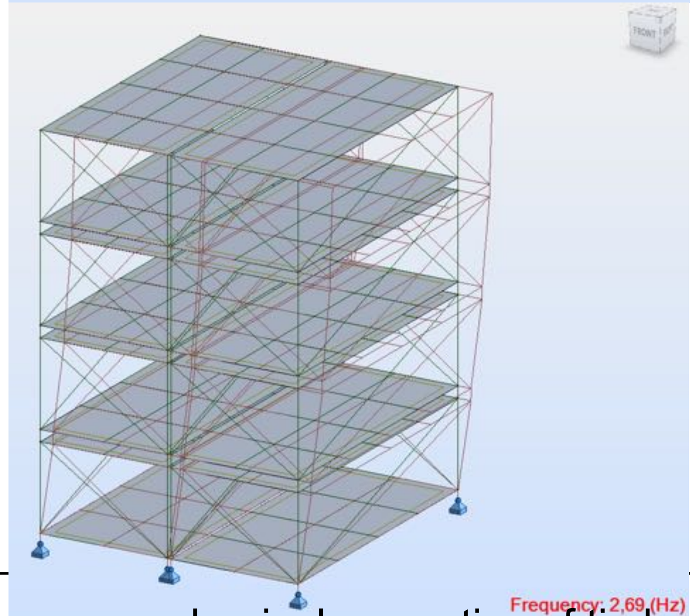
Modules, simplified models

- Simplified FEM-model of module
- Tuned with the same:
  - mass,
  - stiffness and
  - frequency properties

as the tested modules.

- Up to 4 levels of stacked modules
- Module stacks:
  - Much stiffer than the overall stiffness of the glulam frame





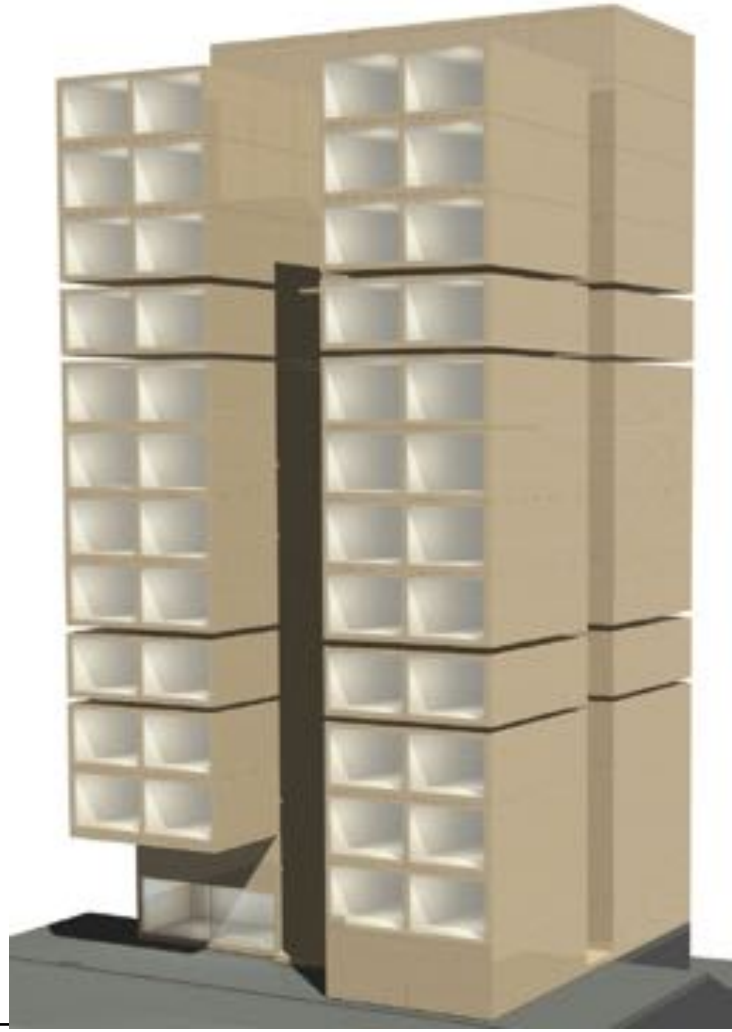
“The tree” typical plan

- Modules 4x8,7 m^2 and 5,3x8,7 m^2 :

7. Structural modelling

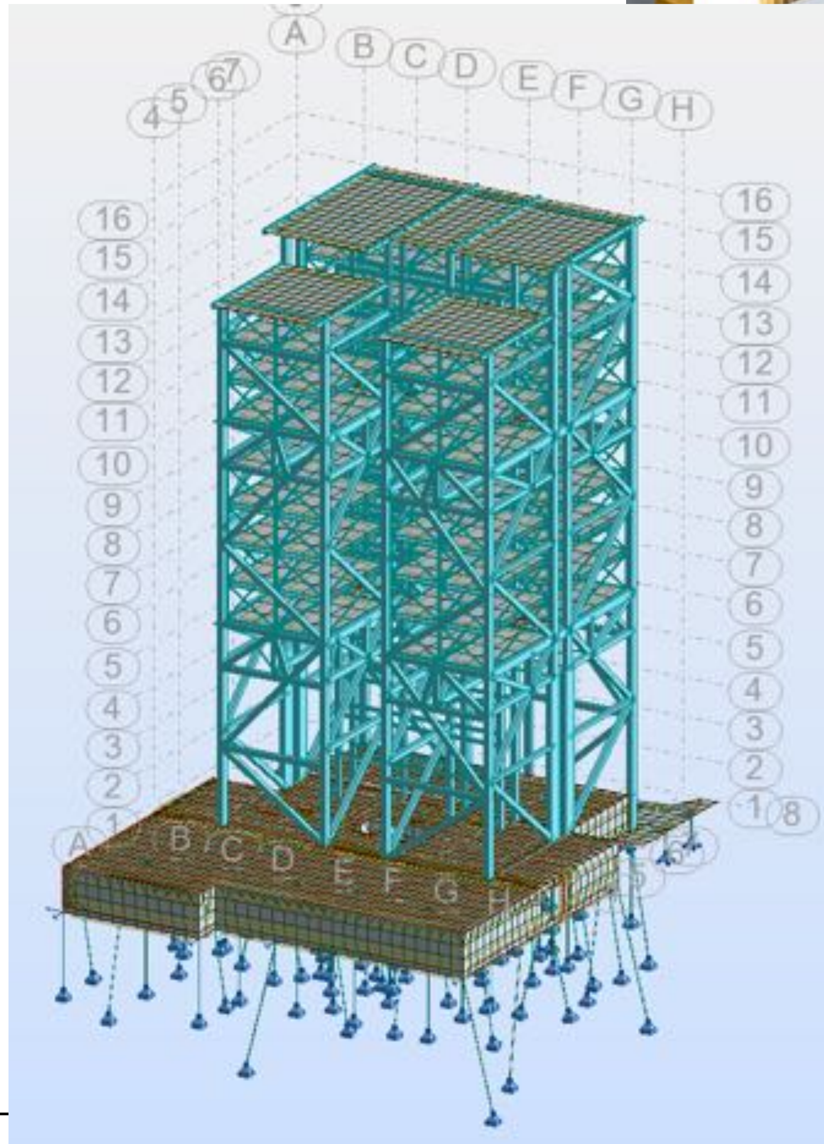
•Building modules:

- Stacked modules in four levels
- Single level in the power storey
- Only connected in the bottom to the slabs.
- First four levels not included in the FEM – analysis (not connected to the truss work)



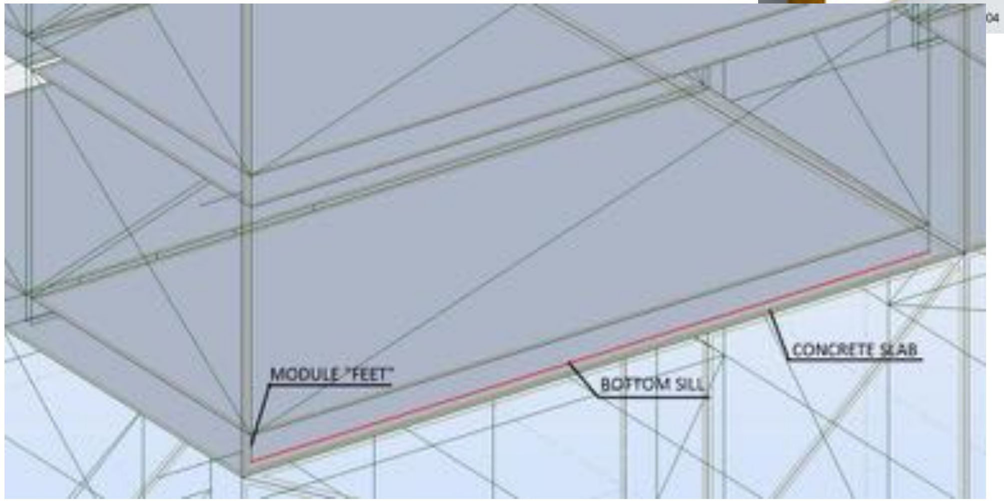
Global FEM – analysis, model

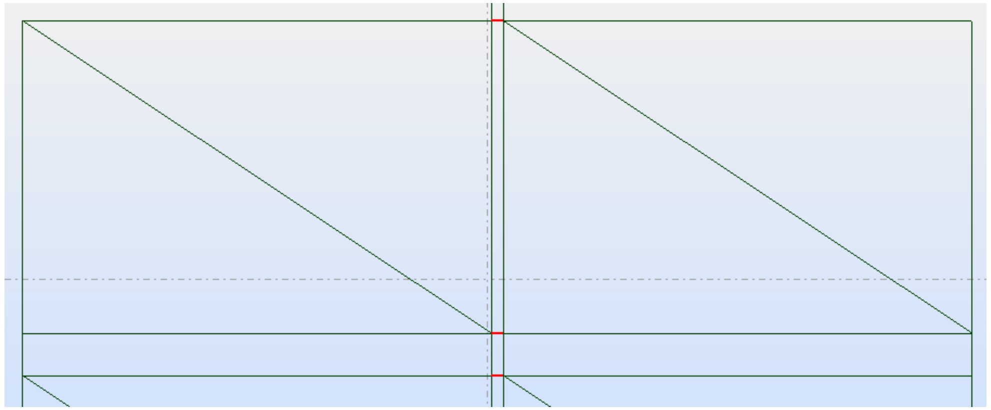
- Dynamic behaviour found with a FEM-model using Robot Structural Analysis.
- Actual geometry and stiffness of glulam truss work, concrete slabs and basement (including piles) were modelled.
- Simplified building modules added from each power storey.
- Mass added for all components from the top of the basement.



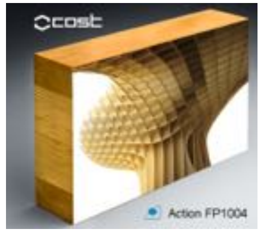
Global FEM – analysis

- Rigid beams added in the connection towards the slabs. Done to avoid local effects in the slab.
- The simplified building modules were interconnected in the top and bottom.
- 30 % of the live load in each module was added as mass.

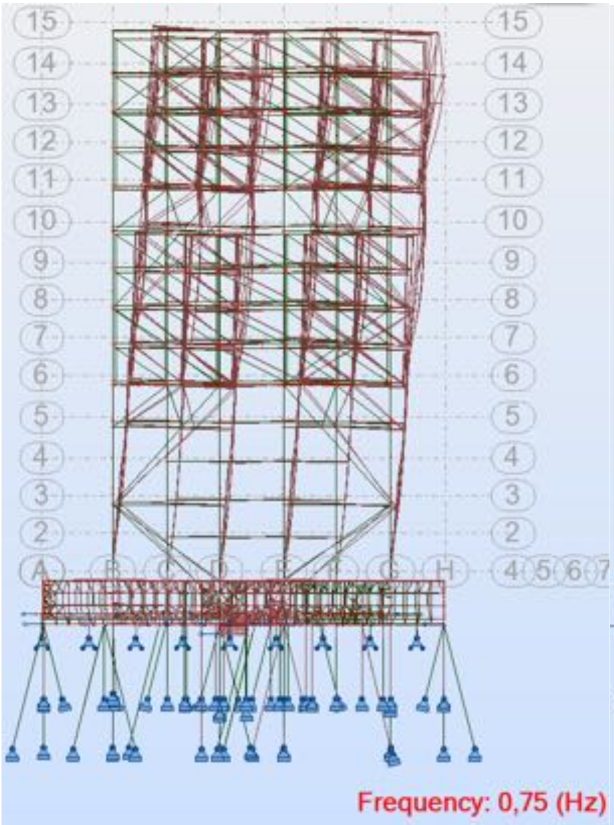


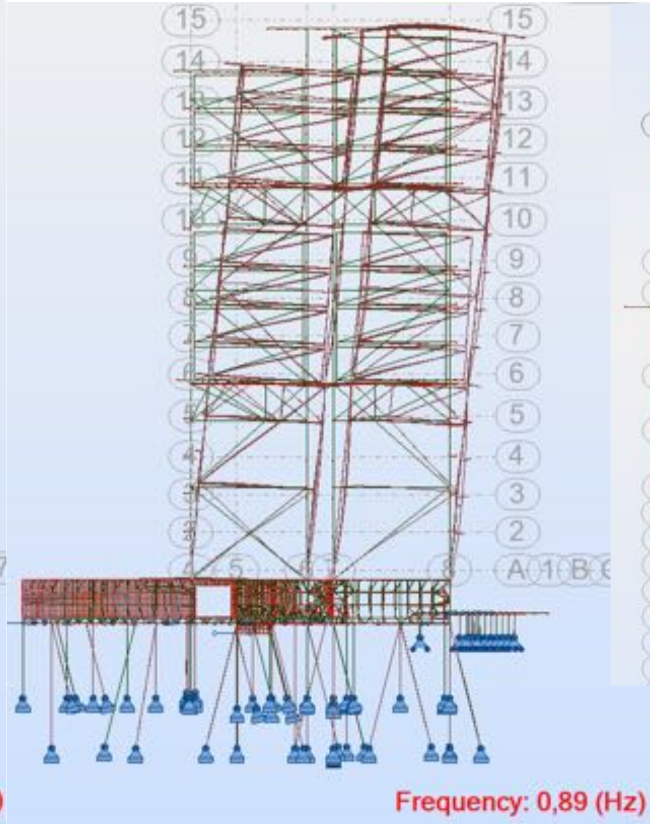


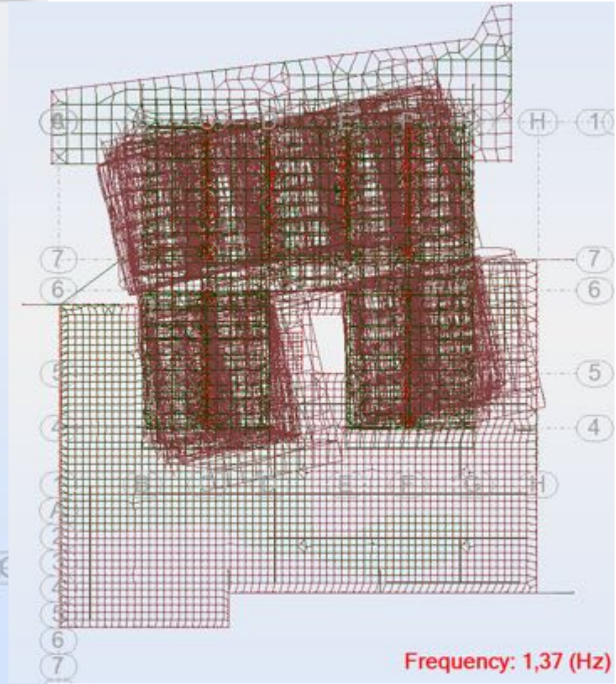
Results, global FEM-analysis



- 1. Mode 2. Mode 3. mode





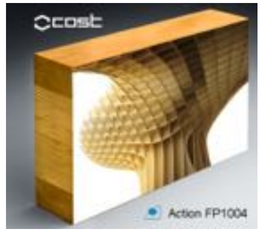


•Modules follow the vibrational modes mainly as rigid bodies.

8. Design verification for wind loading

- Natural frequencies of the building:
  - in the domain of annoying motions or nausea.
- Eurocode 1 NS-EN 1991-1-4:
  - guidelines on peak accelerations.
- ISO 10137:
  - recommended design criteria for wind-induced vibrations (serviceability).
- D. Boggs:
  - Acceleration index for human comfort in tall buildings-peak or rms, (human response to vibrations).

Results, peak accelerations



- Only the lowest transversal modes 1 and 2 of interest for wind-induced vibrations.
- Further evaluations were based on these two modes.
- The external cladding and glazing of the building are attached to the truss frame. Hence, the wind load will not affect the modules directly.
- By multiplying the standard deviation of the wind-induced accelerations, σ_{ax}, with the peak factor, $k_{p,}$ the characteristic peak acceleration for a point (y,z) is obtained.

Results, peak accelerations

- Standard deviation, σ_{ax}, is given in Eurocode NS-EN 1991-1-4:

$$\sigma_{a,x}(y,z) = c_f \cdot \rho \cdot I_v(z_s) \cdot v_m^2(z_s) \cdot R \cdot \frac{K_y \cdot K_z \cdot \Phi(y,z)}{\mu_{ref} \cdot \Phi_{max}}$$

- Where.

  cf = force factor,
  ρ = air density,
  Iv = turbulence intensity,
  vm = characteristic wind velocity on site,
  R = resonance part of the response,
  Ky, Kz = constants,
  Φ(y,z) = mode shape at a point (y,z),
  μref = equivalent mass per square meter and
  Φmax = max amplitude of the mode shape.

Results, peak accelerations

•The peak factor, $k_{p,}$ is given in Eurocode NS-EN 1991-1-4:

$$k_p = \sqrt{2 \cdot \ln(\nu \cdot T)} + \frac{0.6}{\sqrt{2 \cdot \ln(\nu \cdot T)}}$$

•Where

v = frequency of the evaluated mode shape and

T = 600 sec.

Results, peak accelerations

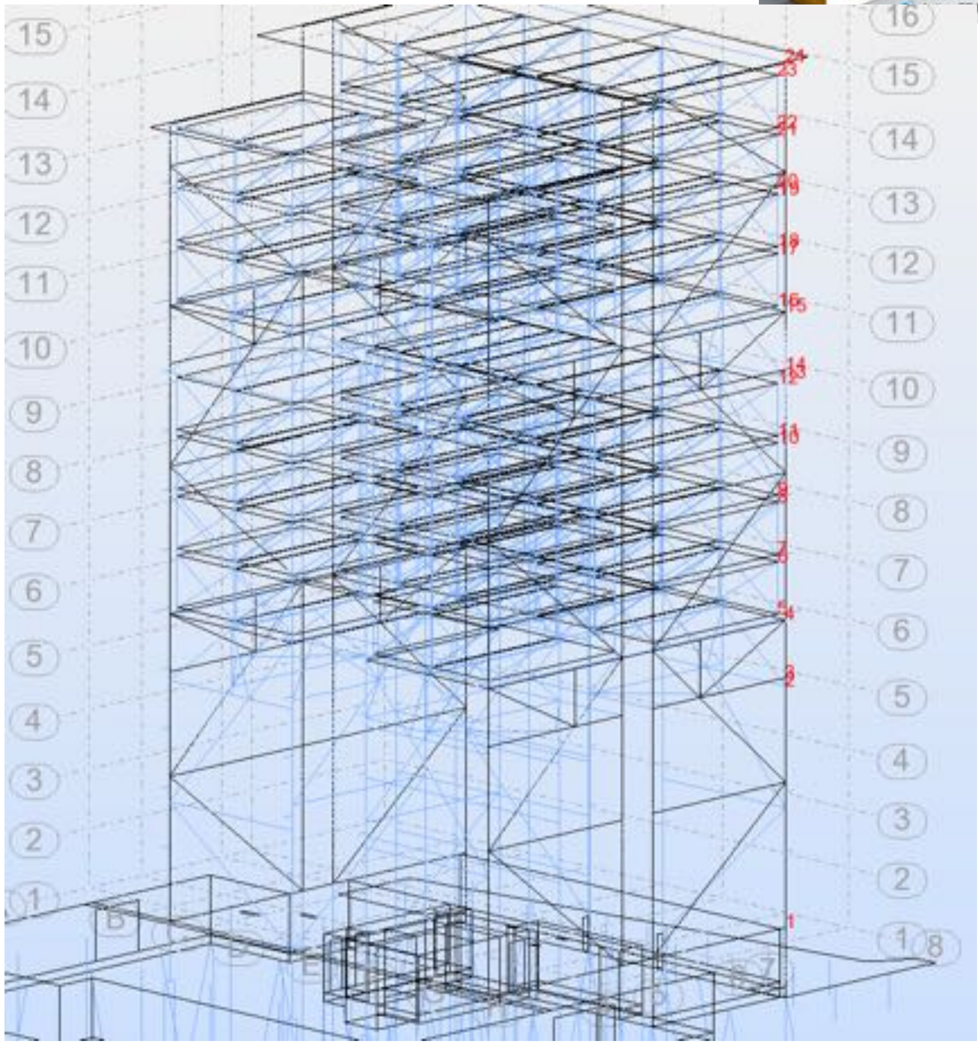
•In order to calculate the standard deviation the equivalent mass per square meter, μ_{ref}, is needed.

$$\mu_e = \frac{\int_0^h \int_0^b \mu(y,z) \cdot \Phi_1^2(y,z)\, dydz}{\int_0^h \int_0^b \Phi_1^2(y,z)\, dydz}$$

- Where:
  $\mu(y,z)$ = mass per square meter,
  $\iint \mu(y,z) \cdot \Phi^2(y,z)\, dydz$ = modal mass and
  $\iint \Phi^2(y,z)\, dydz$ = integrated square of mode shape.

Results, peak accelerations

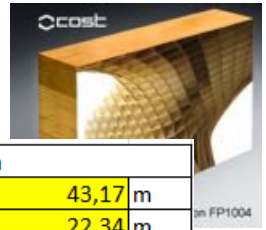
- Mass normalized mode shapes were used:
  - modal mass set to 1.0.
- ∬ $\Phi^2(y,z)$ dydz:
  - two transversal modes, nodes from the top and bottom of each level of modules (not from the truss frame).
- μ_{ref} is given by 1,0 divided by ∬ $\Phi^2(y,z)$ dydz



Results, peak accelerations

- The characteristic wind velocity of one year return period in Bergen is 19,1 m/s.
- The module testing estimated a damping of about 3,0 % for the modules.
- Because the modules are much stiffer than the overall structural system the equivalent viscous damping ratio was set to 1,9 %, (as in the Eurocode 1).

Results, peak accelerations



- **Peak accelerations:**
- Mode 1 on top of building: 0,048 m/s2
- Mode 2 on top of building: 0,051 m/s2

Mode 1; East-West		
Height	43,17	m
Width	20,66	m
Debth	22,34	m
Frequency	0,75	Hz
Ref. height, zs	25,90	m
Force factor, cf	1,35	
Basis wind velocity, vbo	26,00	m/s
Roughness lenght, zo	0,30	m
Reference lenght, Lt	300	m
Reference height, zt	200	m
Alfa	0,61	
Turbulence lenght scale, Lzs	86,3	m
Background factor, B^2	**0,540**	
Terrain roughness factor, kr	0,22	
Roughness factor, cr	0,98	
cprobality	0,75	
vm(zs)	19,13	m/s
Logarithmic damping,s	0,12	
Logarithmic demping,a	0,00	
Logarithmic demping, tot	0,12	
Frequency without dimension, fL	3,38	
Spectral function, SL	0,06	
Factor, øy	9,3	
Factor, øz	19,5	
Constant, Gy	0,5	
Constant, Gz	0,4	
Constant, Ky	1,0	
Constant, Kz	1,5	
Factor, Ks	0,041	
Resonance factor, R^2	**0,098**	
R	0,31	
Turbulence intensity, Iv	0,22	
Max amplitude mode shape, roof plan	1,00	
Standard deviation, σax	0,013	
Frequency, v	0,75	
Peak factor, kp	3,67	
Peak acceleration roof plan	**0,048**	**m/s^2**

Mode 2; North-South		
Height	43,17	m
Width	22,34	m
Debth	20,66	m
Frequency	0,89	Hz
Ref. height, zs	25,90	m
Force factor, cf	1,35	
Basis wind velocity, vbo	26,00	m/s
Roughness lenght, zo	0,30	m
Reference lenght, Lt	300	m
Reference height, zt	200	m
Alfa	0,61	
Turbulence lenght scale, Lzs	86,3	m
Background factor, B^2	**0,536**	
Terrain roughness factor, kr	0,22	
Roughness factor, cr	0,98	
cprobality	0,75	
vm(zs)	19,13	m/s
Logarithmic damping,s	0,12	
Logarithmic demping,a	0,00	
Logarithmic demping, tot	0,12	
Frequency without dimension, fL	4,01	
Spectral function, SL	0,05	
Factor, øy	12,0	
Factor, øz	23,1	
Constant, Gy	0,5	
Constant, Gz	0,4	
Constant, Ky	1,0	
Constant, Kz	1,5	
Factor, Ks	0,028	
Resonance factor, R^2	**0,060**	
R	0,24	
Turbulence intensity, Iv	0,22	
Max amplitude mode shape, roof plan	1,00	
Standard deviation, σax	0,014	
Frequency, v	0,89	
Peak factor, kp	3,71	
Peak acceleration roof plan	**0,051**	**m/s^2**

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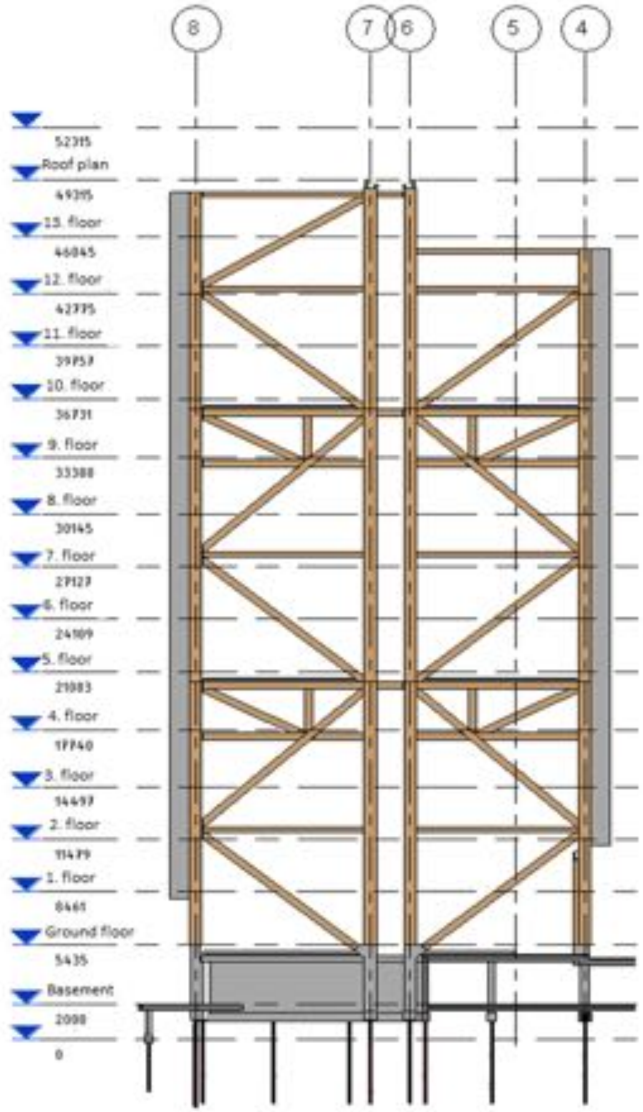
Results, peak accelerations each floor

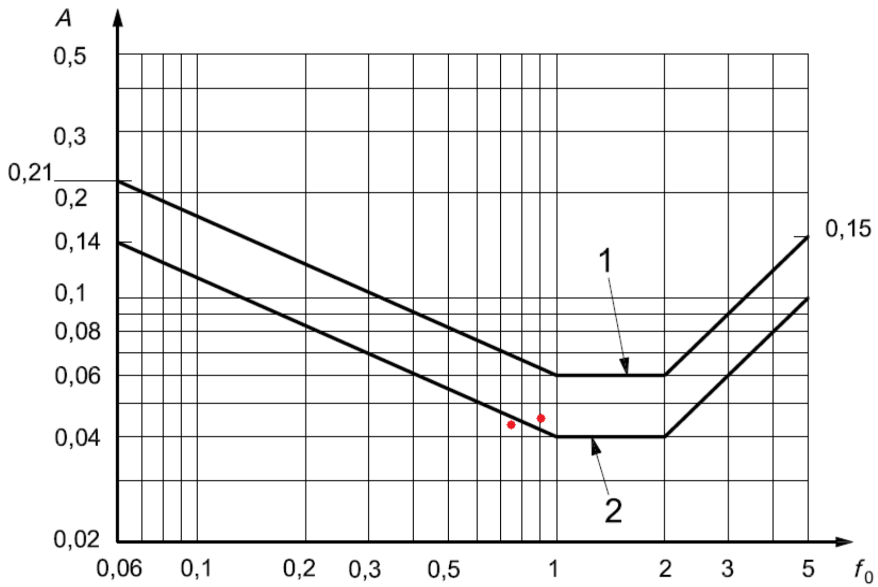
Floor	Height m	Node	East - West: Normalized mode shape	East - West: Acceleration m/s^2	North - South: Normalized mode shape	North - South: Acceleration m/s^2
4.	17,38	3	0,32	0,016	0,28	0,014
	20,31	4	0,37	0,018	0,33	0,017
5.	20,62	5	0,37	0,018	0,34	0,017
	23,28	6	0,40	0,019	0,37	0,019
6.	23,64	7	0,40	0,020	0,38	0,019
	26,30	8	0,43	0,021	0,41	0,021
7.	26,66	9	0,43	0,021	0,42	0,021
	29,32	10	0,45	0,022	0,45	0,023
8.	29,68	11	0,46	0,022	0,45	0,023
	32,34	12	0,47	0,023	0,48	0,024
	32,59	13	0,67	0,032	0,65	0,033
9.	33,02	14	0,68	0,033	0,66	0,033
	35,96	15	0,73	0,035	0,72	0,036
10.	36,27	16	0,73	0,035	0,72	0,037
	38,93	17	0,79	0,038	0,78	0,040
11.	39,29	18	0,79	0,038	0,79	0,040
	41,95	19	0,83	0,040	0,84	0,043
12.	42,31	20	0,84	0,041	0,84	0,043
	44,97	21	0,87	0,042	0,89	0,045
13.	45,33	22	0,87	0,042	0,90	0,046
	47,99	23	0,89	0,043	0,94	0,048
Roof plan	48,67	24	1,00	0,048	1,00	0,051



Results, serviceability

- Results plotted into evaluation curves given in ISO 10137:

ISO 10137:2007(E)



Key

A peak acceleration, m/s^2

f_0 first natural frequency in a structural direction of a building and in torsion, Hz

1 offices

2 residences

Figure D.1 — Evaluation curves for wind-induced vibrations in buildings in a horizontal (x, y) direction for a one-year return period

Conclusion, summary of findings

•The calculated maximum acceleration for "The tree" for mode 2 at the 13th floor is slightly higher than the recommended value, but this is considered acceptable. The 12th floor has accelerations below the recommended value.

•In D. Boggs, “Acceleration index for human comfort in tall buildings-peak or rms” the acceleration limit for nausea is given as 0,098 m/s^2 and perception limit as 0,049 m/s^2 for approximately 50 % of the population.

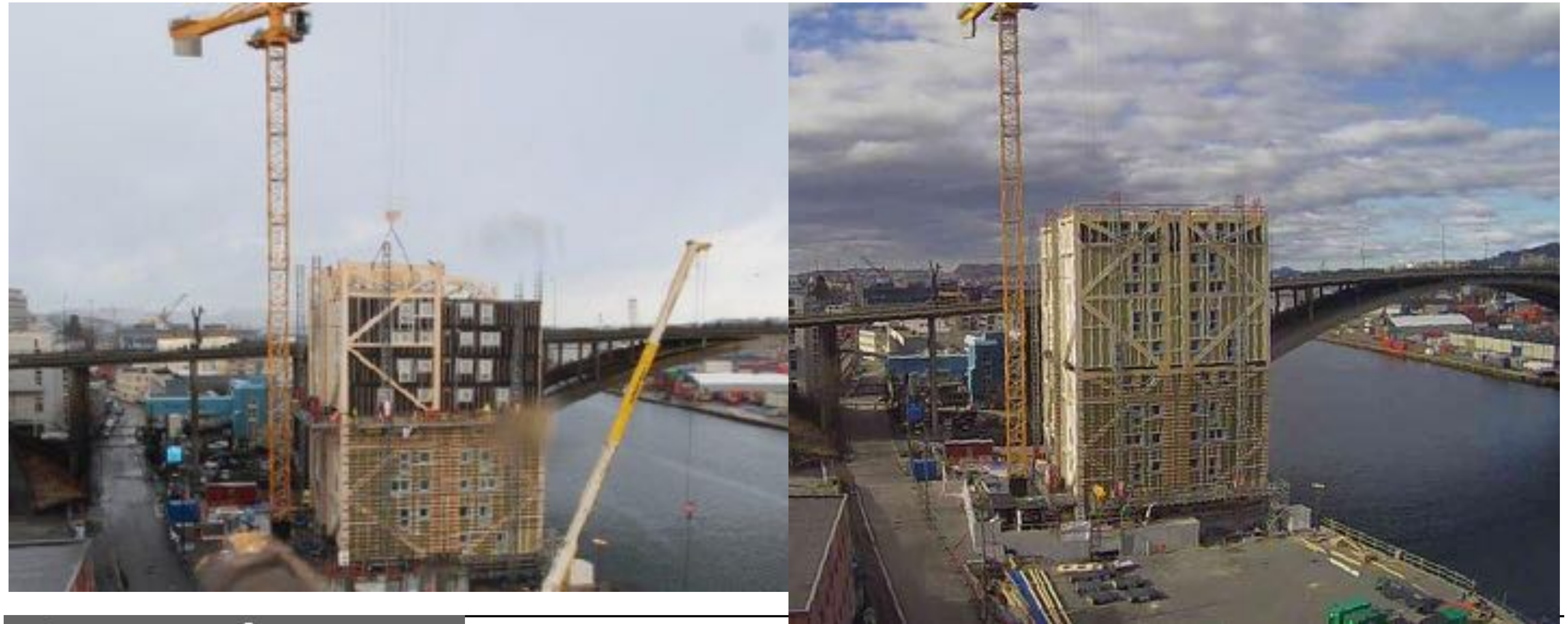
•The perception limit for approximately 2 % of the population is 0,020 m/s^2.

Conclusion, summary of findings

- Residents in the top floors might in rare cases feel vibrations, but it is very unlikely that they will become uncomfortable.
- The chosen structural solution for "The tree" using glulam truss works and stacked prefabricated building modules gives a robust design and most probably insignificant effects from vibrations caused by wind exposure.

9. Conclusive remarks

April 2015



9. Conclusive remarks

Timber high-rise is a good answer to sustainable building in urban areas

The chosen concept is robust and feasible

It's possible to build even higher with this building system

Make a visit to Bergen!

«Power story» apartment

COST FP1004 – Enhance mechanical properties of timber, engineered wood products and timber structures

Gym.

COST FP1004 – Enhance mechanical properties of timber, engineered wood products and timber structures

We can soon enjoy the roof terrace and thank you for your attention!