TALL TIMBER EXTENSION
Design study for a new construction method in the city of Rotterdam

Student
4500113 | Vicente Plaza González

Mentors
Structural Design | Karel Terwel
Computational Design | Michela Turrin
External supervisor | IMd Raadgevende Ingenieurs

# Structural extensions on existing buildings
# Lateral stability systems for tall structures
# Engineered timber products
# Sustainable structures
HOW CAN WE DESIGN AN INTEGRATED TALL TIMBER EXTENSION (TTE) IN THE INTENDED LOCATION?
PART 0 - RESEARCH FRAMEWORK

TTE

→

TECHNICAL GUIDELINES

→

STRUCTURE

→

DESIGN STUDY

LOCATION

→

BUILDING MASS

PROGRAMME

→

ARCHITECTURE
TTE

TALL TIMBER (TT)

EXTENSION (E)

Case studies

Literature

TECHNICAL GUIDELINES
LOCATION

- TALL (T)
- POLICY (P)
- MARKET (M)

BUILDING MASS

PROGRAMME

PART 2
PART 3

DESIGN STUDY → FLOOR → GRAVITY → LATERAL → EXISTING → GUIDELINES
TO WHAT EXTENT IS A TALL TIMBER BUILDING (TT) TECHNICALLY FEASIBLE?
Glulam frame
Prefabricated CLT units
Concrete "power storey" every 4-5 storeys

ALL-TIMBER

Concrete power storey

Honeycomb CLT shear walls
Inner steel tension rods

Glulam frame

Prefabricated CLT units

Precedent height: 53 meters
Lateral stability: Braced glulam frame
Vertical loading: CLT modules
Reinforcement: Concrete power storey
Example: The Treet (Norway)

Precedent height: 32.2 meters
Lateral stability: CLT shear walls
Vertical loading: CLT walls
Reinforcement: Steel vertical tension rods or shear plates
Examples: Forte (Australia), Murray Groove (UK)
Concrete cores

Glulam/CLT

Concrete cores

Concrete link beams

Concrete spandrel

Precedent height: 52.8 meters
Lateral stability: Concrete cores
Vertical loading: CLT walls/columns
Example: UBC Brock Common (Canada)

Precedent height: 120 meters
Lateral stability: CLT shear walls and outrigger glulam columns
Vertical loading: CLT walls/columns
Reinforcement: Concrete spandrel and link beams
Example: Concept study by SOM (unbuilt)
MARKETING

TALLEST - 53 M
MOST SUSTAINABLE
STRUCTURAL CONSIDERATIONS

↓

LATERAL RESISTING SYSTEM

DETAILING

↓

GUIDELINES
UPLIFT

LIGHTWEIGHT BUILDING

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIMBER</td>
<td>140</td>
</tr>
<tr>
<td>STEEL</td>
<td>160</td>
</tr>
<tr>
<td>CONCRETE</td>
<td>300</td>
</tr>
</tbody>
</table>

---

THE TREET (MALO ET AL. 2016)  


Estimated bulk density for a typical tall building  
(dead load by divided by gross volume)
HOWEVER, WIND LOADING REMAINS THE SAME
AVOID UPLIFT

BASE DEPTH > 16 M

SLENDER RATIO < 1/4.4
UPLIFT

MAXIMISE GRAVITY LOADING ON LATERAL RESISTING SYSTEM
NO INNER GRAVITY SYSTEM

Q GRAVITY LOADING

Qb/2 AXIAL LOADING IN COLUMN

WF=WH\frac{3}{2}b

QF=Qb/2 \times\text{NUMBER OF STOREYS}

CLT FLOOR SYSTEM <6m
(vibration controlled)
UPLIFT

INNER GRAVITY SYSTEM (50%G)

BASE DEPTH > 22 M

SLENDER RATIO < 1/3.2
UPLIFT

Base building 20m (Constraint)

Effective base weight
STABILITY

TIMBER
5m
140kg/m3
1.25

CONCRETE
5m
300kg/m3
2.7

CONCRETE
2.5m
300kg/m3
1.25
Up to 90% MORE EFFICIENT, engaging perimeter with wing shear walls

- **Beff = 4.8 m**
- **Core**

- **Beff = 5.5 m**
- **Double H**

- **Beff = 6.7 m**
- **Coupled shear walls**

- **Beff = 8.2 m**
- **Double C**

- **Beff = 8.6 m**
- **Double spine**
Concrete/CLT outrigger

Glulam columns
CLT walls contribute to lateral resisting system
UPLIFT IN FOUNDATION

INCREASE FOUNDATION BASE

Grade beams or foundation slab
UPLIFT IN FOUNDATION

**FRICITION PILES**
- Limited tension capacity (depending on the soil)
- Noise and vibrations
- Cheap

**MICRO PILES**
- High tension capacity
- Low disturbances
- Expensive
INCREASE EFFECTIVE BASE

CONCENTRATE VERTICAL LOADING

INCREASE DEAD LOAD

CONTROL TENSION

WING SHEAR WALLS OUTRIGGERS

NO INNER COLUMNS

CONCRETE FLOOR

STEEL REINFORCEMENT MICRO-PILES
CONCRETE BEAM  
(SOM, 2013)

STEEL BEAM  
(MICHAEL GREEN, 2013)

POST-TENSIONED CABLE INSIDE CLT  
(VAN DE KUILEN, 2010)

COUPLING ELEMENTS  
FURTHER RESEARCH
WEAK PERPENDICULAR TO FIBRE

PLATFORM METHOD

High compressive load from upper storeys

Ductile failure, Crushing timber fibres

COMPRESSION PERPENDICULAR TO GRAIN

LIMITED TO 10 STOREYS
TENSION AT THE BOTTOM

Timber has a fragile failure in tension

Reinforcement with Steel plates/rods inside timber elements

Steel tension rods inside CLT panels

The use of steel tension rods inside CLT shear walls connecting the elements vertically from foundation to top can help in resisting wind-loading and uplift forces and anchoring the building to the concrete base, by absorbing tension forces. In addition, the use of these vertical rods eliminates the need of more complex load-transferring connectors between wall elements.
WIND-INDUCED VIBRATIONS
DIFFERENTIAL SHORTENING

FURTHER RESEARCH

FULL-SCALE MOCK UP TESTS
(Above 10 storeys)
STRUCTURE SHOULD PROVIDE 120M (structural capacity)*

VERTICAL CIRCULATIONS > 60MIN (fire and smoke free)

HORIZONTAL CIRCULATIONS > 30MIN (smoke free)

*can be reduced 30-60 minutes if automatic sprinklers
CONTRIBUTION TO FIRE
SMOKE PRODUCTION
FLAME DROPLET CLASS

D
S1/S2
D0

Cannot be used in fire separation compartments without additional protection
ENCAPSULATION

LIMITED
BEFORE FLASHOVER
60 min

1x15.9mm Type X Gypsum board
CLT

COMPLETE
AFTER FLASHOVER
120 min

2x13mm Type X Gypsum board
CLT

PRE-IGNITION | GROWTH | TEMPERATURE

TIMBER CONTRIBUTES TO FIRE LOADING | TIMBER CONTRIBUTES TO FIRE DURATION

NEED FIRE PROTECTION

Ignition | Flashover | TIME

Decay
Only within fire compartments
Research + approval with fire authorities

CHARRING DEPTH
Type of timber
One or more side exposed

DE-LAMINATION CLT
Thickness of laminations
Adhesive type

Phenol-resorcinol-formaldehyde
NO DELAMINATION
0.65mm/min
Polyurethane (PUR)
DELAMINATION
35mm - 0.65mm/min
30mm - 0.69mm/min
25mm - 0.73mm/min
20mm - 0.78mm/min
De-coupling elements
Soft dampening materials
Airborne >55dB
Impact >54-61dB
THE NETHERLANDS
SCOPE CROSS-SECTION
DETAILING
TOTAL ACOUSTIC PERFORMANCE
SOUND PROOFING

CLT FLOOR

**Prefabricated concrete topping**
- R=64 dB  L=72 dB

**Gypsum fiberboard**
- R=62 dB  L=59 dB

**CLT panel**
- R=39 dB  L=24 dB

---

CLT FLOOR + CEILING

(a) Laminated flooring
- R=63 dB  L=64 dB
  - 6.4mm laminated flooring
  - 10mm low-density fiberboard (PHALTEX)

(b) Wooden topping
- R=67 dB  L=62 dB
  - 2x22mm Particle boards
  - Mineral wool
  - Timber sleepers 40x40mm. o.c 400mm
  - REGULPOL underlayment

(c) Mineral topping
- R=63 dB  L=63 dB
  - 2x13mm Gypsum boards
  - Dry topping (35kg/m²)
  - FERMACELL, cement-fiberboard...

(d) No topping
- R=63 dB  L=59 dB
  - Sound insulation clips
  - Sound absorption material (fiberglass)
  - Metal hat channel, 400mm o.c.
  - 2x13mm Gypsum boards
SOUND PROOFING

CLT WALL

**Double CLT panel**
- 30mm Mineral wool
  - R=55 dB
- 60mm Mineral wool
  - R=60 dB

**CLT panel + studs**
- 120mm Mineral wool
  - R=58 dB

Diagram details:
- Mineral wool
- CLT
- 95-115mm CLT
- 15mm Gypsum board
- 38x83mm Timber studs 400 o.c.
- 15mm Gypsum boards
TO WHAT EXTENT IS A TALL EXTENSION (TE) TECHNICALLY FEASIBLE?
**Lateral stability:**
- Additional stability core
- Composite action with existing

**Vertical loading:**
- Existing structure
- Additional stability core

Demolition required
Medium/Large-scale
Lateral stability:
- Existing structure
Vertical loading:
- Existing structure
No demolition
Small scale

Lateral stability:
- Existing structure
Vertical loading:
- Existing structure
Reduced demolition
Small/medium scale

“SMALL” EXTENSION
<table>
<thead>
<tr>
<th>Type of extension</th>
<th>Extra storeys</th>
<th>Use of existing structure</th>
<th>Demolition</th>
<th>Tall building</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pop-up</td>
<td>1-2</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Topping</td>
<td>2-4</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Stability cores</td>
<td>4-16</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>Outriggers</td>
<td>2-4</td>
<td>+/-</td>
<td>+/-</td>
<td>+/-</td>
</tr>
<tr>
<td>Table structure</td>
<td>2-4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

+ Likely; +/- Partially; - Unlikely
EXTENSIONS

"TALL" EXTENSION

> 4 extra storeys
New stability system
Strengthen existing structure
Demolition
Complex

"SMALL" EXTENSION

< 4 extra storeys
Existing stability system
No demolition

RESPECT EXISTING STRUCTURAL GRID
EVEN DISTRIBUTION OF VERTICAL LOADING
Avoid extra complexity, transfer structures, differential settlements
WHAT IS A TALL BUILDING?
TALLNESS AND HEIGHT

HEIGHT is objective (number of meters)

TALL is subjective (in relation to references)
According to CTBUH, tall building is above 50 meters

According to National Convenant Hoogbouw, tall building is above 70 meters
According to context (CTBUH)

SUBJECTIVE TALLNESS

PERCEIVED AS “TALL BUILDING”

PERCEIVED AS “LESS TALL BUILDING”
According to proportion (CTBUH)

PERCEIVED AS “TALL BUILDING”

PERCEIVED AS “LESS TALL BUILDING”
According to CTBUH a building can be considered tall if it uses tall-building technologies:

- Lateral resisting system
- Damping for wind-induced accelerations
- Fire design
- Vertical transportation
According to Foster et al. 2013, tall building can be defined as any height that exceeds current precedents.

**Tall Timber (TT)**
- The Treet and UBC Brock Commons
- 53 M

**Tall Extension (TE)**
- Karel Doorman
- 70 M
DESIGN STUDY
WHAT IS THE CITY POLICY REGARDING TALL BUILDINGS IN THE INTENDED LOCATION?
LOCATION

Important commercial location
Pedestrian active area
HIGH-RISE ZONING

DESIGN STUDY
BUILDING HEIGHT 50-70M

- **High-rise area**: No height limit
- **Transition zone**: Height limit 70-150m
Urban fabric continuity
20-25 meters high
Urban-attractive programme
SHADOW IMPACT

PROTECTED ZONES

LOCATION

Sunpots. No deterioration allowed during time of use.

Sites with special quality (Slight shadow deterioration is allowed)

MINIMAL SHADOW DETERIORATION

SHADOW INFLUENCE BECAUSE OF NEW BUILDING

SHADOW INFLUENCE ON NEW BUILDING
Optimal locations regarding maximum sunlight in Lijbaan street

CONTEXT
>1h sunlight: 34%
>2h sunlight: 16%

SCENARIO 1
>1h sunlight: 31%
>2h sunlight: 5.7%

SCENARIO 2
>1h sunlight: 34%
>2h sunlight: 16%
- Most optimal position -

SCENARIO 3
>1h sunlight: 32%
>2h sunlight: 14%
MAXIMUM VOLUME

50% volume above plinth

Area: 900m²
Depth: 30m
Diagonal 42m
SCHEMATIC SHAPES REGARDING POLICY MEASURES

DISK

LESS SHADOW IMPACT

2 ISOLATED TOWERS
Minimum Shadow Impact (Rotterdam policy)
Maximum Volume (Economics)
Minimum 42M Diagonal (Rotterdam policy)
1 Solid Mass (Architectural)
SOLAR ENVELOPE

ALL YEAR

More than 50m height average

At least 25% boundaries higher than 70 meters

Maximum sunlight on Lijnbaan street

Sunlight = 69%
Average height = 50
Maximum height = 80

Sunlight = 67%
Average height = 50
Maximum height = 80

Sunlight = 60%
Average height = 50
Maximum height = 80

Sunlight = 57%
Average height = 50
Maximum height = 80

Sunlight = 64%
Average height = 50
Maximum height = 80

Sunlight = 61%
Average height = 50
Maximum height = 80

Sunlight = 58%
Average height = 50
Maximum height = 80

Sunlight = 52%
Average height = 50
Maximum height = 80

Sunlight = 48%
Average height = 50
Maximum height = 80

Sunlight = 43%
Average height = 50
Maximum height = 80

Sunlight = 38%
Average height = 50
Maximum height = 80

Sunlight = 33%
Average height = 50
Maximum height = 80

Sunlight = 28%
Average height = 50
Maximum height = 80

Sunlight = 23%
Average height = 50
Maximum height = 80

Sunlight = 18%
Average height = 50
Maximum height = 80

Sunlight = 13%
Average height = 50
Maximum height = 80

Sunlight = 8%
Average height = 50
Maximum height = 80

Sunlight = 3%
Average height = 50
Maximum height = 80

Sunlight = 3%
Average height = 50
Maximum height = 80

Sunlight = 2%
Average height = 50
Maximum height = 80

Sunlight = 1%
Average height = 50
Maximum height = 80
TO WHAT EXTENT CAN ENGINEERED TIMBER INSPIRE THE ARCHITECTURE OF A TTE?
WOOD AND TIMBER ARE NOT THE SAME THING

WOOD
- Tree in nature
- Dried logs

TIMBER
- Blocked-glue laminated elements
- Erection of Cross-Laminated Timber

A QUEST FOR MORE TECHNICAL PRECISION

TIMBER CONCEPT

Natural
- Calm
- Soft

Precission
- Prefabrication
- Assembly
The expression of the structure is the main leitmotiv for the architecture of the building.
WHAT ARE THE CURRENT MARKET AND USER DEMANDS FOR A TALL BUILDING IN ROTTERDAM?
RECENT RESIDENTIAL HIGH-RISE
PROGRAMME

Increase exclusivity and luxury towards the top
Communal spaces. Indoor or outdoor
Commercial and multi-use plinth
Car-park above commercial plinth
FLOOR LAYOUT

High variety of housing units
80-170m²
Increase size units towards the top
Efficient vertical transportation
Located in high-rise zone
Minimum shadow impact

Respect fabric continuity
*(occupy full plot)*
20-25 meters high
Urban-attractive programme
*(Retail or cultural programme)*

50% max volume above plinth
Area: 900m²
Depth: 30m
Diagonal 42m

Green rooftops

Increase exclusivity and luxury towards the top
Communal spaces. Indoor or outdoor
Commercial and multi-use plinth
Car-park above commercial plinth

High variety of housing units
80-170m²
Increase size units towards the top
Efficient vertical transportation
Penthouses

Variety housing

Outdoor spaces

Car-park

Commercial plinth (Existing building)

Indoor spaces
TIMBER MODIFICATION FACTORS

Humidity
Load duration

kmod
kdef

STRENGTH
CREEP

CLT CROSS-SECTION

ORIGINAL

HOMOGENISATION

E'

E90 = 1/30 E0
INTERACTION LAYERS

80% DECREASE IN BENDING STIFFNESS

Stiffness imaginary fasteners ($k$'s) = Rolling shear stiffness ($Gr$) transverse layers

**COMPOSITE THEORY**
(Blass 2005)

**GAMMA METHOD**
(Eurocode 5)

**UNCONNECTED**
\[ y = 0 \]

**SEMI RIGID**
\[ 0 < y < 1 \]

**RIGID**
\[ y = 1 \]

No connection $y = 0$

Semi-rigid $y = 0.85$

Fully-rigid $y = 1$

\[ El = 8.64 \times 10^9 \text{Nm}^2 \]

\[ El = 1.22 \times 10^9 \text{Nm}^2 \]

\[ El = 1.43 \times 10^9 \text{Nm}^2 \]

6% Composite action

85% Composite action

100% Composite action

\[ K_1 = 0.73 \]

\[ Bending \ stiffness = 1.14 \times 10^{13} \text{Nm}^2 \]

79% Composite action

\[ y = 0.96 \]

\[ Bending \ stiffness = 1.40 \times 10^{13} \text{Nm}^2 \]

97% Composite action
190mm CLT - 8 meters SPAN

NORMAL STRESSES
SHEAR STRESSES

NOT OK
ROLLING SHEAR
DEFLECTION
VIBRATION
FIRE
FLOOR SYSTEM

- Reduce span
- Increase floor depth
- Stiffer material

Concrete + Timber + Soundproofing + Fire resistance

Precamber
Box girder

Increase span
FLOOR SYSTEM

250mm CLT 250mm CLT + Concrete

DEFLECTION
VIBRATION
FIRE
SOUND

21.66mm
31.02mm X
19.04mm

REDUCE SPAN
ADDITIONAL LAYERS
FLOOR SYSTEM
CONCRETE + TIMBER COMPOSITE

50 - 100 mm concrete topping + shear connectors

50% REDUCTION DEFLECTIONS
CONTRIBUTION TO FIRE AND SOUND PERFORMANCE
FLOOR SYSTEM

LIGNATUR

<table>
<thead>
<tr>
<th>Feature</th>
<th>CLT</th>
<th>LIGNATUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRUCTURE</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>SOUND</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>FIRE</td>
<td>✗</td>
<td>✗✖️</td>
</tr>
<tr>
<td>CUSTOMISATION</td>
<td>✗</td>
<td>✔️</td>
</tr>
</tbody>
</table>

**Fire Resistance**
- **30 min**: 
  - CLT: 1 layer
  - LIGNATUR: 2 layers
- **60 min**: 
  - CLT: 2 layers
  - LIGNATUR: 3 layers
- **90 min**: 
  - CLT: 3 layers
  - LIGNATUR: 4 layers

**Sound Insulation**
- **+50kg/m²**
  - CLT: 1 layer
  - LIGNATUR: 1 layer

**Sound Absorption**
- Class B, C, D
  - CLT: 1 layer
  - LIGNATUR: 1 layer

Optimised system “silence 12” can compete with conventional concrete floor systems.
FLOOR SYSTEM

150MM GLULAM + 100 CONCRETE

SOUND ✓
FIRE ✓
STRUCTURE ✗

24 mm

40.4 mm

29 mm
FLOOR SYSTEM

250MM GLULAM + 100 CONCRETE

SOUND ✔️
FIRE ✔️
STRUCTURE ✔️

SLAB CONCRETE C35
SPACE FOR INSTALLATIONS
BEAMS GLULAM C24
FLOOR SYSTEM

100MM CLT - 3M SPAN

250MM CLT - 6M SPAN

COMPOSITE GLULAM + TIMBER - 8M SPAN

---

ADDITIONAL LAYERS FOR SOUND & FIRE
TO WHAT EXTENT THE EXISTING BUILDING AFFECTS THE STRUCTURE OF THE TTE?
TER MEULEN

Heritage for city of Rotterdam
Important commercial location
Boundaries 96x20m
Existing grid 8x10m

Volume simplification
26 shear walls - 5 meters + 13 shear walls - 3 meters

Floor plan and 3D scheme with uncoupled shear walls (Own elaboration)

- Wind load distribution of each separate shear wall is proportional to the bending stiffness

<table>
<thead>
<tr>
<th>Shear wall</th>
<th>Second moment of area Nmm²</th>
<th>Wind loading</th>
<th>Deflections (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 meters</td>
<td>2.06e+12</td>
<td>45%</td>
<td>623mm X</td>
</tr>
<tr>
<td>3.5 meters</td>
<td>4.5e+11</td>
<td>10%</td>
<td>390 X</td>
</tr>
</tbody>
</table>

Need at least three couplings (storey height) along height of the building.
**Couplings**

Alternate couplings in different storeys

Storey height couplings (Own elaboration)
LINTEL DESIGN

3.5m span

G = 3.65KN/m²
L = 1.75KN/m²

G = 29.2KN/m
L = 14KN/m

G = 51.1KN
L = 24.5KN

Supported Beam element

ULS (1.35G + 1.5 x 0.5Q)
49.9KN/m

CLAMPED
Same element with wall panel

87.3KN
50.9KNm

87.3KN
500-600m DEPTH

Fully rigid connections are very complex and costly
Simply supported easier option
Intermediate "partly rigid" stiffness = 0.5

<table>
<thead>
<tr>
<th>Depth of lintel beam</th>
<th>Bending stiffness (reducing 80% composite action)</th>
<th>Final deflections (including creep) SIMPLE SUPPORTED</th>
<th>Final deflections (including creep) CLAMPED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000mm</td>
<td>1.452e+14Nmm²</td>
<td>0.87mm OK</td>
<td>0.174mm OK</td>
</tr>
<tr>
<td>500mm</td>
<td>1.815e+13Nmm²</td>
<td>6.492mm OK</td>
<td>1.30mm OK</td>
</tr>
<tr>
<td>400mm</td>
<td>9.3e+13Nmm²</td>
<td>13.6mm</td>
<td>2.72mm OK</td>
</tr>
</tbody>
</table>

Summary of hand calculations. Deflection limit L/400 = 8.75mm
LINTEL DESIGN

CONNECTION OPTIONS

Monolithic lintel (left) and connection at L/2-3 for the span for simpler connection.

COMPLETE RIGID CONNECTION DIFFICULT TO ACHIEVE IN PRACTICE
STRESSES PERPENDICULAR TO FIBRE DIRECTION

SIMPLE SUPPORTED
- Steel hanger or bracket
- Timber bearing block

"PARTLY" RIGID
- Elements interlocking
- Embedded steel plate
66.7mm

Displacements

5N/mm²
Tension forces

5.67N/mm²
Compression forces
THE END