Edinburgh Napier
UNIVERSITY

Structural Timber Systems

Dr Robert Hairstans
Centre for Offsite Construction + Innovative Structures
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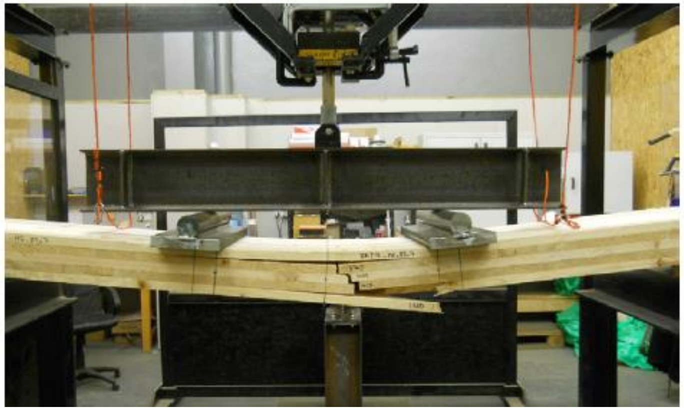
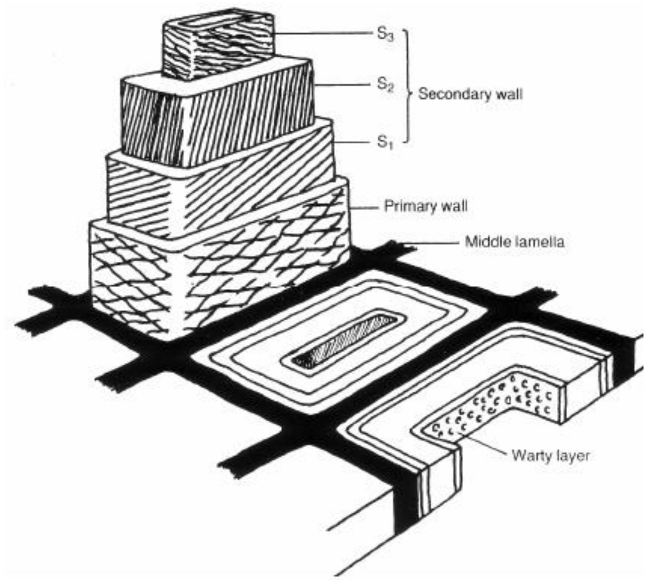


The Queen's Anniversary Prizes
For Higher and Further Education
2015

Introduction



a) Cell wall organisation of a mature tracheid

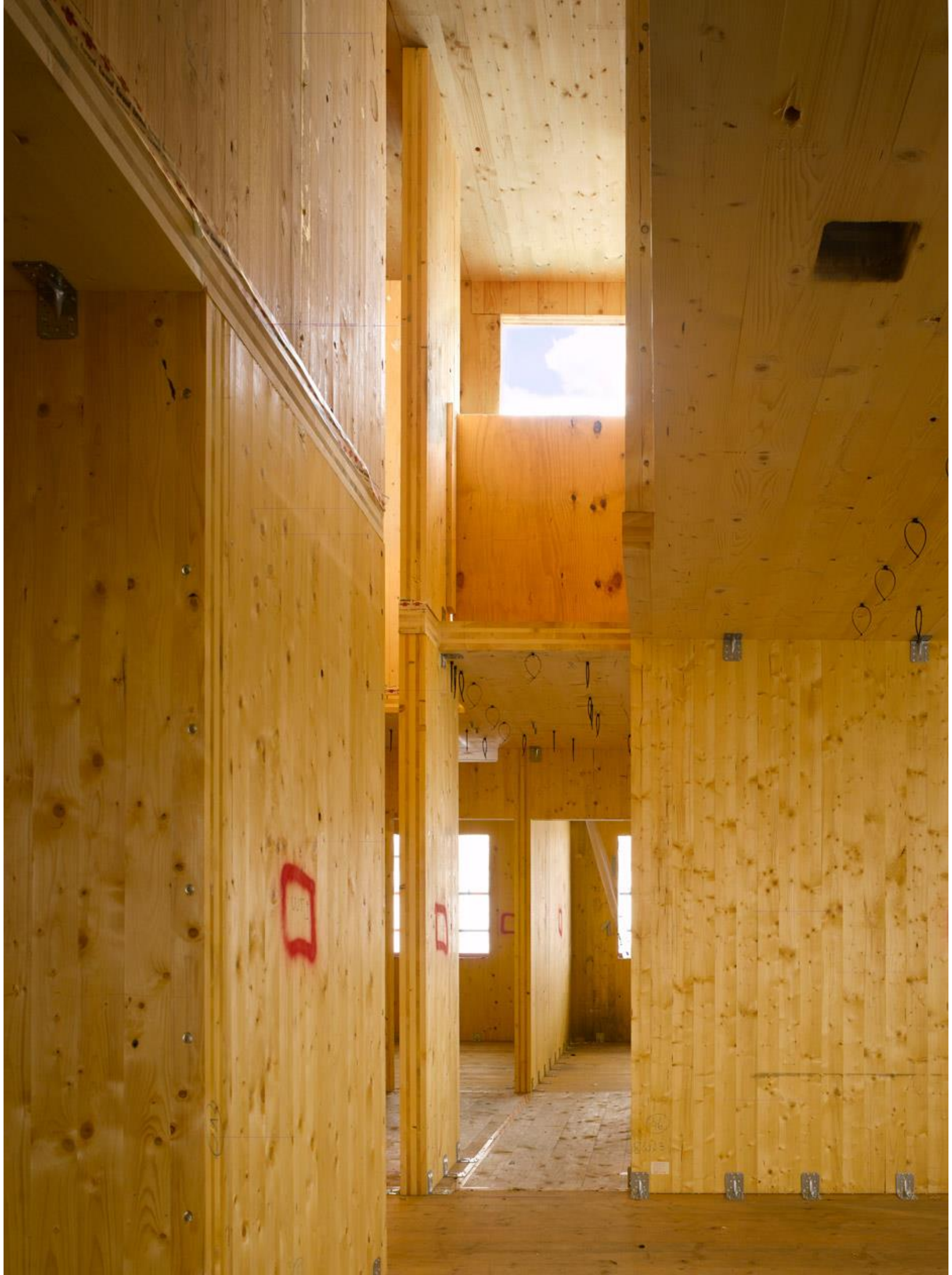
Diagonal

Compression near a knot

Localised cross-grain tension

b) Influence of grain deviation & knots on failure mode of larger samples in bending

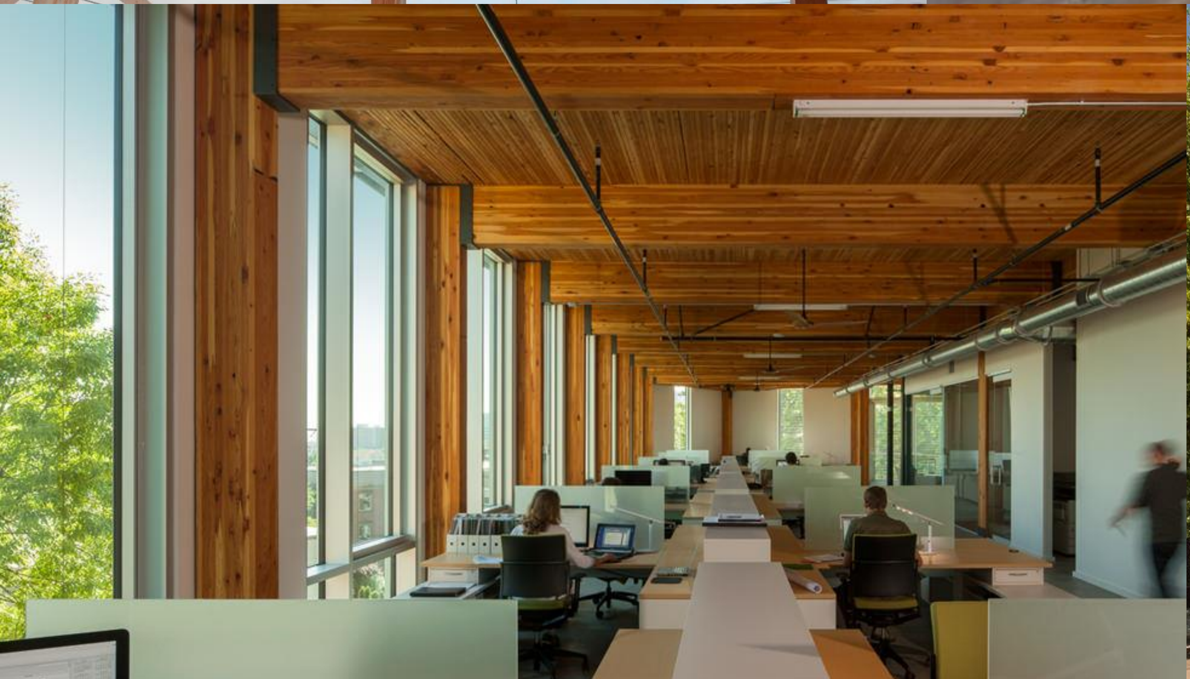
Timber is a **natural, hygroscopic, anisotropic** material that must be **properly understood** if it is to be used efficiently within the built environment. With good silvicultural practices timber can be sourced responsibly and converted (with relatively low energy requirements) to provide **environmentally sound construction products**. Combining timber construction components appropriately through **holistic design, informed detailing and quality-assured building practices** will result in a **highly energy efficient building fabric** that provides user comfort.




Falcon Foodservice Equipment


KIMBERLY ACCESS






2012

TALL WOOD

"Finding the Forest Through the Trees" FFTT: Mass Timber solution for tall buildings:

- A "strong column – weak beam" balloon-frame approach using large format Mass Timber Panels as vertical structure, lateral shear walls and floor slabs.
- The "weak beam" component is made of steel beams bolted to the Mass Timber panels to provide ductility in the system. Concrete is used for the foundations up to grade.
- No further concrete is necessary in the system unless selected for architectural reasons.
- Conceptually engineered to 30 storeys in height for the high seismic areas like Vancouver.

Glulam curtain wall and podium base

THE CASE FOR Tall Wood BUILDINGS

How Mass Timber Offers a Safe, Economical, and Environmentally Friendly Alternative for Tall Building Structures

FEBRUARY 22, 2012

PREPARED BY:
mgb ARCHITECTURE + DESIGN
Equilibrium Consulting
LMDG Ltd
BTY Group

CONTACT:
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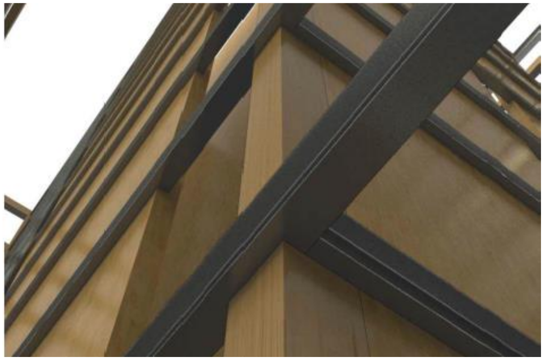
604.778.9262

Funding for this 'Case Study' project was provided to the Canadian Wood Council (CWC) on behalf of the Wood Enterprise Coalition (WEC) by Forestry Innovation Investment (FII). Any results, findings, conclusions or recommendations are those of the author, and do not necessarily represent those of the CWC, WEC - and it's partners, FII or the Province of British Columbia.



Solid panel core and intersecting ductile steel link beams

Forte Victoria Harbour Melbourne:

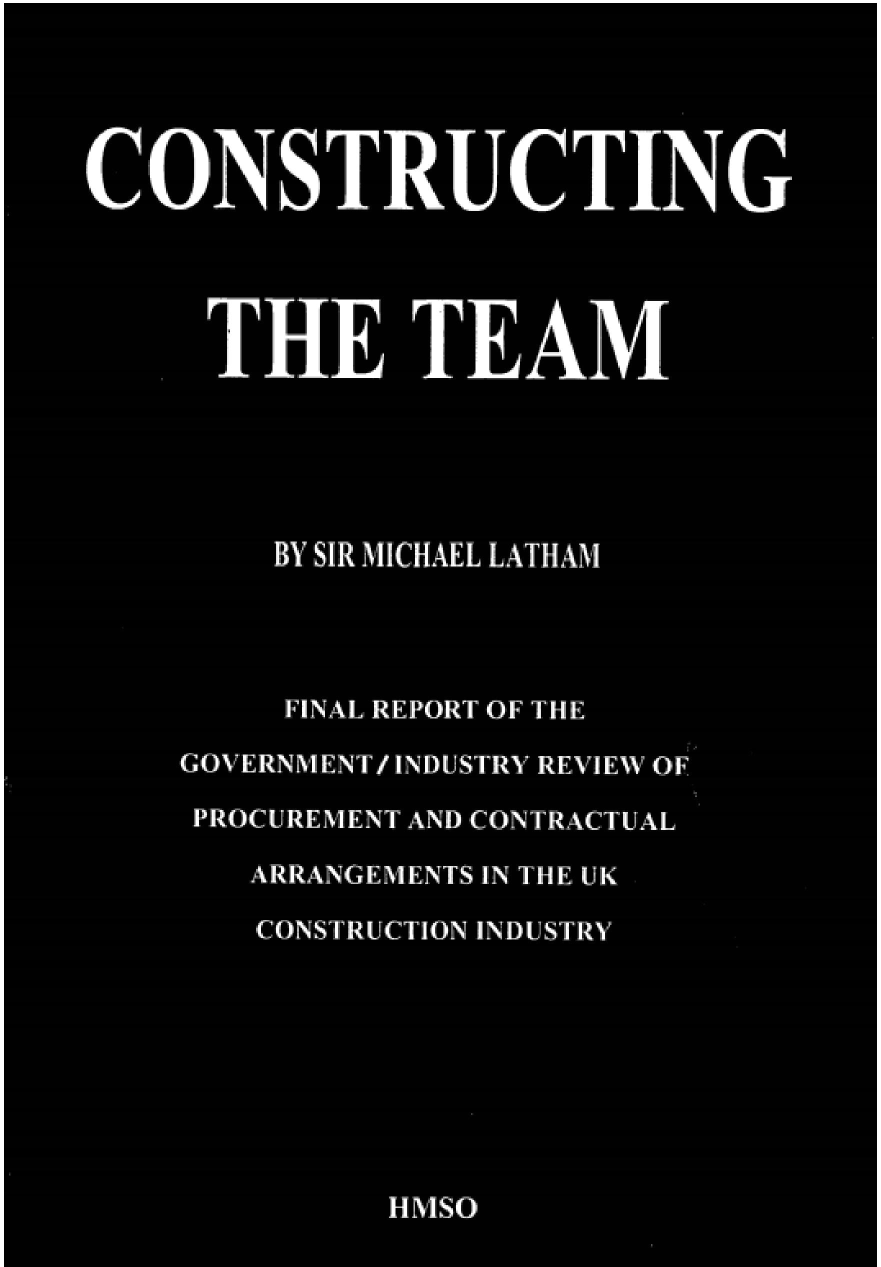
- Scale: 10 floors, 23 apartments, 32m high

Dalston Lane, Hackney:

- Scale: 121-unit development, 33m high

Offsite MMC

1994


CONSTRUCTING THE TEAM

BY SIR MICHAEL LATHAM

FINAL REPORT OF THE GOVERNMENT/INDUSTRY REVIEW OF PROCUREMENT AND CONTRACTUAL ARRANGEMENTS IN THE UK CONSTRUCTION INDUSTRY

HMSO

"The time to choose has arrived. The construction process cannot wait 30 years for another Banwell or 50 years for another Simon."

30 Point Exec Summary, excerpts:

- The state of the **wider economy remains crucial to the industry**.
- Use of **Co-ordinated Project Information** should be a contractual requirement.
- Recent proposals relating to the work of the Construction Industry Training Board (CITB) need **urgent examination**
- The industry should implement recommendations which it previously formulated to improve its **public image**. **Equal opportunities** in the industry also require urgent attention
- A **productivity target** of **30 per cent real cost reduction** (in 6 years)

[2]Report of the "Committee on the Placing and Management of Contracts for Building and Civil Engineering work", chaired by Sir Harold Banwell, HMSO, 1964.

[1] Report of the Central Council for Works and Buildings, chaired by Sir Ernest Simon: "The Placing and Management of Building Contracts", HMSO, 1944.

2013

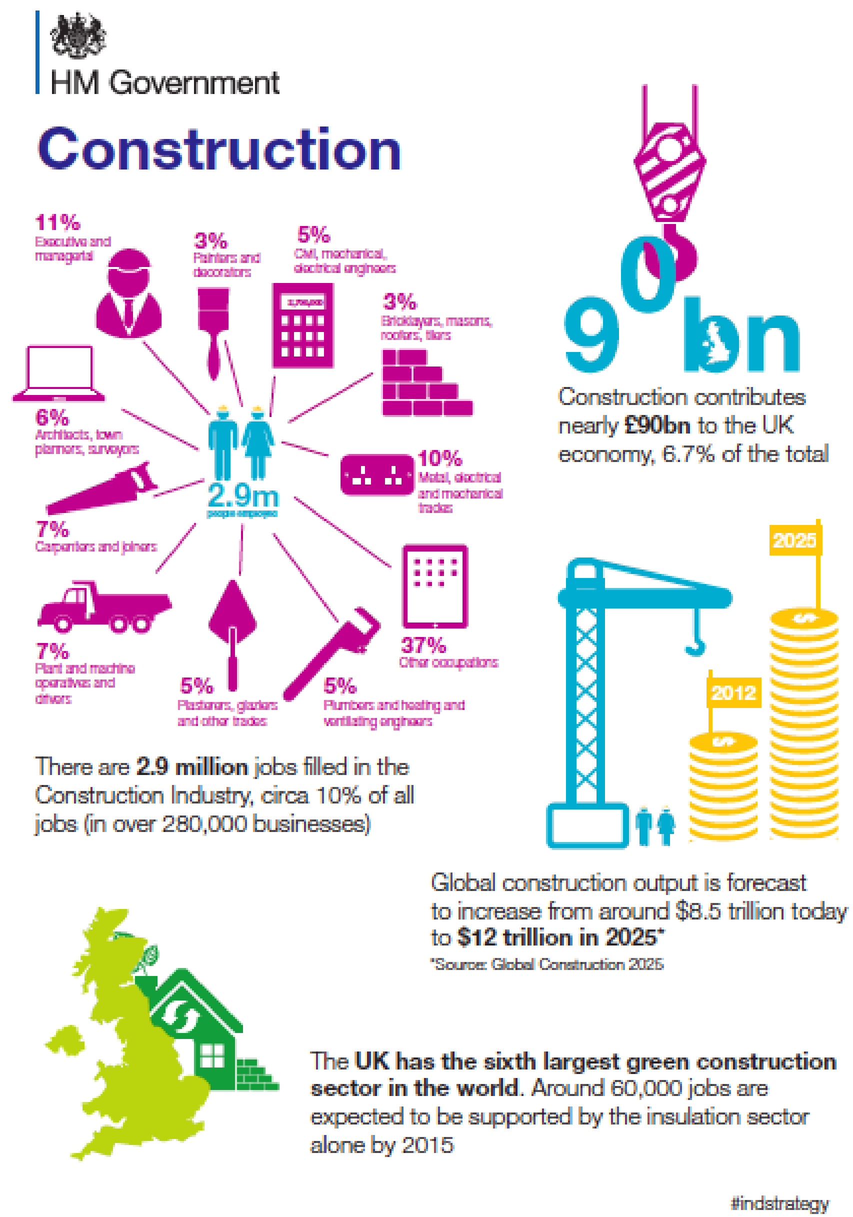
HM Government

- 50% faster delivery
- 33% lower costs
- 50% lower emissions
- 50% improvement in exports

Industrial Strategy: government and industry in partnership

Construction 2025

July 2013



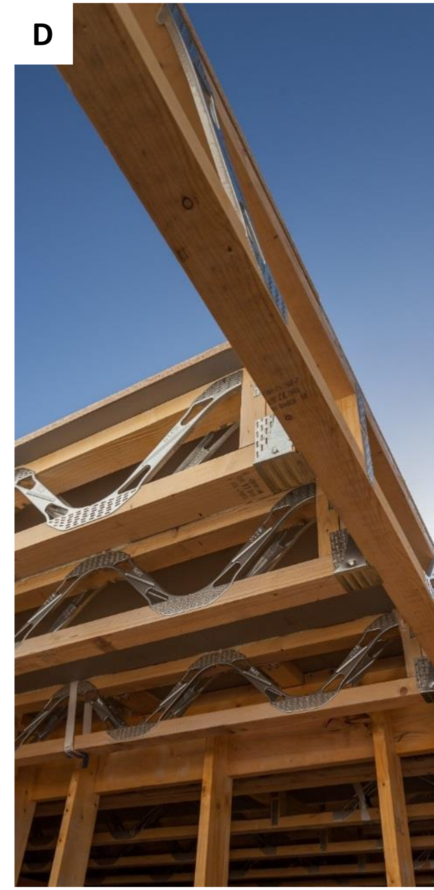
Forms of Offsite Construction

A

B

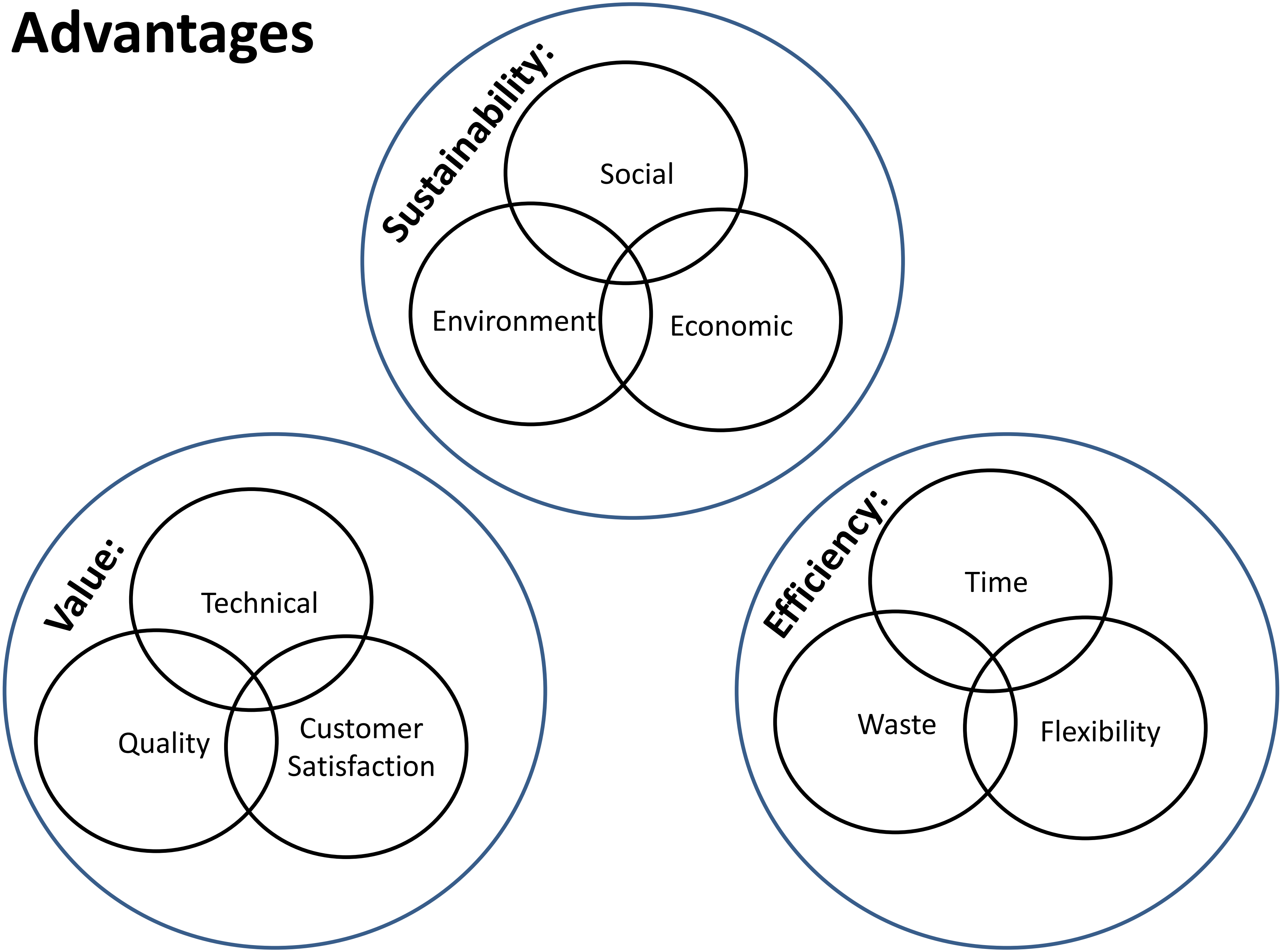
C

D

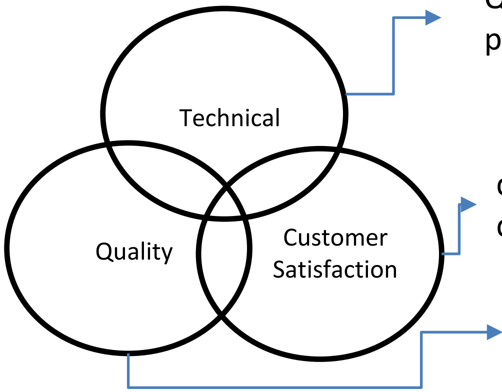


A – Panelised Construction 2-dimensional (2)
B – Modular/Volumetric 3D
C – Hybrid 2D + 3D
D – Sub-assemblies and components

Advantages


Sustainability:
Social
Environment
Economic
Value:
Technical
Quality
Customer Satisfaction
Efficiency:
Time
Waste
Flexibility

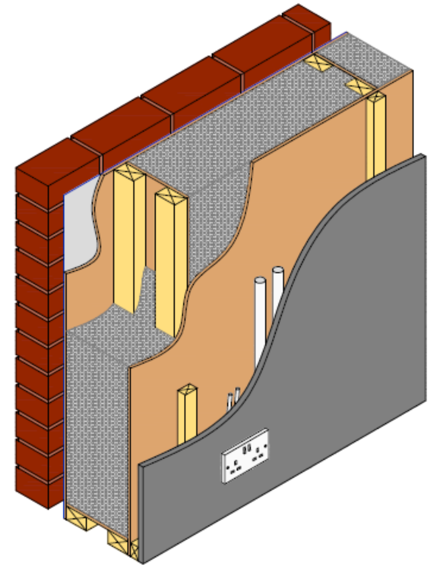
Value:



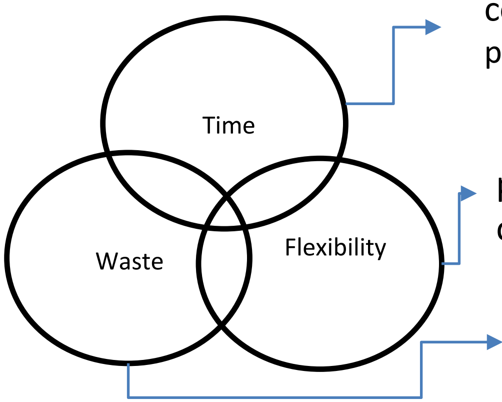
QA = higher levels of thermal and acoustic performance, investment in R+D

quality assurance, reduced snagging + defects.

consistency of process, improved quality, predictable product behaviour.



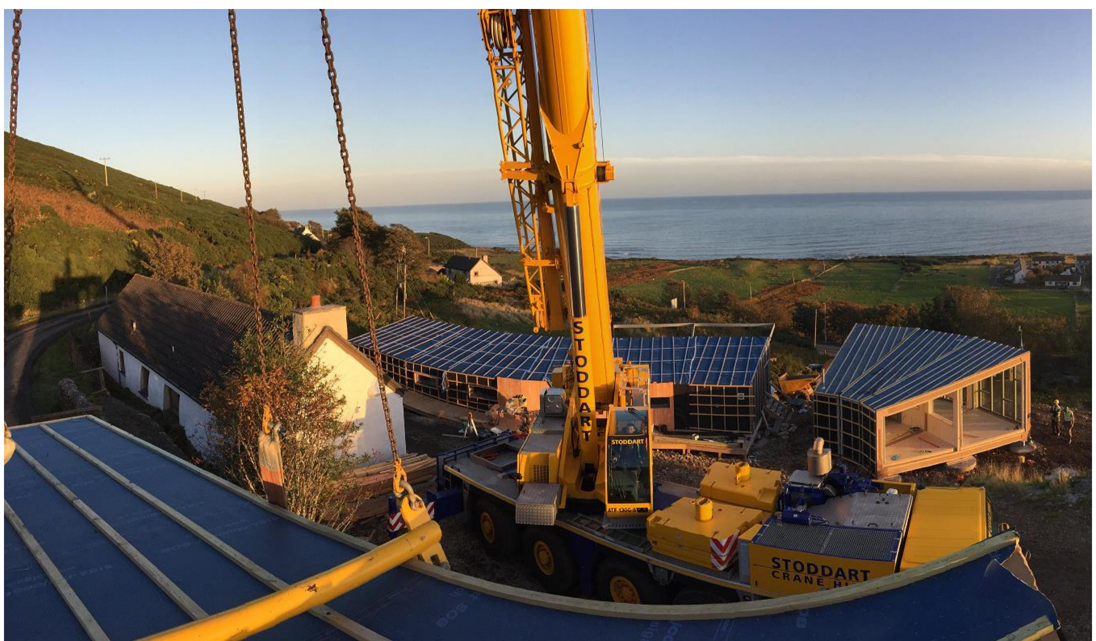
Efficiency:

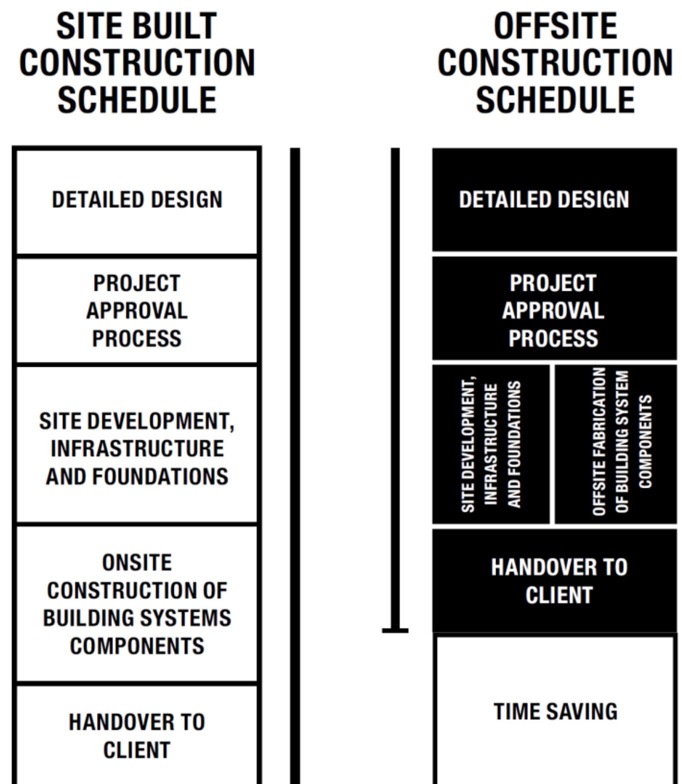


concurrent activities, 'just-in-time' principles

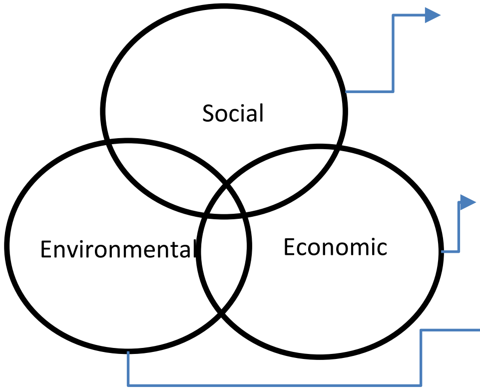
product family architecture, standardisation, mass customisation

CAD/CAM optimisation; 20 and 40% waste reduction (WRAP, 2008).





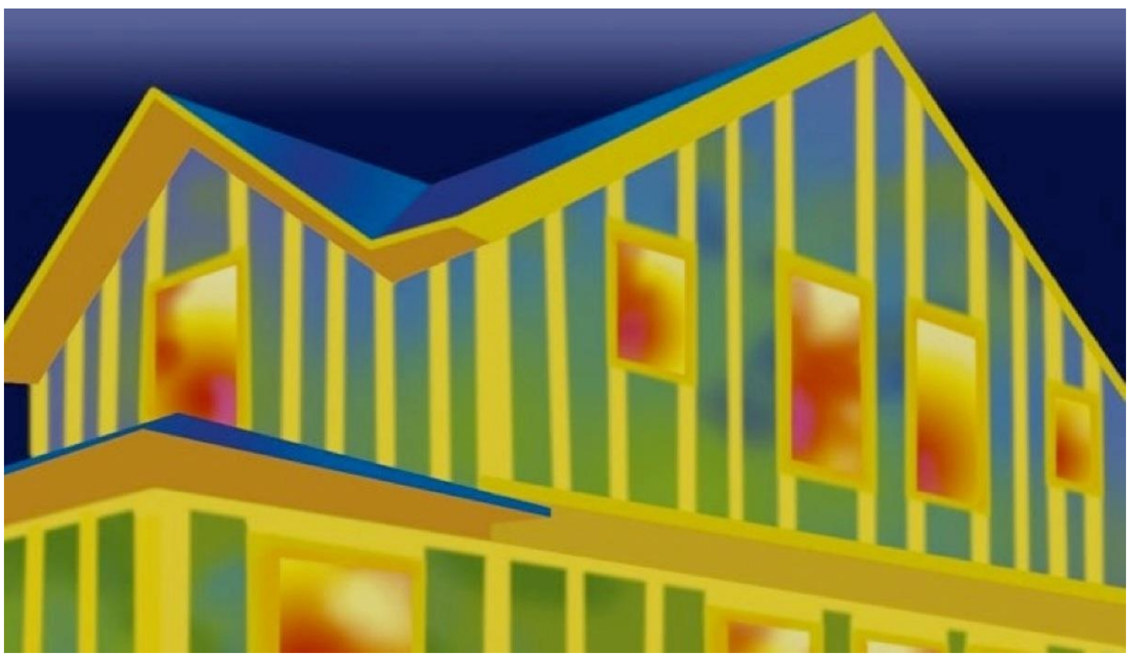
Sustainability:

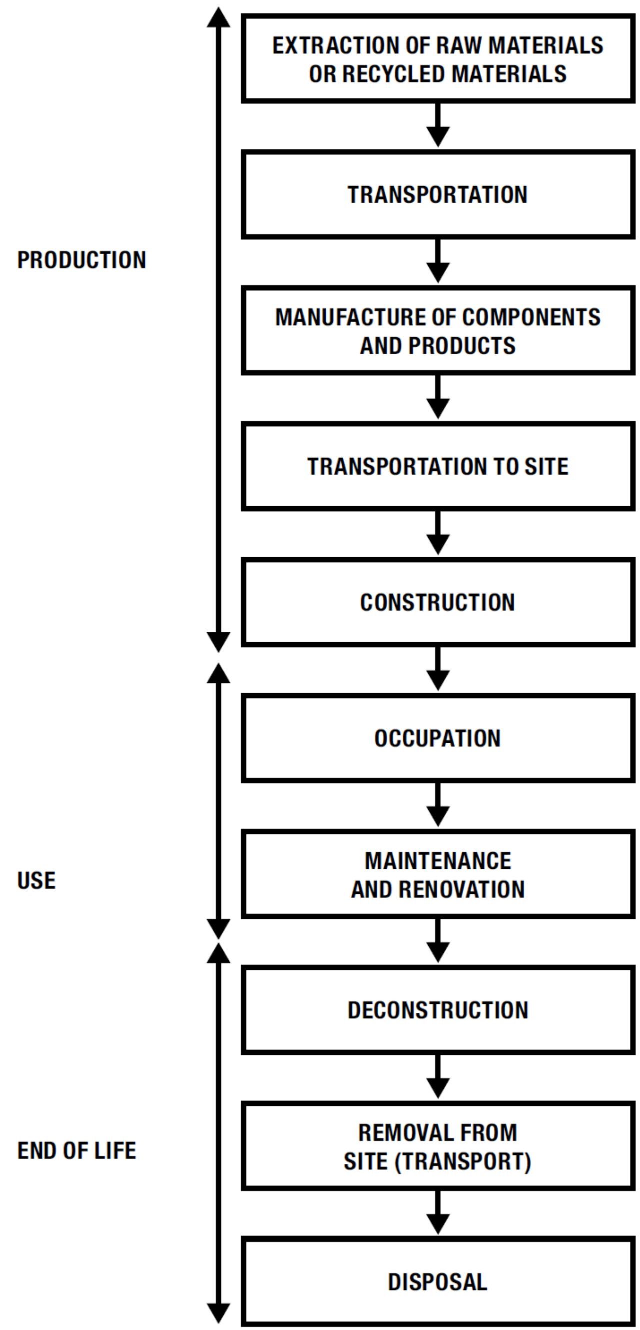


“construction culture”, safe, clean, job security, flexible work patterns

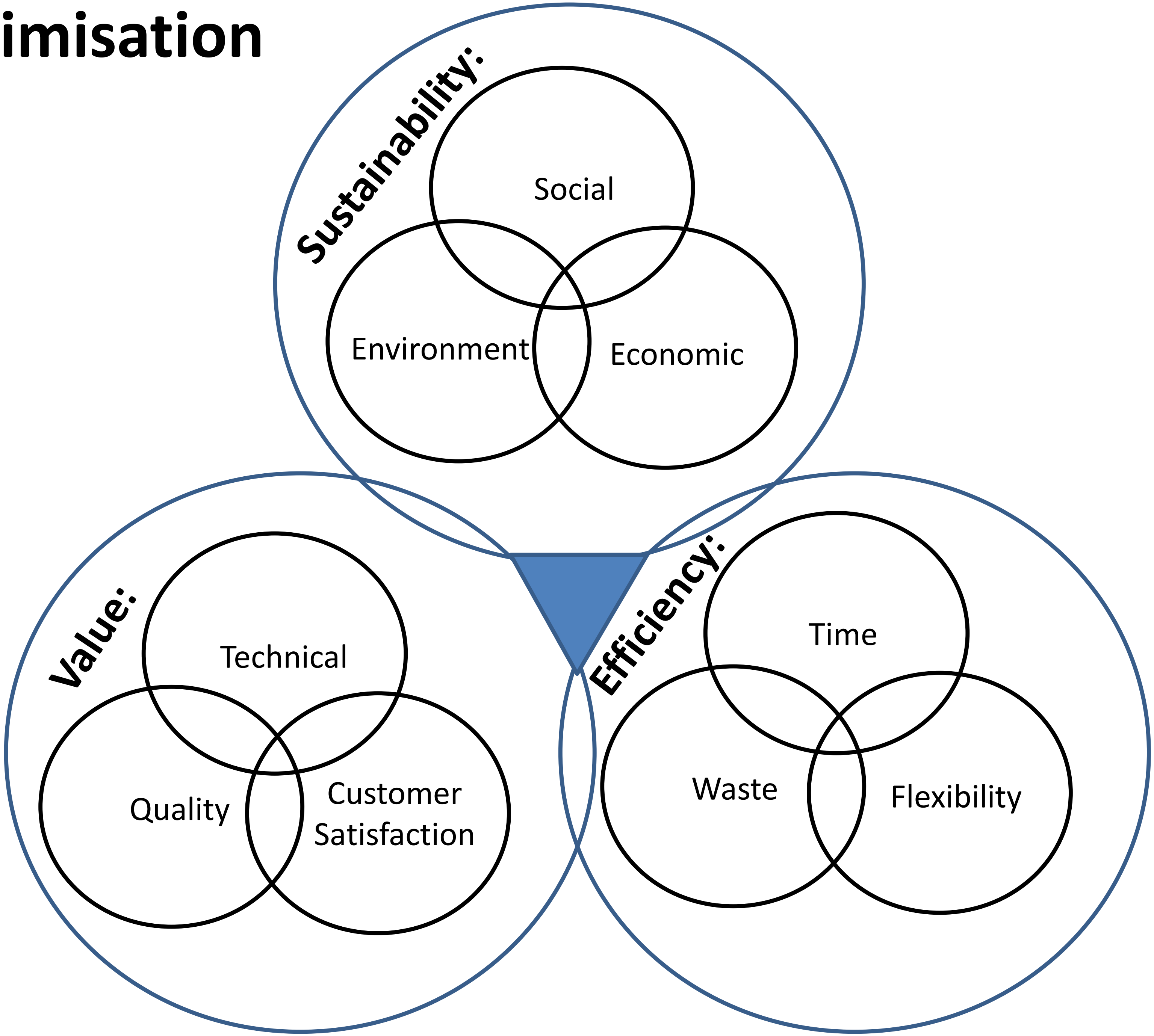
local labour, local supply chain, economic viability

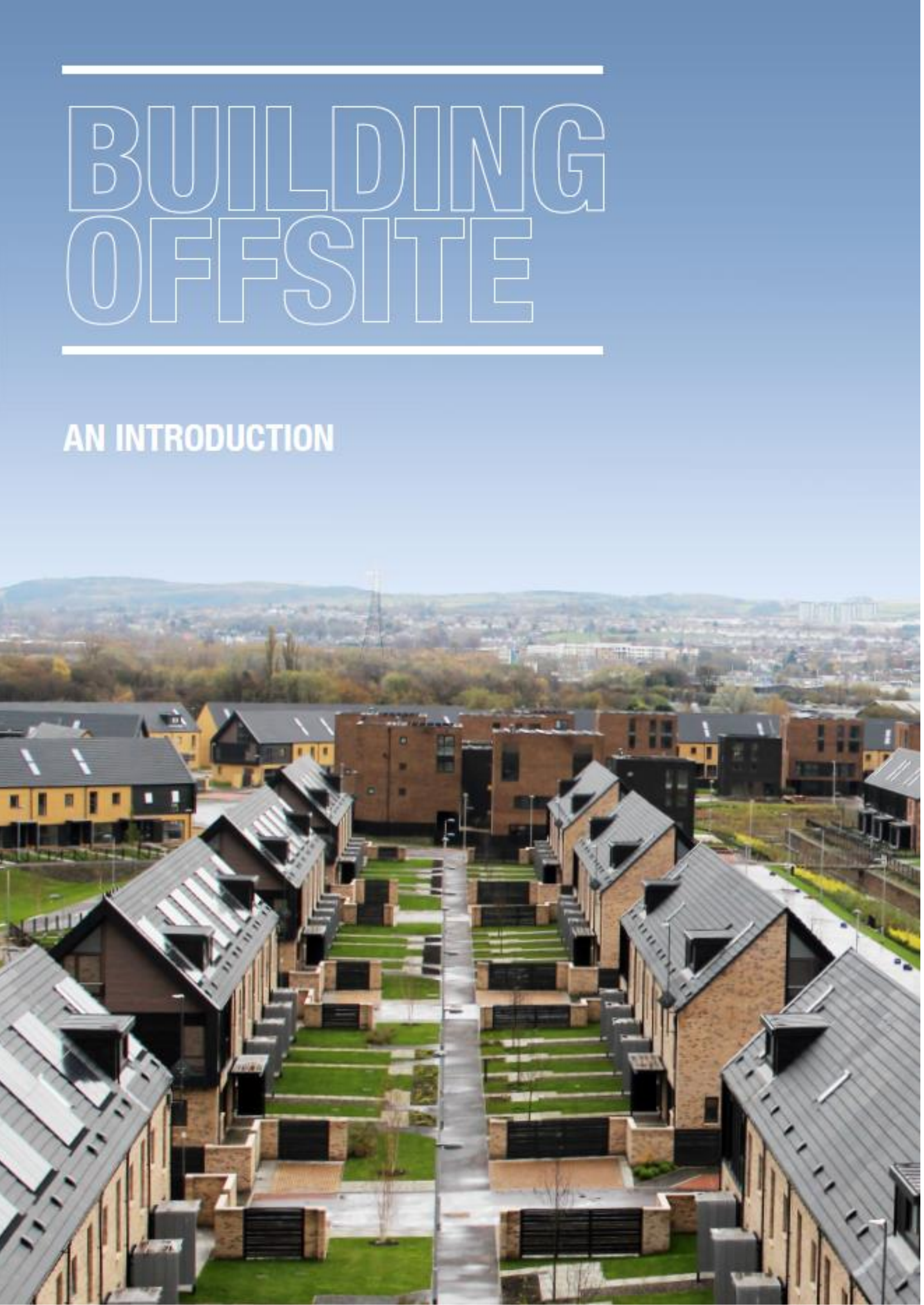
efficiency, qualified supply chain, optimisation, enhance performance





Optimisation

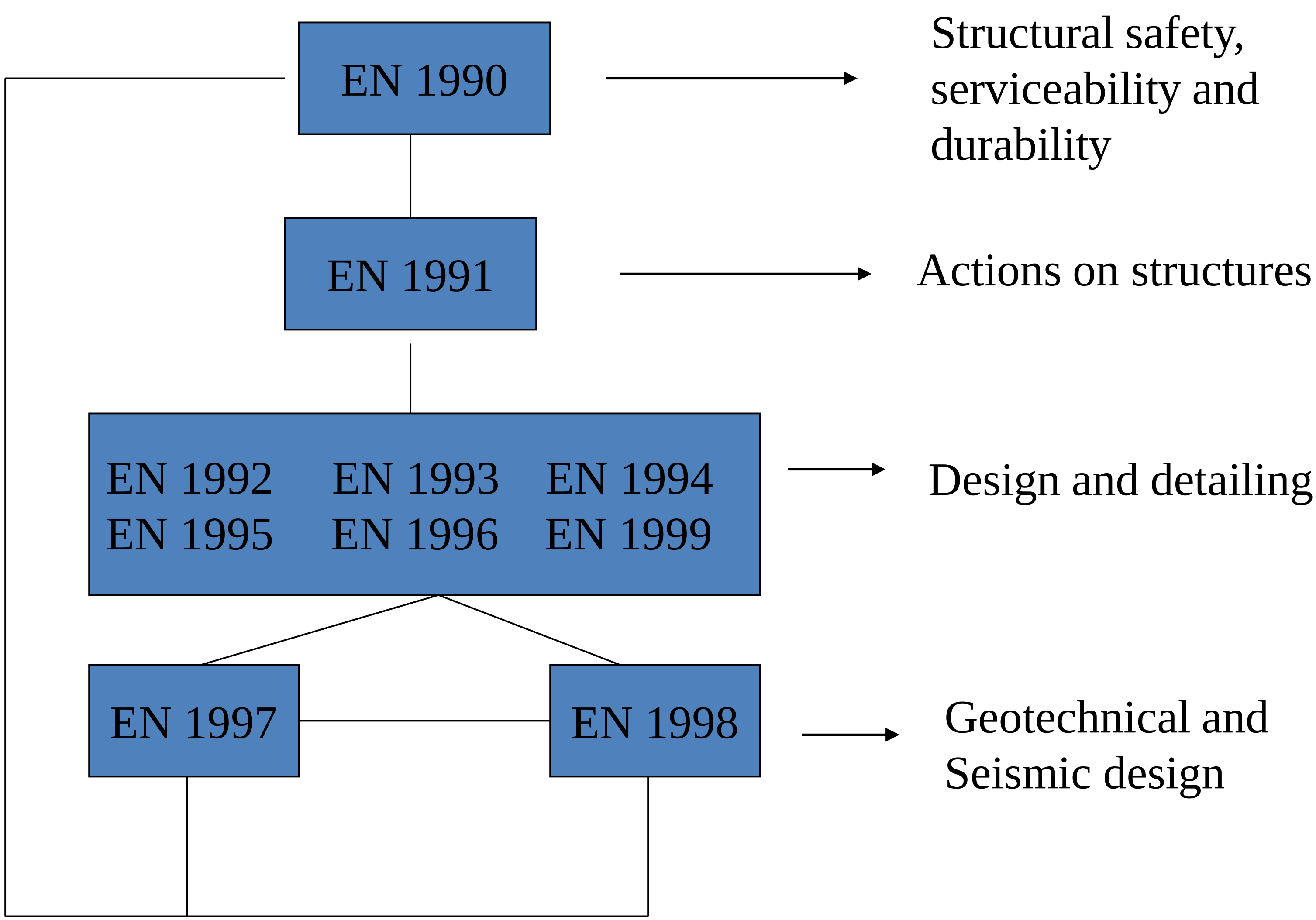




http://www.ads.org.uk/building-offsite-an-introduction/

Structural Considerations

European Structural Code of Practice



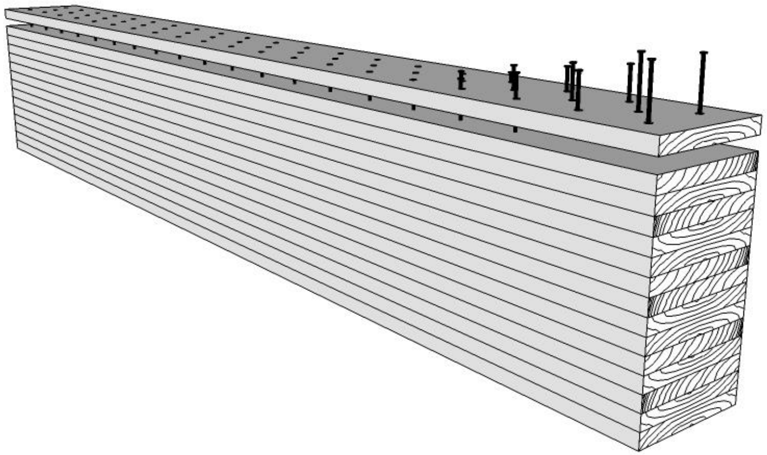
Ultimate limit states:

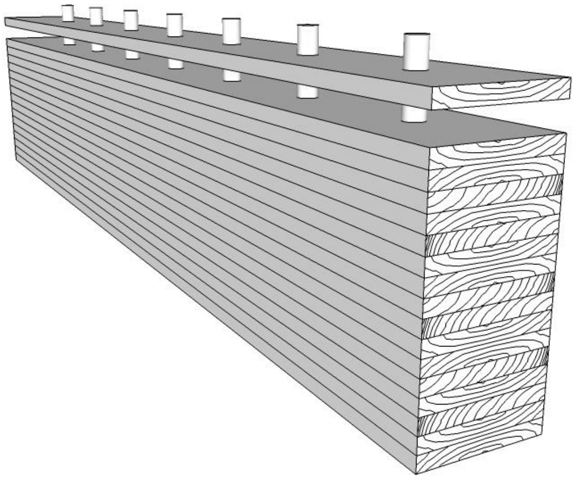
- collapse or with other forms of structural failure.
- loss of equilibrium;
- failure through excessive deformations;
- transformation of the structure into a mechanism;
- rupture; loss of stability.

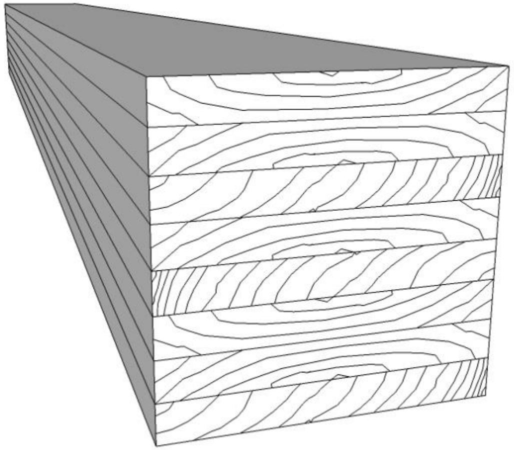
Serviceability limit states:

- deformations which affect the appearance or the effective use of the structure;
- vibrations which cause discomfort to people or damage to the structure;
- damage (including cracking) which is likely to have an adverse effect on the durability of the structure.

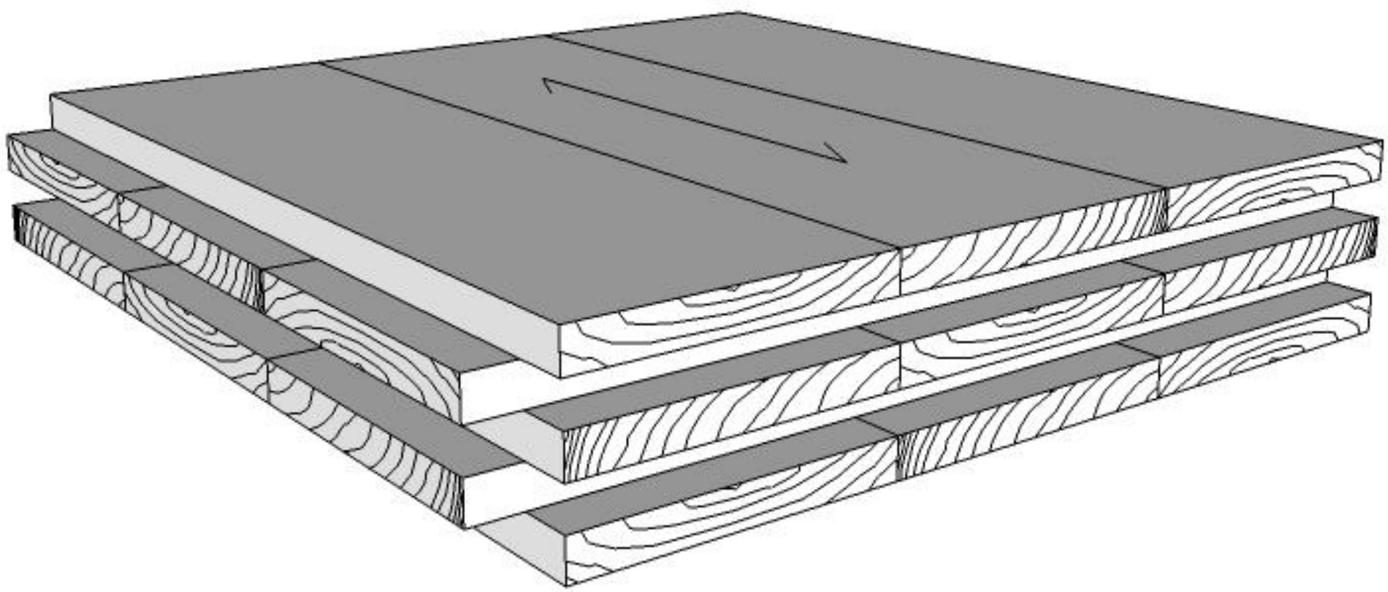
Solid Laminate Timber Systems







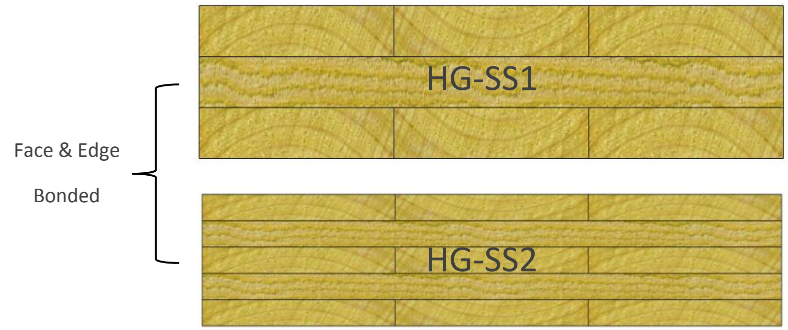
Cross Laminated Timber (CLT)



Raw Material

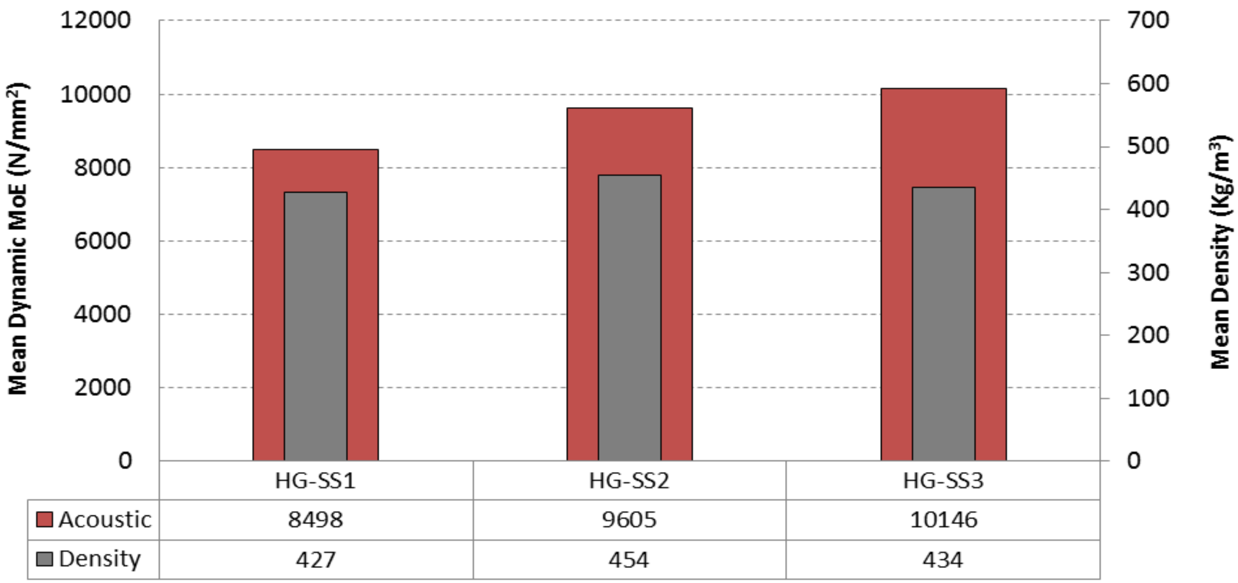
HG-SS1 HG-SS2 HG-SS3

- HG-SS1
    - Sitka spruce – 3 layer
    - Centre-cut material
    - Face and Edge bonded
- HG-SS2
    - Sitka spruce – 5 layer
    - Sawfalling material (sideboards)
    - Face and Edge bonded
- HG-SS3
    - Sitka spruce – 3 layer
    - Centre-cut material
    - Face bonded



Raw Material – Lamella properties

Brookhuis MTG device to measure frequency of each piece within each species and dynamic MoE determined.



BS EN 338:2009

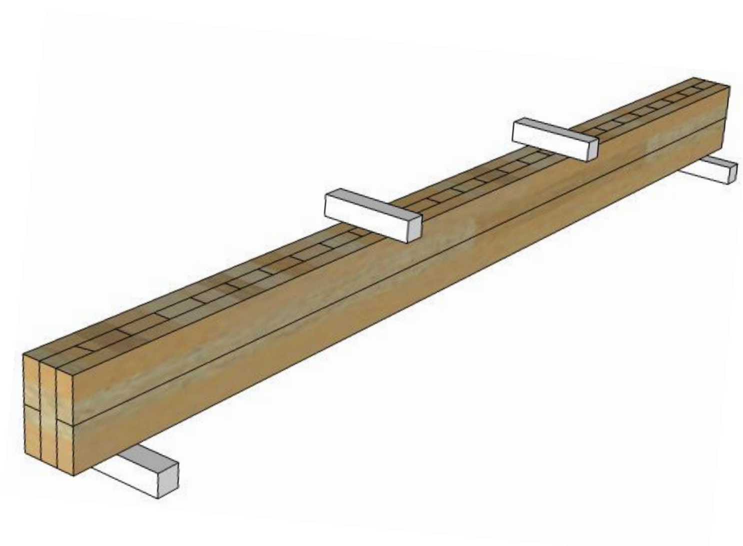
Property	C16	C18	C20	C22	C24
Bending strength (N/mm^2)	16	18	20	22	24
Density (kg/m^3)	370	380	390	410	420
MOE (N/mm^2)	8000	9000	9500	10000	11000

CLT Fabrication

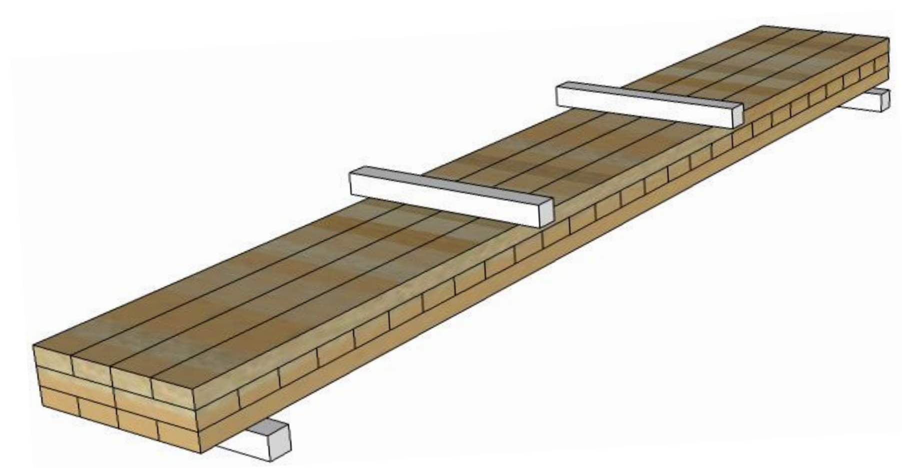
- Small veneer press and handheld glue applicator using PU adhesive

BS EN 408 Test Samples - Dimensions

Sample Ref	Lamella dimensions		Make Up	Panel Dimensions						Nº of Tests
				Edgewise			Flatwise			
	Depth	Width	Nº	Depth	Width	Length	Depth	Width	Length	
	mm	mm		mm	mm	mm	mm	mm	mm	
HG-SS1	40	95	3	140	120	2550	120	380	2550	4
HG-SS2	20	95	5	140	100	2680	100	380	2680	4
HG-SS3	40	140	3	170	120	3200	120	420	3200	4



a) Edgewise



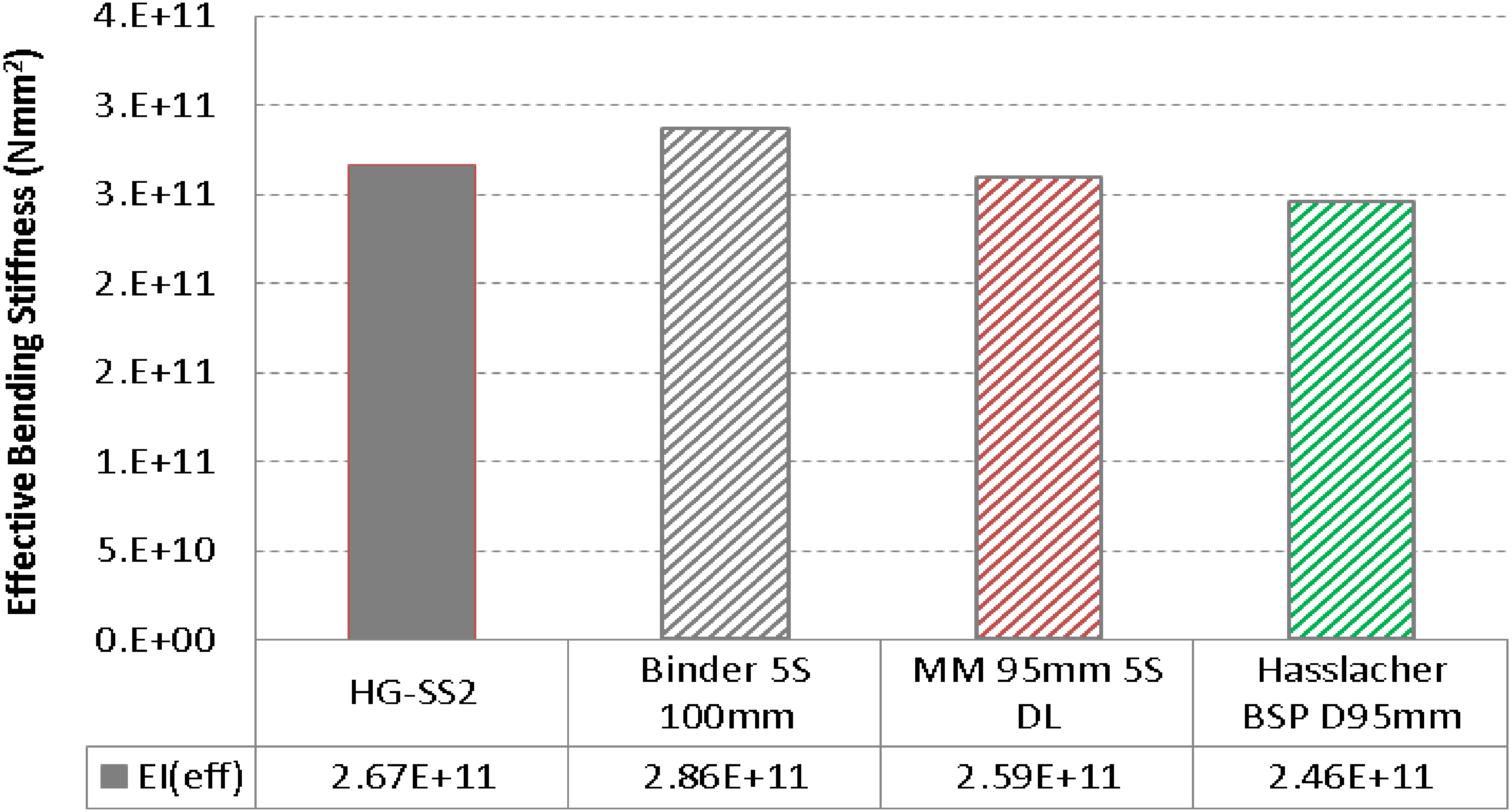
b) Flatwise

Effective Bending Stiffness

- Generally speaking stiffness or vibration is the limiting design criteria when considering CLT for floor or roof elements.
- By increasing the thickness of section to ≈132mm the HG-SS1 now becomes comparable to the European product.

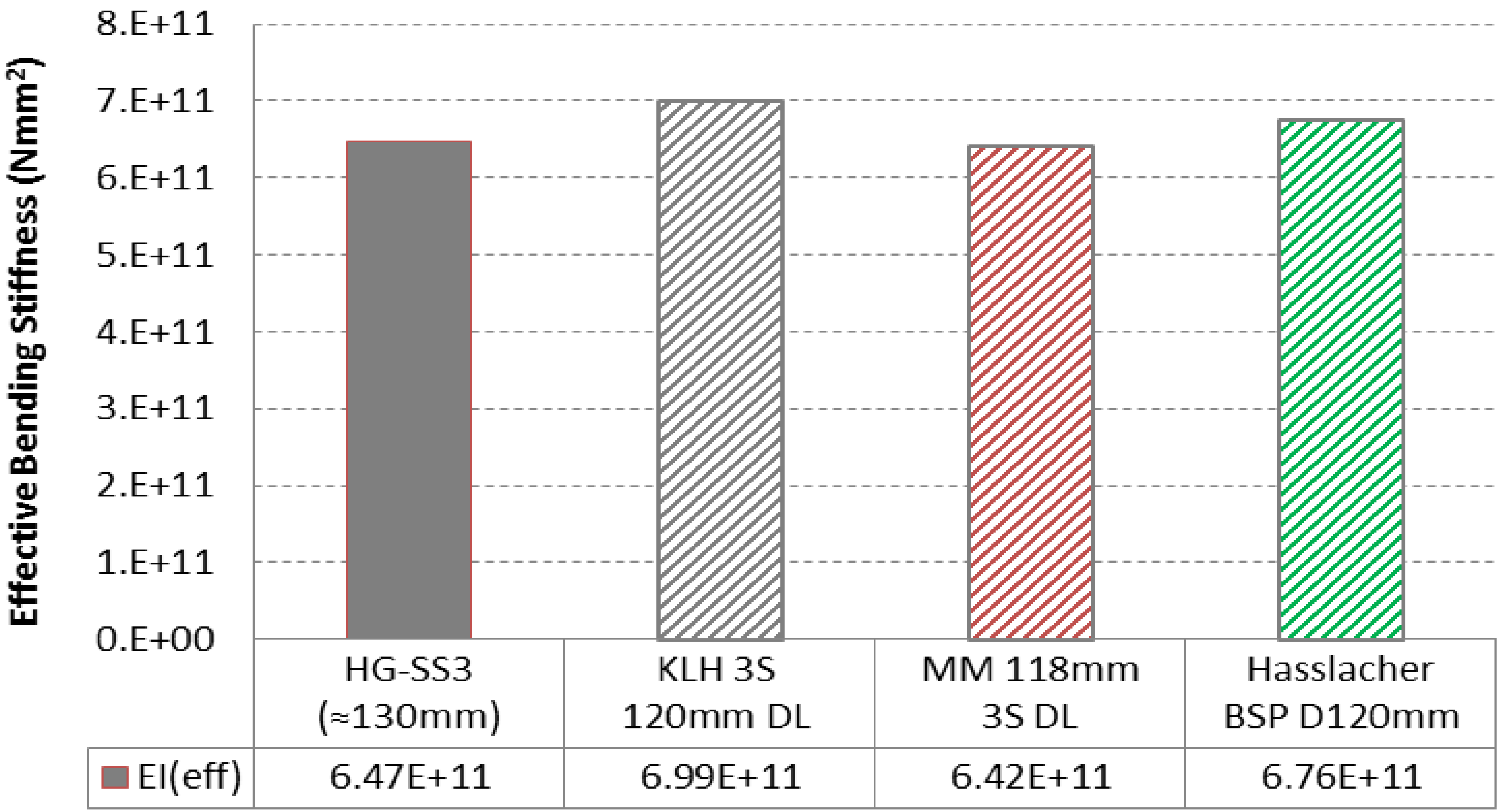
	HG-SS1 (≈132mm)	KLH 3S 120mm DL	MM 118mm 3S DL	Hasslacher BSP D120mm
EI(eff)	6.02E+11	6.32E+11	5.81E+11	6.12E+11

Effective Bending Stiffness



Effective Bending Stiffness

- By increasing the thickness of section to ≈130mm the HG-SS3 now becomes comparable to the European product.



Construction Materials

Viability of cross-laminated timber from UK resources
Crawford, Hairstans, Smith and Papastavrou

ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/coma.14.00064
Paper 1400064
Received 30/09/2014 Accepted 09/12/2014
Keywords: materials technology/research & development/timber structures

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Institution of Civil Engineers
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Viability of cross-laminated timber from UK resources

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3 Simon Smith BEng, CEng, MIStructE
Director, Smith and Wallwork, Cambridge, UK

4 Panayiotis Papastavrou BA, MEng
Structural Engineer, Smith and Wallwork, Cambridge, UK

- A series of designs were optimised for a typical European CLT product and the design utilisation was compared directly with a UK CLT product of similar dimensions.

- For floor design the UK CLT product was capable of spanning a distance (in the worst-case scenario) that is only 80 mm less than the European CLT product when subject to the same load conditions.

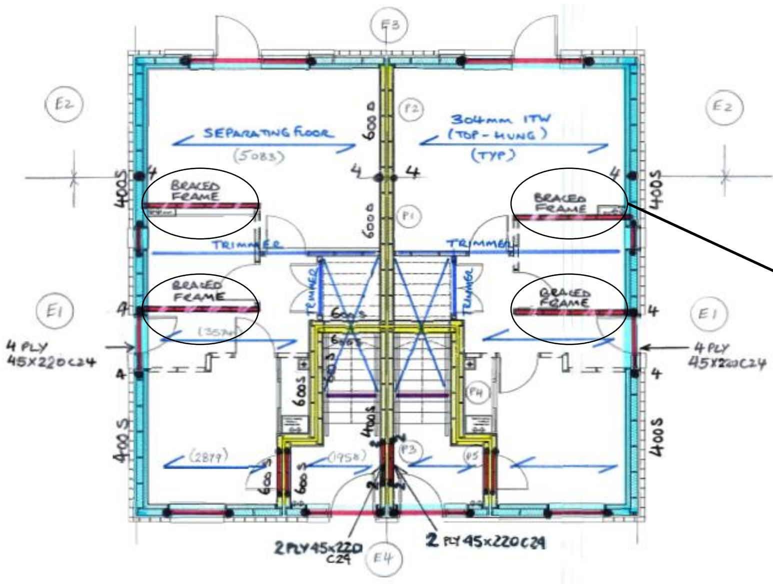
- On average the UK CLT product could span approximately 98% of the equivalent European product.

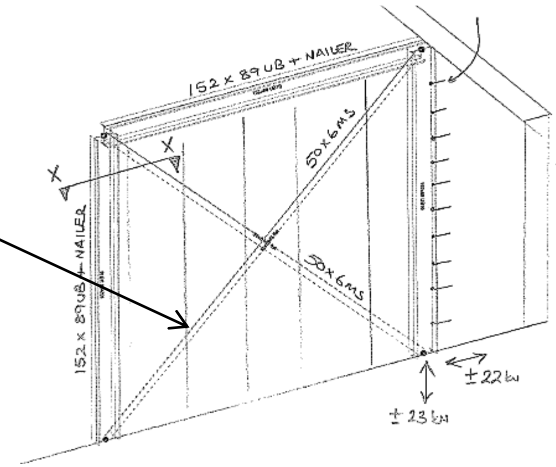
- When considering the wall design examples it was noted that a UK CLT product was only capable of satisfying the design criteria for buckling when at approximately 85.6% of the capacity of its European counterpart. In some instances this would lead to an increase in wall thickness.

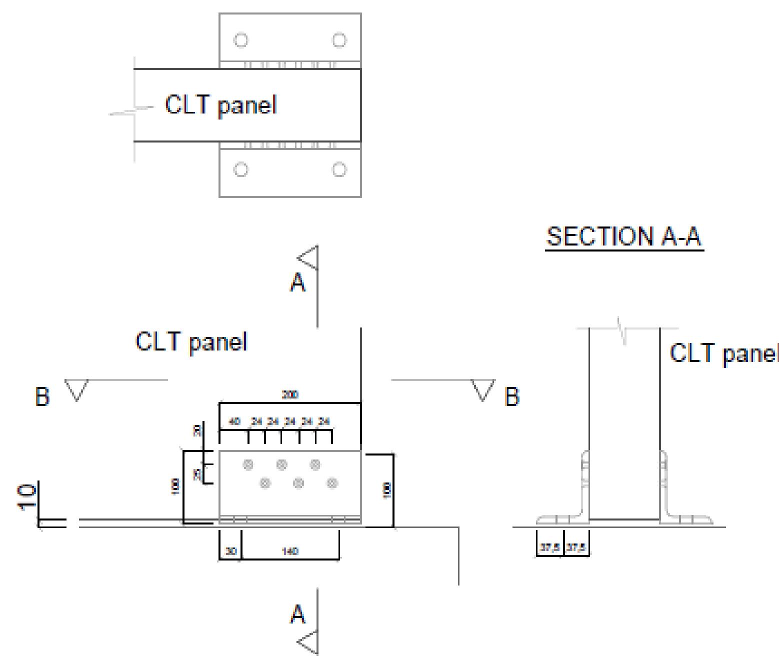
Demonstration projects

Commonwealth Games 2014 – Athletes Village

Braced frame shear wall design



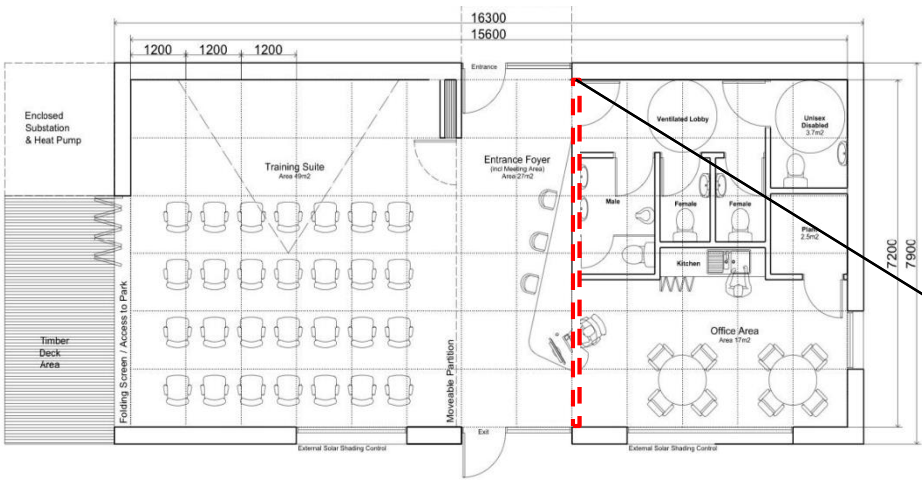




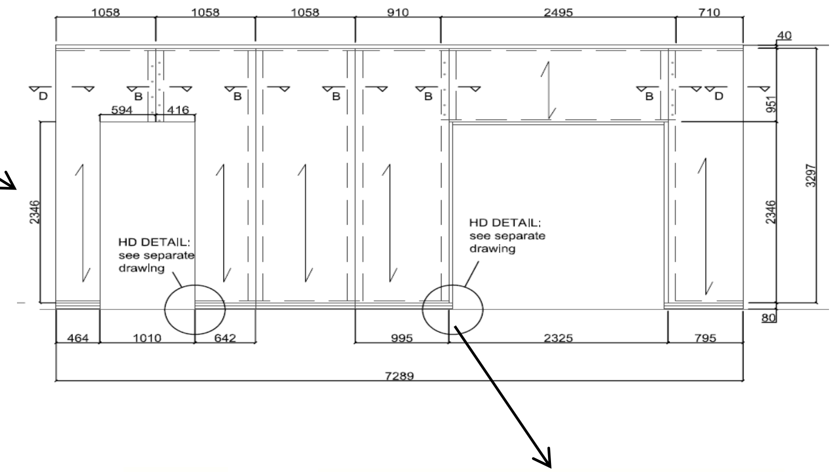
Proposed detail:

- 6 no. M6 fully threaded timber screws. Angled and drilled at 35 degrees and countersunk
- 4 no. 18mm diameter holes for M16 HD threaded bar

BRE Ravenscraig Visitor Centre

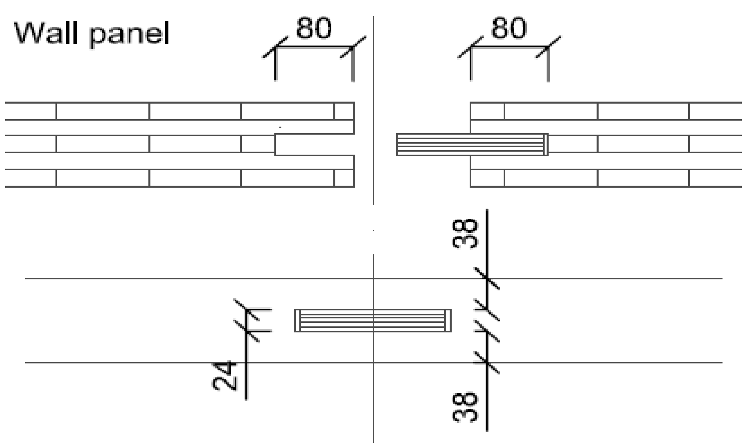


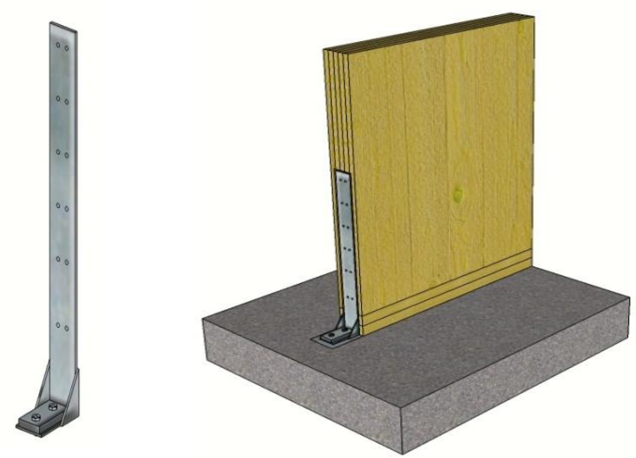
UK Sitka spruce CLT panels



Panel to panel joints:

- Edges grooved + glued and screws plywood splines

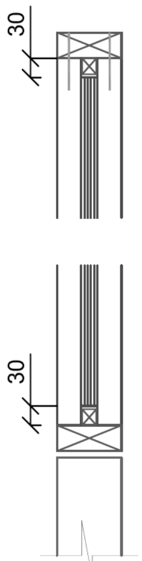




BRE Holding down detail

Top and bottom rail fixing

Fix roof trusses to head binder to CLT panel with 3.1x90 nails at 200mm c/c or 3no into each nogging between trusses at 600mm c/c



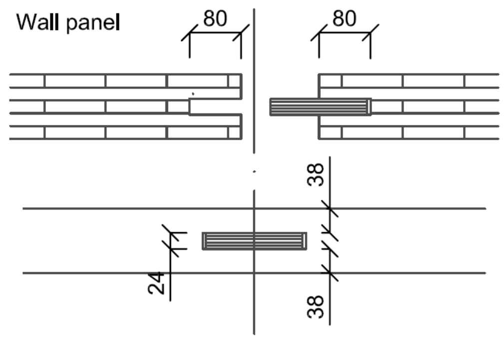
Fix 40x100 C16 head binder to CLT panel with 3.1x90 nails at 200mm c/c staggered.

22x22 locating timbers pinned to sole plate and head binder with nominal nailing.

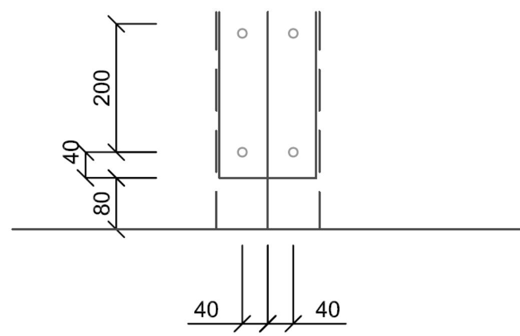
Fixing to sole plate to be 2no 8x140 part threaded, self tapping screws at 600mm c/c in pairs, one from each side. At least two pairs of fixings per panel element.

Fix 40x100 C16 sole plate to concrete upstand with 6mmx70 Tapcon CSK screws with 32mm embedment at 600mm c/c. Fix on alternate sides of locating timber.

Joint type B



Rebate joint:
machine post CLT manufacture all round each panel 25mm wide rebate. Fit 24x150 structural grade plywood fillet in all vertical joints. Fix to one panel only with adhesive to same specification as for panel manufacture and clamp with 6x90 csk part threaded self tapping screws at 200mm c/c

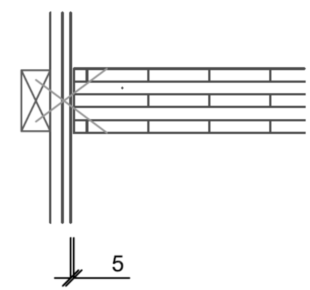


Use part threaded self tapping screws 6x90mm long, countersunk.
Fix at 300mm centres unless noted otherwise. Fix spline such that 80mm clearance given at top and bottom of panel

All panel to panel screw fixings to be made from the rear face so not visible on exposed face.

NOTES:

Joint type D



Square edge:

Fixing to external wall to be 2no 8x140 part threaded, self tapping screws at 600mm c/c in pairs, one from each side.

Provide studs in timber frame wall to fix into. (by others)

Edinburgh Napier UNIVERSITY
Centre for Offsite Construction & Innovative Structures
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Rev1 3/2/12-joints amended and top and bottom fixing added
Rev2 20/2/12-rebate and fixings amended

Client: CCG (Scotland)	Drawing: **Sections**
Project: BRE Ravenscraig CLT internal wall	Scale: 1:10 at A4 / Date: 17/01/12 Drawing No.: E4358-06-2 / Revision No.: 2





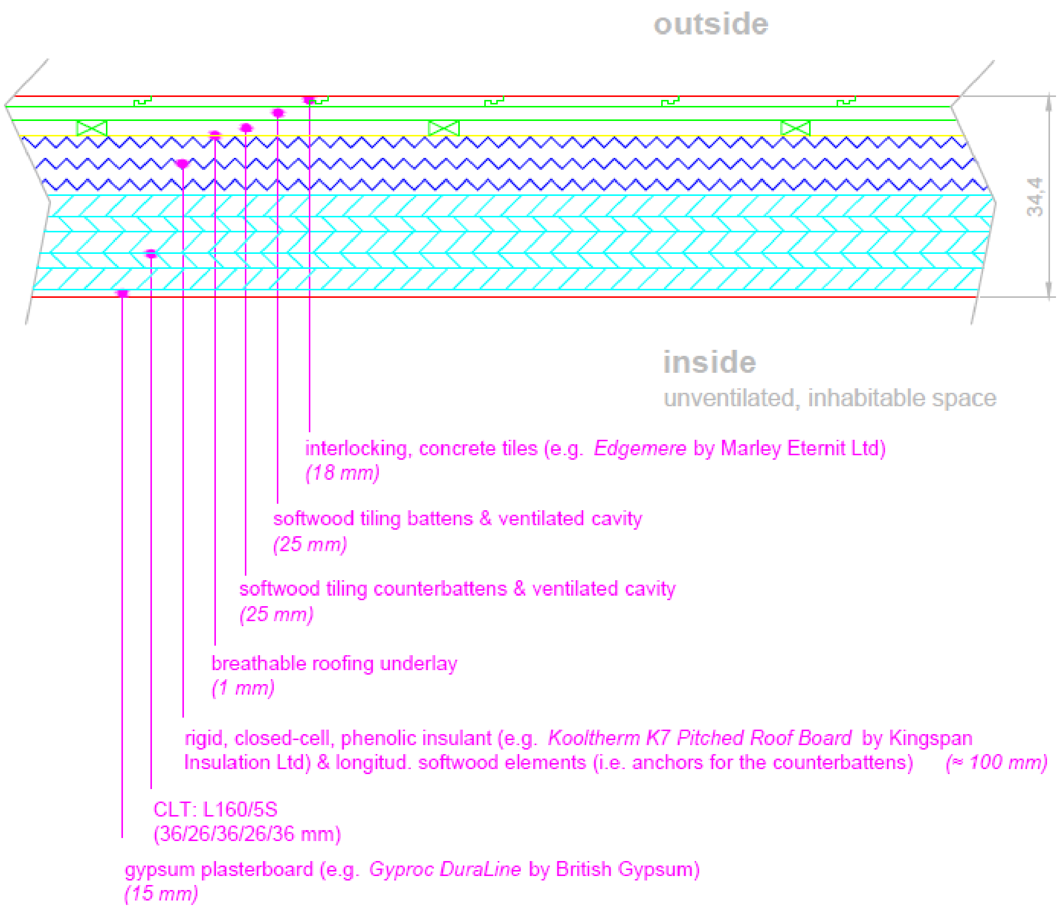


bre
BRE INNOVATION PARK
@RAVENSCRAIG
Part of the BRE Innovation Parks Network

CLT – Future steps

- Offsite pre-fabrication:

Roof (R-1):
Cross-Laminated Timber (CLT)
cross-section



= 0.16

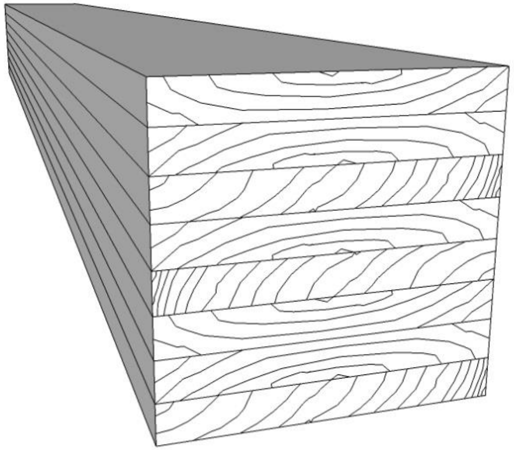
$R_w + C_{tr} = 46\text{-}48$

= 60 mins

CLT – CCG Yoker 7 Storey Accommodation

GABLE ELEVATION

Glue-Lam



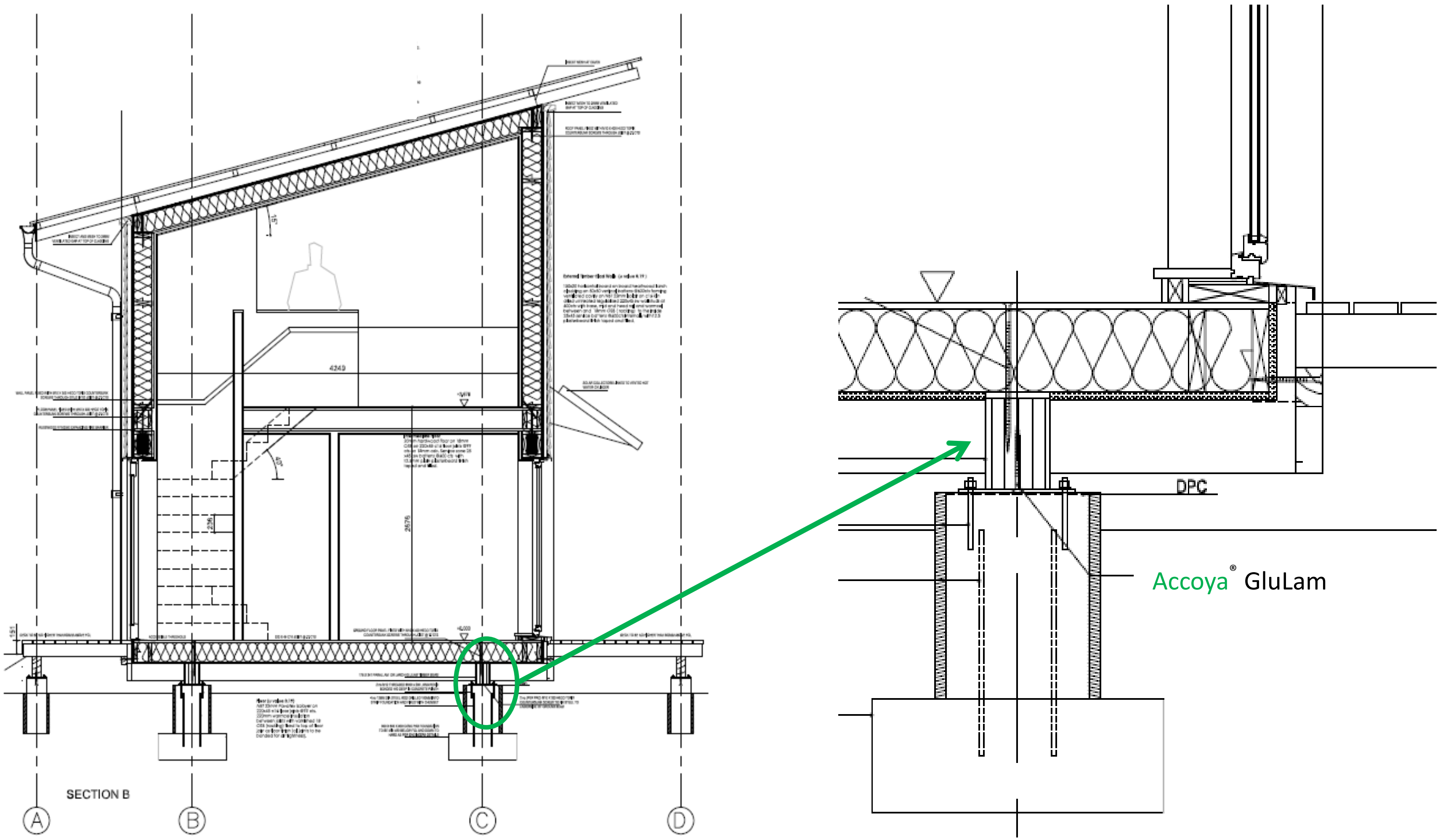
accoya®

MAKAR

NATURAL CONSTRUCTION

Foundation support Detail

Closed panel timber frame system manufactured offsite



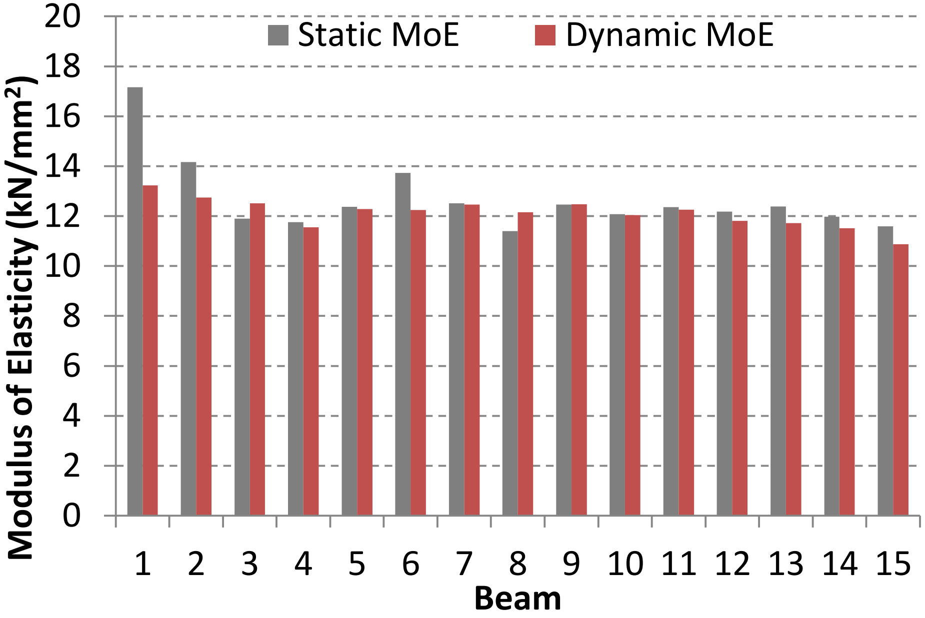
Dunsmore House – Foundation detail

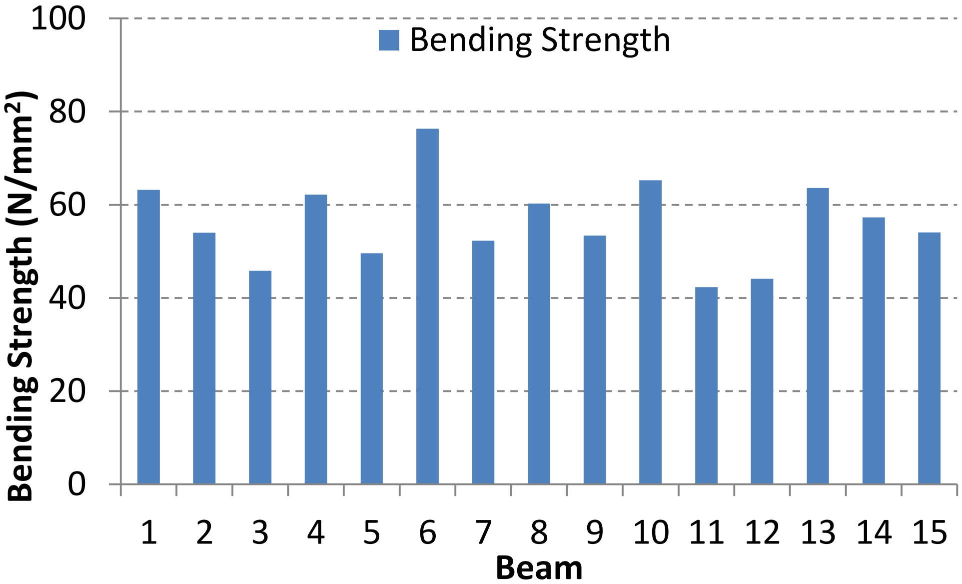
Homogenous and combined Glulam fabrication

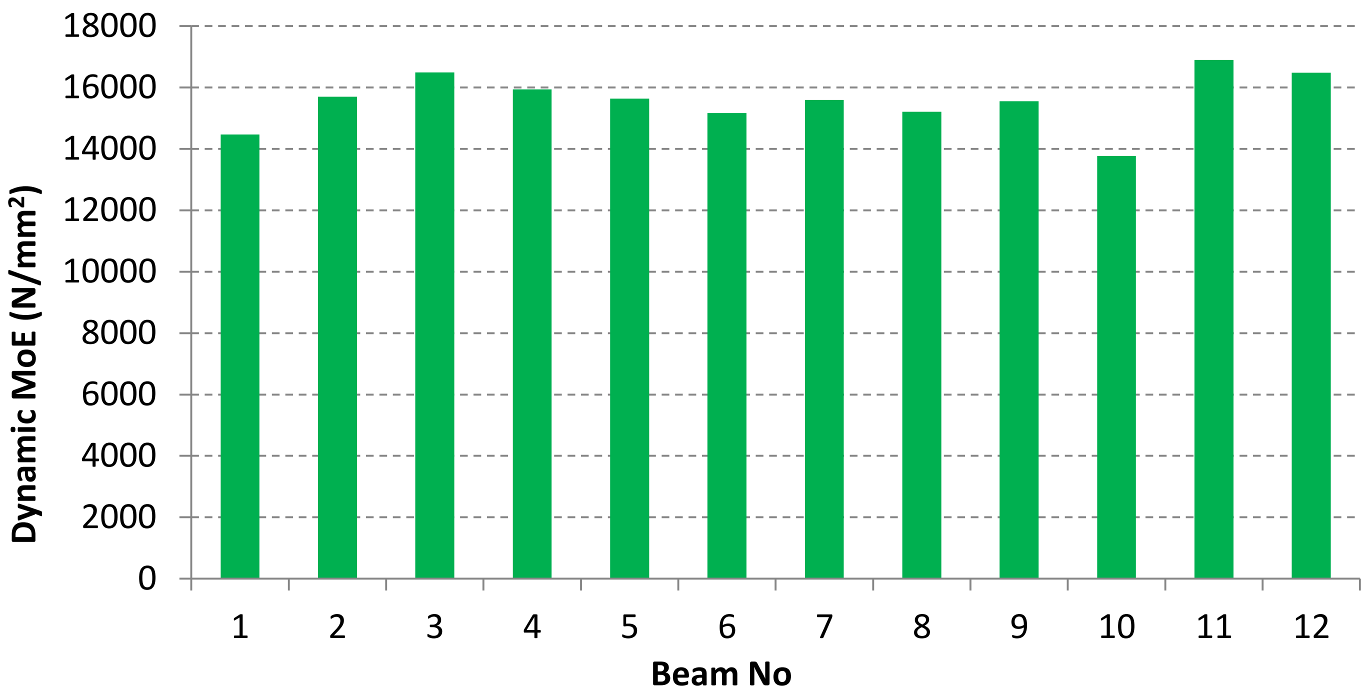
Lamella	Accoya® - GluLam														
	1	1	3	4	5	6	7	8	9	10	11	12	13	14	15
	Homogeneous				Combined										
1	C35	C35	C30	C27	C35	C35	C35	C35	C35	C35	C35	C35	C35	C27	C27
2	C35	C35	C30	C27	C30	C30	C30	C30	C30	C30	C30	C30	C27	C27	C22
3	C35	C35	C30	C27	C24	C24	C24	C24	C24	C24	C24	C24	C24	C22	C22
4	C35	C35	C30	C27	C30	C30	C30	C30	C30	C30	C30	C27	C27	C27	C24
5	C35	C35	C30	C27	C35	C35	C35	C35	C35	C35	C35	C35	C35	C35	C27

Note: Strength classes based purely on the dynamic MoE values obtained from Acoustic sorting process and other material properties should not be associated with these. The strength class is used merely as an indication of the predicated stiffness of each lamella.

Accoya Glulam Testing: BS EN 408 of 15 Accoya Glulam sample

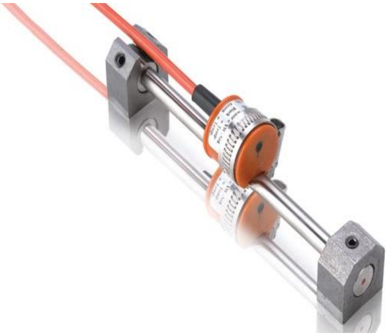


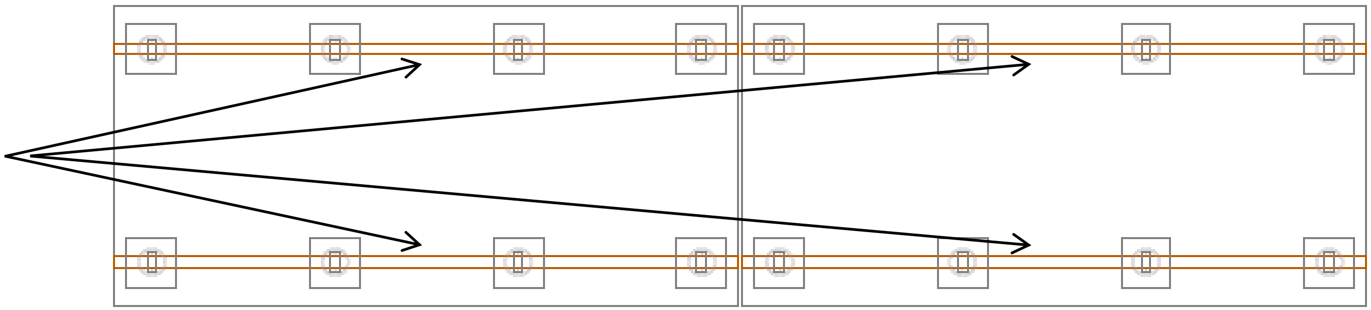


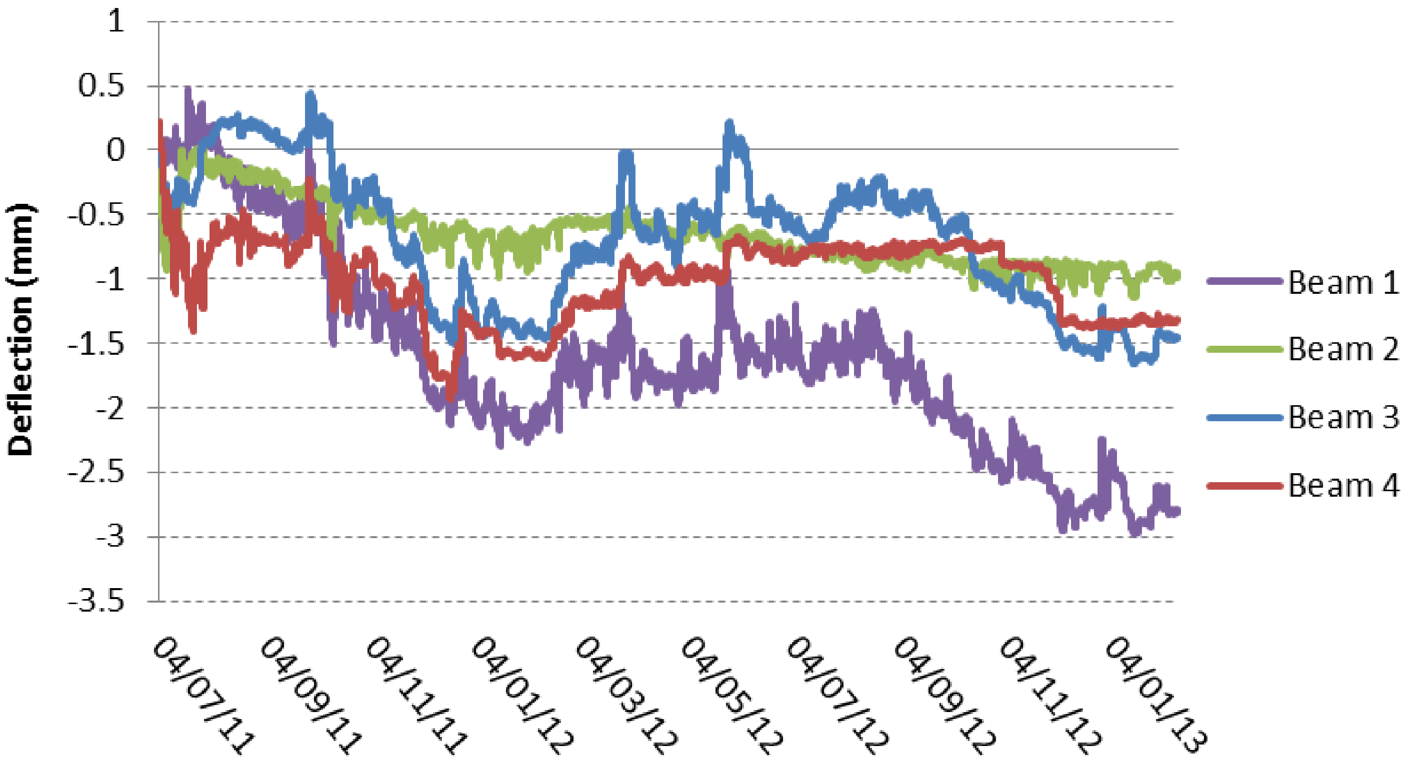

Dynamic MoE (N/mm²)
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1
2
3
4
5
6
7
8
9
10
11
12
Beam No


F1
F2
F3
7
8
9
4
5
6

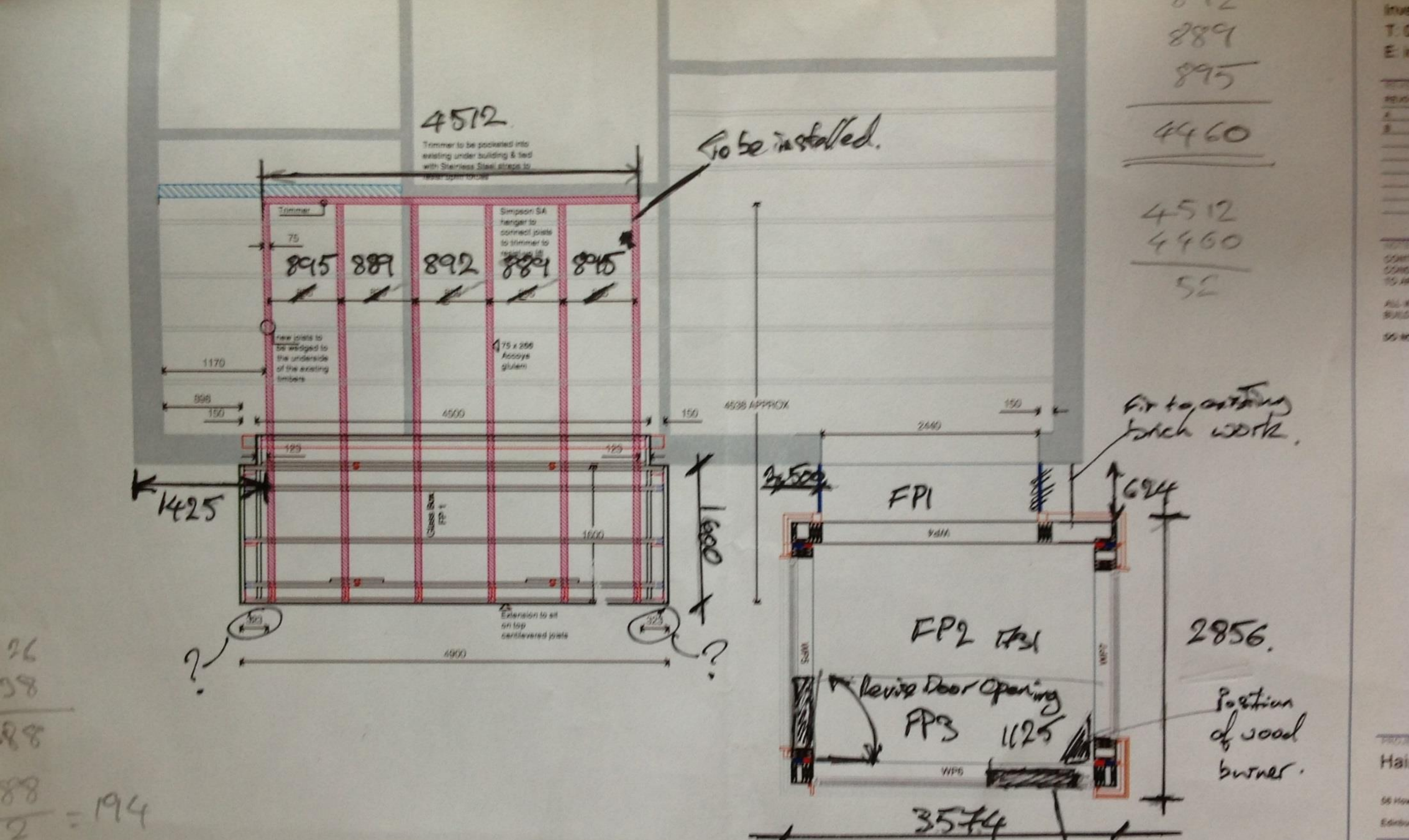
6 Month Post Completion Monitoring







Dunsmore House Accoya Ground Beams		Dwelling B		Dwelling A	
		Beam 1	Beam 2	Beam 3	Beam 4
Dynamic MoE	N/mm^2	14465.5	16496.9	15934.9	15704.5
Depth	mm	296	296	296	296
Width	mm	124	124	124	124
Cross sectional Area	mm^2	36704	36704	36704	36704
Length	mm	2946	2946	2949	2944
Max Deflection	mm	-2.98	-1.15	-1.66	-1.94
EC5 Allowable deflection	mm	11.78			



Glass Box Extension: Floor Structure

* Joist still to be installed.

1731
1125


HEWDEN
002988
HEWDEN

accoya

modified wood by Accsys Technologies

STRUCTURAL DESIGN GUIDE TO EUROCODE 5

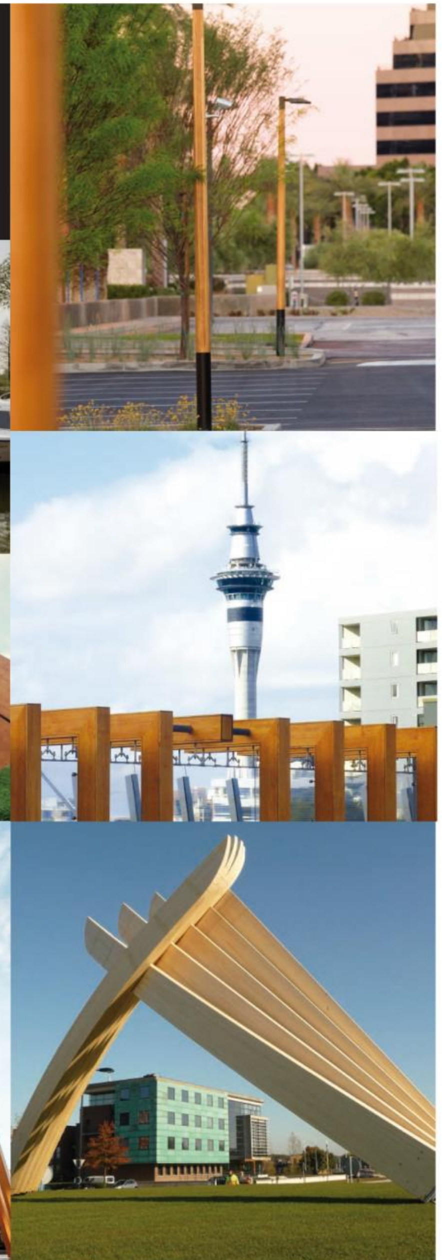
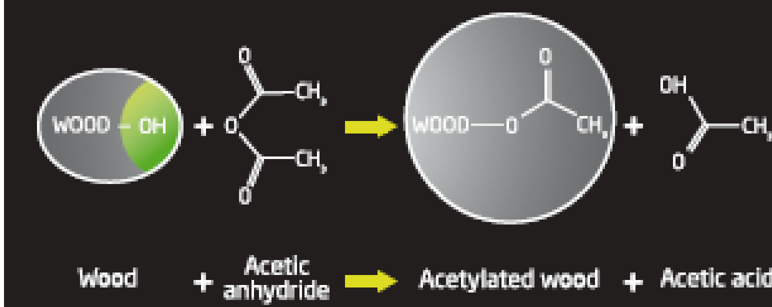
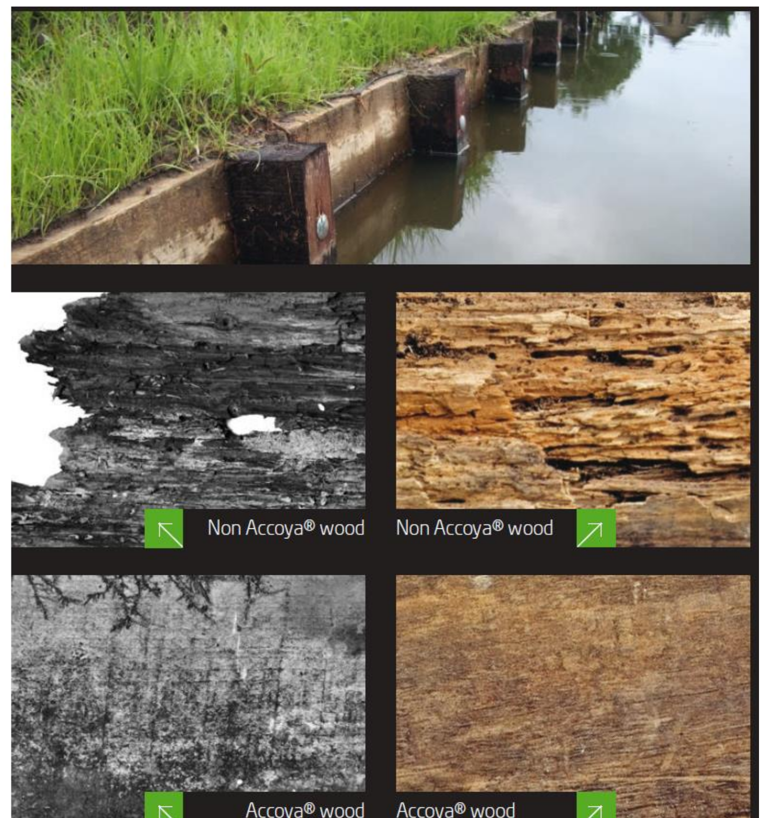


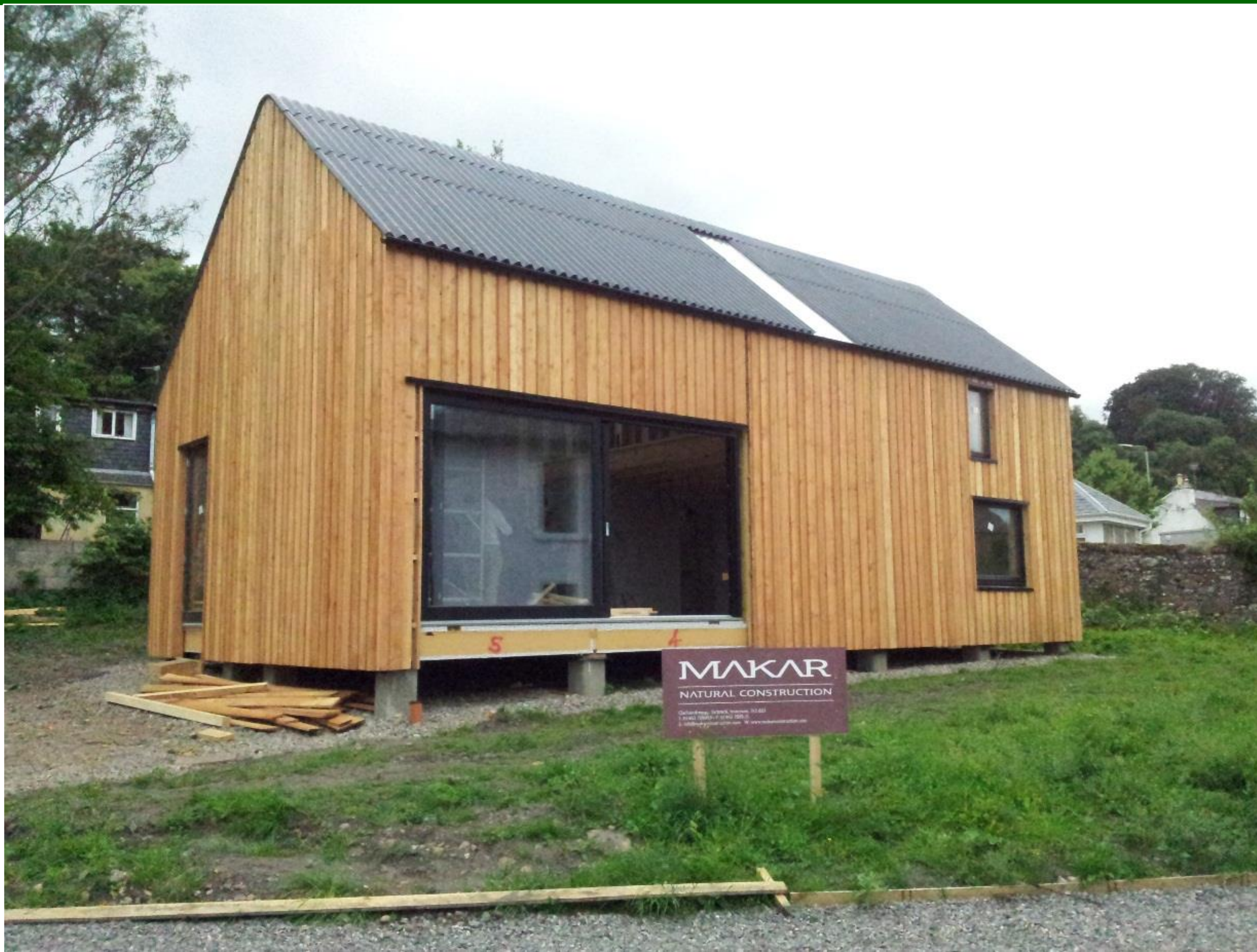
Figure 1:





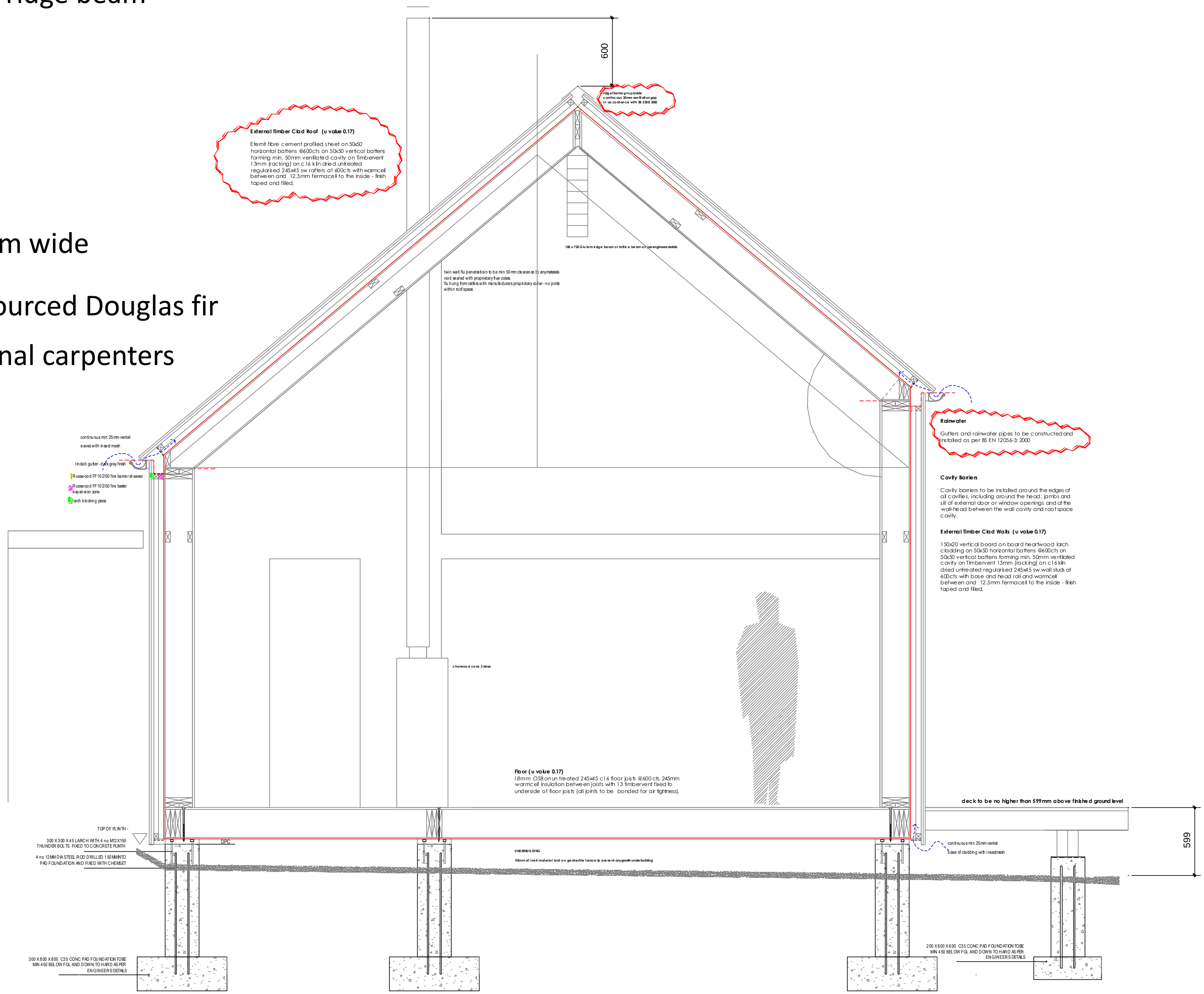
Engineered Timber Systems

Engineered Truss Systems



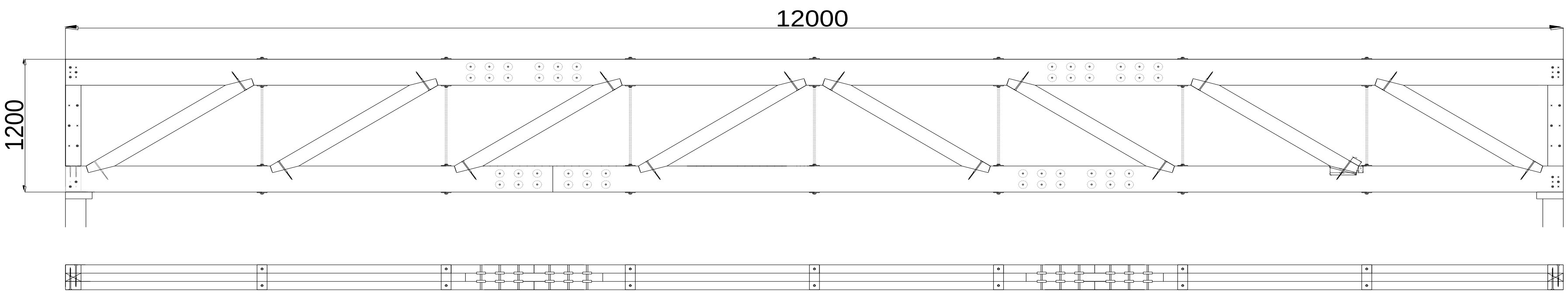
Design Brief

- Specify the design of a ridge beam
- Geometric restraints:
  - 12 metres long
  - 1.2 metres deep
  - maximum 300 mm wide
- Timber will be locally sourced Douglas fir
- Constructed by traditional carpenters



TYPICAL DETAIL SECTION

15th iteration truss layout



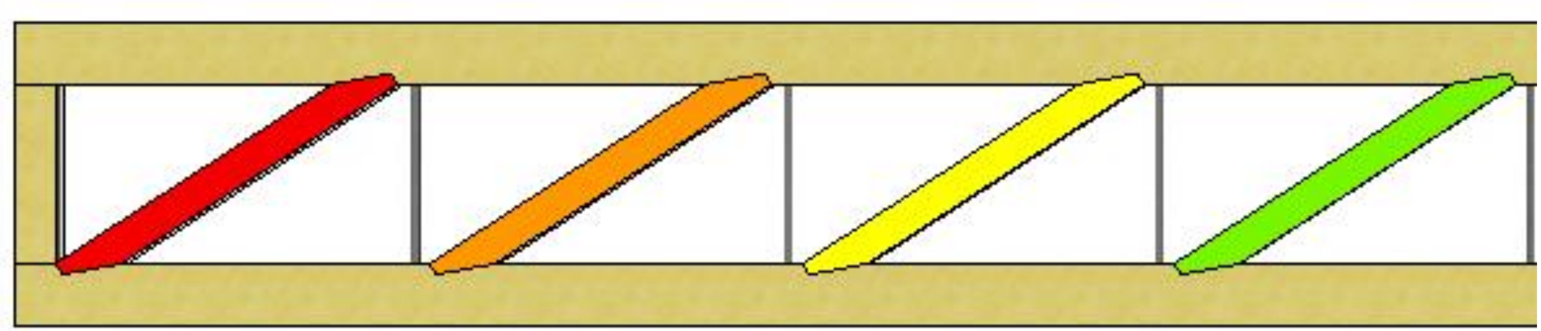
5th iteration of connection details

- Cogging joints
- Steel rods
- Splice plates
- Joint reinforcement

Characterisation of Resource

Property	BS EN 338 Values					UK Sitka Spruce (J. Moore, 2011)	Truss material (Douglas Fir)
	C16	C18	C20	C22	C24		
Mean MoE (kN/mm^2)	8	9	9.5	10	11	8.3	9.7
Characteristic Density (kg/m^3)	310	320	330	340	350	330	480 (> C50)
Bending Strength (N/mm^2)	16	18	20	22	24	19.6	NA

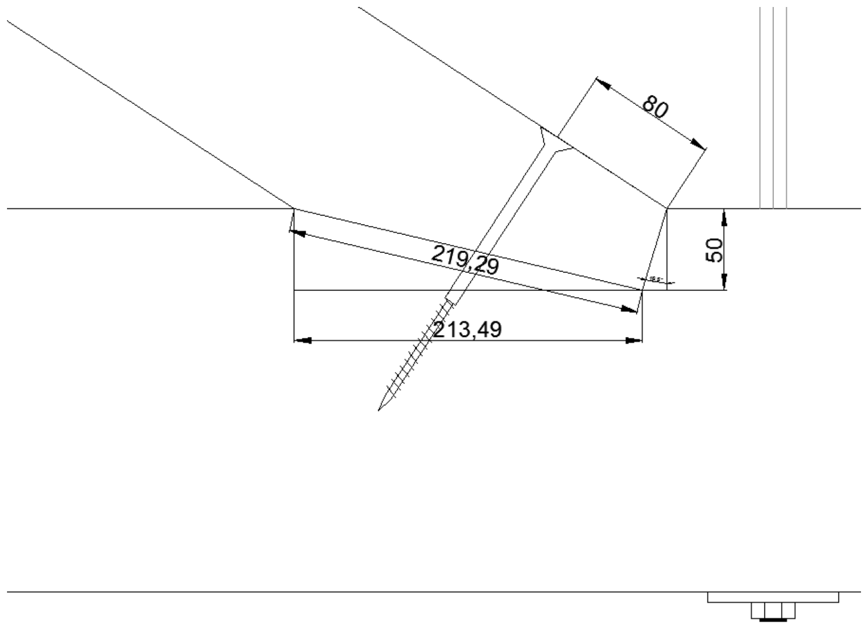
Characterisation of Resource



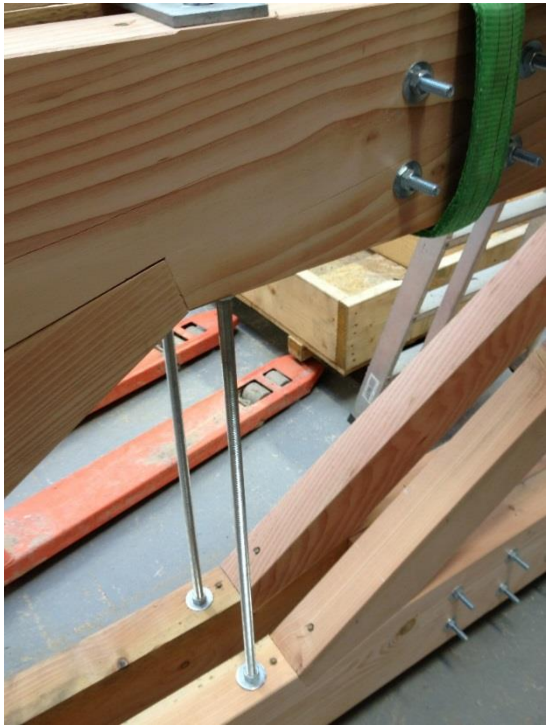
	Colour	Axial force (kN)	MoE (kN/mm^2)	Grade
	Red	59.5	12.2	C30
	Orange	47.3	10.23	C22
	Yellow	33	8.85	C16
	Green	20	7.42	C14

Connection Details

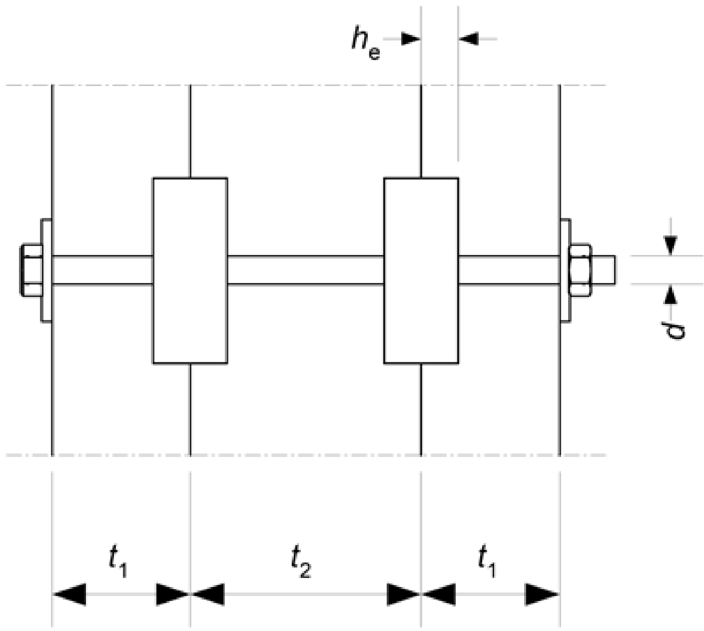
– Cogging joint

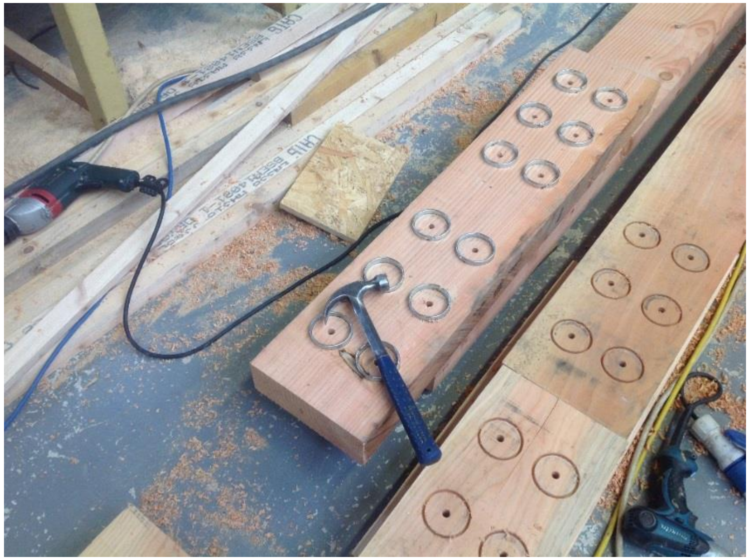


– Steel rod

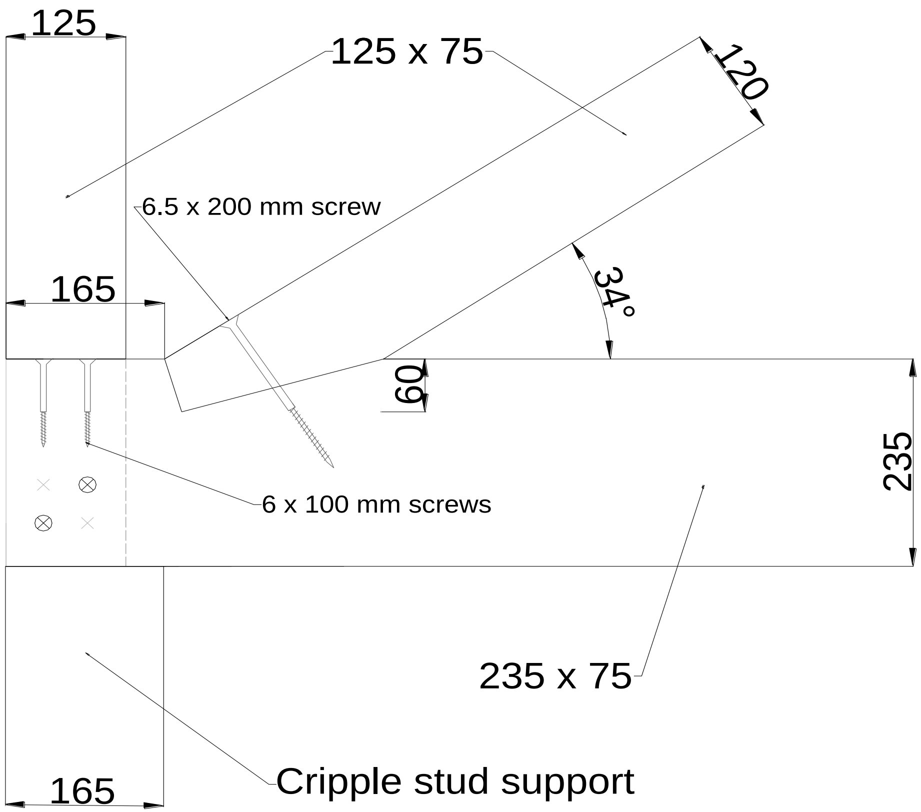


Splice plates





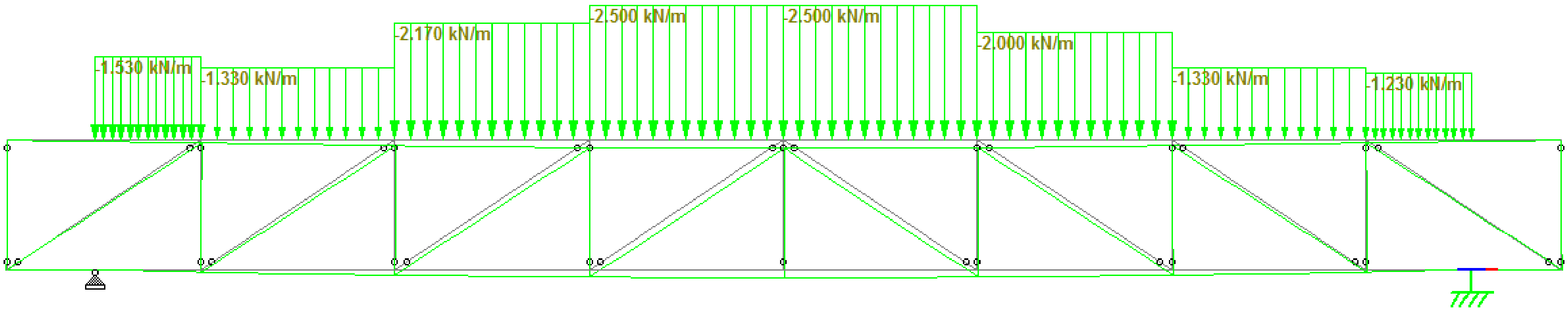
Joint reinforcement

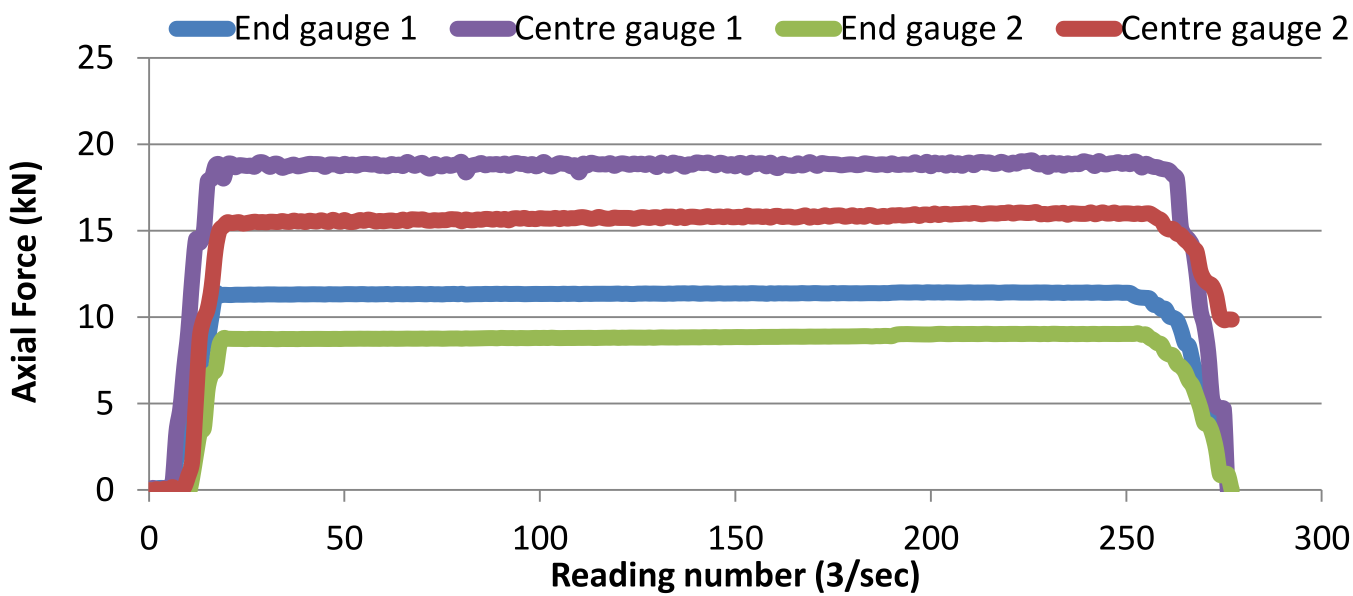


Structural testing

- Strain gauges were used to measure the incremental changes in
- 20 kN of load distributed along the length of the system
- Each chord had a gauge located at mid-span and at end bays.
- Results were compared to analytical model for verification of performance

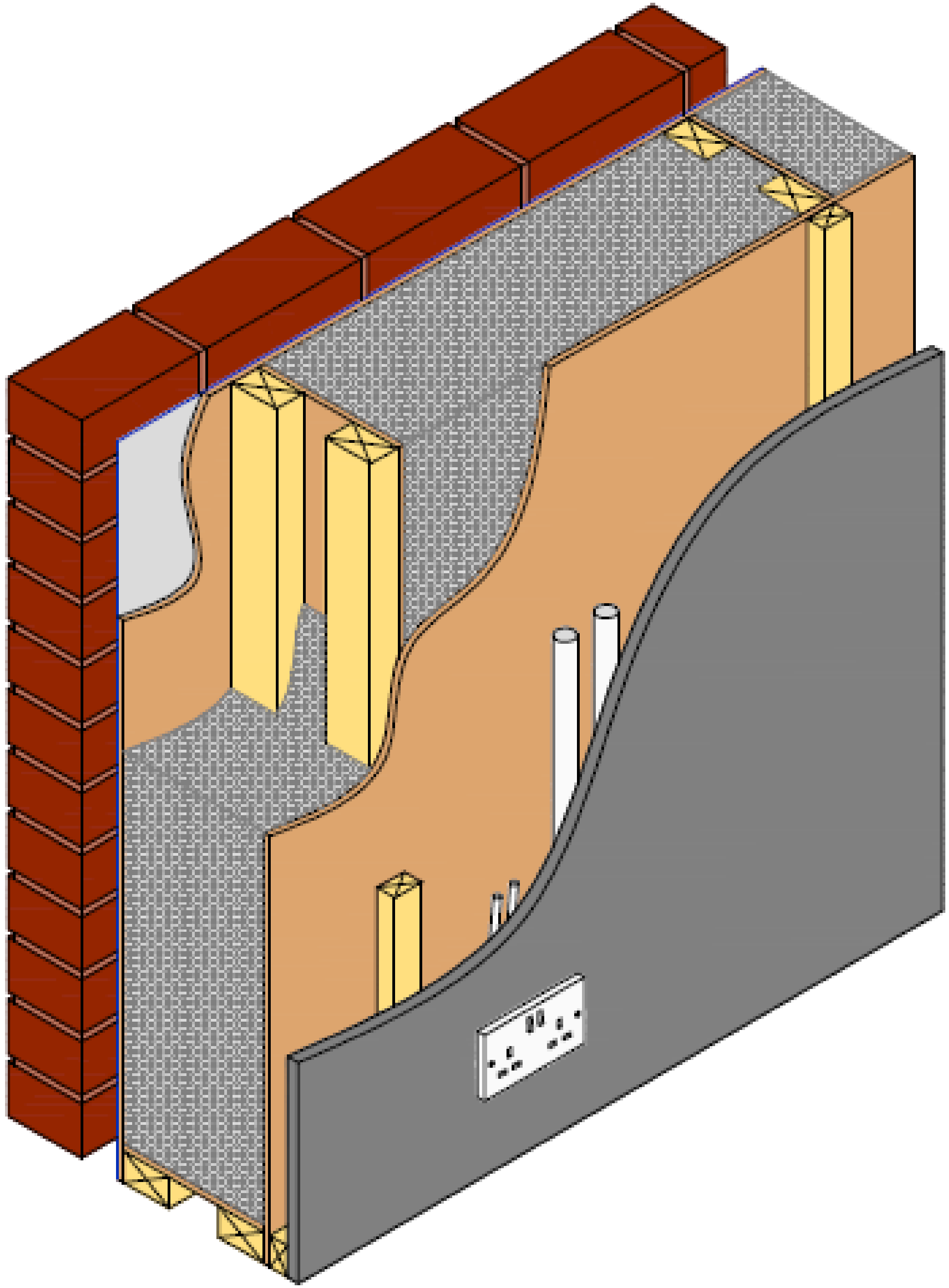
Structural testing

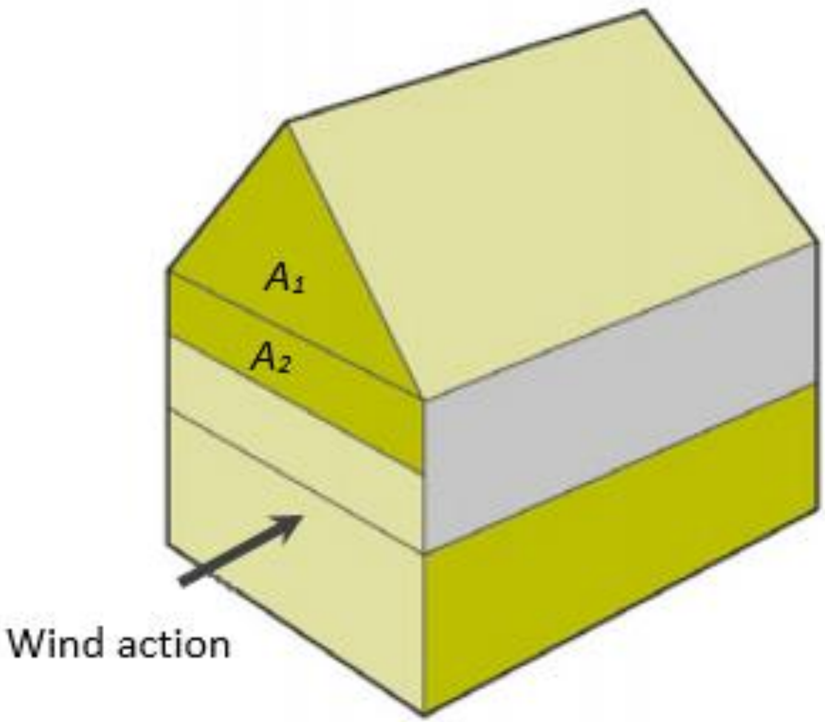




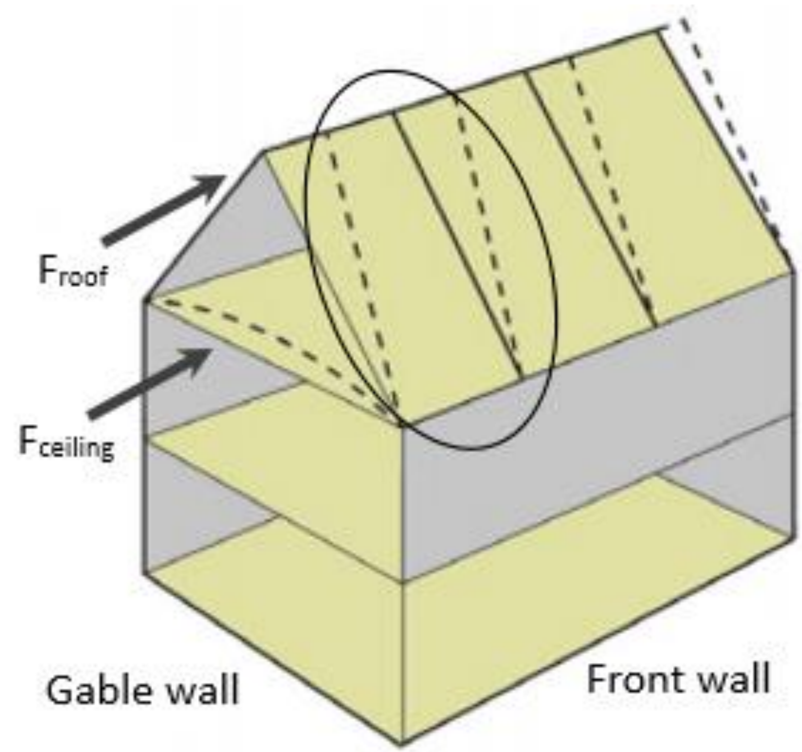
	Gauge 1	Gauge 2	Mean	Calculated Testing Force	Staad.Pro Estimated Force	Variance
Centre (kN)	16	19.1	17.6	35.1	33.8	4%
End (kN)	11.45	9.1	10.3	20.5	22.2	-8%

Closed Panel Timber Systems





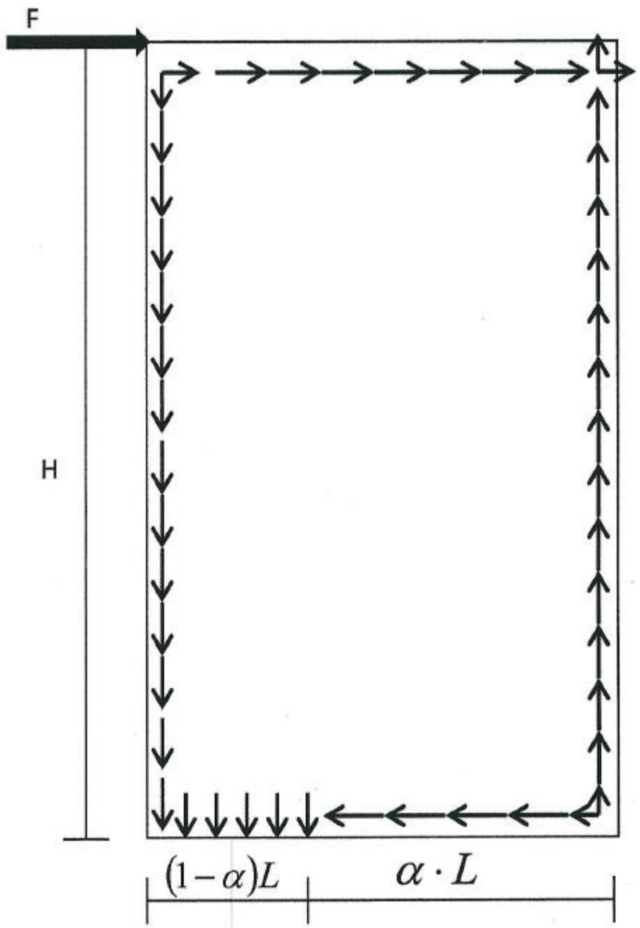
a) Area of gable wall transferring wind load to the roof and front



b) Diaphragm action of roof and ceiling transferring wind on gable wall to front wall

DESIGN PRINCIPLES: Basis of Unified method

$$\sum F_x = 0 \quad \sum F_y = 0 \quad \sum M = 0$$



$$L - \frac{1}{2}(1-\alpha)\cdot L = L \cdot -(0.5L - 0.5\alpha L)$$

$$= 0.5L + 0.5\alpha L = 0.5L(1+\alpha)$$

At top rail, $r_{t,n} \cdot L = F$

At bottom rail, $r_{b,n} \cdot \alpha \cdot L = F$

$\sum M = 0$ (at bottom rail)

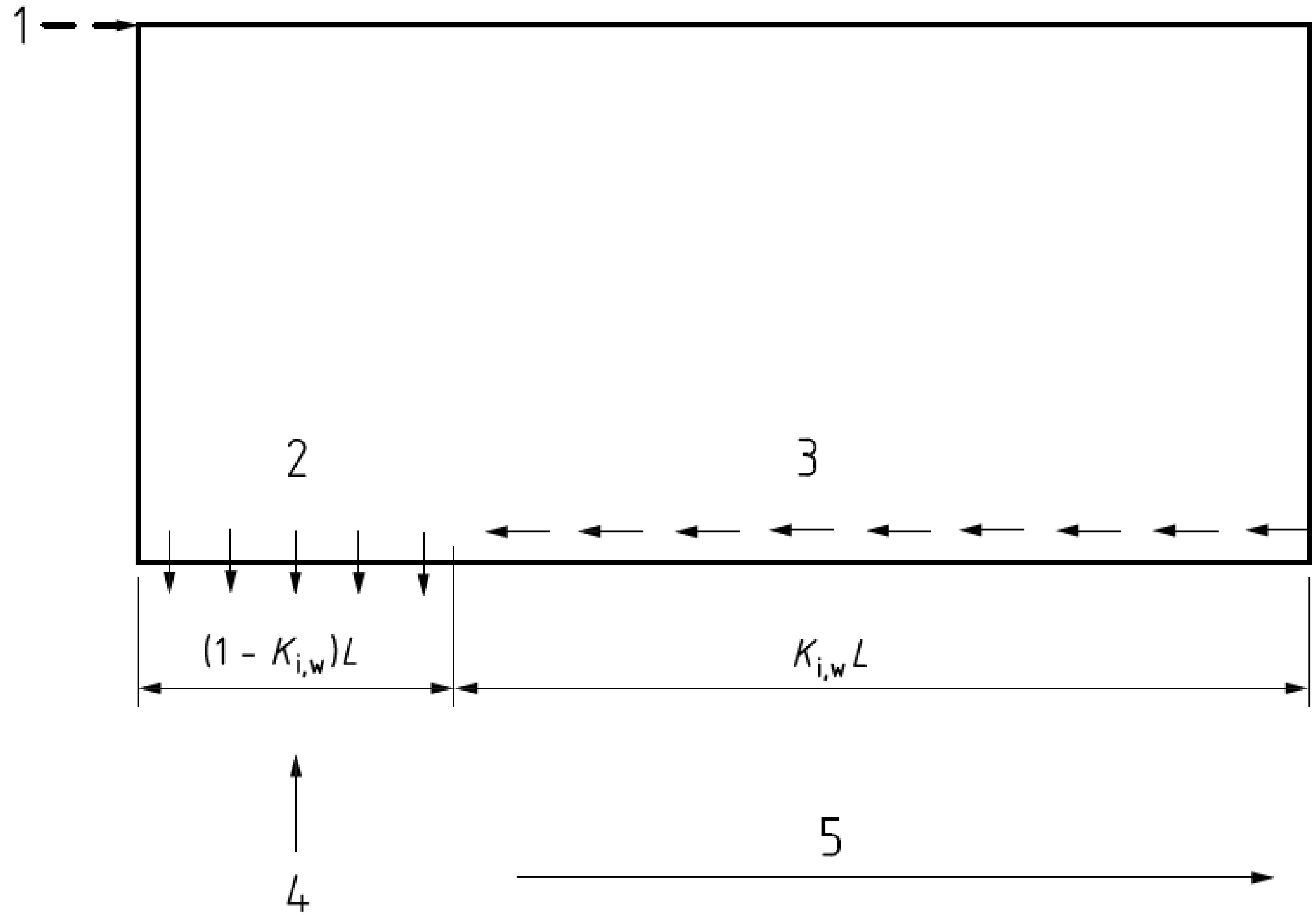
$$F \cdot H = \left[(1-\alpha)L \cdot r_{b,n}\right] \cdot \left[0.5L(1+\alpha)\right]$$

$$F \cdot H = 0.5 \cdot r_{b,n} \cdot L^2 \cdot \left[(1-\alpha)(1+\alpha)\right] = 0.5 \cdot r_{b,n} \cdot L^2 \cdot (1-\alpha^2)$$

$$\alpha = 0.5\left(\frac{L}{H}\right)(1-\alpha^2) \qquad 0.5 \cdot \left(\frac{L}{H}\right)\alpha^2 + \alpha - 0.5\left(\frac{L}{H}\right) = 0$$

$$\alpha = \frac{-1 \pm \sqrt{1 + 4\left(\frac{0.5L}{H}\right)\left(\frac{0.5L}{H}\right)}}{2\left(0.5\frac{L}{H}\right)}$$

$$\alpha = \frac{\sqrt{1 + \left(\frac{L}{H}\right)^2} - 1}{\frac{L}{H}}$$



Key

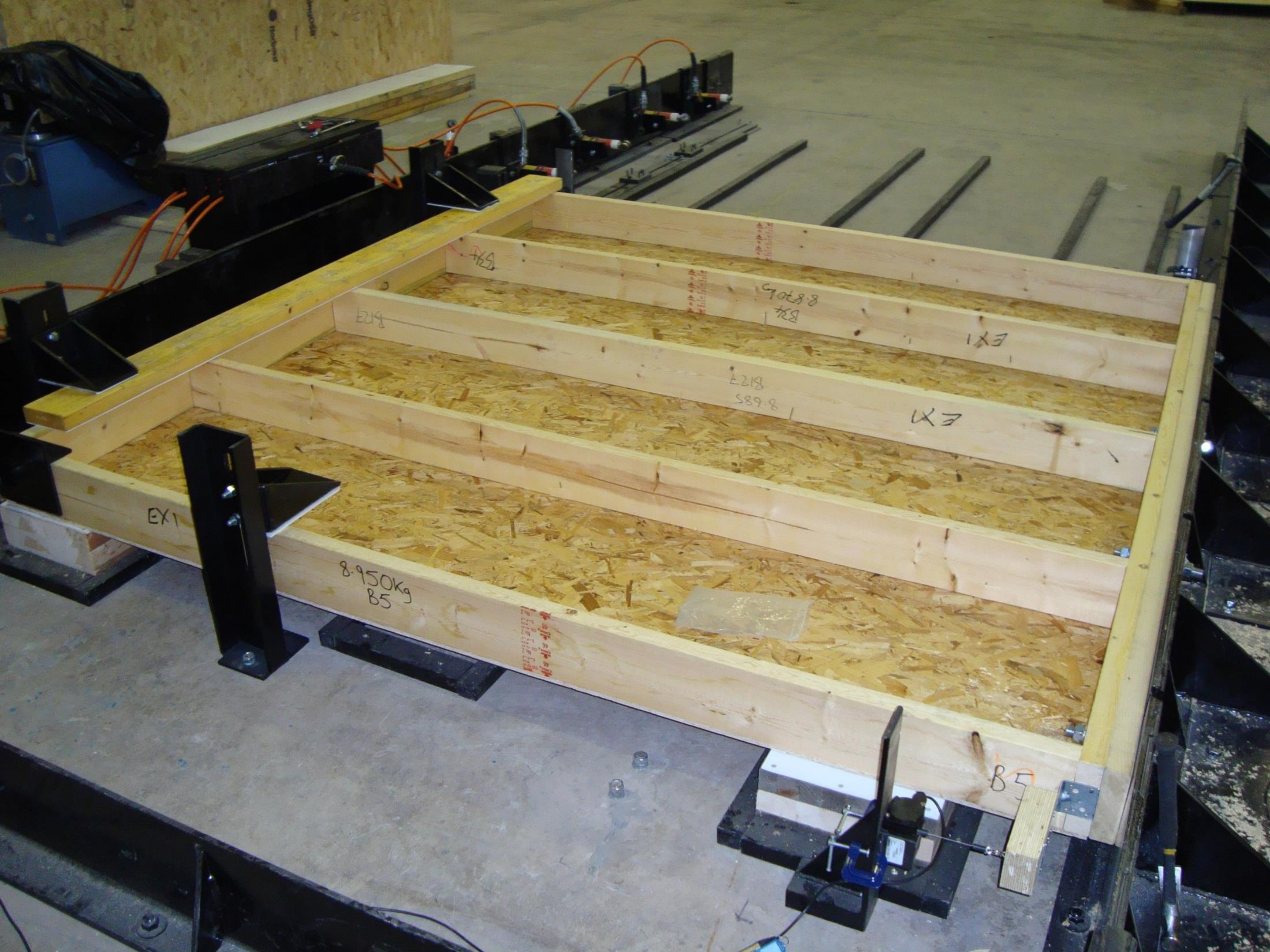
1 Design horizontal wind load

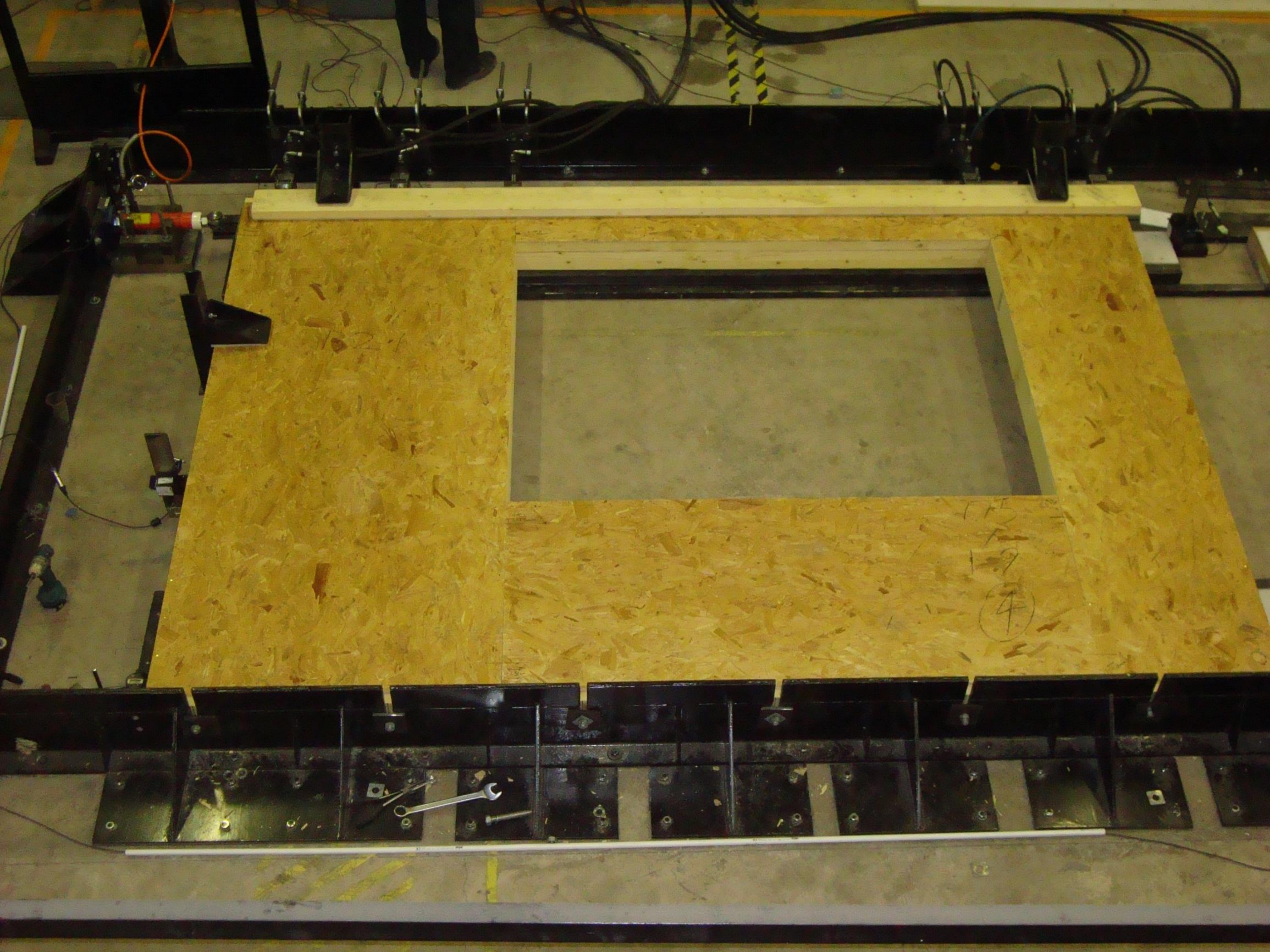
2 Sheathing-bottom rail fasteners providing uplift resistance per unit length of $\mu f_{p,d,t}$ (=$f_{w,d}$)

3 Sheathing-bottom rail fasteners providing horizontal shear resistance per unit length, $f_{p,d,t}$

4 Uplift resistance required from underlying construction (including at foundation level) of (1 - $K_{i,w}$)$f_{w,d}L$

5 Racking resistance transmitted to underlying construction of $K_{i,w}f_{p,d,t}L$

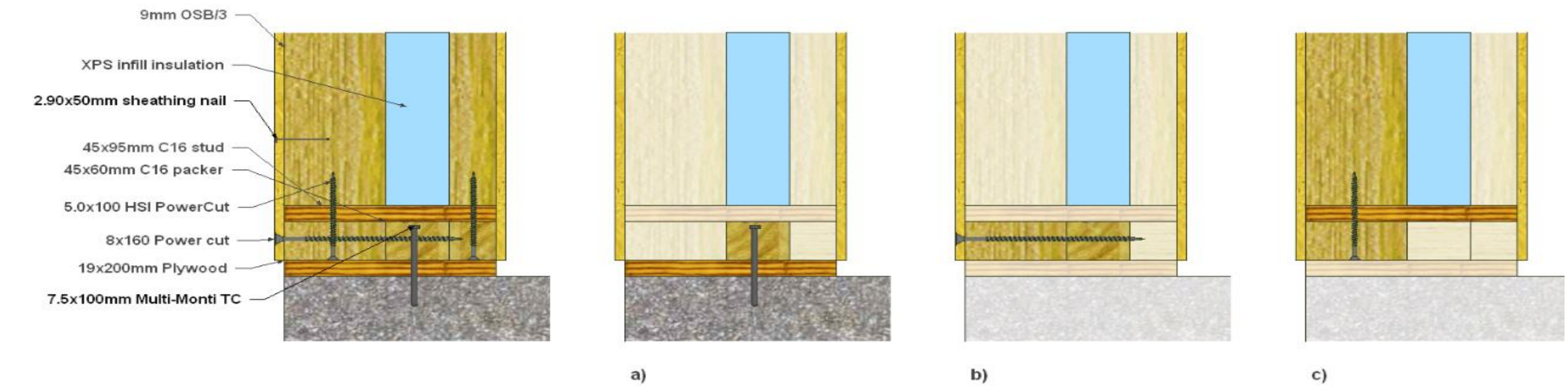

EX1
8·950Kg
B5
B5



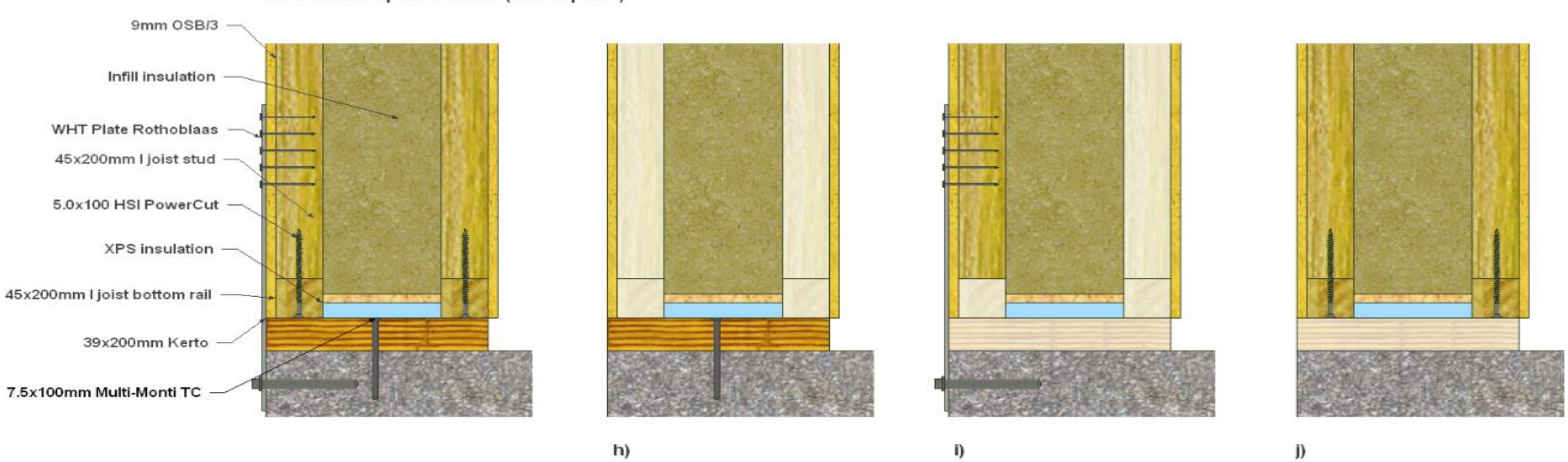

Norbord
Norbord

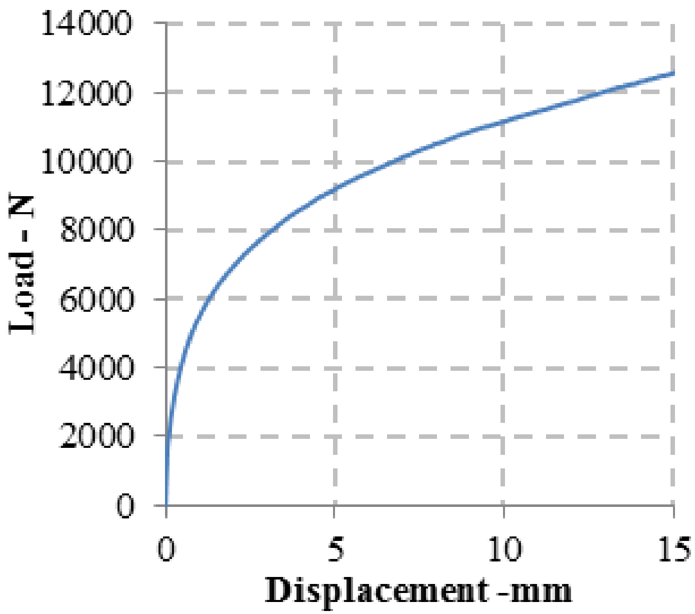

NAP08_P1
NAP08_P3
NAP08_P5
NAP15_P2

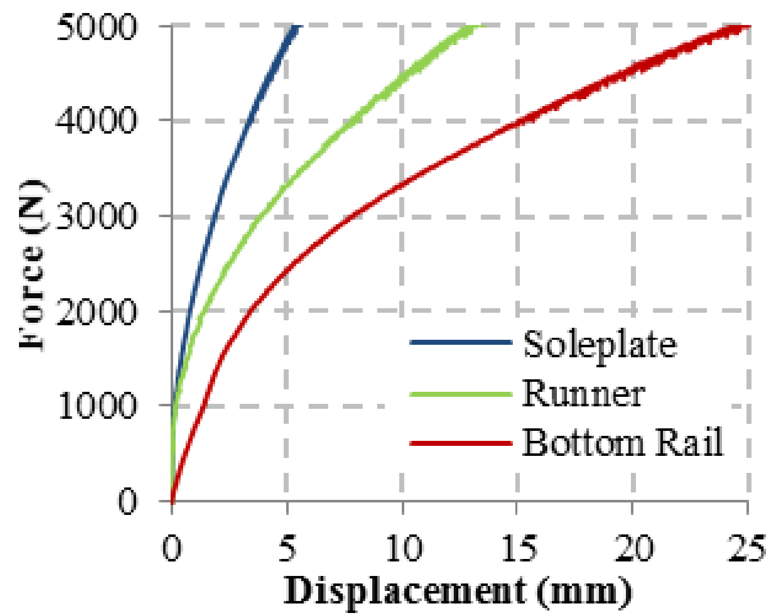

473
B017
DOWDING & MILLS



RTC closed panel detail (metal plate)







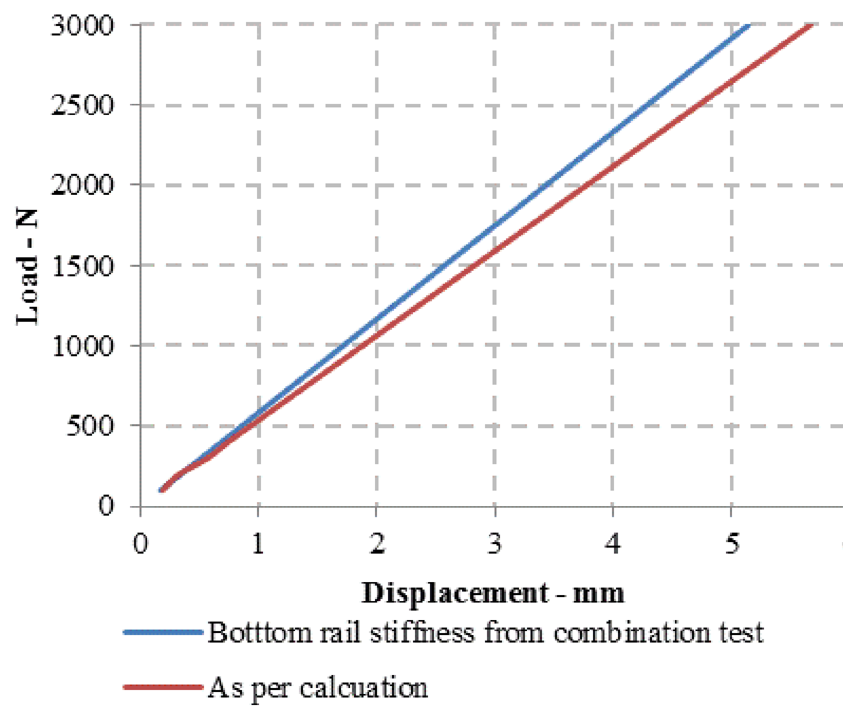
$$K_{ser} = \sum \left(\frac{\frac{F}{N_{nail}}}{K_{ser'}} \right)$$

Where:

F *is the applied shear force*

N_{nail} ***is the number of nails in the shear plane***

$K_{ser'}$ *is the stiffness of the individual shear plane*

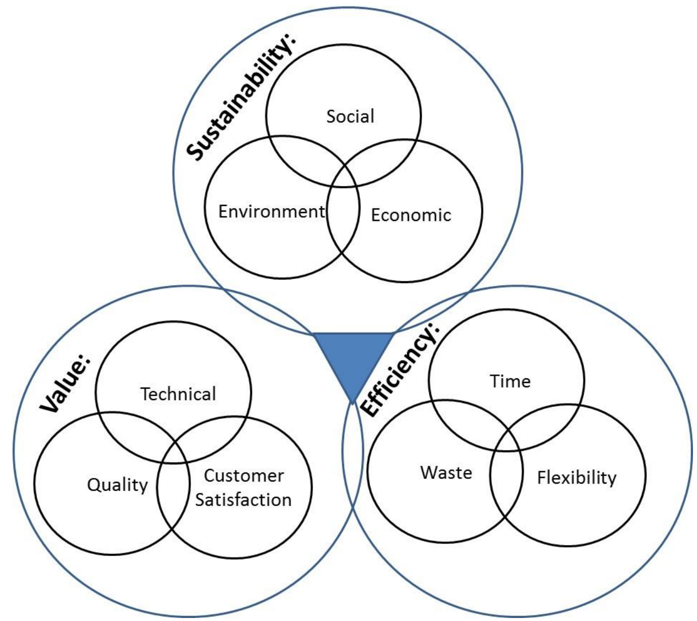


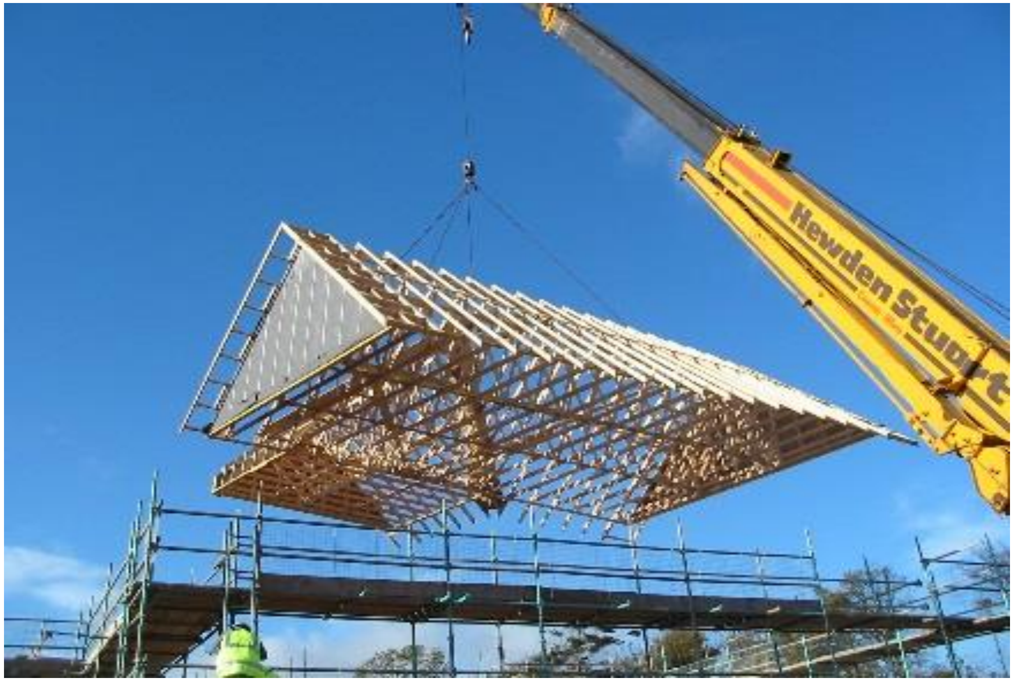
Summary:

- For offsite MMC systems to be part of a sustainable design solution they require to be at the centre of a **holistic** process ensuring **longevity through structural robustness** and building performance (thermal and acoustic) given the impact that this can have on efficiency, user comfort and overall life cycle cost.

- An offsite MMC solution requires to be **fully engineered for robustness** taking into account the manufacturing and assembly processes as well as operational performance prerequisites such as durability and design life.

- Due consideration at the design stage is required to consider the application of different loading configurations during **logistical operations, tighter tolerances** due to design freeze as well as **system interfacing** requirements.





Additional Offsite MMC Considerations

Criteria	Design Consideration
Durability	The integrity of “non-load bearing” items where fixings have safety implications should be considered such as the attachment of external cladding systems.
Standardisation	Standardisation of components or parts can result in a degree of over-specification that has to be balanced with overall efficiency gains in production and construction.
Design Life	The structural adequacy of a factory-produced systems and components has to be considered during the transportation and construction phases as the applied actions will in most cases be different from those experienced in service such as the lifting of wall assemblies or modules into location.
Movement	Panelised systems and modules require to be designed and detailed with adequate levels of tolerance and allowance for movement giving due consideration to applied actions during transportation and assembly as well as interfacing with other assembled components which are in-situ for example pre-formed foundations. .
Robustness	The system should be suitably robust during the whole design life including for accidental actions, transportation and assembly such as the inclusion of additional members or tying in methods to provide alternative load paths. In this respect redundancy is important consideration particularly in systems susceptible to progressive collapse such as panellised building; the loss of one component redistributes load or adds debris loading and leads to the sequential failure of other elements.
Access	Due consideration should be given to the sequence of operations during the assembly process in order that components can be interfaced and connected. Adequate provision should also be made where applicable for future access to allow routine maintenance and inspection to take place or decoupling for change of use.

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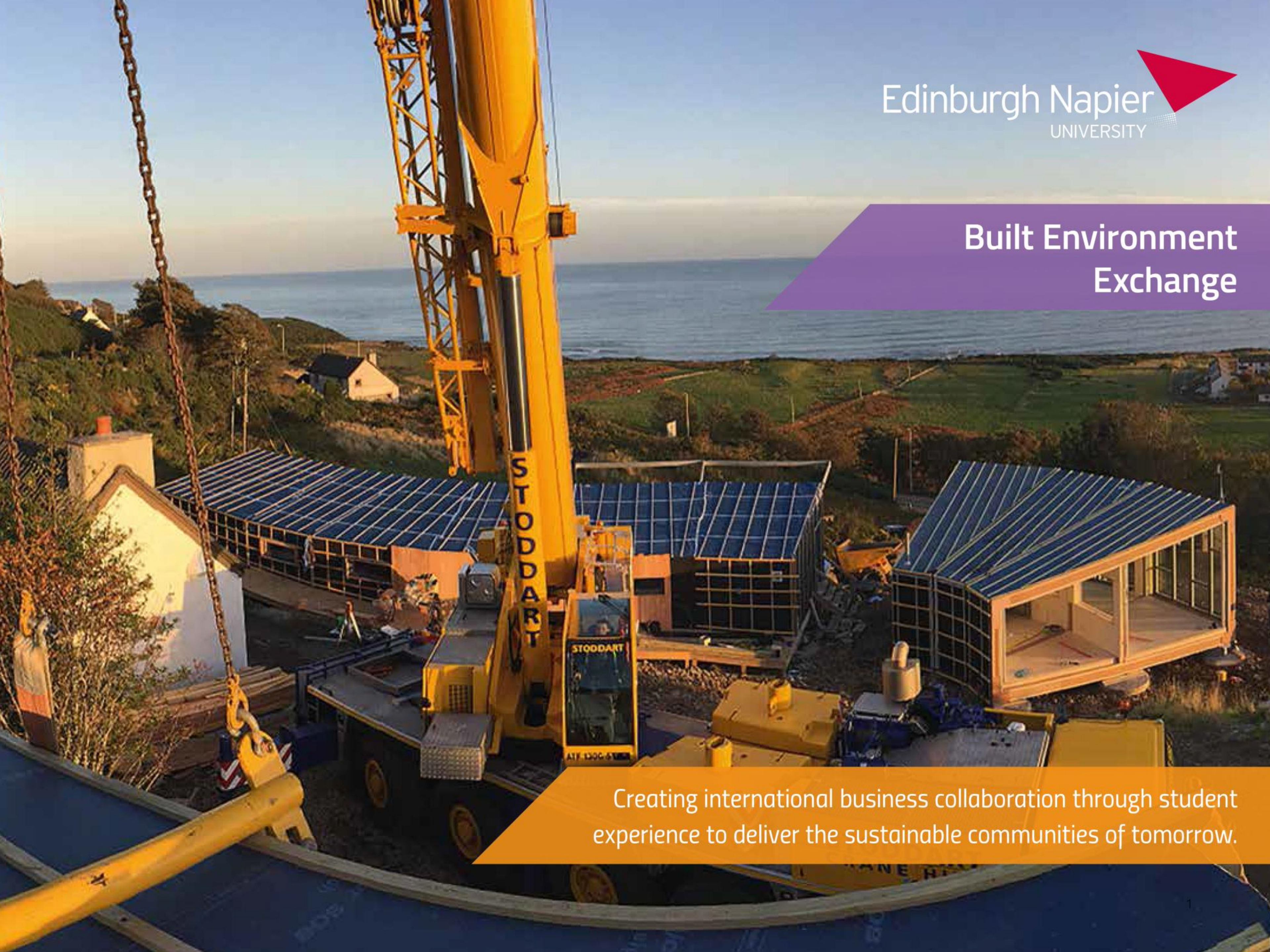
Built Environment Exchange



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