

Steel-timber-concrete composite shallow floor beam: Large-scale Experimental beam tests

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Abstract

In pursuit of sustainable construction aligned with the European Green Deal and Taxonomy Regulation, this study investigated the structural performance of a steel–timber–concrete composite (STCC) shallow floor beam as a low-carbon alternative to traditional steel–concrete systems. The cross-laminated timber (CLT) used in the STCC configuration replaces most of the concrete and profiled steel sheeting, enabling reduced floor heights. The comprehensive experimental test campaign was conducted to evaluate the bending capacity, stiffness, and failure mechanisms under service and ultimate limit states. The beam consisted of two parallel welded HEA200 steel sections filled with concrete, flanked by CLT panels on the left and right sides. The top fiber of the CLT was aligned with the top of the steel flange. Both are covered by a 65 mm reinforced concrete slab and CTC (concrete-timber-connectors) to achieve composite action. A strain-based method was employed to estimate the bending resistance, with assumptions of different configurations. The results were validated against the experimentally determined values. The findings demonstrate that the strain-controlled approach is a step towards a reliable prediction of the bending capacity of STCC beams. The study highlights that STCC beams offer a promising solution for low-carbon building design with reduced floor height.

1 Introduction

Reducing embodied CO₂ in building structures, in line with European policy targets, is accelerating the adoption of hybrid systems in which steel acts compositely with timber and low-carbon concrete. Shallow floor beams enable reduced floor heights, efficient service integration, and potential increases in storey count while maintaining structural performance. Within this context, steel–timber–concrete composite (STCC) systems leverage the strength and ductility of steel, the favourable stiffness-to-weight and sustainability attributes of cross-laminated timber (CLT), and the mass and robustness of concrete.

Despite growing interest in steel–timber composites, large-scale experimental evidence is currently limited, constraining design guidance on bending capacity and failure modes under realistic loading.

This paper presents an experimental study of STCC shallow floor beams. Large-scale four-point bending tests were performed on beams comprising S460 steel, five-layer spruce CLT, and low-carbon concrete, with detailing to promote composite action. The test programme combined cyclic preloading with deflection-controlled loading to failure, and instrumented slip, deflection, and strain along the span. Results indicate a shear connection between the materials

with a negligible end-slip and failure governed by concrete crushing; analytical predictions captured the bending moment capacity and deflection. Implications for connector detailing and buildability are outlined.

2 Experimental Campaign

2.1 System cross section

The test member is a simply supported STCC shallow floor beam subjected to four-point bending. The composite cross-section (see Figure 1) is described in table 1:

Table 1 Summary of material properties

Material	Details
Steel Section	S460 welded box girder from two HE 200 A rolled sections
Timber	5-Layer spruce CLT Panel; seated on the bottom steel flange (450mm × 180mm)
Concrete	low-carbon concrete slab cast in and over the steel beam (65mm × 1200mm)

Reinforcement	reinforcement ($\varnothing 8 - 150$), and U-bars over the steel beam to resist uplift ($\varnothing 12 - 150$)
Shear Connector	mechanical shear connectors (CTC screws) providing composite action between concrete to timber ($\varnothing 7\text{mm} \times 160\text{mm}$ length, every 150mm).



Figure 3 Assembly detail of the STCC beam (CLT protection, connectors, rebar and U-bars)

After assembly, formwork was installed and the concrete was cast.

2.3 Loading Procedure

The loading programme consisted of force-controlled loading cycles followed by deflection-controlled loading to failure (see Figure 2):

1. Initial ramp: increase load to 5% of the estimated capacity over 5 minutes.
2. Cyclic preloading: 25 cycles between 5% and 40% of the estimated capacity, then unload to 5%.
3. Incremental blocks: repeat three-cycle blocks, increasing peak load by 10% per block; hold the peak load for 5 minutes in the third cycle, then unload to 5%.
4. Pre-failure limit: after reaching 80% of the estimated capacity, unload to 5%.
5. Deflection-controlled phase: impose 40 mm midspan deflection and hold for 3 minutes; increase by 40 mm increments (with 3-minute holds) until failure.

2.4 Test Setup and instrumentation

The beams were tested in four-point bending. A spreader beam introduced two-point loads spaced 75 cm apart (see Figure 4).

The support spacing was 4.75 m, and the overall beam length was 5.25 m, providing a simply supported boundary condition (see Figure 5).

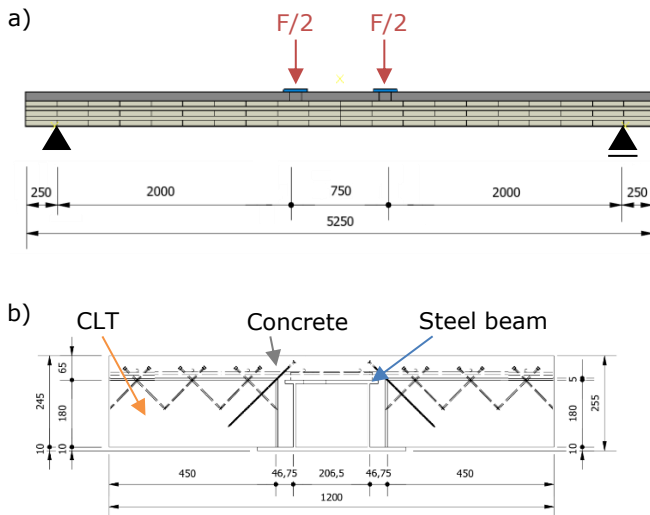


Figure 1 a) Structural System, span and loading; b) Cross-section of the STCC Beam

2.2 Assembly of the experimental specimen

CLT panels were prepared and protected prior to installation. The face in contact with the concrete was fully taped with Speedyband 300 to limit moisture ingress. An acoustic foil was applied on the CLT and sealed at the edges with Speedyband 60; overlapping sections were bonded with a tar strip. CTC screws (shear connectors) were installed before placing the CLT panels adjacent to the steel beam on the bottom flange. The bottom steel flange was fitted with a neoprene strip (with double-sided tape) to control relative movement. After placing the rebar mesh mats, U-bars were installed over the steel beam to prevent uplift (see Figure 3).

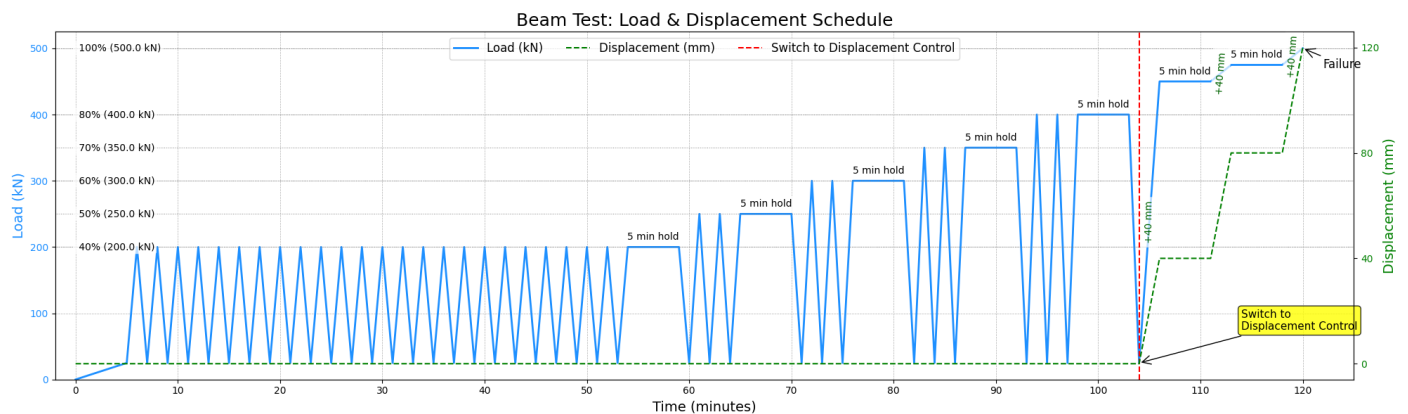


Figure 2 Test loading Scheme



Figure 4 Spreader beam for four-point bending



Figure 5 Specimen in testing frame

Instrumentation captured global response, composite interaction, and local strains:

- Interface slip: measured at five points along the beam and at both ends (concrete-CLT and CLT-steel interfaces).
- Deflection: recorded at five locations, including mid-span and under the load introduction points.
- Separation: monitoring of CLT-bottom steel flange separation.
- Steel strain: eight strain gauges (DMS) placed on webs/flanges of the steel beam.
- Concrete strain: gauges on the top surface of the concrete slab near the compression zone.

The following figure 6 depicts the position of the instrumentations on the beam:

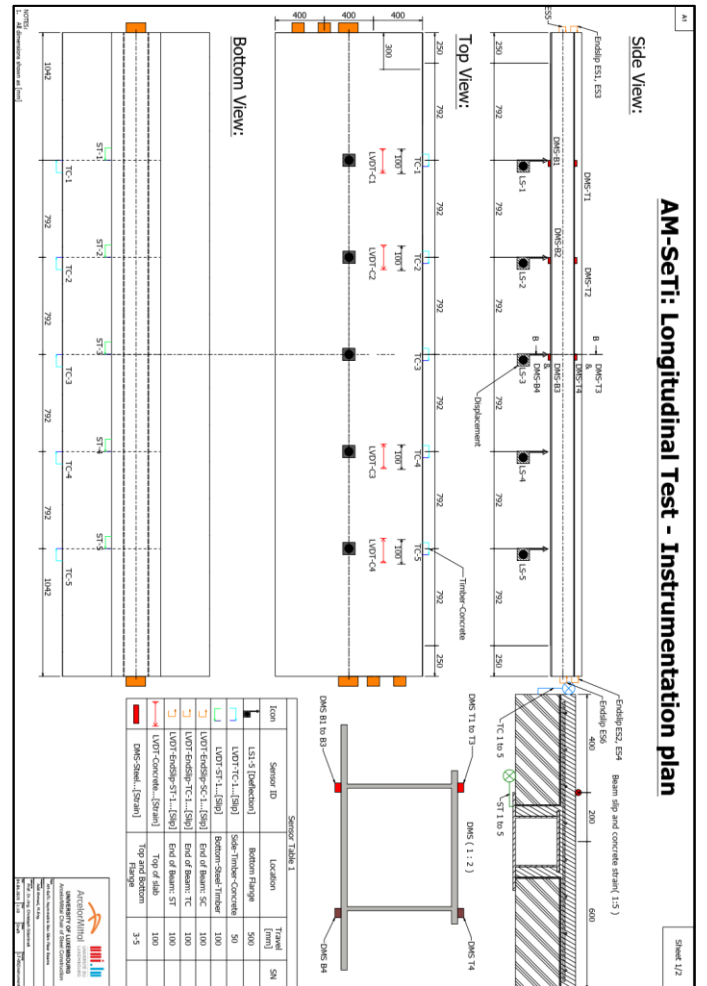


Figure 6 Instrumentation plan of the beam

2.5 Results

2.5.1 Load-Deflection response

The global load-deflection behaviour at midspan shows an initially quasi-linear response, followed by progressive plasticisation of the steel beam and then abrupt fall off as concrete cracking and compressive damage develop. The preconditioning cycles stabilised stiffness prior to the monotonic phase, with no indications of instability.

A comparison of the test curves with the analytical plastic estimations derived by the strain-controlled method indicates close agreement in ultimate capacity and good correspondence in stiffness (see Figure 7).



Figure 7 Midspan load-deflection curves: experimental curves vs. $M_{pl,a}$ and $M_{full, \eta=1}$ strain-controlled full composite

2.5.2 Failure Mode and ductility

Observed failure:

Failure was governed by crushing of the concrete compression zone at midspan, accompanied by minor spalling and no visible delamination of the CLT, nor any rolling shear (see Figure 8). The steel section did not exhibit global instability.

Connection behaviour:

End-slip at both supports remained negligible throughout loading and at failure (max end-slip ≤ 0.1 mm), confirming a very stiff connection. Along-span slip readings were small and smoothly distributed, indicating near-full interaction under the adopted detailing.

Ductility:

Based on the deflection-based index $\mu_\delta = (\delta_{u80} - \delta_{y80})/\delta_{y80}$, the beam exhibited the following ductility μ_δ at 80% of the max. load pre- (δ_{y80}) and post- peak(δ_{u80}):

Specimen-1: $\mu_{\delta 1} = (108 - 34.95)/34.95 = 2.09$

Specimen-2: $\mu_{\delta 2} = (106 - 34.36)/34.36 = 2.08$

Specimen-3: $\mu_{\delta 3} = (99.8 - 34.74)/34.74 = 1.87$

with sustained load capacity beyond first nonlinearity, consistent with concrete-controlled failure and steel reserve capacity.

The ultimate midspan deflection was observed at a deflection of $L/64 = 74$ mm, $L/69 = 69$ mm, $L/61 = 77$ mm respectively.



Figure 8 Failure mode: crushing of the concrete in the compression zone

3 Comparison to strain-based ultimate bending moment resistance

3.1 Design Method of the algorithm

To assess the bending moment capacity of the composite beam, a strain-based method was used.

This approach assumes that even as slip occurs all parts of the beam are under the same curvature, and the section remain plane. The section is discretised into "strain boxes" (steel, concrete slab, CLT layers), and material strain limits govern the maximum strain and hence curvature and the associated bending capacity [1,2].

The neutral axis is determined by force equilibrium, and the bending moment is obtained by stress integration across the section.

Figure 9 shows the boundary conditions for the STCC Cross section. Here the compressive ($\epsilon_{i,c}$), and tensile limits ($\epsilon_{i,t}$), of steel (ϵ_a), timber (ϵ_{ti}) and concrete (ϵ_c) are shown.

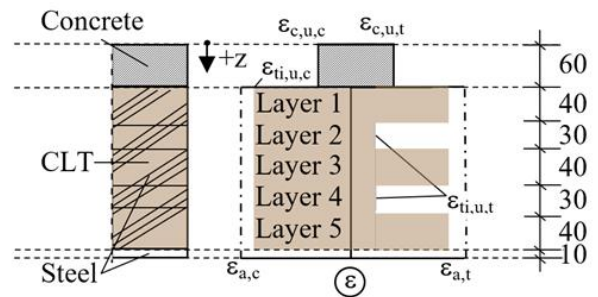


Figure 9 Division of the cross-section of the STCC Beam into strain boxes.

Material stresses follow the adopted constitutive laws $\sigma(\epsilon)$. The neutral axis satisfies:

$$\sum_i \sigma_i(\epsilon_i) A_i = 0 \quad (1)$$

and the bending moment is:

$$M(\kappa) = \sum_i \sigma_i(\epsilon_i) A_i (z_i - z_n) \quad (2)$$

Capacity is taken at the governing strain limit:

$$\kappa_{\max} = \min \left(\frac{\epsilon_{a,lim}}{z_a - z_n}, \frac{\epsilon_{c,lim}}{z_c - z_n}, \frac{\epsilon_{clt,lim}}{z_t - z_n} \right) \quad (3)$$

as such the resulting bending moment capacity $M_R \approx M(\kappa_{\max})$ for full shear connection ($\eta=1.0$).

Partial shear connection ($\eta < 1.0$) can be incorporated via reduced compressive force in the slab.

Iterative redistribution is used to achieve force equilibrium and then the bending moment capacity is calculated.

This is not required for the presented beam since full shear connection is assumed.

3.2 Materials

Three primary materials were employed: low-carbon concrete, S460 structural steel, and spruce CLT. Since not all of the material were yet experimentally tested, available nominal values and values derived by the technical specification (e.g. CLT and Rebars) were used [3,4]. The material models used for analytical checks are illustrated in Figures 10 and 11:

- Low-Carbon Concrete:
Mix targeting $\approx 90 \text{ kg CO}_2/\text{m}^3$ embodied carbon via high slag (SCM) content, with resultant greenish discolouration observed.
- S460 Steel:
High-strength S460 selected to meet strength and stiffness targets while limiting steel tonnage.
- Spruce C24-CLT (5-layered):
Lay-up (2 longitudinal / 3 transverse layers). (rolling shear was neglected)

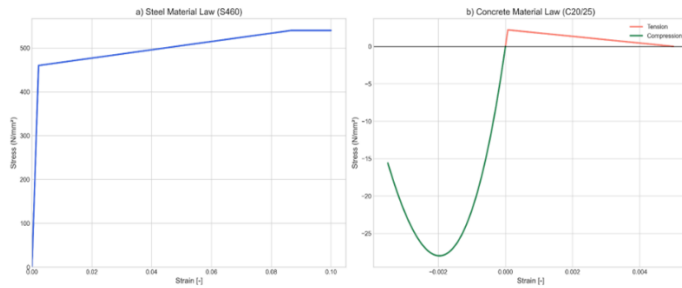


Figure 10 a) Steel material law b) Concrete material law for the beam

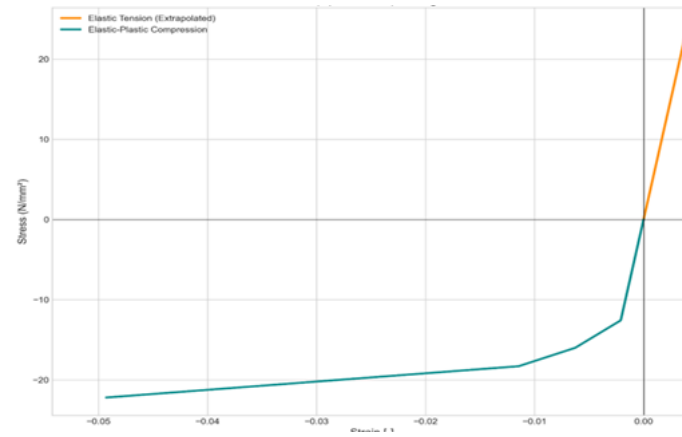


Figure 11 Stress-Strain Material law for CLT

Table 2 shows the key parameters of the primary materials.

Table 2 Summary of material properties

Material	Key parameters
Low-carbon Concrete	$f_{ck} = 20 \text{ N/mm}^2$, $E_{cm} = 28848 \text{ N/mm}^2$

S460 Steel $f_{yk} = 460 \text{ N/mm}^2$, $E_a = 210000 \text{ N/mm}^2$

C24 - CLT $f_{m,k} = 24 \text{ N/mm}^2$, $E_{0,m} = 12000 \text{ N/mm}^2$

$f_{c,90,k} = 2,7 \text{ N/mm}^2$, $E_{90,m} = 450 \text{ N/mm}^2$

3.3 Overview of different configurations

The overview considered four configurations and their bending capacity and estimates their contributions to the composite action (see Figure 12):

1. Steel beam alone (S460 box from two HE 200 A; concrete/CLT neglected),
2. Steel-concrete composite (full interaction),
3. Full STCC composite (concrete + steel + CLT; timber tension neglected),
4. Experimental specimen test result specimen 1.

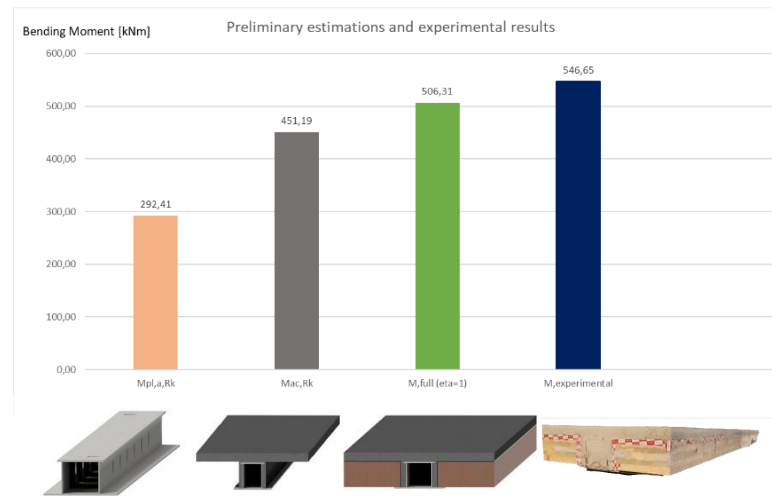


Figure 12 Estimated bending moment capacities and test result.

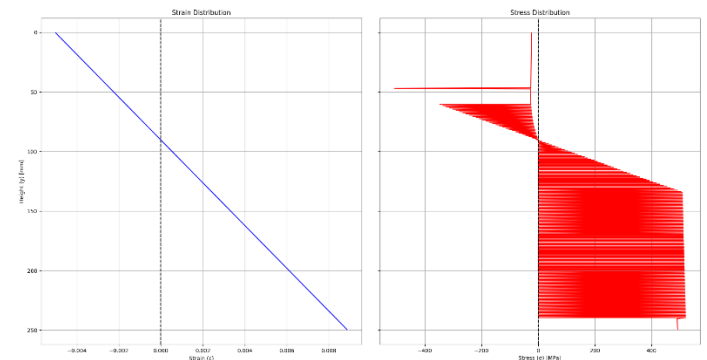


Figure 13 Strain-controlled method: strain state at $\kappa_{\max}$ (concrete top fibre limit)

Figure 13 shows the strain and stress distribution over the height of the analytical method, while Figure 14 shows the bending moment to midspan – deflection curve of the experimental beam 1 against the curve derived by integration of the curvature. The simulated graph shows sufficient compliance with experimentally derive graph.

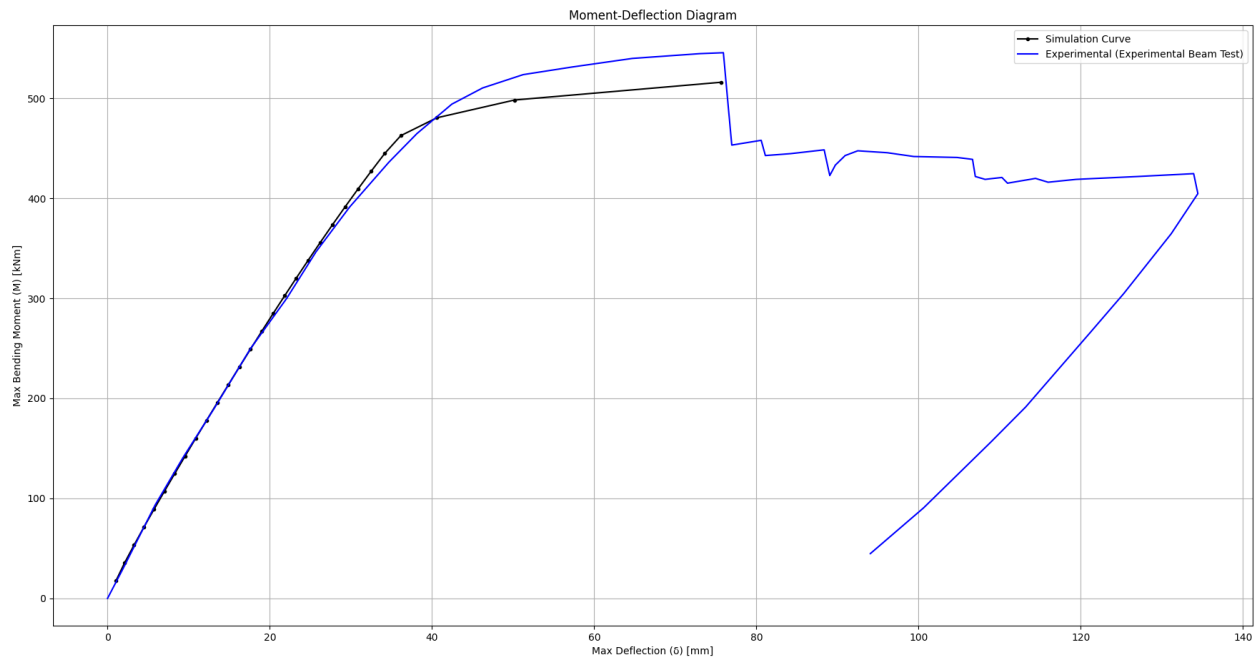


Figure 14 Experimental curve (Beam 1) vs. $M_{full,\eta=1}$ strain-controlled full composite curve

4 Conclusion and Outlook

4.1 Conclusion and Outlook

Large-scale four-point bending tests on steel-timber-concrete composite (STCC) shallow floor beams comprising S460 steel, five-layer spruce CLT, and low-carbon concrete demonstrated near-full composite action and robust global performance. The beams exhibited a stiff connection with negligible end-slip (≤ 0.1 mm) and failure governed by crushing of the concrete compression zone at midspan; no delamination of the CLT or rolling-shear symptoms were observed. Analytical plastic and strain-controlled predictions captured ultimate capacity, stiffness trends, supporting the suitability of the strain-based predesign as an early-stage appraisal tool when timber tension is neglected.

Design implications include: (i) the tested detailing achieves very high interaction stiffness suitable for shallow floor applications;

(ii) the CLT layer contributes to bending resistance and composite stiffness despite neglecting timber tension in capacity checks;

(iii) constructability may be improved by headed/bolted shear connectors and CLT cut-outs to facilitate concrete flow and compaction without compromising moisture/acoustic protection.

Limitations concern the focus on monotonic bending with preconditioning, a single geometry and detailing family, and the absence of long-term (creep/moisture), fatigue, fire, and progressive collapse assessments.

Priorities for future work are: (1) quantification of partial interaction via connector stiffness calibration against

measured slip; (2) parametric studies on CLT thickness/lay-up, connector type/spacing, and slab geometry; (3) evaluation of long-term effects (timber and concrete creep/shrinkage, moisture cycling) and serviceability; and (4) development of design guidance for STCC shallow floors (capacity, stiffness, detailing) grounded in combined test and validated FE evidence.

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