Timber-Concrete Composites (TCC): validation of Finite Element modelling techniques and environmental sustainability insights

Compositi legno-calcestruzzo: validazione delle tecniche di modellazione a elementi finiti e valutazione della sostenibilità ambientale

Laura Corti[1,2], Giovanni Muciaccia[1,3]

[1] *Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy*

[2] Email: laura.corti@polimi.it

[3] Email: giovanni.muciaccia@polimi.it

L'autore di riferimento per questo paper è: Laura Corti

ABSTRACT: This study develops and validates a three-dimensional Finite Element (FE) modelling technique to capture the mechanical be-haviour of Timber-Concrete Composite (TCC) beams and their shear connections. The numerical models reproduce bending and push-out tests, with the aim of recording load-slip relationships, stiffness, and failure modes. Experimental tests available in literature are considered as benchmarks, in order to validate the modelling techniques adopted; moreover, comparison with analytical modelling according to new generation of Eurocode 5 is performed. The analysis of stress profiles highlighted the improved performances of notched and screws+notches connections, with respect to screws-only systems. Eventually, a complementary Life Cycle Assessment (LCA) analysis on modelled TCC beams confirmed their considerably lower environmental impact on climate change, measured in terms of Global Warming Potential, with respect to equivalent reinforced concrete beams. / Questo studio sviluppa e valida una metodologia di modellazione tridimensionale agli elementi finiti per simulare il comportamento meccanico delle travi composite legno-calcestruzzo e delle loro connessioni. Il modello numerico si focalizza su test a flessione e push-out, allo scopo di individuare curve carico-spostamento, rigidezza e modalità di rottura. Alcuni test sperimentali disponibili in letteratura sono considerati come riferimento, allo scopo di validare la metodologia di modellazione adottata; inoltre è stato effettuato un confronto con i risultati ottenuti tramite modellazione analitica seconda la nuova genera-zione diell'Eurocodice 5. L'analisi dei profili degli sforzi ha evidenziato le migliori prestazioni dei collegamenti realizzati con intagli e viti+intagli, rispetto ai sistemi con sole viti. Infine, un'analisi complementare del ciclo di vita (LCA) sulle travi TCC modellate ha confermato il loro impatto ambientale significativamente inferiore sul cambiamento climatico, misurato in termi-ni di Potenziale di Riscaldamento Globale, rispetto a travi equivalenti in calcestruzzo armato.

KEYWORDS: Timber-Concrete Composite (TCC); shear connections; environmental sustainability / compositi legno-calcestruzzo; connessioni a taglio; sostenibilità ambientale

1 INTRODUCTION

Timber-concrete composite (TCC) solutions have become an increasingly attractive option for floor systems because they exploit the complementary mechanical properties of both materials. Concrete provides high compressive strength, stiffness, mass for vibrations and acoustic issues, and durability, while timber offers low self-weight, high tensile strength, and a markedly lower embodied environmental burden than conventional building materials (Ceccotti 2002; Duan et al. 2022). The extent to which the two layers can work together, however, depends on the degree of composite action transmitted through the connection. Interlayer slip directly affects deflections, stress transfer, and failure modes; consequently, the characterization of connection behaviour remains one of the key issue in TCC design.

The benefits of TCC systems are noticeable with respect to timber floors, providing higher stiffness and capacity, longer achievable span, increased sound insulation, reduced vibration issues, better fire performances (Dias et al.2018); moreover, TCC slabs exhibit advantages with respect to reinforced concrete (RC) solutions too, considering construction times speeding up thanks to higher prefabrication level, reduced structural mass, higher environmental sustainability (Zhang et al. 2023). Experimental campaigns clarified the influence of connector typology, notch geometry, and fastener layout on stiffness and resistance, but full-scale tests are time-consuming and expensive, particularly when several geometric and material variables are involved (Gutkowski et al. 2008; Hu et al. 2021). For this reason, validated numerical models are needed to support design choices and to interpret the local mechanics that are difficult to observe experimentally (Fragiacomo & Ceccotti 2006;

Lukaszewska et al. 2010). In parallel, the transition toward low-carbon constructions requires structural performances to be evaluated together with environmental performance. In TCC systems this dual perspective is especially relevant, because structural efficiency depends on connection details while environmental gains depend on the relative use of timber, concrete, and steel, as well as End-of-Life (EOL) assumptions (Balasbaneh et al. 2022).

Although several experimental studies and analytical formulations are available for TCC systems, a limited number of works provide a consistent validation of a three-dimensional FE workflow across both beam-scale bending tests and connection-scale push-out tests, with additional linking to environmental indicators. Existing approaches generally focus either on connector mechanics, on global flexural response, or on environmental comparison separately. The gap addressed in this paper is therefore the validation of a practical FE modelling strategy for two different shear-transfer mechanisms, screws only and screws combined with notches, and the use of the validated models to interpret effective bending stiffness, composite action, and GWP impact for structurally equivalent solutions.

Within this context, this paper presents the following main findings: (i) development of a 3D Finite Element (FE) framework able to reproduce the global and local behaviour of TCC beams; (ii) validations of the model considering benchmark bending and push-out tests; (iii) comparison of FE-derived effective bending stiffness with experimental values and with analytical predictions based on Eurocode 5 γ–method (EN 1995-1-1:2025); (iv) discussion of the environmental implications of the TCC solution through a simplified LCA. Within this context, a special focus is dedicated on the connections technology, especially considering screws only and screws+notches solutions.

2 METHOD

2.1 *Benchmark validation tests from literature*

The primary validation benchmarks are the four-point bending tests reported by Cvetković et al. (2023), who investigated timber-concrete composite beams with different connecting systems. Two beam families are considered here. The BF series uses coach screws as a unique shear-transfer mechanism (Figure 1). The BN series combines screws and notches, thus providing mechanical interlock in addition to fastener action.

A separate push-out literature benchmark is taken from the study by Shi et al. (2022), who tested hybrid notch-screw specimens. The selected configuration is the RSS one, with rectangular notch and a single screw (Figure 1); additionally, a configuration with screw connections only is designed, in order to assess the difference with notched ones.

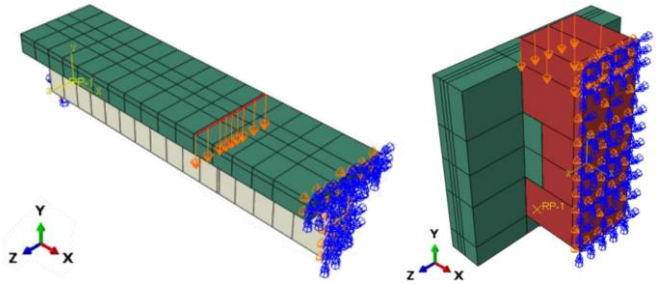


Figure 1. On the left: TCC beam subjected to four-point bending test (Cvetković et al., 2023); on the right: TCC specimen with screw+notch connection subjected to push-out test (Shi et al., 2022). / A sinistra: Trave TCC sottoposta a test a flessione su quattro punti; a destra: provino TCC con connessione con vite e intaglio sottoposto a test di push-out.

2.2 *Finite Element (FE) modelling techniques*

The FE analyses are conducted in Abaqus/CAE 2022. To limit computational cost without compromising the global response, the beam models exploit the geometric and loading symmetry and they are therefore built as half-width models. Three-dimensional 8-node reduced-integration hexahedral elements (C3D8R) are used for all solid parts, with mesh refinement concentrated around interfaces, fasteners, and regions of high stress gradient. The loading procedure is displacement-controlled: a downward displacement is imposed, and the global response is traced back according to load-deflection curves.

Concrete is modelled through an elastic law combined with concrete damage plasticity in order to reproduce cracking in tension and non-linear compression; based on the benchmark study, concrete C30/35 is modelled both for Cvetković and Shi models, with elastic modulus of 34 GPa and tensile strength of 3.5 MPa. Timber is introduced as an orthotropic material so that longitudinal stiffness ($E_{//}$=11 GPa) is the main one, while the transversal one is considered as 10% ($E_{\perp}$=1.1 GPa). Steel connectors are treated as elasto-plastic elements consistent with S355 steel grade used in the reference campaigns. This combination of constitutive laws allows for straightforward models' parametrization, maintaining the ability to capture the expected non-linear mechanisms and failure modes affecting the TCC response.

Contact assumptions are selected after iterative model refinement. At the timber-concrete interface, the formulation allows stresses transfer without compenetration ("Hard contact") and frictional tangential response ("Penalty method"). At the steel connections interfaces, both explicit contact and tied

conditions were explored; the second option can be considered an idealised upper boundary simulating the case of full composite action where no slip is exhibited between the timber and the concrete layer. However, the two approaches yielded almost coincident predictions during the initial linear-elastic phase, which is the range most relevant for evaluating service stiffness and effective bending stiffness. For the validated models, the tied fastener interfaces were retained because they provide numerical stability while preserving the observed initial response. The use of tied constraints at the steel fastener interfaces is a numerical idealization and may lead to an upper-bound representation of local contact stiffness if post-yield slip or local failure is the target response. For this reason, the global timber-concrete interface was not tied, but was modelled through hard normal contact and frictional tangential behaviour. A sensitivity comparison between explicit fastener contact and tied fastener interfaces showed negligible differences in the initial linear range used to evaluate service stiffness and EI_{eff}. Therefore, the tied fastener idealization was retained to improve numerical stability, while the interpretation of the results is restricted to global stiffness and stress-field assessment. The same modelling philosophy is used in the push-out analyses, thereby ensuring consistency between local and global simulations.

2.3 *Evaluation of effective bending stiffness*

The main structural performance indicator is the effective bending stiffness, EI_{eff}, because it condenses the degree of composite action into a single quantity directly linked to serviceability and global flexural response. For the benchmark beams, EI_{eff} is evaluated in three ways: from digitized experimental load-deflection curves derived from simply-supported beam under a four-point bending test (Equation 1), from the FE curves, and from the analytical Eurocode 5 γ–method (Equation 2) (EN 1995-1-1:2025).

$$EI_{eff} = \frac{P \cdot b \cdot (3L^2 - 4b^2)}{48 \cdot \delta} \quad (1)$$

$$EI_{eff} = \sum_{i=1}^{2} (E_i I_i + \gamma_i E_i A_i a_i^2) \quad (2)$$

Where:

- P is the total applied load
- L is the beam span
- δ is the midspan deflection
- b is the distance from the support to the loading point
- E_i is the elastic modulus of layer i
- I_i is the moment of inertia of layer i
- Ai is the area of layer i,
- a_i is the distance from the layer centroid to the neutral axis
- γ_i is the composite action level, depending on the connection slip modulus Ks.

For the BF series, both the standard Eurocode slip-modulus estimation and a calibrated numerical K_s obtained from push-out simulations is used. For the BN series, the conventional analytical route is inadequate because the combined screw–notch mechanism is not shown explicitly in the standard formulation. A hybrid approach is adopted: a calibrated push-out FE model is used to assess an equivalent K_s, which is then inserted into the γ–method equation. This procedure preserves the efficiency of the analytical framework while importing tailored information from a calibrated numerical model.

2.4 *Environmental performances assessment*

Environmental performance is assessed with a Life Cycle Assessment (LCA) analysis, focusing on the impact on climate change category, measured with Global Warming Potential (GWP); the analysis is carried out according to EN 15804:2012 + A2:2019 standard, considering Cradle to gate with options (modules C1-C4 and module D). The adopted scenario assumes timber recycling at EOL stage, considering the biogenic carbon with the "–1 in / +1 out" rule according to ISO 21930 standard. The LCA is performed according to Environmental Footprint method (v. 3.1) with SimaPro software (v 9.6.1), considering Ecoinvent database (v 3.11).

The BF TCC slab is compared with a structurally equivalent RC slab designed to provide comparable bending stiffness and load-bearing capacity. Although simplified, this comparison is sufficient to identify the order of magnitude of the CO_2 emissions associated with the validated composite solution.

3 RESULTS AND DISCUSSION

3.1 *Validation of the benchmark bending tests*

The comparison between FE and experimental load-deflection curves for the primary Cvetković benchmarks (Cvetković et al. 2023) confirms that the modelling framework reproduces the global response with satisfactory accuracy (Figure 2). For the BF series, which relies on screw connectors only, the numerical curve captures the initial linear branch and the overall flexural stiffness with strong fidelity. This result indicates that the adopted material laws, contact assumptions, and fastener idealization are sufficient to reproduce the global behaviour of a relatively flexible connection system. The model also captures the peak-response regime closely enough to support subsequent extraction of stiffness indicators and internal stress distributions.

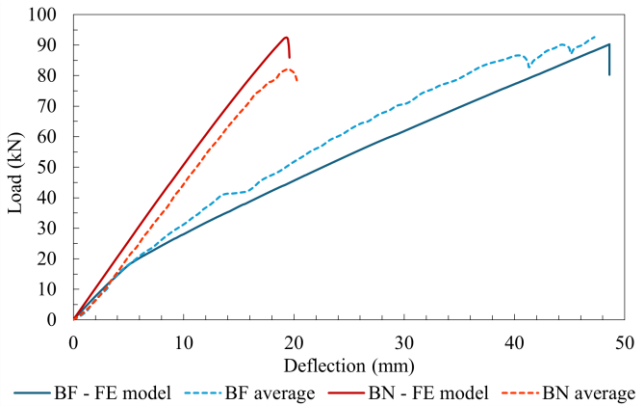


Figure 2. Calibrated FE load-deflection curves for bending tests with respect to average ones from three experimental tests derived from literature (Cvetković et al. 2023). / Curve carico-spostamento per test a flessione ottenute tramite modellazione a elementi finiti rispetto alla media delle tre curve ottenute tramite valutazioni sperimentali da letteratura.

On the other hand, the BN series requested more demanding calibration because the presence of notches modifies load transfer, local stress fields, and the interaction degree between timber and concrete; however, also in this more complex case, good agreement is observed between experimental and numerical curves. The model correctly reproduces the increased stiffness of the hybrid system and its overall deformation pattern, thus showing that the proposed FE strategy remains valid when the connection includes an explicit mechanical interlock.

3.2 *Effective bending stiffness: FE modelling and analytical evaluation*

Table 1 summarizes the effective bending stiffness values obtained from the different routes. Two trends emerge very clearly: the FE model is highly consistent with the experimental estimates for both beam families, while the direct analytical route based on standard slip-modulus assumptions is noticeably less reliable, particularly for the screw-only case. These findings support the use of calibrated numerical models as a bridge between experiments and simplified design equations.

Table 1. Effective bending stiffness of the benchmark beams. BF=screws only connections; BN=screws+notches connections / Rigidezza flessionale efficace delle travi di riferimento. BF=connessioni con le sole viti; BN=connessioni con viti+intagli.

Beam type	Method	EI_{eff} (kN·m^2)
BF	Experimental tests	885
	Finite Element model	896 (+1%)
	Analytical approach with standard K_s	1246 (+41%)
	Analytical approach with calibrated K_s	1052 (+19%)
BN	Experimental tests	1285
	Finite Element model	1387 (+7%)
	Analytical approach with calibrated K_s	1539 (+20%)

For the BF beam, the FE estimate is aligned with the experimental average. By contrast, the standard Eurocode 5 route results 1246 kN·m^2, which overestimates the experimental value by about 40.8%. This gap indicates that, for the investigated screw-only connection, the conventional slip-modulus estimate does not represent the real deformability of the connection with sufficient accuracy. However, when K_s is derived from a calibrated numerical push-out model, the analytical prediction improves substantially, although it still remains 18.9% higher than the experimental mean. The implication is clear: analytical design remains useful, but it benefits significantly from calibration of the connection stiffness rather than exclusive reliance on code-based equations.

For the BN beam, the FE model again remains close to the experiments, with a difference of 7.1%. This confirms that the numerical framework captures the mechanical benefit introduced by the notch. The analytical result obtained through the hybrid route still overestimates the experimental average by about 19.8%, but it also reveals a second important point: even when K_s is informed by FE analysis, simplified analytical models struggle to represent complex load-transfer mechanisms when geometry contributes strongly to interlock. For hybrid connections the quality of the prediction is limited not only by the value of K_s, but also by the assumptions embedded in the γ–method itself. This suggests that analytical rules for TCC should be refined when notches and mixed transfer mechanisms are involved.

3.3 *Push-out validation tests*

The push-out validation against the RSS specimen of Shi et al. (2022) provides the local-scale confirmation needed to support the global beam simulations. The FE load-slip curve reproduces the initial stiffness, the yielding trend, and the ultimate load level with good agreement (Figure 3). This is an important result because the slip modulus used later in the analytical comparisons is meaningful only if the local connection response is realistically captured.

The successful push-out validation therefore strengthens the interpretation of the beam-level results, and it gives confidence in the use of the numerical framework for calibrated connection characterization.

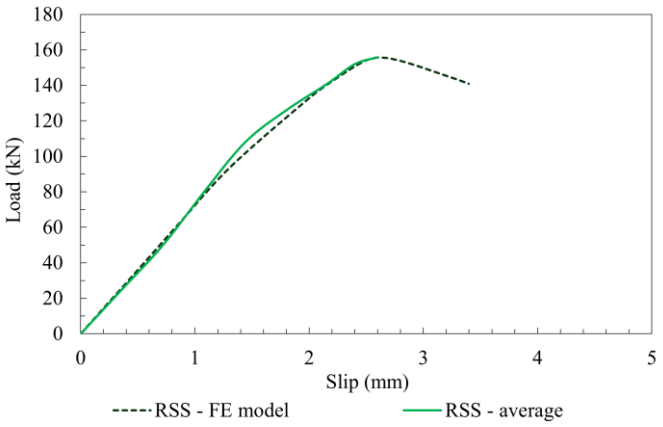


Figure 3. Calibrated FE load-slip curve for push-out test with respect to experimental test derived from literature (Shi et al. 2022). / Curve carico-scorrimento per test di push-out ottenuti tramite modellazione a elementi finiti rispetto alla valutazione sperimentali da letteratura.

3.4 *Composite action evaluation*

A major advantage of the FE approach lies in the possibility of examining internal stress fields that are difficult to measure directly in laboratory tests. The validated simulations show that the BN beam develops a substantially more efficient stress distribution than the BF beam (Figure 4). In the hybrid system, the neutral axis shifts upward, and the longitudinal stress profile becomes almost continuous across the timber-concrete interface, which indicates reduced interlayer slip and stronger composite action. In the BF beam, by contrast, the interface displays a more pronounced stress discontinuity, consistent with a more flexible connection and lower structural efficiency. This mechanical picture is fully coherent with the observed increase in effective bending stiffness for the BN series.

The simulations also provide insight into local failure mechanisms. Critical stress concentrations are predicted near loading regions and around connection zones in the timber, in agreement with the failure patterns described in the benchmark experiments. For steel fasteners, the yielding demand is not uniform: connectors close to the supports experience the strongest shear stresses. From a design perspective, this information is valuable because it shows where local reinforcement, detailing refinement, or spacing reduction is needed. More broadly, it confirms that mechanical interlock does not merely increase global stiffness, as it reorganizes the internal force path in a way that reduces local incompatibility between timber and concrete.

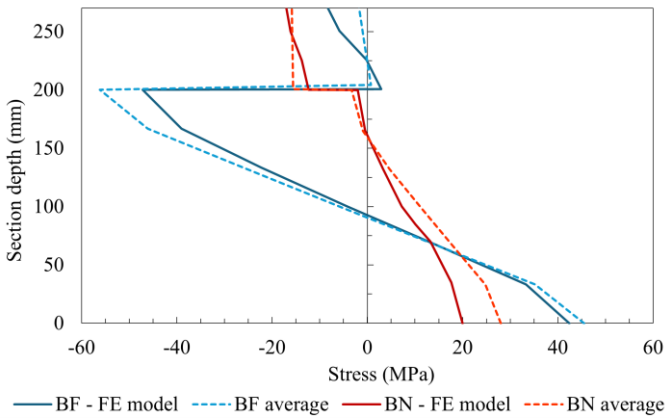


Figure 4. Stress profiles for BF and BN bending tests, at midspan section (Cvetković et al. 2023). / Profili di sforzo per prove a flessione su provini BF e BN, misurati nella sezione centrale.

3.5 *Environmental sustainability assessment*

The simplified LCA complements the structural results by comparing the benchmark BF TCC beam with a structurally equivalent RC beam designed to achieve similar bending stiffness and load-bearing capacity. The adopted scenario considers timber recycling for EOL scenario, and standard manufacturing and EOL scenario both for concrete and steel. Even under these simplified assumptions, the environmental advantage of the TCC solution is substantial, as summarized in Table 2.

Table 2. GWP evaluated for structurally equivalent solutions. / Potenziale di riscaldamento globale per soluzione equivalenti dal punto di vista strutturale.

Component	TCC beam – BF solutions (kg CO_2 eq./m^2)	RC beam (kg CO_2 eq./m^2)
Timber CLT C24 (recycling scenario)	6.3	0.0
Concrete C30/35	25.2	90.0
Steel	5.8 (steel class S355)	2.2 (steel mesh B450C)
Total GWP	**37.3**	**92.2**

The TCC beam reaches a total GWP of 37.26 kg CO_2 eq./m^2, whereas the equivalent RC beam reaches 92.21 kg CO_2 eq./m^2. The TCC solution is therefore associated with an approximately 59% lower climate-change impact. The difference is driven primarily by the large concrete contribution in the RC alternative, while the timber layer in the TCC system benefits from a favourable End-of-Life recycling scenario. These values should be considered as valid for the time and the geographic location chosen for the evaluations, because they depend on product data and EOL assumptions, but they also act to identify those environmental hotspots and to help reducing them.

The structural and environmental findings are synergistic. The connections firstly make the composite action possible and then, through their optimisation, the composite level can be adjusted; in this way, also material quantities – timber and concrete – are optimised, supporting GWP reduction. This coupling suggests that structural optimization of the connection is not a narrow serviceability problem,

but one of the principal levers for sustainable TCC design. At the same time, the results underline the importance of circular-economy assumptions: if timber is recovered or recycled at end of service life, the environmental advantages are shrunk. Design for disassembly and low-carbon concrete therefore remain the next targets to the sustainability of TCC structures.

4 CONCLUSIONS

This paper presents a validated FE framework for some selected timber-concrete composite beams and their connections. A computationally efficient three-dimensional FE model, based on non-linear concrete behaviour, orthotropic timber, and elasto-plastic steel connectors, is able to reproduce benchmark four-point bending and push-out tests with good accuracy. Moreover, the FE estimates of effective bending stiffness are very close to the experimental values for both screw-only and hybrid notch-plus-screw beams, with differences of 1.25% and 7.1%, respectively. Concerning the analytical model, Eurocode 5 γ–method is sensitive to the adopted slip modulus and tends to overestimate stiffness, especially when connection behaviour is complex. Calibrating K_s through numerical push-out analysis significantly improves the prediction, however it does not fully remove the limitations of the simplified analytical framework.

The internal stress distributions explain the superior behaviour of mechanically interlocked systems: notches reduce interlayer slip, shift the neutral axis upward, and produce a more coherent composite stress field. Fifth, the simplified LCA shows that the validated TCC solution is able to reduce Global Warming Potential by nearly 2/3 relative to a structurally equivalent RC beam, thus confirming that structural efficiency and environmental performance can be pursued jointly.

Overall, the study supports the use of calibrated FE models as practical design tools for the analysis, optimization, and sustainability assessment of TCC floor systems. Future developments should address other connections typologies (e.g., bolts, staples, etc.), long term phenomena such as creep and shrinkage, in order to improve predictive capability of numerical modelling, supporting analytical equations and experimental campaigns. Starting from this research, a set of computationally robust models that can be universally adapted can be developed, as a more comprehensive future development.

Questo articolo presenta un modello agli elementi finiti (FE) validato per casi selezionati di travi composte legno-calcestruzzo e per le loro connessioni. Un modello FE tridimensionale computazionalmente efficiente, basato sul comportamento non lineare del calcestruzzo, sul comportamento ortotropo del legno e su connettori in acciaio elastoplastici, è in grado di riprodurre con buona accuratezza prove di riferimento di flessione a quattro punti e prove push-out. Inoltre, le stime FE della rigidezza flessionale efficace risultano molto vicine ai valori sperimentali sia per travi con sole viti sia per travi ibride con intaglio più viti, con differenze pari rispettivamente all'1,25% e al 7,1%. Per quanto riguarda il modello analitico, il metodo γ dell'Eurocodice 5 è sensibile al modulo di scorrimento adottato e tende a sovrastimare la rigidezza, specialmente quando il comportamento della connessione è complesso. La calibrazione di Ks mediante analisi numerica push-out migliora significativamente la previsione, ma non elimina completamente i limiti del quadro analitico semplificato.

Le distribuzioni interne degli sforzi spiegano il comportamento superiore dei sistemi con interblocco meccanico: gli intagli riducono lo scorrimento tra gli strati, spostano verso l'alto l'asse neutro e producono un campo di tensioni composto più coerente. Inoltre, l'LCA semplificata mostra che la soluzione TCC validata è in grado di ridurre il Global Warming Potential di quasi 2/3 rispetto a una trave in calcestruzzo armato (RC) strutturalmente equivalente, confermando così che efficienza strutturale e prestazioni ambientali possono essere perseguite congiuntamente.

Nel complesso, lo studio supporta l'impiego di modelli FE calibrati come strumenti pratici di progetto per l'analisi, l'ottimizzazione e la valutazione della sostenibilità dei solai TCC. Gli sviluppi futuri dovrebbero riguardare altre tipologie di connessione (ad esempio bulloni, graffe, ecc.) e fenomeni di lungo termine quali creep e ritiro, così da migliorare la capacità predittiva della modellazione numerica, a supporto delle formulazioni analitiche e delle campagne sperimentali. Partendo da questa ricerca, si può sviluppare un set di modelli robusti dal punto di vista computazionale, adattabili universalmente, nell'ottica di uno sviluppo futuro più esaustivo.

ACKNOWLEDGEMENTS

The authors would like to thank Syed Ubaidul Amin, former master's student at Politecnico di Milano, for his contribution to the development of the numerical analysis presented in this study.

REFERENCES

Ceccotti, A. 2002. Composite concrete-timber structures. *Progress in Structural Engineering and Materials*, 4(3): 264-275.

Duan, Z., Huang, Q., Zhang, Q. 2022. Life cycle assessment of mass timber construction: A review. *Building and Environment*, 221, 109320.

Dias, A., Schänzlin, J., Dietsch, P. 2018. Design of Timber-Concrete Composite Structures: A State-of-the-Art Report

by COST Action FP1402/WG 4, Shaker Verlag, Aachen, Germany.
Zhang, X., Huang, W., Khajehpour, M., Asgari, M., Tannert, T. 2023. Seismic Performance and LCA Comparison between Concrete and Timber-Concrete Hybrid Buildings. *Buildings*, 13(7), 1714.
Gutkowski, R., Brown, K., Shigidi, A., Natterer, J. 2008. Laboratory tests of composite wood-concrete beams. *Construction and Building Materials*, 22(6), 1059-1066.
Hu, Y., Wei, Y., Chen, S., Yan, Y., Zhang, W. 2021. Experimental Study on Timber-Lightweight Concrete Composite Beams with Ductile Bolt Connectors. *Materials*, 14(10), 2632.
Fragiacomo, M., Ceccotti, A. 2006. Long-Term Behavior of Timber-Concrete Composite Beams. I: Finite Element Modeling and Validation. *Journal of Structural Engineering*, 132(1), 13-22.
Lukaszewska, E., Fragiacomo, M., Johnsson, H. 2010. Laboratory Tests and Numerical Analyses of Prefabricated Timber-Concrete Composite Floors. *Journal of Structural Engineering*, 136(1), 46-55.
Balasbaneh, A. T. , Sher, W., Yeoh, D., Koushfar, K. 2022. LCA & LCC analysis of hybrid glued laminated Timber-Concrete composite floor slab system. *Journal of Building Engineering*, 49, 104005.
CEN, 2025. Eurocode 5: Design of Timber Structures - Structural design of timber-concrete composite structures - Common rules and rules for buildings, European Committee for Standardization, Brussels.
Cvetković, R., Ranković, S., Mišulić, T. K., Kukaras, D. 2024. Experimental Analysis of Mechanical Behavior of Timber-Concrete Composite Beams with Different Connecting Systems. *Buildings*, 14(1), 79.
Shi, B, Dai, Y., Tao, H., Yang, H. 2022. Shear performances of hybrid notch-screw connections for timber-concrete composite structures. *BioResources*, 17(2), 2259-2274.
Dassault Systèmes, SIMULIA, Abaqus/CAE 2022.
ISO, 2017. ISO 21930: Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services, International Organization for Standardization, Vernier.
CEN, 2021. EN 15804:2012 + A2:2019: Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, European Committee for Standardization, Brussels.