Behaviour of a Timber-Concrete Composite Beam with Glued Connection at Strength Limit State

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Summary

The paper reports the results of a collapse test performed on a 6 m span timber-concrete composite beam with glued re-bar connection. The beam was first ramp loaded to failure, then some push-out tests were performed on specimens cut from the end of the beam in order to fully characterise the connection. During the tests all relevant quantities such as deflections, slips and strains were monitored. The experimental results are compared with those carried out using a FE numerical software and the analytical procedure proposed by Ceccotti according to the Eurocode 5 (EC5). An overall good correspondence was found, as long as realistic properties of the connection such as those obtained through push-out tests are used. Conversely the approximate formulas suggested by the EC5 for evaluating the connection properties are too conservative. Their use may lead to too stiff and strong connections, with possible undesirable brittle failure of the whole composite beam.

1. Introduction

Timber-concrete beams (TCCs) represent a structural technique widely used for strength and stiffness upgrading of existing floors and new constructions. This technique consists of connecting an existing or a new timber beam with a concrete slab poured above a timber decking using a connection system [1]. A steel mesh is placed into the slab to resist possible tensile stresses due to bending, and to reduce crack width of concrete.

The performance of the composite beam at strength limit state markedly depends upon the properties of the connection system. Several types of connection systems are manufactured [1], and almost all are deformable. Consequently, a vertical deflection of the composite beam occurs together with a relative slip between the timber beam and the concrete slab. The TCC is therefore an internally statically indeterminate system where the solution depends on the stress-strain laws adopted for timber, concrete and connection system. Furthermore, the connection system exhibits a non-linear shear force-relative slip relationship even for low value of the load [2,3].

Due to the complexity of the problem, a series of experimental tests is desirable in order to investigate the real behaviour of the composite structure. The results of the tests may be used to check the accuracy of approximate design procedures such as that proposed by Ceccotti [1] in accordance with provisions of Eurocode 5 [4,5], and by Frangi and Fontana [6]. Furthermore, experimental tests provide useful data for the calibration of non-linear Finite Element numerical models [7]. Quite a few collapse tests have been performed so far. Bonamini et al. [8] tested composite beams made of ancient solid timber with glued re-bar connection. Kenel and Meierhofer [9] tested composite beams made of solid timber with SFS screw connectors. Grantham et al. [10] reported some results on a full-scale test performed on a timber floor strengthened with SFS screws and lightweight aggregate concrete. Capozucca [11] described some collapse tests performed on a composite beam with a particular type of connection. A wide series of collapse tests on different types of connection systems is described in [2]. A strong dependency of the collapse load and type of failure upon the type of connection system was found.

This paper reports the outcomes of a collapse test performed on a TCC with glued connection. After a long-term test lasting for 5 years in outdoor conditions, the beam was ramp loaded to failure. Eventually, some push-out tests were performed on specimens cut from the end of the beam in order to fully characterize the connection. The most important quantities such as deflection, slip, and strains were monitored during the test. The experimental results are critically discussed and compared with numerical and analytical outcomes based on the use of the Eurocode 5 approximate formulae. Some recommendations for the design of timber-concrete composite beams at strength limit state are finally given.

2. Description of the composite beam

The TCC subjected to the experimental test is represented in Fig. 1. This structure is a model in smaller length of a real 10 m span composite floor realized in Forlì, Italy [12]. Two glued laminated beams made of European spruce timber were connected to a normal weight concrete slab cast above a corrugated steel sheathing. The glulam was purchased as strength class GL24h according to prEN 1194 [13]. However, on the basis of the material tests performed, a Young's modulus of timber E_w=10000 MPa was measured. This result proves that the timber used in the test was in the lower tail of the statistical distribution of stiffness. The concrete was characterized by a mean value of the cylindrical compressive strength f_{cm}=30.4 MPa. The connection system was realized through 18 mm diameter corrugated re-bars made of Italian steel Fe B 44 k (yield strength $f_{yk} \geq 430$ MPa, tensile strength $f_{tk} \geq 540$ MPa, elongation at maximum force $\varepsilon_{uk} \geq 7.5$ %). The bars were placed inside holes drilled in the timber beams and filled with epoxy resin. The spacing of connectors varied from 150 mm over the supports to 300 and 450 mm in the middle of the span, according to Fig. 1.

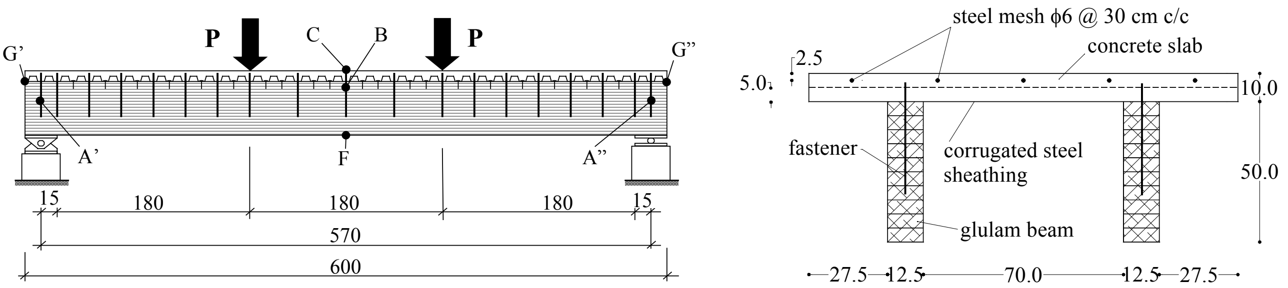


Fig 1 Longitudinal view and cross-section of the composite beam (measures in cm)

3. Testing programme

The TCC was first subjected to a long-term test under sustained load lasting for 5 years [12,14]. After the end of the long-term test, the composite beam was subjected to a preliminary four-point loading test where the beam was twice loaded and unloaded in elastic range in order to check out the instrumentation and to estimate the position of the neutral axis. The beam was then tested to failure. Eventually, two push-out specimens were cut from the end of the beam and tested to failure in order to measure the connection properties.

3.1 Collapse test

The test was performed by applying a four-point loading cycle up to the total load $2P$=80 kN first. The beam was then ramp loaded to failure in controlled displacement at 0.035 mm/s rate. The following quantities were continuously monitored during the test for both glulam beams No.1 and No. 2 (Fig. 1):

- total $v_{\max,t}$ mid-span deflection using LVDTs with 100 mm base applied at the bottom fibre of the timber beam (point F);
- compression Δv perpendicular to the grain over the supports using dial gauges (points A', A");
- net $v_{\max}$ mid-span deflection, obtained by reducing the total deflection $v_{\max,t}$ by the compression perpendicular to the grain Δv of the timber beam over the supports;
- relative slips $s_{\max}$ between concrete slab and timber beam over the supports using LVDTs with 25 mm base (points G', G");
- mid-span timber strains at the bottom fibre $\varepsilon_{w,l}$ (point F) and at 50 mm from the upper fibre $\varepsilon_{w,u}$ (point B) using strain gauges;
- mid-span concrete strains at the upper fibre $\varepsilon_{c,u}$ (point C) above the timber beams, using strain gauges.

The collapse occurred under a total load $2P$=500 kN due to tensile failure of timber beam No. 2 at the level of 23.6 MPa in the weaker regions of the laminations such as knots and finger joints. Such a value of stress is closer to the characteristic strength of GL24h glulam timber under bending coupled with tension, which is 20.9 MPa according to the Eurocode 5 [4], than the corresponding medium strength of 29.9 MPa. This result, which is in accordance with the reduced Young's modulus measured in the material tests, confirms that the glulam timber was in the lower tail of the statistical distribution for both strength and stiffness.

Figs. 2, 3, 4, 5, 6 and 7 display the total load $2P$ vs. net mid-span deflection, slip, lower timber stress, upper timber stress, upper concrete stress, and distance of the neutral axis from the upper timber fibre, respectively (thin solid lines). Each figure reports also the theoretical limit cases of rigid and no connection between timber and concrete slab (thick solid lines). The design loads for Serviceability Limit State (SLS), $2P_s$=204.9 kN, and for Ultimate Limit State (ULS), $2P_u=2P_s\gamma_Q$=307.4 kN, are plotted as well (thin dotted lines), γ_Q=1.5 denoting the partial factor for variable actions. Looking at the figures, the following remarks can be made:

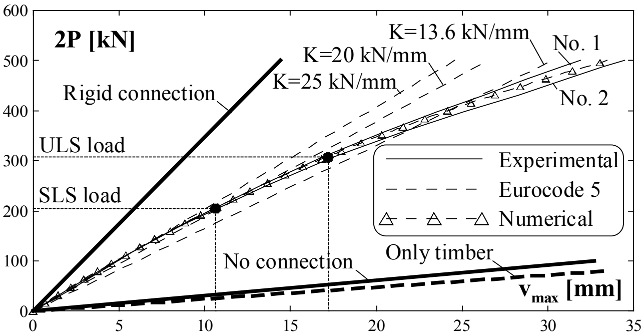


Fig 2 Total load vs. mid-span deflection

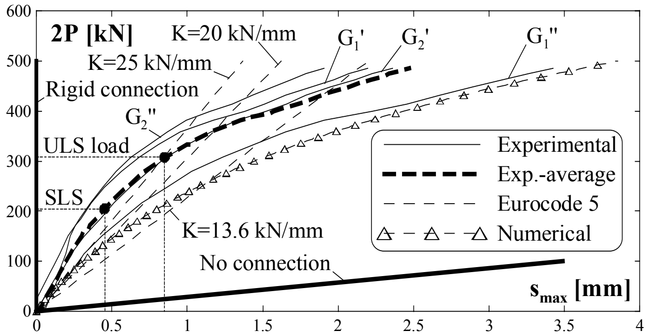


Fig 3 Total load vs. slip over the supports

The experimental collapse load, which can be regarded as a medium value, was 1.63 times as large as the design load for ULS, which was calculated using the approximate procedure proposed by Ceccotti [1] and described in Section 5.1. The actual connection properties as measured from the push-out tests (see Section 5.3) were employed. The design load for ULS is the maximum load that makes the first material among timber, connection and concrete reach the design stress $f_d=k_{mod}f_k/\gamma_M$, where k_{mod}=0.9 is the strength modification factor, f_k is the characteristic strength, usually assumed as 70 % of the medium strength f_m, and γ_M=1.25 is the partial factor for material strength. Based on such considerations the expected medium collapse load for failure in tension of the timber beam would be $2P_c = \gamma_M 2P_u/0.7$=548.9 kN, which is about 10 % larger than the actual collapse load. Such a difference is mainly due to the actual strength of timber, which was lower than the medium value. The collapse was brittle, as can be observed in Fig. 2 where there is almost no plastic phase and the load-deflection relationship has only a slight curvature. The connection was, in fact, very stiff and resistant being the same as that used for the 10 m span composite floor realized in Forlì [12].

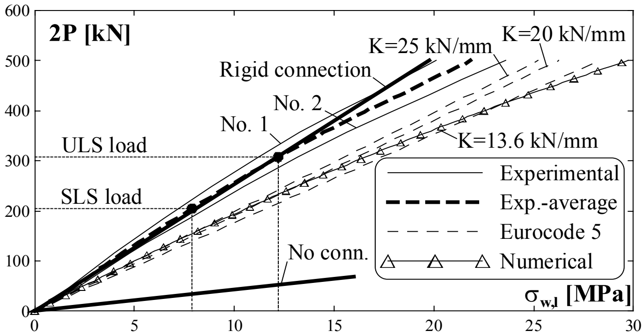


Fig 4 Total load vs. timber stress in the lower fibre at mid-span

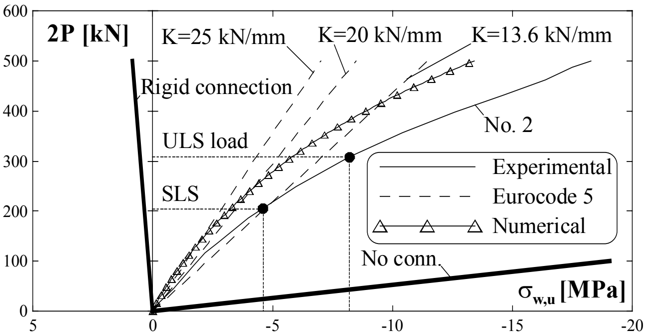


Fig 5 Total load vs. timber stress at 50 mm from the upper fibre at mid-span

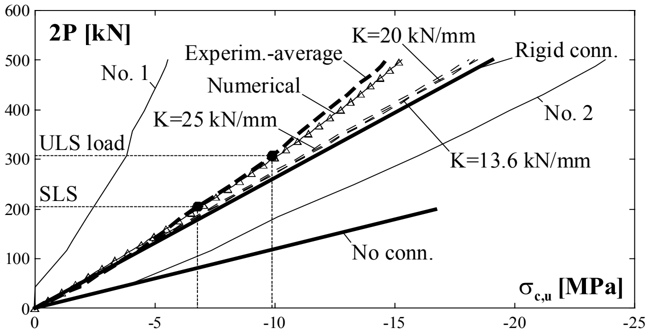


Fig 6 Total load vs. concrete stress in the upper fibre at mid-span

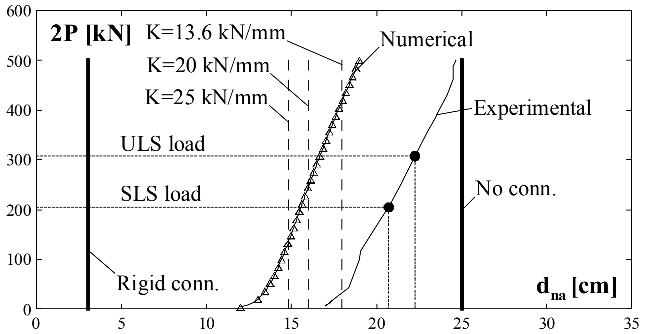


Fig 7 Total load vs. distance of the neutral axis of beam No. 2 from the upper timber fibre

The composite action achievable by interconnecting timber and concrete can be estimated by the quantity E, usually defined as composite efficiency, which is given by:

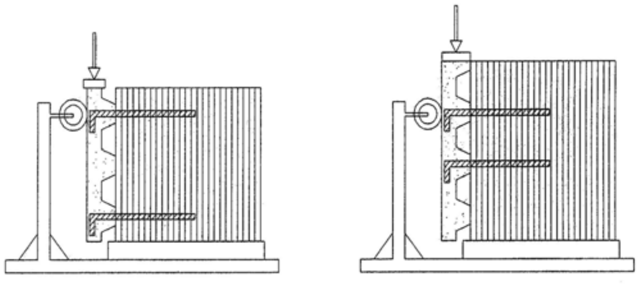
$$E = \frac{v_{nc} - v}{v_{nc} - v_r} \cdot 100 \qquad [1]$$

where v signifies the mid-span deflection and the subscripts nc, r refer to the cases of no and, respectively, rigid connection. For the tested beam, the values 93 % to 87 % were achieved from half SLS load to the actual collapse load. The large value of the composite efficiency achieved throughout the test confirms that the connection was very stiff. The beneficial effect of the concrete slab can be achieved only by interconnecting it with the timber beam. A timber beam (thick dashed line) and a composite beam with no connection (thick solid line) do not exhibit, in fact, significant differences (see Fig. 2).

There is a scatter of experimental results in terms of relative slips (Fig. 3) and, mostly, stresses in the upper fibre of the concrete slab $\sigma_{w,u}$ (Fig. 6), which have been computed from the corresponding measured strains $\varepsilon_{w,u}$ using the Saenz law. The relative slips and the timber stress at 50 mm from the upper fibre exhibit non-linear behaviour while the timber stresses in the lower fibres and the stress in the concrete have more linear trends (Figs. 3, 4, 5, and 6). The distance of the neutral axis from the upper timber fibre increases from 17 cm for low load levels to 24.6 cm at collapse (Fig. 7), a value very close to the limit case of no connection. Such an increase takes place because of the plasticization in compression of the concrete slab and some non-linear behaviour of the connection.

3.2 Push-out tests

After the collapse test, push-out tests were performed on two adjacent segments cut from the end of timber beam No. 1. The specimens were ramp loaded to failure. Both load and relative slips were monitored, the latter ones using LVDTs. The experimental set-up is depicted in Fig. 8. The shear load vs. slip curves are reported in Fig. 9 where the shear load *F* refers to one connector. The specimens exhibited quite different behaviour. Specimen No. 1 was, at the beginning, stiffer but collapsed earlier at 28.6 kN because of several cracks occurring in the concrete slab. Specimen No. 2 however exhibited a more regular trend with lower stiffness and higher collapse load of 39.7 kN. In Fig. 9 the point corresponding to the slip monitored at collapse of the composite beam is also reported. The evidence that such a beam did not fail in the connection suggests that the most reliable curve is the one exhibited by specimen No. 2.



Specimen No. 1

Specimen No. 2

Fig 8 Experimental set-up of the push-out test

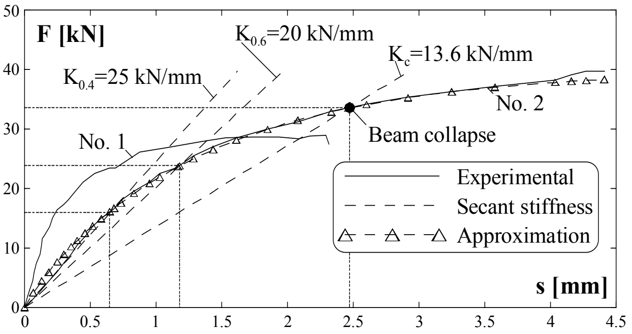


Fig 9 Shear force vs. relative slip during the push-out test

4. Comparison with numerical solutions

The experimental results have been compared with the numerical outcomes carried out using a non-linear software based on the use of one-dimensional finite elements. The software, originally developed for long-term and collapse analyses of steel-concrete composite beams [7], accounts for the deformability of the connection system and for the non-linear mechanical behaviour of the component materials (steel profile, concrete slab, reinforcement and connection system). A modification was made in order to replace the steel profile with a timber beam, for which an elasto-brittle relationship in tension and an elasto-plastic relationship in compression were introduced. The shear force-relative slip curve obtained from the push-out test for Specimen No. 2 has been approximated (Fig. 9) using the equation reported below:

$$F = F_{\max}(1 - e^{-\beta s})^{\alpha} \qquad [2]$$

with $F_{\max}$=40 kN, α=0.9 and β=0.7 mm^{-1}.

The numerical curves, represented with small triangles in Figs. 2 to 7, are very close to the experimental ones in terms of deflection and upper concrete stress. Some differences can be recognised for the slip, timber stresses and position of the neutral axis, as can be observed also from Table 1, when experimental and numerical results are compared at the serviceability (SLS), ultimate (ULS) and actual collapse loads. Despite the differences, however, the numerical curves always follow the experimental trends. At the experimental collapse, the stress in the lower fibre of timber reaches the value of $\sigma_{w,l}$=29.7 MPa (Table 1). The medium value of strength in bending coupled with tension for GL24h glulam timber is equal to 32.2 MPa according to Eurocode 5 [4] for the tensile and bending stresses computed by the software. This means that a slightly larger medium collapse load than that observed in the experimental test would be predicted using the numerical software. However, it must be highlighted that the prediction of the actual collapse load is a very difficult task, mainly because of the scatter in the strength properties of timber. A probabilistic approach such as that based on the Monte Carlo simulation should be followed when the prediction of the collapse load is of interest for a timber-concrete composite beam.

Table 1 Experimental-numerical-analytical comparison (K in kN/mm)

	SLS load 2P=204.9 kN			ULS load 2P=307.4 kN			Actual collapse load 2P=500.0 kN			
	Exp.	Num.	Anal. K=25	Exp.	Num.	Anal. K=20	Exp.	Num.	Anal. K=13.6	Anal. K=20
v_{max} [mm]	10.6	10.5	10.1	17.2	17.1	16.3	33.2	33.4	30.3	26.5
s_{max} [mm]	0.45	0.80	0.58	0.85	1.51	1.03	2.47	3.85	2.20	1.62
$\sigma_{w,l}$ [MPa]	7.9	10.6	10.3	12.2	16.6	8.98	21.8	29.7	28.3	26.2
$\sigma_{w,u}$ [MPa]	-4.60	-3.25	-2.87	-8.20	-5.80	-5.22	-18.3	-13.4	-11.4	-8.49
$\sigma_{c,u}$ [MPa]	-6.80	-6.95	-7.60	-9.9	-10.1	-11.3	-14.7	-15.3	-18.1	-18.3
d_{na} [cm]	20.7	15.6	14.8	22.3	16.7	16.0	24.6	19.0	18.0	16.0

5. Comparisons with the Eurocode 5 analytical solutions

5.1 The simplified approach

A simplified approach in accordance with Eurocode 5 [4,5] for SLS and ULS verifications of TCCs was proposed by Ceccotti [1]. The procedure assumes linear elastic behaviour of all component materials (timber, concrete and connection) for instantaneous loading. The flexibility of the connection system is taken into account using the approximate formulae suggested by the Annex B of Eurocode 5 [4] for timber-timber composites. The actual non-linear behaviour of the connection is accounted for by adopting different values of elastic stiffness for SLS and ULS verifications. For the former verifications, the secant value $K_{0.4}$ at 40 % of the collapse shear load is used, while for the latter ones the secant stiffness $K_{0.6}$ at 60 % is suggested (Fig. 9).

5.2 Evaluation of the connection properties

In order to obtain the best accuracy when studying TCCs, it is crucial to know the actual connection properties. When experimental results are not available, the Eurocode 5 - Part 2 [5] suggests the use of the formulae proposed for timber-timber joints in the Part 1-1 [4] by multiplying the corresponding stiffness $K_{0.4}$, $K_{0.6}$ and shear strength $F_{v,rm}$ by 2 and 1.2, respectively. The comparison between the mean analytical values, which were obtained by dividing the characteristic ones by 0.7, and the values measured in the experimental push-out test is reported in Table 2. Although the analytical values are conservative, the errors with respect to the experimental ones are significant (about 50 %). The use of the Eurocode 5 formulae would lead, for the case under study, to markedly underestimate connection stiffness and strength and, hence, to larger resistance but brittle failure of the composite beam. The evaluation of the actual connection

Table 2 Experimental-analytical comparison for the push-out test on the connection system

	Experimental	Analytical	Error %
$K_{0.4}$ [kN/mm]	25.0	14.9	-40.2
$K_{0.6}$ [kN/mm]	20.0	10.0	-50.2
$F_{v,rm}$ [kN]	39.7	23.0	-42.2

properties using push-out tests is hence recommended for the best design of TCCs. In the absence of experimental results obtained through push-out tests, the stiffness of glued re-bar connections may be approximately evaluated by doubling the value proposed by Turrini and Piazza [15]:

$$K_{0.4}=0.16E_{w}d \qquad [3]$$

where E_w and d are, respectively, the Young modulus of timber and the diameter of re-bar. For the case under study, such a formula would lead to the more realistic values $K_{0.4}$=28.8 kN/mm and $K_{0.6}$=2/3·$K_{0.4}$=19.2 kN/mm.

5.3 Prediction of the behaviour at strength limit state

The thin dashed lines displayed in Figs. 2 to 7 represent the analytical solutions evaluated assuming different values of the connection secant stiffness: $K_{0.4}$=25 kN/mm, $K_{0.6}$=20 kN/mm and K_c=13.6 kN/mm (Fig. 9 and Tab. 2), where K_c is the secant stiffness for the collapse point of the composite beam on the push-out curve of the connection system. The comparison with the experimental and numerical results is summarized in Table 1 for the SLS design load, ULS design load, and actual collapse load. An overall good approximation can be noted when the values $K_{0.4}$, $K_{0.6}$ and K_c of the connection stiffness are employed, respectively, under the SLS, ULS and actual collapse load. The use of the analytical approach leads to fairly accurate predictions for almost all quantities to check. Conversely the use of $K_{0.6}$ for predicting the actual medium collapse load would lead to underestimate nearly all effects. Thus it is important to assume lower value of secant stiffness such as $K_{0.8}$ or K_c when predicting medium experimental collapse loads.

6. Conclusions

In this paper the results of a comprehensive collapse test performed on a 6 m span timber-concrete composite beam with glued-in connection have been presented. The beam was subjected for 5 years to sustained load in unsheltered outdoor conditions and eventually ramp loaded to failure. Some push-out tests were also performed on specimens cut from the composite beam with the purpose to investigate the connection properties. The most important quantities, such as mid-span deflection, slip over the support, and timber strains were all monitored during the tests. Experimental results have then been compared with those computed using a non-linear FE software and using the analytical formulae suggested by Ceccotti in accordance with Eurocode 5.

It is found that the composite beam exhibited a very stiff behaviour during the collapse test. The collapse, due to timber failure in tension under a total load equal to 2.44 times the service design load, was brittle and no important plasticization of the connection system was observed. The connection has to be stiff enough to achieve a good composite efficiency. In order to increase the structural ductility and to allow for the plasticization, however, the connection should not be too resistant. It is then recommended that the connection properties be evaluated by performing experimental push-out tests since the use of the analytical formulae suggested by the Eurocode 5 largely underestimate both stiffness and strength of connection. The use of such formulas for the design, hence, may lead to too stiff and resistant connections, with undesirable brittle failures of the whole composite beam.

The comparison between experimental and numerical results carried out using a FE software based on the use of a one-dimensional element with deformable connection, highlights an overall good approximation mainly in terms of deflection, while local quantities such as slip and stresses in timber are more difficult to predict. The experimental non-linear trends are followed with reasonable accuracy provided the actual constitutive law of the connection is implemented. However, the prediction of the actual collapse load is a difficult task mainly because of the scatter of the timber properties.

The analytical procedure proposed by Ceccotti leads to reasonable approximations, as long as actual values of the connection properties are employed. The use of the connection secant stiffness at 40 % and 60 % of the collapse shear load, as evaluated in push-out tests, allows the designer to accurately predict all relevant quantities to be checked under, respectively, the SLS and ULS design load.

7. References

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