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ORIGINAL ARTICLE

Short- and long-term performance of the "Tecnaria" stud connector for timber-concrete composite beams

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Abstract The paper presents the results of some experimental tests performed on the shear stud connection system for timber-concrete composite beams manufactured by the Tecnaria Ltd. Some push-out specimens constructed using both normal weight (NW) and light weight (LW) concrete were subjected to collapse and long-term creep tests. During the collapse test, the connector exhibited significant strength and stiffness. In the creep test performed in constant environmental conditions, delayed (creep) deformations took place mainly during the first days after loading. The next part of the creep test, conducted under cycles of environmental relative humidity, was characterized by an increase in delayed deformations (the so-called mechano-sorptive effect) due to the hygroscopic behaviour of timber around the connector. The amount of delayed deformation depended upon the cycle duration and was negligible for short period (less than one week) cycles. The use of LW concrete instead of NW concrete was found not to significantly affect the performance of the connection system neither in the long-term, nor in the collapse tests.

Keywords Stud connector · Creep · Timber-concrete composite beams · Wood · Structural engineering

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1 Introduction

The timber-concrete composite beam (TCC) is a construction technique which has become quite common in many countries. By connecting a sawn or glue-laminated timber beam with a concrete slab it is possible to achieve a number of advantages, such as [1]:

- the possibility to keep the original timber structures, particularly important in ancient buildings of great value, with at the same time a significant increase in stiffness and strength;

- the creation of a rigid floor diaphragm, which markedly improves the seismic performance of the building;
- an increase in the acoustic separation, thermal mass, and fire resistance of the floor.

In terms of static performance, the materials are exploited at the best in the TCC, with the timber web mainly subjected to tension and bending, the concrete flange mainly subjected to compression, and the connection system subjected to shear. However, a stiff and strong connection system has to be used in order to achieve a suitable bending strength and stiffness of the TCC. Only in this way, in fact, the relative slip between the bottom fibre of the concrete slab and the top fibre of the timber beam can be kept low, and a high composite efficiency is achieved. Several types of connection systems are currently manufactured [1–4]. The so-called ''dry'' connectors, generally made of screws, dowels, or bars screwed or driven into the timber beam after drilling a pre-hole, are extensively used. The main advantage is their relative inexpensiveness, since they do not involve the use of glue [5–8]. Among them, there is the stud connector manufactured by the Tecnaria Ltd. (http://www.tecnaria.com), which is made of a 12 mm diameter steel stud welded on a 4 mm thick, 50 × 50 mm square metal plate. The corners of the plate are bent so as to form four ''crampons'' which are embedded into the timber beam for about 7 mm (Fig. 1).

Fig. 1 ''Tecnaria'' connector

The connection with the timber beam is also achieved by means of two 8 mm diameter screws embedded for a length of 110 mm.

According to current codes of practice [1, 9–10], TCC's must be checked for Ultimate (ULS) and Serviceability Limit States (SLS). The former verifications require the control of the strengths of all component materials (concrete, timber, and connection system), while the latter ones require the verification of the maximum deflection in the short- and long-term under, respectively, the rare and quasi-permanent load combination. Hence the effectiveness of a connection system needs to be measured in terms of strength, which affects the ULS control, and stiffness, which affects both the ULS and SLS controls. Since the deflection control has to be carried out also in the long-term (i.e. at the end of the service life of the structure), the creep and shrinkage/swelling of the component materials need to be taken into account [11, 12]. Hence, in addition to the short-term (collapse) behaviour, it is important to investigate the long-term (creep) behaviour of the connection system. While several studies were performed to characterize the connection behaviour in the short-term [2–8], little research has been done in order to investigate the creep of the connections [5, 13–15]. In the few long-term tests performed, however, the authors recognized that the connection creeps, and the amount of delayed slip seems to be affected by the environmental relative humidity.

This paper reports the results of an experimental investigation performed on the ''Tecnaria'' connection system. The tests were undertaken at the Laboratory for Structures and Materials of the University of Trieste, Italy. The behaviour of the connector was fully characterized in terms of shear strength and stiffness at strength and serviceability limit state, in both short- and long-term. Some push-out specimens were tested to failure, while some others were tested in the long-term under sustained load in both constant and variable (cyclic) environmental relative humidity. Based on the experimental results, the statistical values such as the average and 5th percentile are provided for the most important quantities affecting the design of the composite beams such as stiffness, strength, and creep coefficients. Some simplified and more advanced rheological models for the time-dependent behaviour of the connection system are also proposed.

2 Experimental programme

The experimental campaign on the ‘‘Tecnaria’’ connection involved 18 push-out specimens, half of which with slab made of C20/25 class normal weight (NW) concrete according to the Eurocode 2, Part 1–1 [16], and half with slab made of LC9/11 class light weight (LW) concrete according to the Eurocode 2, Part 1–4 [17]. The LW concrete was obtained by mixing expanded clay, sand, class 42.5 cement, water, and super plasticizer admixture. The reduced strength of the LW concrete does not question the validity of the tests since the failure always occurred on the timber side. In each push-out specimen, two connectors per side linked the GL28h class glue-laminated timber beam, according to the prEN 1194 [18] regulation, to the two concrete flanges poured on a timber decking which was discontinuous above the timber beam. A 6 mm diameter, 100 × 100 mm steel mesh was placed at the middle fibre of each concrete flange. Figure 2 depicts the specimen during the collapse push-out test, while Fig. 3 shows a plot of the specimen cross-section with the dimensions, and Fig. 4 represents the experimental set-up for the long-term test under sustained load.

Fig. 2 Collapse push-out test

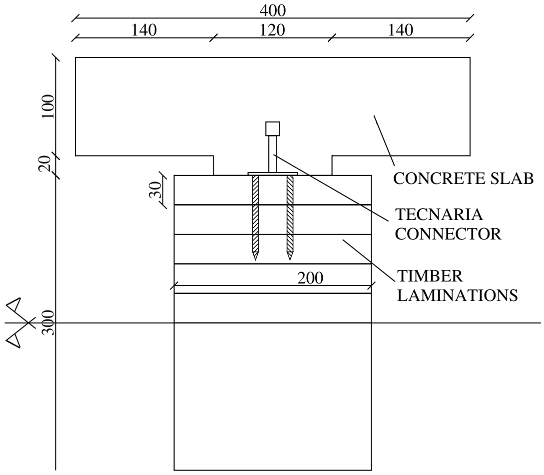

Fig. 3 Half cross-section of the push-out specimens (dimensions in mm)

The tests were performed in the following order:

- preliminary collapse tests on six specimens (three with NW and three with LW concrete), in order to measure the strength and stiffness in the short-term;
- long-term tests (under sustained load) in constant environmental conditions on twelve specimens different from the previous ones (six with NW and six with LW concrete), in order to measure the creep coefficient;

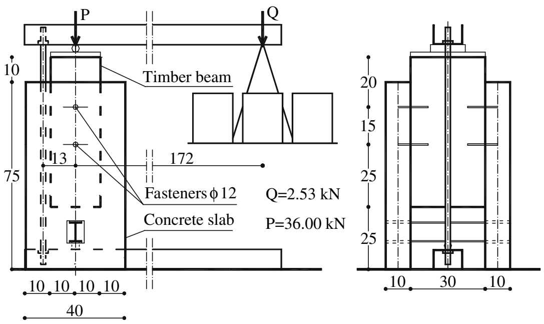

Fig. 4 Lever apparatus used in the long-term test to apply a sustained load (dimensions in cm)

- long-term tests (under sustained load) on the same twelve specimens but in variable environmental conditions, characterized by cycles of relative humidity with different durations, in order to measure the increase in delayed slip due to the variation of relative humidity;
- unloading of the twelve specimens in constant environmental conditions, in order to measure the creep recover;
- final collapse tests on all twelve specimens previously subjected to the long-term tests, in order to measure strength and stiffness in the short-term, and to establish whether such quantities are affected by the previous load history.

3 Collapse tests

The collapse tests were performed in two phases:

- before the long-term tests, on three specimens with NW concrete and three specimens with LW concrete (preliminary collapse tests);
- after the long-term tests, on six specimens with NW concrete and six specimens with LW concrete (final collapse tests).

The load was applied by means of a 600 kN capacity hydraulic jack. The relative slips between the timber beam and the concrete slab were measured with four 50 mm base Linear Voltage Displacement Transducers (LVDTs) located on the four corners of the specimens (Fig. 2). The average of the four slips was calculated for every specimen and each value of the load applied. During the final collapse tests, the loading protocol suggested by the EN 26891 [19] regulation which applies a loading-unloading cycle before the final ramp loading to failure was followed. All experimental outcomes were processed according to the aforementioned regulation. The moisture content of timber was 10.5%.

3.1 Preliminary collapse tests

The shear force vs. slip curves for the preliminary collapse tests are depicted in Fig. 5, where the shear force refers to one connector. The outcomes of the tests are reported in Table 1 as statistical values for the specimens with normal weight (NW), light weight (LW) concrete, and all the specimens (NW+LW) together. The quantities F_{max}, k_i, k_s, $k_{0.6}$ and $k_{0.8}$ represent, respectively, the shear strength, the initial secant shear modulus, the secant shear moduli at 40%, 60%, and 80% of the shear strength. The results for each specimen separately considered are reported in [20].

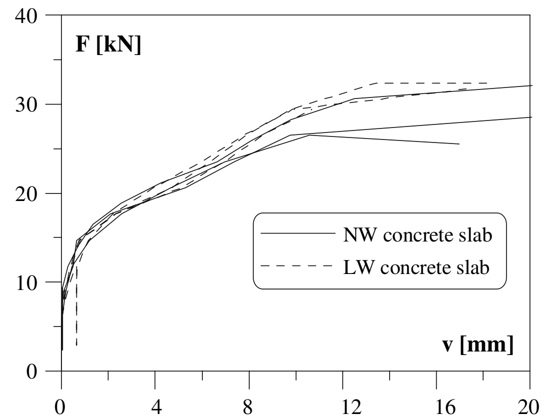

Fig. 5 Shear force-relative slip curves measured in the preliminary collapse tests

3.2 Final collapse tests

Figure 6 depicts the shear force vs. relative slips curves monitored during the final collapse tests performed at the end of the long-term tests, with the shear force referred to one connector. Table 1 reports the statistical values computed by leaving out the outcomes of one atypical specimen (the one characterised by the lower curve in Fig. 6). The results for each specimen separately considered are reported in [20].

3.3 Discussion of the results

Based on the results of the collapse tests, the following remarks can be made:

- The ‘‘Tecnaria’’ connection exhibited a very stiff behaviour with limited relative slips for low values of the shear force ($F < 0.2\ F_{max}$), thanks to the contribution provided by the crampons of the steel plate (Fig. 1). This is particularly evident in the preliminary collapse tests (Fig. 5). When the load increased,

Table 1 Statistical outcomes of the preliminary and final collapse tests evaluated on specimens with normal weight (NW), light weight (LW) concrete slab, and on the sum of all specimens (NW + LW)

Type of specimens	Quantity	Preliminary collapse test					Final collapse test				
		F_{max} [kN]	k_i [N/mm]	k_s [N/mm]	$k_{0.6}$ [N/mm]	$k_{0.8}$ [N/mm]	F_{max} [kN]	k_i [N/mm]	k_s [N/mm]	$k_{0.6}$ [N/mm]	$k_{0.8}$ [N/mm]
NW	Minimum	26.5	28793	21595	7726	3349	33.5	7570	13309	3556	2905
	Maximum	31.1	33049	25013	10720	4131	36.2	18053	21533	5808	3684
	Average	28.4	31268	23526	9187	3659	35.1	11880	16208	5018	3295
	Stand. Dev.	2.4	2211	1752	1498	416	1.2	3920	3328	923	340
LW	Minimum	29.4	20171	15172	5206	3393	28.6	8940	14092	3886	2785
	Maximum	32.4	30646	23191	7657	3944	36.1	25118	27668	6652	3455
	Average	30.9	24451	18455	6460	3587	32.4	18302	22138	4875	3170
	Stand. Dev.	1.5	5494	4202	1226	310	2.8	6668	5332	1045	280
NW + LW	Minimum	26.5	20171	15172	5206	3349	28.6	7570	13309	3556	2785
	Maximum	32.4	33049	25013	10720	4131	36.2	25118	27668	6652	3684
	Average	29.7	27859	20991	7823	3623	33.6	15383	19442	4940	3227
	Stand. Dev.	2.3	5289	4001	1931	330	2.6	6295	5314	945	299

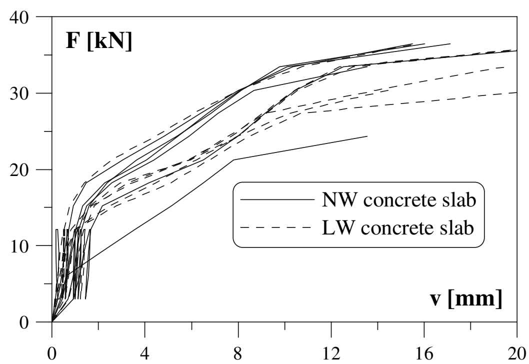

Fig. 6 Shear force-relative slip curves measured in the final collapse tests

some larger slips took place with a consequent reduction in stiffness up to the collapse of the specimen, which occurred into the timber for pull-out failure of the screws.

- The type of concrete of the slab did not markedly affect the connection behaviour neither with reference to the strength, nor to the shear moduli, which did not considerably differ in both preliminary and final collapse tests (Table 1). This agrees with the evidence of both connection strength and stiffness being mainly dependent upon the properties of timber, which is softer and weaker with respect to concrete.
- A clear dependence of the connection shear strength on the previous loading history could not be recognized. However, the shear moduli of the specimens previously subjected to the long-term test were lower than those of the specimens not loaded before, especially for the initial shear modulus k_i.

Based on the aforementioned considerations, the average and 5th percentile of the shear strength and shear moduli were computed by considering the population of all the specimens tested in the preliminary and final collapse tests. The specimen with anomalous behaviour was ignored, and no distinction was made between NW and LW concrete. Only for the initial shear modulus k_i, reference to the final collapse tests was conservatively made, by ignoring the outcomes of the preliminary tests. Table 2 reports the results, where the 5th percentiles were computed by assuming a normal and lognormal distribution, as suggested by the Eurocode 5-Part 1–1 [9]. The 5th percentile of the shear strength F_{max} and the mean values of the secant shear moduli k_s and $k_{0.6}$ are reported in bold. The quantities F_{max} and $k_{0.6}$ are employed for ultimate limit state verifications of timber-concrete composite beams, while the quantity k_s is employed for serviceability limit state verifications, according to the design procedure suggested by Ceccotti [1].

The shear force-relative slip relationship can be approximated using the Ollgard et al. [21] equation:

$$F = F_{max}(1 - e^{-\beta v})^{\alpha} \tag{1}$$

Table 2 Statistical outcomes of all collapse tests performed on the "Tecnaria" connection

Quantity	F_{max} [kN]	k_i[N/mm]	k_s [N/mm]	$k_{0.6}$ [N/mm]	$k_{0.8}$ [N/mm]
Minimum	26.5	7570	13309	3556	2785
Maximum	36.2	25118	27668	10720	4131
Average	32.2	15383	**19989**	**5957**	3367
Stand. deviation	3.1	6295	4820	1934	358
5th percent.-Norm	27.2	5059	12065	2777	2778
5th percentile-Log	**28.4**	5352	11576	2710	2878

which can be used for slips $v < 15$ mm, by assuming the following values: $F_{max} = 77.3$ kN, $\alpha = 0.3408$, and $\beta = 0.00558$ mm^{-1}. Such values were obtained by interpolation of the experimental outcomes "cleaned" by the initial loading-unloading cycle. The analytical-experimental comparison is depicted in Fig. 7. Eq. (1) can be used for non-linear analyses of TCC's, for example by implementing it into numerical packages such as ABAQUS or into non-linear finite element programs purposely developed for composite structures [22, 23].

4 Long-term tests

The long-term test lasted from the 13th June 2000 till the 3rd June 2002 and was conducted in three phases:

- creep tests (under sustained load) in constant environmental conditions;
- creep tests (under sustained load) in variable environmental conditions;
- unloading of the specimens in constant environmental conditions.

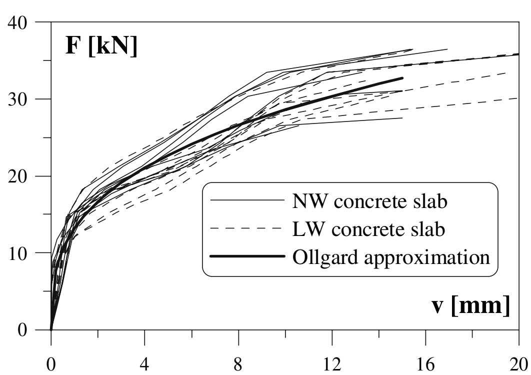

Fig. 7 Analytical-experimental comparison for the collapse test using the Ollgard equation

The tests were performed on twelve push-out specimens, six with NW and six with LW concrete slab. A load Q equal to 30% of the mean shear strength measured in the preliminary short-term tests was applied by means of the lever apparatus depicted in Fig. 4. Such a load level corresponds to the shear load in the connection due to a load combination intermediate between the frequent and the quasi-permanent one.

All the specimens were placed into a climate chamber (Fig. 8) where the temperature was kept constant at 24 Celsius degrees throughout the test. The relative slips between concrete and timber were automatically recorded using four LVDTs per specimen with 0.01 mm accuracy. For every specimen, the average value of slip was calculated at each time. The timber moisture content was manually measured on four specimens at 5 mm, 45 mm and 60 mm depths using a moisture metre.

4.1 Creep tests in constant environmental conditions

The tests were conducted in climate chamber for 103 days under a constant relative humidity

Fig. 8 Picture of the push-out specimens in climate chamber during the long-term test

RH = 70%. Three specimens, two with NW concrete and one with LW concrete slab, were subjected to a loading-unloading cycle up to 30% of the mean shear strength before the beginning of the creep test. The purpose was to investigate whether the previous loading history affects the time-dependent behaviour of the connection. The trends in time of the creep coefficient φ are depicted in Fig. 9, where:

$$\varphi(t, t_0) = [v(t) - v(t_0)]/v(t_0) \tag{2}$$

v being the relative slip between the concrete slab and the timber beam, t and t_0 being the current time and the time of load application, respectively. Despite the rather marked scatter of the results, the creep behaviour of the connection can be clearly appreciated. Two specimens exhibited anomalous behaviour characterized by very low elastic slips. The corresponding curves are the upper and the lower ones in Fig. 9. The specimens previously subjected to the loading-unloading cycle showed a more gradual increase in the creep coefficient compared with the other specimens. However, all the curves approached a nearly horizontal asymptote after the 40th day. No appreciable difference could be noticed between the specimens with NW and LW concrete slab.

The mean creep coefficient, evaluated by averaging the creep coefficients of the six specimens characterized by the most regular behaviour, can be approximated using the generalized rheological model of Kelvin:

$$\varphi(t, t_0) = \varphi(t - t_0) = \sum_i J_i\{1 - \exp[-(t - t_0)/\tau_i]\} \tag{3}$$

where the coefficients τ_i and J_i can be assumed as τ_1 = 0.0677 days, J_1 = 0.1631, τ_2 = 2.9004 days, and J_2 = 0.3245 in the case of two Kelvin's chains. Despite the fairly large load level, the mean creep coefficient at the end of the test was pretty low (about 0.5) when compared, for example, with the corresponding value measured on concrete.

4.2 Creep tests in variable environmental conditions

The tests were performed at the end of the creep tests in constant environmental conditions. The specimens were subjected to cycles of relative humidity characterized by time intervals T at relative humidity RH = 50% followed by time intervals T at RH = 90%. The tests were performed in two phases:

- first phase, lasting for 470 days, when 8 cycles with period $2T$ of 14 days followed by 3 cycles with period $2T$ of 56 days were applied, with eventually a 70-day period with constant relative humidity RH = 50% (Fig. 10);

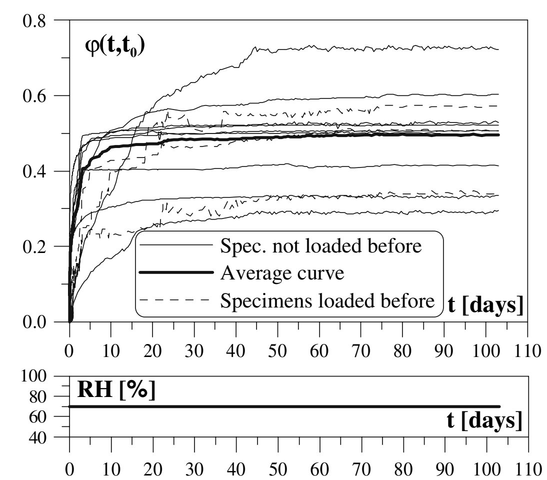

Fig. 9 Trend in time of the creep coefficient of all specimens during the creep test in constant environmental conditions

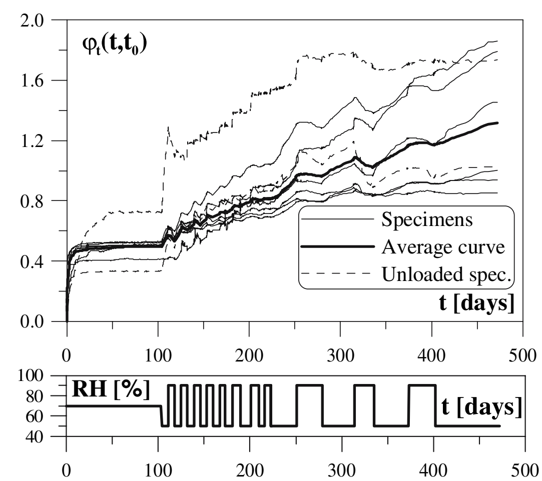

Fig. 10 Trend in time of the creep coefficient of the most representative specimens during the creep test in constant and variable (first part) environmental conditions

- second phase, lasting for 37 days, when 5 cycles with period $2T$ of 7 days followed by 3 cycles with period $2T$ of 1 day were applied (Fig. 13).

The first phase represents environmental changes taking place over medium/long periods of time (1 week/1 month) such that a significant moisture content variation can occur in the timber beam (5%/8% at 5 mm depth, respectively, see Fig. 11). The second phase represents environmental changes taking place over short periods of time (half week/half day) and, as such, is characterized by low moisture content fluctuations in the timber (2.4%/1%, respectively). The outcomes of the first and second phase of test can then be used to measure, respectively, the effect of seasonal and daily relative humidity variations.

A period of time lasting for 169 days elapsed between the two phases. During such a period, no measure was taken and the climate conditions were not conditioned.

4.2.1 First phase

The experimental outcomes during the first phase pointed out a significant scatter of the measures. Some specimens exhibited large increases in slip, while some other specimens were almost insensitive to relative humidity cycles. Among them, two specimens were unloaded 313 days after the loading time. The purpose was twofold: to obtain some information on the slip recover of the specimens in variable environmental conditions, and to have two dummy specimens available against which to compare the slips of the loaded specimens in the second phase. Figure 10 reports the creep curves of the six specimens characterized by the most regular time-dependent behaviour (thin solid line) together with the mean curve (thick solid line). In the same figure, the curves of the two specimens which were unloaded are plotted (thin dashed line). The delayed slip, after approaching an almost horizontal asymptote during the test in constant environmental conditions, markedly increased during the cycles of relative humidity. A reduction in relative humidity led to an increase in slip which is larger for longer period cycles, while a reduction of slip occurred due to an increase in relative humidity. However for the loaded specimens the amplitude of the first increase in slip was larger than the amplitude of the second decrease, thus resulting in an overall increase of delayed slip over time with slightly decreasing rate. The two unloaded specimens were characterized by decreases in slip during moistening periods larger than the increases during the drying periods, thus resulting in an overall decreasing trend of the creep coefficient after the load removal.

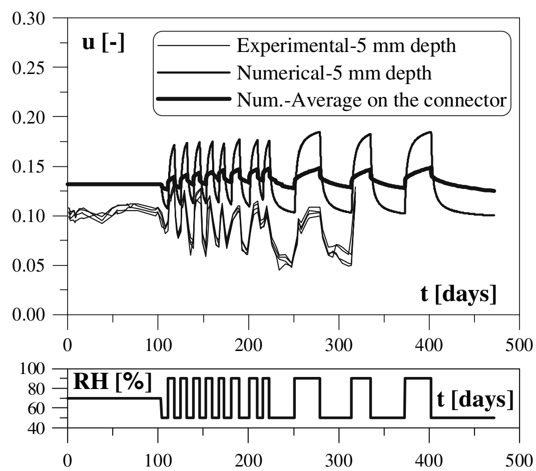

Fig. 11 Trend in time of the experimental and numerical timber moisture content (at 5 mm depth and mean value at the connector location)

This hygroscopic behaviour, called "mechano-sorptive effect", is typical of wood and has been extensively investigated to date [24–26]. It can be concluded that also the connection systems experience such phenomenon due to the hygroscopic behaviour of wood at the interface between the timber beam and the connector. The mean value of the total creep coefficient φ_t measured in the creep test under variable conditions (thick solid line in Fig. 10) can be approximated using the Toratti's model [24], which is based on the following equation:

$$v(t,t_0) = \int_{t_0}^{t} J(t-t_0)\mathrm{d}F(\tau) + J^{\infty}\int_{t_0}^{t}\left\{1-\exp\left[-c\int_{\tau}^{t}|\mathrm{d}u(\tau_1)|\right]\right\}\mathrm{d}F(\tau) - \int_{t_0}^{t} bv(\tau)\mathrm{d}u(\tau) \quad (4)$$

where v, F, u, t, t_0, τ, J signify, respectively, the slip, the connector shear force, the moisture content of timber at the interface with the connector, the final time of analysis, the loading time, the current time, and the creep function of the connection. J^{∞}, b, c are material parameters which assume, for spruce timber, the values of $0.7/E_{\mathrm{w}}$, 1.3, and 2.5, respectively, E_{w} being the Young's modulus of timber [24]. For a long-term test under constant shear load, Eq. (4) can be simplified as follows:

$$\begin{aligned} v(t,t_0) &= \frac{F}{k}[1+\varphi_{\mathrm{t}}(t,t_0)] \\ &= \frac{F}{k}[1+\varphi(t,t_0)+\varphi_{\mathrm{ms}}(t,t_0)] - \int_{t_0}^{t} b v(\tau)\mathrm{d}u(\tau) \end{aligned} \tag{5}$$

where k is the shear modulus of connector, φ_{t}, φ, φ_{ms} are, respectively, the total creep coefficient measured during the test, the creep component (first term at second member of Eq. (4)), and the mechano-sorptive component (second term in Eq. (4)). The quantities φ and φ_{ms} are given, respectively, by Eqs. (3) and (6):

$$\varphi_{\mathrm{ms}}(t,t_0) = K^{\infty}\left[1-\exp\left(-c\int_{t_0}^{t}|\mathrm{d}u(\tau)|\right)\right] \tag{6}$$

where K^{∞} is the limit of the mechano-sorptive component for a large number of cycles of relative humidity. The last term at second member of Eq. (5) represents the fluctuating component of the slip v during the relative humidity cycles. By dividing the members of Eq. (5) by F/k, which represents the elastic slip $v(t_0)$, it is possible to express the total creep coefficient as:

$$\begin{aligned} \varphi_{\mathrm{t}}(t,t_0) &= \varphi(t,t_0)+\varphi_{\mathrm{ms}}(t,t_0) \\ &\quad - b\int_{t_0}^{t}\varphi_{\mathrm{t}}(\tau,t_0)\mathrm{d}u(\tau) - b[u(t)-u(t_0)] \end{aligned} \tag{7}$$

The experimental trend in time of the quantity φ_{t} (thick solid line in Fig. 10), obtained by averaging the curves of the six most representative specimens, was fitted with Eq. (7) in order to find out the best approximation for the parameters K^{∞}, b and c. The history of timber moisture content $u(t)$ considered in Eq. (7) was obtained by averaging the moisture content of the three laminations surrounding the connector (Fig. 3). Such a curve (thick solid line in Fig. 11) was computed by solving the diffusion problem of the moisture content over the timber cross-section using a numerical program which accounts for the history of environmental relative humidity [22, 24, 27]. The cyclic relative humidity $RH = RH(t)$ of the climate chamber was assumed as input, and the moisture content at 5 mm depth in the laminations was computed using the aforementioned program. Numerical and experimental values of the moisture content measured during the test at 5 mm depth are compared in Fig. 11. A good correspondence can be observed in terms of amplitude of fluctuation (about 0.05), however a larger difference appears in terms of total value (about 0.03). Such a difference, due to the unavoidable approximation of the measurement during the experimental test and to the difficulty of modelling the diffusion process, does not affect the accuracy achieved when evaluating the parameters K^{∞}, b and c. The mechano-sorptive effect, in fact, depends on the differences in moisture content Δu, while it is independent of the total value of moisture content u, as can be observed from Eq. (4) and (6). The best accuracy of the quantity φ_{t} was obtained by assuming $K^{\infty} = 1.5$, $b = 0.9$ and $c = 0.7$. The comparison between the analytical (thick solid line) and experimental (thin solid line) curves is depicted in Fig. 12 and demonstrates an overall good accuracy.

The same figure also reports the analytical curve (thick dashed line) carried out using the simplified equation:

$$\varphi_{\mathrm{t}}(t,t_0) = \varphi(t,t_0)+\varphi_{\mathrm{ms}}(t,t_0) \tag{8}$$

based on the use of the generalized Kelvin rheological models (Eq. (3)) for the components φ (see values reported in par. 4.1) and φ_{ms} ($\tau_1 = 5.46$ days, $J_1 = 0.04$, $\tau_2 = 497.28$ days, and $J_2 = 1.45$). Such a model, which does not explicitly consider the dependency on the variations of timber moisture content, can be used for a simplified representation of the rheological

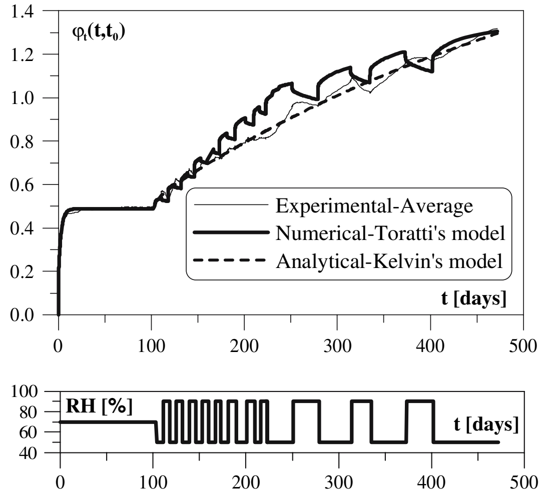

Fig. 12 Trend in time of the mean experimental creep coefficient for the six most representative specimens, and analytical prediction using the Toratti's and Kelvin's rheological models

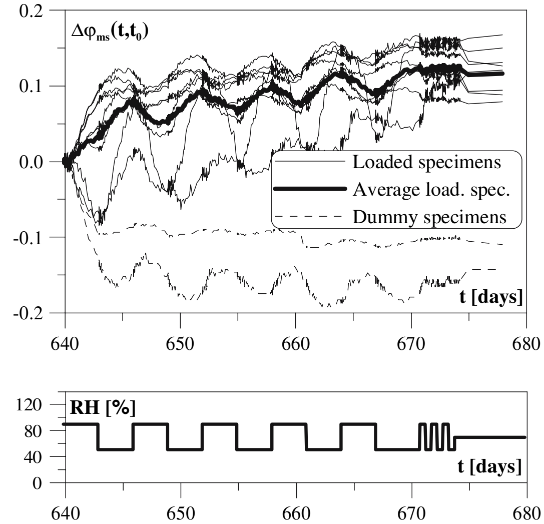

Fig. 13 Trend in time of the increase in total creep coefficient during the second phase of the creep test in variable environmental conditions

behaviour of the connection in variable environmental conditions. The accuracy is, however, as good as that achievable using the more complex Toratti's model. The use of the Toratti's and Kelvin's models for the evaluation of the mechano-sorptive component of the creep coefficient at the end of the service life (50 years) leads to a final value $\varphi_{ms} = 1.5$. This is, however, only a numerical prediction since at the end of the first phase test the slip in the connection was still increasing.

4.2.2 *Second phase*

The experimental outcomes of the second phase of the creep test in variable environmental conditions are depicted in Fig. 13. The thin dashed curves refer to the unloaded (dummy) specimens. Such curves represent the slip fluctuations caused by the inelastic deformations of timber due to the moisture content variations. The thin solid lines in Fig. 13 refer to the increase in time of the pure mechano-sorptive component $\Delta\varphi_{ms}$ of the total creep coefficient. Such curves are obtained by reducing the total slips of the loaded specimens by the mean slip of the dummy specimens. The mean trend of the loaded specimens (thick solid line) shows some fluctuations due to the mechano-sorptive effect. The cycles with period $2T = 7$ days led to a larger amplitude fluctuation than the cycles with period $2T = 1$ day. The overall increase of the coefficient φ_{ms} was about 0.10 during the weekly cycles, while the daily cycles did not cause any appreciable increase in such a quantity.

4.3 Unloading of the specimens in constant environmental conditions

At the end of the second phase of the creep test in variable environmental conditions, all the specimens were unloaded and the creep recover was monitored for an 80-day period in constant environmental conditions ($RH = 70\%$). The creep coefficient $\varphi(t,t_0)$ given by Eq. (2), where t_0 signifies the unloading time and $v(t_0)$ signifies the elastic slip recover measured at the unloading time, is displayed in Fig. 14 for each specimen together with the mean value.

The creep recover occurred more slowly than the corresponding creep increase under loading and seemed not be exhausted after 80 days. This means that the connection system is characterized by non-linear creep behaviour. The delayed slip due to a shear load is only partially recovered in time and more slowly than during the loading phase. This phenomenon can be justified because of the non-linear mechanical behaviour of the

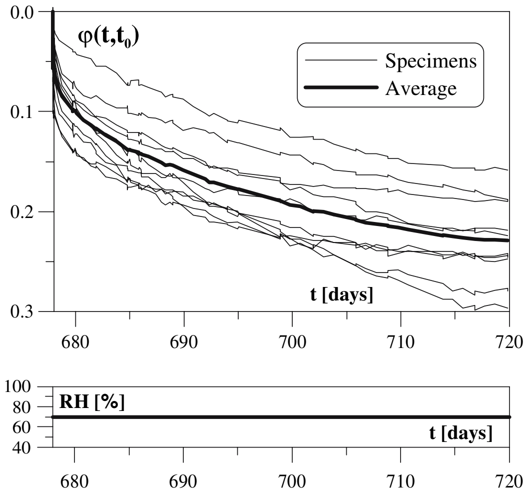

Fig. 14 Trend in time of the creep coefficient during the unloading of the specimens in constant environmental conditions

connection, already noticed in the collapse tests, which is due to plasticization of the timber surrounding the connector. The mean creep coefficient in the unloading phase can be represented with the Kelvin's generalized rheological model (Eq. (3)), the coefficients τ_i and J_i being, for two Kelvin's chains: $\tau_1 = 0.0598$ days, $J_1 = 0.0783$, $\tau_2 = 16.8156$ days, and $J_2 = 0.1621$. The use of such model leads to a creep coefficient at the end of the service life $\varphi(t, t_\infty) = 0.24$, which is about half the long-term creep coefficient under loading. It has to be pointed out, however, that this is only a numerical prediction since at the end of the unloading test the creep recover was not exhausted yet.

4.4 Discussion of the results

The outcomes of all creep tests are summarized in Table 3, where the different contributions to the total creep coefficient are reported for all the specimens and for the different types of test and period of the relative humidity cycle. The mean values, on which the coefficients of the rheological models (Eq. (3)) were calibrated, were calculated by averaging the six specimens which provided the most uniform results (specimens 6NW, 7NW, 4LW, 5LW, 6LW and 7LW). Based on the outcomes obtained, the following remarks can be made:

- No dependence of the creep coefficient on the type of concrete (NW or LW) was noticed.

Table 3 Final outcomes of the long-term tests on the "Tecnaria" connection

Phase of test	Loading-pure creep	8 cycles T = 14 days	3 cycles T = 56 days	5 cycles T = 7 days	3 cycles T = 1 day	Unloading-creep recover
Start	13/6/00	25/9/00	22/1/01	15/3/02	15/4/02	18/4/02
End	24/9/00	22/1/01	20/7/01	15/4/02	18/4/02	3/6/02
Duration [days]	103.0	119.1	179.1	31.4	3.4	80.0
Creep Coeff.	$\Delta\varphi$	$\Delta\varphi_{ms}$	$\Delta\varphi_{ms}$	$\Delta\varphi_{ms}$	$\Delta\varphi_{ms}$	$\Delta\varphi$
Specimen number						
4NW	0.57	2.62	2.32	0.08	0.03	0.19
5NW	0.34	1.26	1.71	0.15	–0.02	0.22
6NW	0.51	0.54	0.49	0.08	0.00	0.25
7NW	0.53	0.22	0.12	0.10	–0.02	0.19
8NW	0.60	0.11	0.07	0.11	–0.02	0.28
9NW	0.72	0.80	–	–	–	–
4LW	0.51	0.39	0.74	0.15	0.00	0.25
5LW	0.50	0.19	0.22	0.12	0.00	0.25
6LW	0.52	0.19	0.20	0.14	–0.01	0.22
7LW	0.41	0.37	0.39	0.14	0.01	0.30
8LW	0.30	1.54	1.65	0.09	0.00	0.16
9LW	0.33	0.53	–	–	–	–
Average	0.49	0.32	0.29	0.12	0.00	0.24

- When loaded in constant environmental conditions, the connection crept, with final creep coefficient $\varphi = 0.5$. When unloaded, a smaller and slower creep recover characterized by a final creep coefficient $\varphi = 0.24$ was noted.
- When loaded and subjected to cycles of environmental relative humidity, an increase of the creep coefficient due to the mechano-sorptive effect of timber was observed. Such an increase was larger for more numerous humidity cycles with longer periods and wider amplitudes. The daily variations of relative humidity caused almost no effect, while those with weekly or larger period rose the slips. Based on the extensive research carried out on mechano-sorptive effect in wood [24–26], it is reasonable to assume that the increase in creep coefficient of the connection will approach a limit value for a large number and amplitude of the humidity cycles. Such a limit value can be estimated as $\varphi_{ms} = 1.5$ on the basis of the approximation of the experimental outcomes with the numerical models described in par. 4.2.
- The final creep coefficient of the connection φ_{tot} for long-term verifications of composite structures should be related to the number of humidity cycles with period of at least 7 days and 40% amplitude that can be expected in the climate region and service class (i.e. exposure) of the structure. The use of the Toratti's model as calibrated on the experimental results is a possible way of achieving that. A simplified criterion is to assume $\varphi_{tot} = \varphi = 0.5$ for indoor structures (1st service class according to the Eurocode 5 [9, 10]) and $\varphi_{tot} = \varphi + \varphi_{ms} = 2$ for outdoor structures (3rd service class according to the Eurocode 5), with an intermediate value for the 2nd service class.
- The creep and mechano-sorptive creep of the connection are not negligible phenomena. For service class 3 structures, according to the effective modulus method employed for long-term verifications of timber-concrete composite beams [1, 12], the shear modulus of the connection should be divided by one plus the creep coefficient in order to account for the rheological phenomena. This would lead to the use of one-third of the elastic shear modulus for long-term verifications of composite beams in the 3rd service class.

5 Conclusions

The experimental campaign on the ‘‘Tecnaria’’ stud connector involved 18 push-out specimens that were tested in the short-term to failure and in the long-term under sustained load, in constant and variable (cyclic) environmental relative humidity. The primary conclusions are reported herein after.

- The use of light weight concrete slabs instead of normal weight concrete slabs markedly affected neither the outcomes of the collapse tests, nor those of the long-term tests.
- A sustained load, i.e. a constant load applied on the specimen for long time, did not significantly affect the shear strength, whereas it reduced the initial shear modulus.
- The connection system crept under sustained load. The creep coefficient at the end of the service life (50 years) in constant environmental conditions can be estimated as $\varphi = 0.5$ under loading, and $\varphi = 0.24$ for the creep recover when the connection is unloaded. Such values are far less than the long-term creep coefficients of timber and concrete.
- The connection system demonstrated mechano-sorptive creep, i.e. a significant increase of the delayed slips when the loaded specimens were subjected to relative humidity cycles with period greater than seven days and amplitude of 40% at least.
- Based on the experimental tests, however characterized by significant scatter of the results, the final value of the increment in creep coefficient due to the mechano-sorptive effect can be estimated as $\varphi_{ms} = 1.5$.
- The 5th percentile of the shear strength and the mean values of the secant shear moduli and creep coefficients were computed on the basis of the outcomes of the experimental tests. Such values are needed for the ultimate and serviceability limit state verifications of

timber-concrete composite beams with the "Tecnaria" connection.
- Some analytical formulas for modelling the shear force-relative slip relationship and the creep coefficients in constant and variable environmental conditions were also proposed. Such formulas can be used for more refined verifications, for example by implementing them in finite element programs.

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