Long-Term Behaviour of Wood-Concrete Composite Beams with Notched Connection Detail

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Summary

The paper investigates the long-term behaviour of wood-concrete composite floor/deck systems with shear key/anchor connection detail. The beam specimens were first monitored in time after the concrete placement on the wood deck, and then subjected to a sustained load. The experimental results have also been extended to the entire service life of the structure using a Finite Element model. The primary observations are: (i) the bleeding of the fresh concrete is not an issue for the durability of the wood deck; (ii) the type of construction (shored, unshored) is of little influence for the structural performance; (iii) the deflection increases quite significantly over the time because of the rheological phenomena of the component materials. The use of concrete with reduced shrinkage and the pre-cambering of the wood deck are two possible ways to reduce the long-term deflection. The experimental and numerical results are finally compared with those obtained using a simplified approach, showing that the simplified approach leads to reasonably good accuracy.

1. Introduction

Wood-concrete composite floor/deck systems are constructed by interconnecting a wood deck with a concrete slab placed atop. In this way it is possible to exploit both materials at the best since the wood is subjected to tension coupled with bending, and the concrete slab is mainly compressed [1]. The choice of the connection system is crucial in order to make the composite system structurally effective and, at the same time, economically competitive with wood and reinforced concrete floors. Several types of connectors have been proposed [1,2]. In this paper, the attention is paid on the use of the notched detail, where the interconnection between wood and concrete is achieved by direct bearing of the concrete in the notch on the wood surface [3,4]. Advantages of the notch detail with respect to mechanical connectors such as dowels, etc. for interlayer transfer of horizontal forces include the higher composite action (i.e. stiffness of the composite system) and larger capacity achievable, and the relative inexpensiveness.

Despite the many merits, the composite structure is still not used in some countries such us the USA and the UK. However, there is a large potential market for both multi-storey building floors and replacement or rehabilitation of deteriorated short-span wood bridges. For this reason, an extensive experimental programme is being conducted at Colorado State University (USA) in order to explore the performance of wood-concrete composites with notched connections [5]. The long-term performance may be of concern for the composite system. Many complex phenomena take place in the component materials (concrete, wood, and the notched detail) such as creep, mechano-sorptive creep, shrinkage/swelling, thermal strain, and concrete cracking. It is hence important to perform experimental tests [6] and, at the same time, to develop numerical tools for the prediction of the time-dependent behaviour [7,8].

The paper reports the results of a long-term experimental test performed on wood-concrete composite beams with notched connections. The beams were monitored during the construction process, i.e. during the concrete placement, in order to evaluate the influence of the type of construction (shored or unshored) and the effect of the concrete pouring on the wood layer as an increase in moisture content. Then a live load was applied for 133 days, and the deflection and environmental conditions were monitored over the time. The experimental results are first compared with the outcomes of a Finite Element model developed for long-term analyses of wood-concrete composite systems. The FE program is then used to extend the experimental results in the long-term (50 years). The use of an approximate approach based on closed form solutions is also proposed and the accuracy achievable is evaluated by comparison with the numerical results.

2. Construction of the specimens

The wood-concrete composite beams used in this research were constructed using the notched shear key/anchor connection detail [3] at four locations, as depicted in Figure 1. The cross-section and the longitudinal view of the beam are represented in Figure 2. The wood deck was made by nailing together five sawn lumber boards, which were surface dry Grade 2 of the Hem-Fir species type. The shear notches were then cut out of the beam. The Hilti connector was screwed into a hole drilled in the deck and filled with epoxy resin. A plastic sleeve was placed on the top end of the bolt which was not in the wood but would be surrounded by the concrete layer (Figure 1). This sleeve would insure that no bond took place between the concrete and the bolt. Some reinforcement was then placed over the wood layer, and then the concrete was cast. Plastic insulation sheets were placed over the concrete to help it cure, and consequently removed after 7 days of curing. At that time a torque moment was applied to the bolts, essentially vertically prestressing the concrete to retighten the notch after shrinkage of concrete and drying of wood take place during the curing. The benefit of this connection is to provide a better bond between the concrete and the wood.

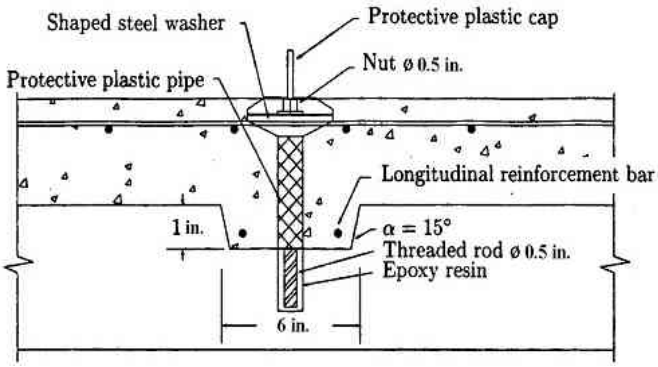

Fig 1 Shear key/anchor connection detail

In order to evaluate the mechanical properties, physical tests were performed on the components of the composite beam: wood, concrete, and the shear key/anchor connection detail. The mean values of the modulus of elasticity (MOE) of wood, E_w, the cylindrical compressive strength of concrete, f_c', and the slip modulus of the shear key/anchor connection detail, k_f, were found to be 8.605 GPa, 30.51 MPa (corresponding to a MOE E_c of 26.1 GPa), and 156.2 kN/mm respectively. The slip modulus of the connection was obtained by subjecting to pure shear at the interface some slip specimens (Fig. 3).

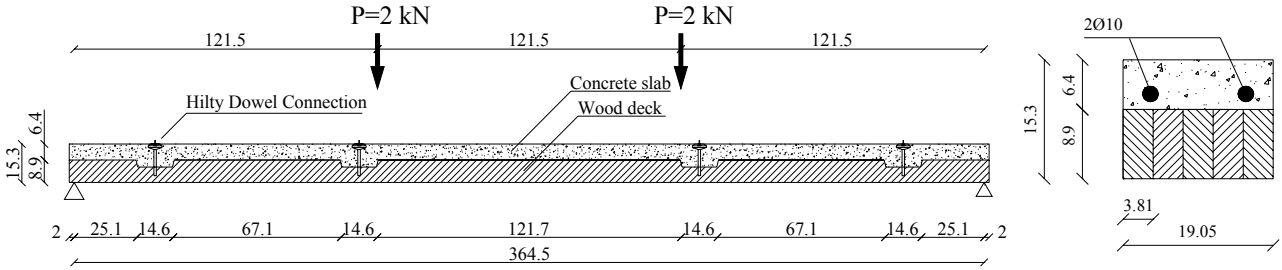

Fig 2 Longitudinal view (left) and cross-section (right) of the composite beam (measures in cm)

3. Long-term experimental tests

Eight beam specimens constructed according to the procedure detailed above were subjected to the creep test. The test was conducted inside the Structural Engineering Laboratory of Colorado State University, in uncontrolled environmental conditions. During the concrete placement four specimens were vertically supported at the third point while the other four specimens were left unshored. The shores were then removed after 36 days from the concrete pouring. The dead load (concrete cylinders) weights of 2 kN, which correspond to an estimated 12.5% of the ultimate capacity of the wood-concrete composite beam, were suspended at the third points of the span after 185 days from the concrete pouring. The weights were left on the specimens for 133 days. The monitoring of the environmental conditions (temperature and relative humidity) and mid-span deflection was conducted during two periods: (i) the first 35 days after the concrete pouring, in order to investigate the time-dependent behaviour at the early stage of the construction process; (ii) the first 133 days after the application of the dead load weights of 2 kN, in order to investigate the time-dependent behaviour of the composite beam when the service load is applied. The moisture content u of wood was also monitored during the first 40 days using a wood moisture meter and the permanent insertion of 38 mm pins into the wood deck at some locations (Fig. 4). During the first 5 days, the moisture content at the interface with concrete rose from 6.5% to 14% because of the concrete bleeding. However, a reduction to the initial value of 6.5% was observed during the next 10 days, followed by a slightly decreasing trend in time. The other locations experienced only small increases in moisture content during the first days (from 6.5% to 8%). Since the moisture content never exceeded the value of 20% during the whole construction process, it can be concluded that the possible decay of wood due to the bleeding of concrete is not an issue for the composite beam.

The mid-span deflections v (experimental values, thin dotted lines, and average of the specimens, thick dashed line) and the environmental conditions (relative humidity RH, thin solid line, and

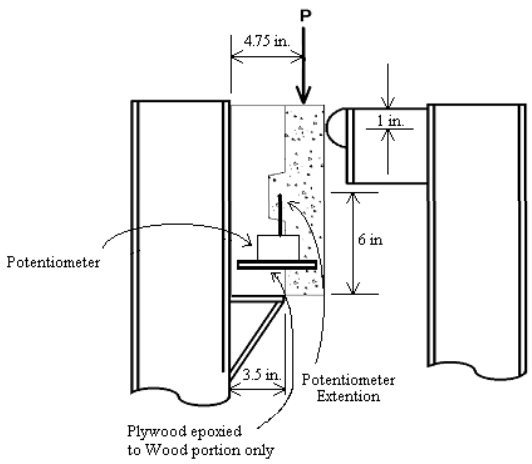

Fig 3 Schematic of the slip test set-up

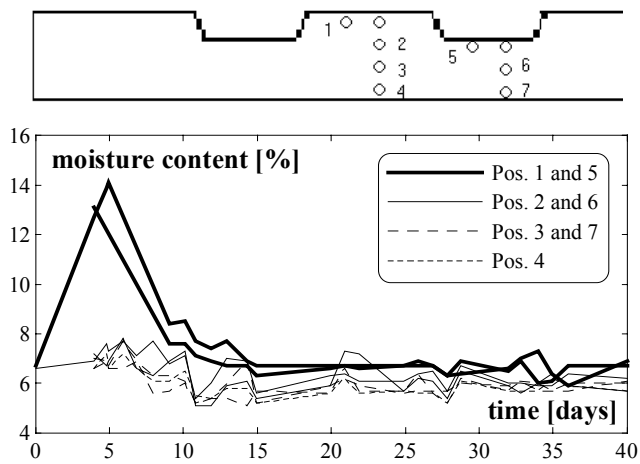

Fig 4 Trend in time of the wood moisture content at different locations after the placement of the concrete

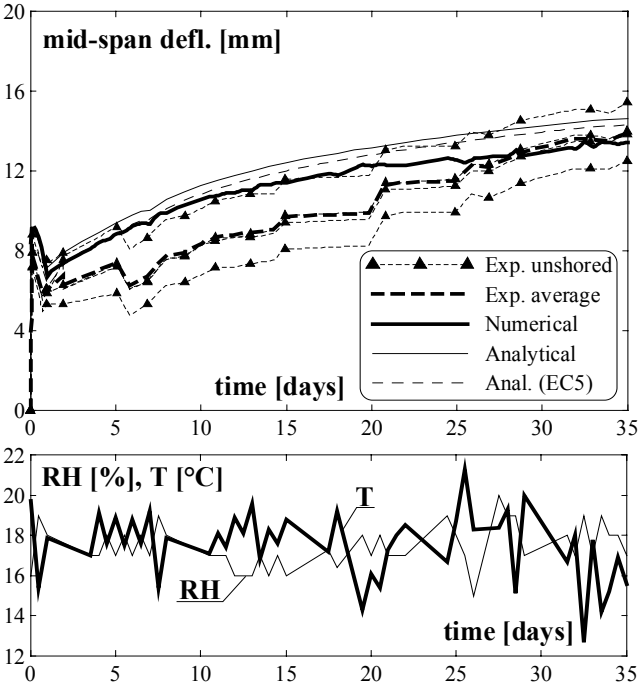

Fig 5 Trend in time of the mid-span deflection (top) and environmental conditions (bottom) after the placement of the concrete

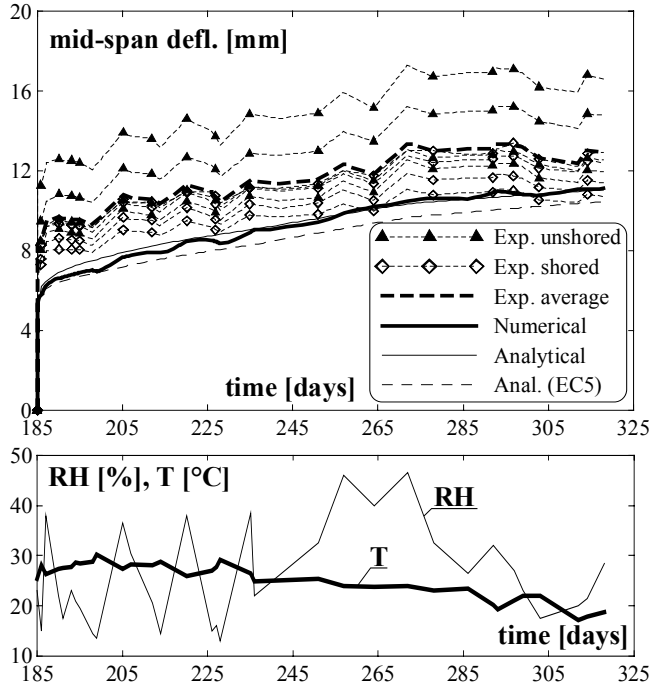

Fig 6 Trend in time of the mid-span deflection (top) and environmental conditions (bottom) after the application of the dead load weights

temperature *T*, thick solid line) are reported in Fig. 5 for the 36-day period after the concrete cast, and in Fig. 6 for the 133-day period after the dead load weight application. In Fig. 5 only the deflection of the unshored specimens is reported, since the shored specimens exhibited negligible mid-span deflections. The following remarks can be made: (i) a scatter of values can be recognized in terms of elastic and delayed deflections, which is due to the natural high variation of the mechanical properties of wood; (ii) the unshored beams exhibited larger elastic deflection and slightly larger increase in time of deflection than the shored specimens. Such differences are too small to draw final conclusions about the influence of the type of construction that, however, appears to be small; (iii) the increase over time of the deflection with respect to the initial elastic value was on average 68% during the first 35-day period after the concrete is placed and 56% during the 133-day period after the dead load application; (iv) the relative humidity monitored during the test was very low (15% to 46%). An important consequence of that is that a quite large concrete shrinkage and creep is expected, which ultimately leads to an increase in deflection over time; (v) the reduction of deflection monitored during the first day after the concrete is placed can be explained by the heating that occurs during the concrete curing and the resulting thermal strains. The concrete slab was in fact constrained to the wood deck by the shear key/anchor connection detail, and the elongation of the slab due to the heating resulted in an upward deflection.

4. Finite Element numerical modelling

The long-term behaviour of wood-concrete composite beams is quite difficult to predict because of several complex interrelated phenomena occurring in the component materials. Wood is characterised by time-dependent phenomena such as creep, mechano-sorptive creep, shrinkage/swelling due to moisture content and temperature variations, with the moisture content being governed by the diffusion laws of the environmental humidity over the wood cross-section [9]. Concrete experiences shrinkage, creep, thermal strains, and possible cracking in the tensile zones [10]. The shear connections, even the stiffest ones such as the shear key/anchor connection detail, allow a relative slip between the concrete and the wood fibres at the interface [3,4]. Such

flexibility should be considered when modelling the composite beam, as well as the creep and mechano-sorptive creep resulting by the interaction between the connector, the wood, and the concrete.

In this paper, a FE model purposely developed [7] and validated against the outcomes of a number of long-term experimental tests performed on composite beams with mechanical connectors [11] is used to investigate the composite beams with notched connection. The model is based on a 1D FE with shear connection smeared along the longitudinal axis (Fig. 7). The notches are modelled by smearing the shear stiffness measured in the shear tests performed on the connection system over the length of the notch, while elsewhere a very low value of stiffness is implemented so as to represent the lack of connection. This type of modelling has the disadvantage with respect to 2D and 3D schematisations [4,12] of neglecting the interaction between the materials (concrete, wood, and anchor) at the local level. However, it allows a remarkable saving in terms of computational time while, at the same time, taking into account the interaction between the wood deck and the concrete slab at the global level.

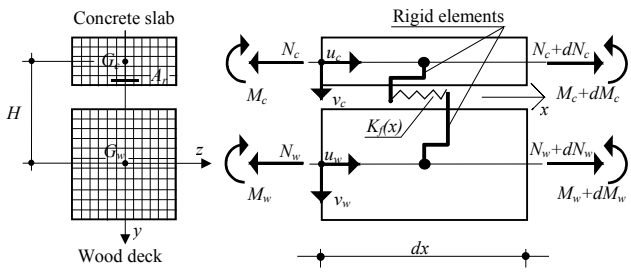

Fig 7 FE model used for the long-term numerical analyses

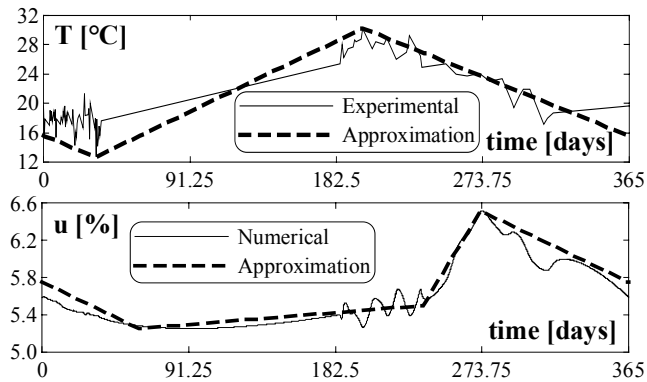

Fig 8 Annual fluctuation of the environmental temperature (above) and average moisture content of the wood deck (below)

The numerical analysis was run for the unshored specimens by assuming the mean values of the MOE for wood and concrete, and for the slip modulus of the notched connection. The histories of environmental temperature and relative humidity monitored during the test (Figs. 5 and 6) and extended to the entire service life (see Fig. 8 for the annual fluctuation of temperature) were assumed. The moisture content of wood which affects the time-dependent behaviour of the deck was evaluated by solving the diffusion problem of the environmental humidity over the cross-section. The annual fluctuation of the average moisture content over the wood cross-section is displayed in Fig. 8. The rheological phenomena (creep and shrinkage) of concrete were computed according to the CEB-FIB Model Code 90 [10] prediction model. The time-dependent behaviour of wood was modelled according to the rheological model proposed by Toratti [9]. The creep coefficient of the connection was obtained by fitting the experimental values measured by Michelfelder and Kuhlmann [4] in a long-term push-out test on a notched connection system similar to that used in the beams under investigation. The analysis was carried out until the end of the service life, estimated as 50 years from the load application. The results are compared in Figs. 5 and 6 (thick solid lines) with the experimental outcomes. Fig. 9 reports the prediction of the mid-span deflection v over the entire service life, while Fig. 10 displays the trends in time of the stresses σ at the top and bottom fibre of the concrete slab (subscript c) and wood deck (subscript w) during the entire service life. In Figs. 9 and 10, the time axis is represented in logarithmic scale for the period between 0 and 5000 days, and in linear scale for the period between 48.5 and 50.5 years, so that the yearly fluctuations due to the annual changes of environmental conditions can be better appreciated.

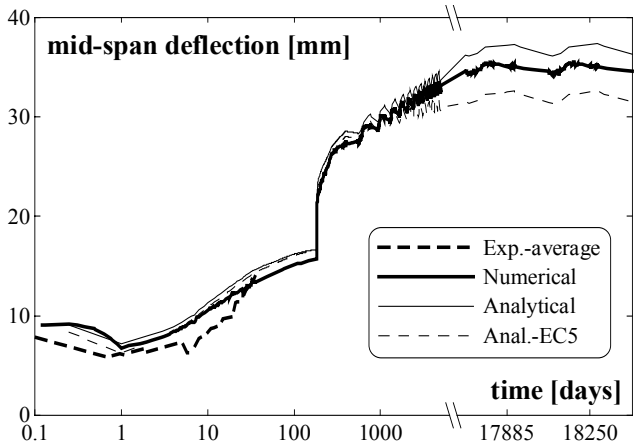

Fig 9 Trend in time of the mid-span deflection during the entire service life

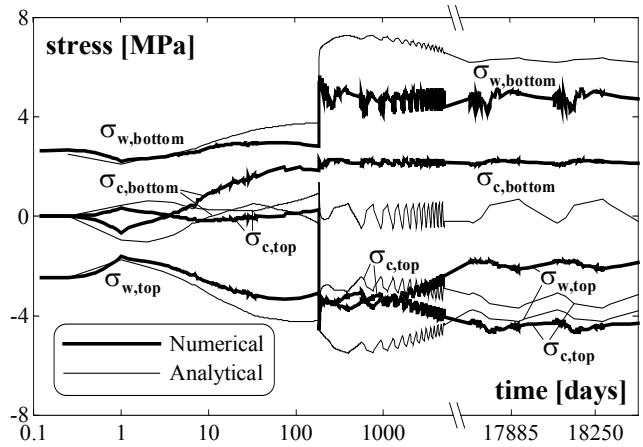

Fig 10 Trend in time of the mid-span stresses at the top and bottom fibres of concrete slab and wood deck during the entire service life

The following remarks can be made: (i) the FE model underestimates the elastic deflection. This may be due to the scatter of values of the wood MOE and slip modulus of the notched connection detail. Another possible reason is that some local effects inside the notch, such as small gaps at the concrete-to-wood bearing surfaces, shear deformability of wood, etc. might not be fully accounted for by the 1D FE model. However, the approximation is considered to be acceptable for practical design purposes; (ii) the experimental time-dependent behaviour is captured with good accuracy by the numerical solution; (iii) the maximum value of deflection predicted over the entire service life of the composite structure is v_{max}=35.5 mm. An important reason for such a quite large value is the high value of concrete shrinkage and creep, due to the low environmental relative humidity *RH* and notational thickness *h* (cross-sectional area to perimeter ratio). At the same time, because of the very stiff connection detail, the shrinkage of concrete prevented by the connection with the wood deck results in a high value of the deflection. When the limitation of the deflection is an issue, some measures such as the use of admixtures for reducing the concrete shrinkage, and the choice of pre-cambering the wood deck, should be taken; (iv) the seasonal fluctuation due to the environmental condition variations is not significant; (v) the variation in time of the stresses due to the rheological phenomena is not as significant as the increase of the deflection. Based on that remark, it can be concluded that the time-dependent phenomena mainly affect the serviceability limit state.

5. Simplified approach

The deflection of a notched composite beam can be approximately predicted using the simplified approach recently proposed for shored wood-concrete composite beams with mechanical connectors [13]. The approach is based on the use of the elastic formulas for composite beams with shear connection smeared along the beam axis subjected to external load and inelastic strains. The approximation consists in regarding the notched connection as smeared on the entire length of the beam. In the case under study, for example, it is assumed that the connection system is made of 4 notched connector details with stiffness k_f=156.2 kN/mm and spacing s_f=817 mm, s_f being the distance between the external notches (Fig. 2). The long-term solution is obtained by superimposing the solutions due to: (i) the dead load *q*, which is considered as applied on the wood deck between 0 and 1 days, the time when the rheological phenomena (creep and shrinkage) are assumed to begin in the concrete slab. After 1 day and until the end of the service life (50.5 years), the dead load *q* is considered as applied on the composite section for the evaluation of the creep effect; (ii) the shrinkage of concrete between 1 day and 50.5 years, which causes effects (deflections, stresses) on the composite section; (iii) the inelastic strains due to environmental (temperature and average

moisture content) variations, approximated by piecewise linear curves (Fig. 8), which causes effects on the composite section from 6 hours (the time when the concrete is assumed to have cured) till 50.5 year; (iv) the loads *P* applied on the composite section between 185 days and 50.5 years.

The results are reported in Figs. 5, 6, 9 and 10. Two curves are drawn: the thin solid one (Analytical), which represents the results when the same rheological models for wood (the Toratti's one) and the notched connection detail as those use in the numerical solution are used, and the thin dashed one (EC5), which represents the results when the creep coefficients of wood and connection suggested by the Eurocode 5 [14] for the service class 1 (RH<65%, u<12%) are employed. The former curve is then directly comparable with the numerical curve in order to assess the accuracy of the analytical procedure, while the comparison with the latter curve demonstrate the influence of the creep model suggested by the Eurocode 5 for timber and connection on the results of the composite beam. The following remarks can be made: (i) the use of the analytical approach leads to fairly accurate and conservative results in terms of deflection with respect to the numerical solution. However, both analytical and numerical solutions underestimate the elastic experimental deflection; (ii) larger differences are found in terms of stresses, however the numerical trend is followed over the entire service life. It has also to be pointed out that the prediction of the stress is less important, in the long-term, with respect to the deflection; (iii) the use of the creep functions suggested by the Eurocode 5 leads to similar results, which are however slightly not conservative; (iv) the analytical approach may hence be effectively used for the design of notched wood-concrete composite beams. The approach is based on the use of closed form solutions which can be easily implemented in an Excel spreadsheet and do not involve the use of any specific numerical program.

6. Concluding remarks

In this paper, the results of some long-term experimental tests performed on wood-concrete composite beams with notched connection detail are reported. The tests included the characterization of the component materials (concrete, wood deck, and shear key/anchor connection detail), and the monitoring over the time of the most important quantities such as mid-span deflection and environmental conditions. The effect of shoring during the construction process was also investigated, as well as the increase in moisture content into the wood deck due to the bleeding of the fresh concrete. The experimental outcomes were compared with the numerical results carried out using a 1D FE model with flexible shear connection. The FE model was then been employed to extend the experimental results over the whole service life. A simplified approach proposed for shored composite beams with smeared connection was also extended to the case of the unshored composite beam with notched connection. Obtained results were then compared against the numerical and experimental ones.

The primary observations are: (i) the increase in moisture content observed after the concrete placement was not so large to lead to possible decay of the wood deck; (ii) the influence of the construction type (shored or unshored) appeared to be negligible; (iii) the increase in deflection measured after the concrete pouring on the unshored beams and after the application of the service load is significant. The effect of shrinkage is, in fact, quite important for the composite beam because of the high stiffness of the notched connection. In addition, a fairly large concrete shrinkage and creep are expected due to the low relative humidity and high perimeter of the slab cross-section exposed to the atmosphere; (iv) the FE model underestimates the elastic deflection of the notched beam, however the overall time-dependent behaviour is predicted with reasonable accuracy; (v) the prediction of the total deflection over the service life leads to quite high values (about one hundredth of the beam length). If the limitation of the maximum deflection is required for serviceability considerations, some measures such as the use of admixtures for reducing the concrete shrinkage, and the choice of pre-cambering the wood deck, should be taken; (vi) the variation of the stresses during the service life is not as significant as for the deflection, hence it can

be concluded that the time-dependent phenomena mainly affect the serviceability limit state; (vii) the analytical formulas proposed for timber-concrete composite beams with mechanical connectors can be extended to unshored composite beams with notched connection. Obtained results are fairly accurate, especially in terms of deflection; (viii) the creep functions proposed by the Eurocode 5 are slightly non-conservative with respect the rheological model proposed by Toratti.

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