The Durability of Wood-Concrete Composite Bridges

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Summary

In wood-concrete composite bridge decks glued-in are bars are simple connectors to join the two materials. For the design of the bars a simple truss model is introduced. Durability of the wood-concrete connections was tested by two long-term test series. The purpose of the tests was to find out, if outdoor condition or ageing affects the behaviour of the connections. First of the tests series consisted of pull-out tests of glued-in bars. Prepared specimens were divided into two control groups. One group of specimens was newly tested and the other group after ten years outdoor storing. In the second test fatigue loading was applied to full-size composite beam in three time periods. The beam was first newly loaded, then after two years and finally after 10-years outdoor storing. Connections with compression bars turned out to be stable and non-sensitive to ageing. Remarks of the current condition of two wood-concrete composite bridges are given.

Keywords: composite construction, wood-concrete connectors, long-term testing, durability.

1. Introduction

Many wood-concrete composite bridges have been built in Finland during the last two decades. The oldest one, *Kruununmylly Bridge*, was built already in 1993. In the longest timber bridge in Finland, the *Vihantasalmi Bridge*, a composite deck structure is used in all the five spans. [1]

The connectors can be formed simply using reinforcing steel glued-in bars. The behaviour of the connectors and a simple truss analysis to design the bars is explained in Chapter 2.

Results of long-term pull-out tests of glued-in bars and the fatigue bending test of a full-size composite beam are reported in Chapters 3 and 4. The purpose of the long-term tests was to study experimentally the influence of outdoor condition and ageing on the behaviour of the joint used in composite beams.

In Chapter 5 some remarks are given on the current condition after inspection of the two bridges mentioned above.

2. Behaviour and design of connectors

The principle of a composite beam in bending is shown in *Fig. 1*. Without any connectors slip occurs between the two materials as they both work separately and rotate around their own neutral axis. Putting connectors between the two materials the slip is prevented and the beam acts as a composite structure. Consequently, the stiffness of the whole structure increases considerably and deflection decreases.

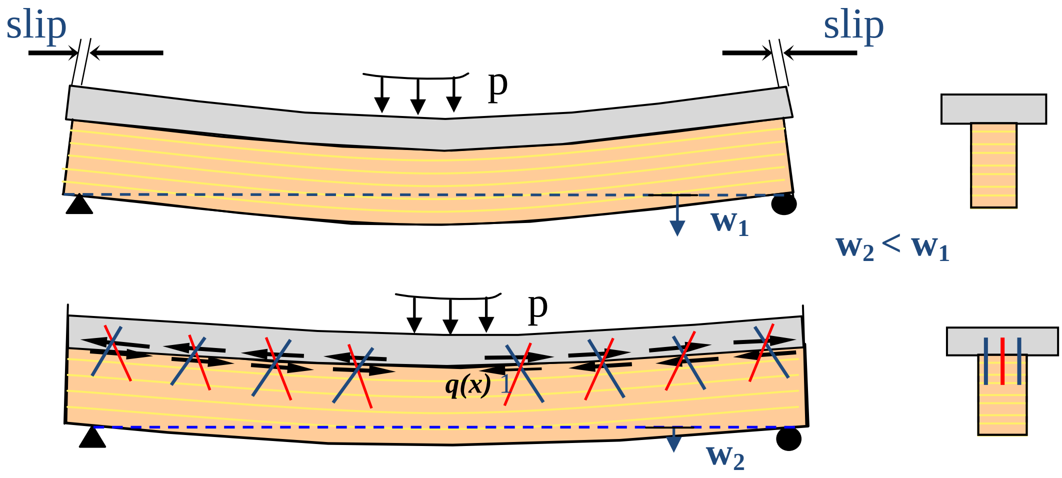

Fig. 1. The principle of joining a timber beam and a concrete slab using glued-in steel bars.

In the design of the connectors the distribution and magnitude of the horizontal shear flow *q(x)* is needed *(Fig. 1)*. This is dependent on the stiffness of the materials, flexibility of the connectors and distribution of external loading. Simple formulas and methods to determine the horizontal shear are explained in references [1, 2].

The connection between wood and concrete can easily be constructed simply by using tension and compression bars embedded in wood and anchored in concrete. If the friction, dowel action and notches between the two materials are not considered, the capacity of the joint is only dependent on the pull-out or push-in capacities of the glued-in bars.

The shear force *Q* to be transferred by one connector unit is then

$$Q = q(x) \cdot s \qquad (1)$$

where *q(x)* is the shear flow and *s* is the spacing between two adjacent connectors. The tension and compression forces in bars may be determined simply by using a truss model and applying the force diagram as shown on the right hand side of *Fig. 2*.

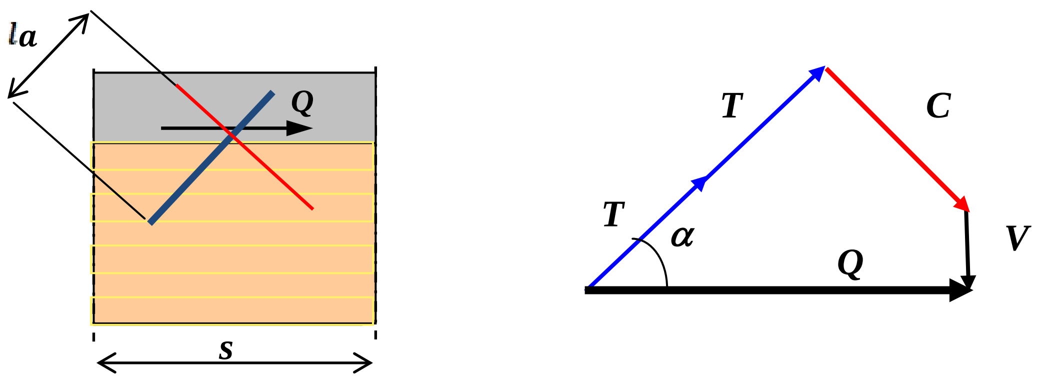

Fig. 2. Force equilibrium in a joint, where two tension bars and one compression bar is used.

The strength of the connectors is dependent either on the shear capacity of the wood or the bonding capacity of the glue layer within the anchoring length l_a in *Fig. 2*. If the shear capacity of wood is governing the strength, the capacity formula in *Eurocode 1995-1-1, Annex A, A.2.2.1*, may be used.

In this case the ultimate capacity of the bars in inclined direction can be defined as

$$T_c = \pi d_a l_a f_{v\alpha k} \qquad (2)$$

where d_a is the diameter of the embedded bore hole in wood. The characteristic ultimate shear strength of wood can be expressed as

$$f_{v\alpha k} = k_\alpha \left(\frac{\rho_k}{\rho_o}\right)^{3/2} \left(\frac{d_o}{d_a}\right)^{1/5} \cdot f_{vo} \qquad (3)$$

where

$$k_\alpha = \frac{1}{\sin^2 \alpha + \frac{3}{2}\cos^2 \alpha} \qquad (4)$$

is a dimensionless coefficient depending on the angle α between the bar and the grains, ρ_k is the characteristic density of wood and ρ_o = 500 kg/m^3, d_o = 10 mm and f_{vo} = 8,465 MN/m^2 are constants.

The ultimate shear strength of the real joint is usually much higher than predicted by the truss model, if friction, dowel action or notches are taken into account.

When the capacity of the joint depends on the shear strength of the glue, the ultimate strength should be verified by testing. Usually the anchoring length and adhesive are selected so that this will not be the case.

3. Long-term pull-out tests of the glued-in bars

Altogether 24 specimens were prepared and divided into two control groups. The first group of 12 specimens was tested after three weeks from gluing. Remaining group, other 12 specimens, was tested after ten years outdoor storing to find out the long-term environmental effect on the behaviour of the connection. [3]

The specimens were square glulam sections with side length 300 mm. One corner was cut so that the hole for steel bar could be drilled in 45 degrees angle to grains. The steel bars were threaded M12 plain rods with the outer diameter of 11,7 mm.

Two types of adhesives were used; 12 pieces were glued using epoxy (E-specimens) and 12 pieces using polyurethane (PU-specimens), respectively. The diameter of the bore holes in wood was slightly larger than the diameter of bar being 11,8 mm for E-specimen and 16,2 mm for PU-specimen, respectively. The glued anchoring length was 130 mm in each specimen.

The loading procedure followed the ISO standard [4].The relation between the load and displacement was measured using load arrangement shown in *Fig. 3*.

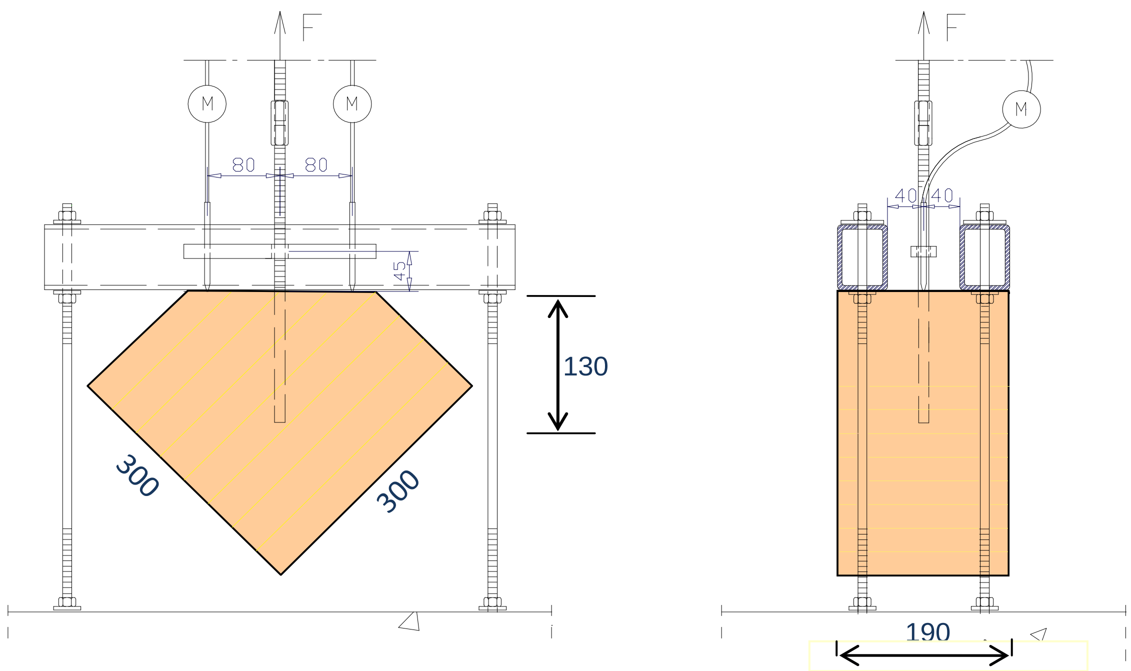

Fig. 3. Test arrangement of the pull-out test of the specimens. Measures in millimeters.

The force-displacement relations obtained in pull-out tests for 10 years old epoxy specimens are presented graphically in *Fig. 4.*

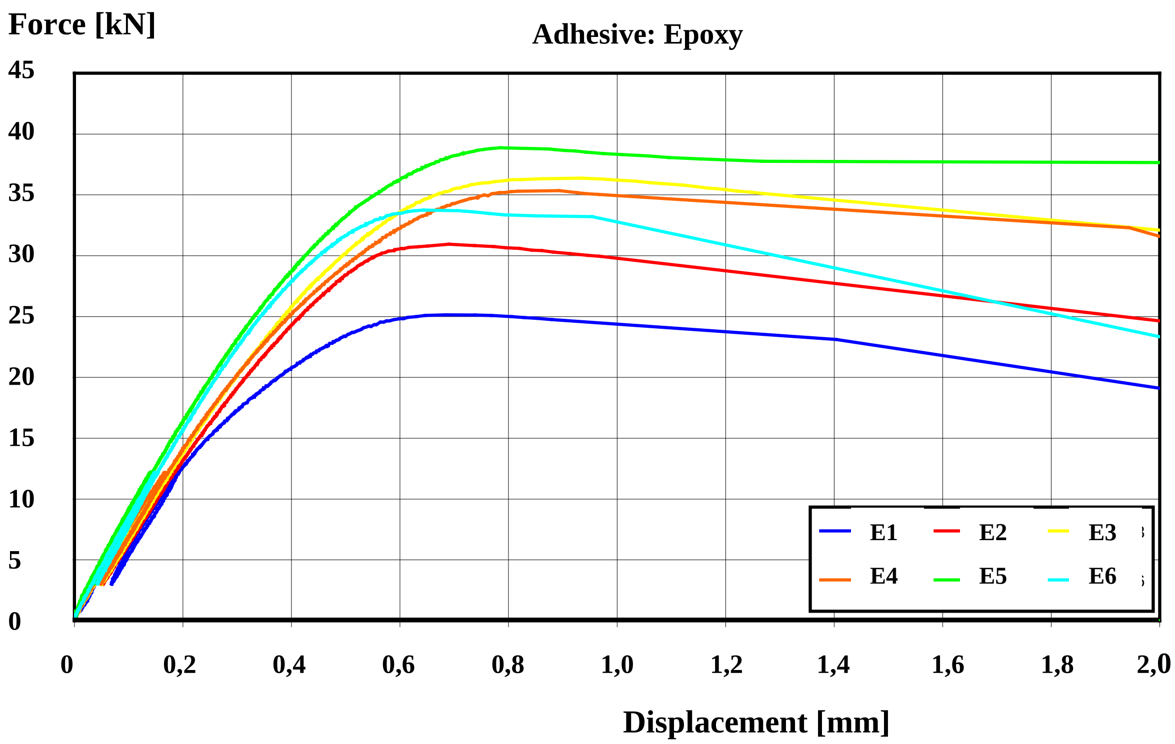

Fig. 4. Load-displacement curves of six E-specimens tested after ten years outdoor condition.

The glued-in connections were ductile as can be seen from the curves in *Fig. 4*. The ultimate load obtained varied usually between 30 – 38 kN, but for one E-specimen it was only 25 kN. By closer inspection it turned out that in this specimen 30 mm of the desired glue length was without adhesive, and that explains the obtained lower test values (blue curve in *Fig. 4*).

The newly fabricated specimens failed as contact shear failure between wood and adhesive. After the tests the surface of the adhesive of E-specimens was noticed to be smooth, but the surface of the PU-specimens was porous indicating that moisture of wood may have reacted with the PU-adhesive.

Generally the failure modes of aged specimens were very similar to those of the failures in tests of the control group of the just fabricated specimens.

The results of pull-out tests are presented in *Table 1*, where the mean values of the measured ultimate load F_u, elastic stiffness k_s and moisture content of different groups are shown. In determination of the elastic stiffness of the joint, the method given in ISO standard was followed [4].

The test results show that adhesive quality affects both the ultimate strength and the elastic stiffness of the connection. The ultimate load capacity by using epoxy as adhesive produced more than 1,2 times as high pull-out capacity as what was achieved using polyurethane in gluing.

The same trend can be seen when the values of elastic stiffness are compared. By using epoxy the stiffness of the connection is approximately three times as high as the stiffness obtained by using polyurethane.

The test results presented in *Table 1* show that the ultimate strength and elastic stiffness increase due to aging of the joint. The increase of mean ultimate pull-out force was 12 % for PU-specimens and 26 % for E-specimens. Also the increase of the mean stiffness of the aged specimens was more than 13 % compared to newly tested specimens.

Table 1. Mean values for ultimate load F_u and stiffness k_s of different groups of specimens.

Adhesive:	Testing age	Group	F_u [kN]	k_s [kN/mm]	Moisture %
Epoxy	Three weeks	E-0	26,16	63,91	15,2
	10 years	E-10	33,05	72,13	18,1
	Ratio	E-10/E-0	1,26	1,13	1,19
Polyurethane	Three weeks	PU-0	21,42	20,79	15,4
	10 years	PU-10	23,93	28,70	16,7
	Ratio	PU-10/PU-0	1,12	1,38	1,09

4. Long-term fatigue tests of a composite beam

The deck of the *Vihantasalmi Bridge* is composed of glued-laminated timber girders and concrete slab. Reinforcing steel bars and notches are used as connectors (*Fig. 5).* Many laboratory tests were made during the design phase of the bridge. [5, 6]

To investigate the fatigue behaviour and the influence of the long-term outdoor condition, two equal full-size beams were prepared (*Fig. 6*). The beams were tested for fatigue loading in three periods.

The first fatigue test was applied to newly fabricated beams and the second after two years outdoor condition. The third and last test was applied to one beam only after it was stored outside ten years period. [7]

Fig. 5. The connectors and notches of the timber girders in the deck of the Vihantasalmi Bridge.

Fig. 6. Test arrangement and the wood-concrete composite test beam.

The beam selected for long-term fatigue testing experiment was equipped with two different connector arrangements. Half of the beam was equipped with tension and compression bars, the other half with tension bars only. The structure of the beam is shown in *Fig. 7*. Additionally, wedge-shaped notches on the upper surface of the timber beam were machined on both sides to improve the shear capacity between wood and concrete (*Figs 5-7*).

The beams were loaded by a sinusoidal pulsating load with a frequency of 1 Hz and constant amplitude generated by two hydraulic jacks. During the first two tests series the maximum load *P* in one jack was 200 kN, which corresponded to the design load of one beam of the bridge deck. During the last 100 000 cycles the test was carried out by raising the maximum load *P* up to 300 kN.

The minimum load was 10 kN in all fatigue tests.

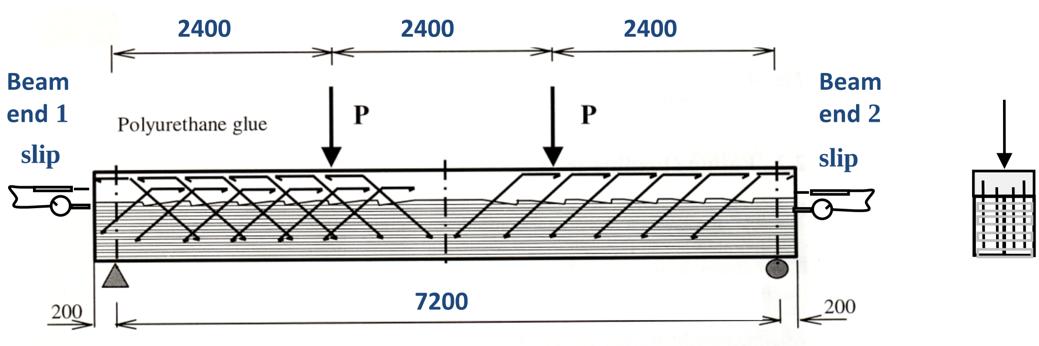

Fig. 7. Test arrangement in fatigue tests. Slips were measured at both ends of the beam.

The third fatigue test was applied to the beam, which had been kept outdoors without shelter approximately 10 years. The maximum load *P* in the last fatigue test was increased up to 330 kN.

Complete loading history of the three fatigue tests is shown in *Fig. 8*.

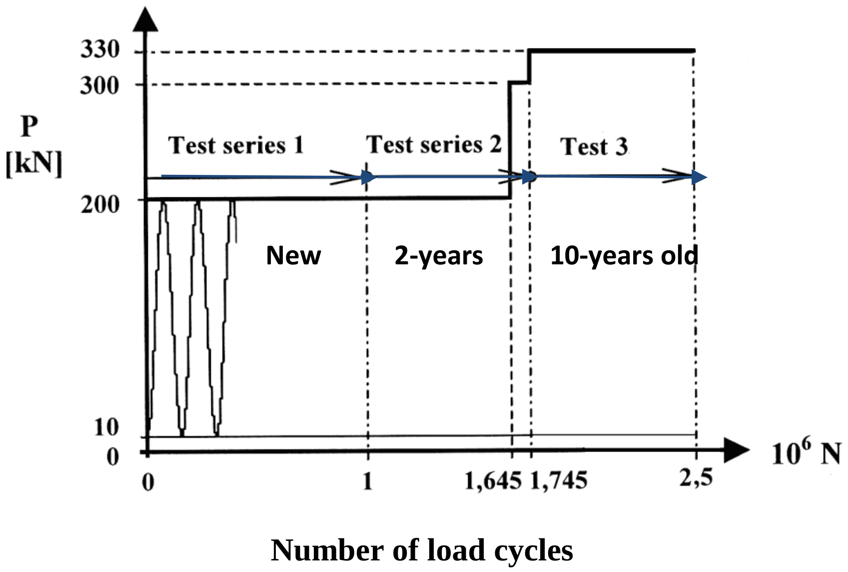

Fig. 8. The loading history of the three fatigue test series of the composite test beam.

The fatigue test was completed when the total number of load cycles *N* reached 2,5 million. No visible damage could be observed. The change of the stiffness due to cyclic loading was controlled by measuring the force-slip relation subjecting the beam under static test after regular number of load cycles. Two test results after 1,8 and 2,5 million load cycles are shown in *Fig. 9*.

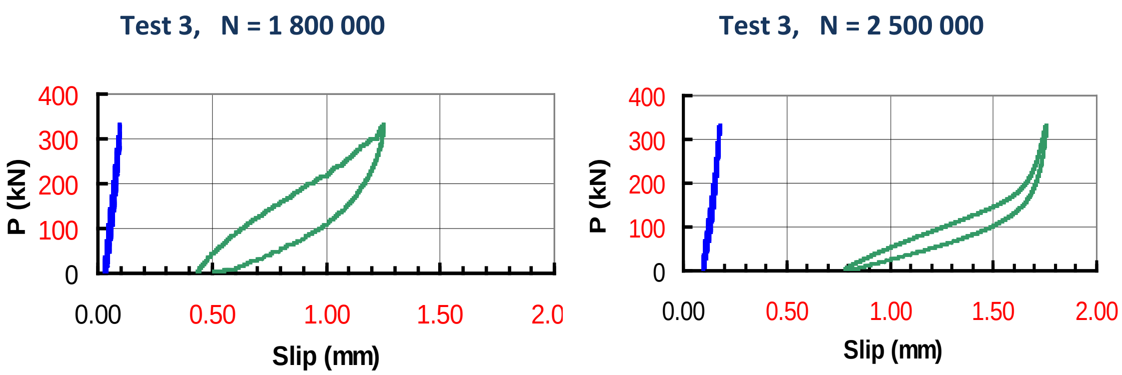

Fig. 9. Relation between applied load and slip after 1,8 and 2,5 million load cycles, respectively. The blue curve describes the measured slip at the end with compression bars (beam end 1) and the green curve at the end without compression bars (beam end 2).

At the end of the beam in which the compression bars were used, the joint was stiff and behaved linearly elastic. The permanent slip was very small even after 2,5 million load cycles.

At the other end of the beam, where compression bars were not used, the maximum slip increased constantly with increasing number of load cycles. Similarly, the permanent slip grew gradually and the connection behaved nonlinearly. Plain notches are not able to carry the compression force until the displacement in the joint is large enough.

The measured slips at both ends of the beam after different number of load cycles are shown in *Table 2*.

Table 2. Maximum slips measured during the three fatigue tests.

Fatigue test	Testing age	Max. Load [kN]	Number of load cycles [N]	Slip at beam end 1 (compression bars) [mm]	Slip at beam end 2 (without compr. bars) [mm]
Test 1	0 years	200 200	1000 1 000 000	0,066*) 0,09*)	0,33*) 0,40*
Test 2	2 years	300	1 745 000	0,09**)	0,50**)
Test 3	10 years	330 330	1 745 001 2 500 000	0,09 0,19	1,19 1,80

*) Slip value was scaled using load factor 330/200 = 1,65
**) Slip value was scaled using load factor 330/300 = 1,10

The test results show that ten years outdoor condition did not cause any changes to the stiffness at beam end 1, where compression bars were used, and the absolute value of slip was very small.

At beam end 2, where the compression bars were missing, the slip was significantly greater than at beam end 1. Moreover, in the beginning of the third test (N = 1 745 001) the measured slip 1,19 mm was 2,4 times as big as it was 8 years earlier (0,50 mm). After 755 000 further load cycles the slip grew up to the value of 1,8 mm. On the basis of the test results, both ageing and increasing number of load cycles affected the slip growth in the joint at beam end 2.

It can be concluded that compression bars are essential to keep the slip on low level and to preserve the stiffness in a long run.

After the last fatigue test was finished, the wooden part of the test beam was cut and opened. Inner wood was inspected and found to be in perfect condition (*Fig. 10*).

The bottom end of the glued-in bar in wood was also uncovered and examined. No damage due to fatigue loading could be observed and no signs of slip could be found. The surface of the glue was smooth (*Fig. 11*).

Fig. 10. Cross-section of the test beam after ten years outdoor condition and fatigue tests.

Fig. 11. The bottom end of the glued-in bar in wood after ten years outdoor condition and fatigue tests.

5. Remarks of the current condition of two composite timber bridges

Kruununmylly Bridge is the oldest wood-concrete composite bridge built in the Nordic countries (*Fig. 12*). The beams of the deck are glued-laminated timber beams with salt impregnation.

The connectors are glued-in reinforcing bars in two inclined directions.

The bridge has been in service for vehicle traffic without any special problems for twenty years.

The connectors are glued-in reinforcing bars in two inclined directions, similarly as shown in *Fig. 5*.

The span of the bridge is 8 m and the effective width is 12 m.

Fig. 12. Kruununmylly Bridge after completion in 1993.

The current outlook of the bridge has somewhat suffered during years. Bushes have grown wildly hiding partly one side of the deck. Additionally, the surface of the concrete edge beams and the wooden railings need refurbishment (*Fig. 13*).

The glulam beams were inspected and found to be in perfect condition *(Fig. 14).* Cracks or other damages in the wooden beams were not discovered. The moisture content of several beams was measured and found to be on normal level in a range from14,2 % to 18,2 %.

Fig. 13. Kruununmylly Bridge in 2013.

Fig. 14. Outer surface of the glulam beam.

Vihantasalmi Bridge is the largest timber bridge in Finland with its three 42 m long main spans.

Fig. 15. One span of the *Vihantasalmi Bridge in 2013.*

Due to its unique structure the bridge has been under continuous survey after its inauguration in 1999.

Some remarks about the current condition may be noted after 14 years service.

The zinc coating of the railing poles has caused runs on the surface of the utmost beam causing visible harm to the aesthetics of the side view (*Fig. 15*).

The wooden rail on the deck is worn out and needs to be replaced (*Fig. 16*).

The southern end of the bridge needs clearing of bushes (*Fig. 16*).

Fig. 16. Worn top guide of the railing. On the background wildly growing bushes are seen.

Fig. 17. Water pocket and crack at the end of the inclined load-carrying member.

Two inclined load-carrying members of the superstructure were inspected by removing the protecting wooden cover on the beams. Water pockets were found at the ends of the members and the beam ends were practically wet. A long crack in the direction of grains was noticed (*Fig. 17*).

At the height of 500 mm from the deck surface, the moisture content of the inclined members was on a normal level varying between 17,2 % and 18,5 %.

High moisture contents were reported earlier at the same joint, but at the ends of the wooden beams under the concrete deck [1]. The problem of the connection is that the ends of wooden members are on all sides confined by steel walls. The situation is even worse at the top part of the connection, where concrete cover encloses the joint.

The problematic joints need to be inspected and repair actions planned.

6. Conclusions

The joint made of glued-in bars is simple and offers an effective way to connect a wooden beam with a concrete slab. The behaviour of the connection is easy to understand, design and analyse.

The results of long-term pull-out tests showed that glued-in bars are ductile and stable connectors. Ten years outdoor condition did not reduce the strength or stiffness of the connection. Furthermore, the test results of old specimens indicated a little higher strength and stiffness values than obtained for newly fabricated specimens.

Epoxy is recommended to be preferred as adhesive, when strong and stiff connectors are needed. However, gluing procedure of the bars is sensitive to mistakes, especially when PU-adhesive is used. Additionally, the work has to be carried out with special care.

The fatigue tests showed that the connectors are ductile. No fatigue damage could be observed even after 2,5 million load cycles. When the compression bars are used in the connection, the joint behaves practically linearly. It became evident during fatigue tests that compression bars are essential to guarantee the long-term strength and stiffness properties. It was also pointed out that the ageing and environmental exposure did not influence negatively on the behaviour of the joint.

Wood-concrete composite deck is most suitable to be used in small or medium-span simple road bridges. This was confirmed during the inspection of the beams of the oldest bridge of this type, Glulam beams are in perfect condition after 20 years period of service.

In small wood-concrete composite bridges the moisture content of the wooden beams stays on a low level. In more complicated bridges there are a lot of details and connections, which require special actions to avoid excessive moisture content.

In any case, timber bridges must be designed and maintained so that the wooden parts can be kept dry during the service life of the bridge. Consequently, 100 years service life can be reached.

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