EXPERIMENTAL AND NUMERICAL RESULTS ON SEMI PRESTRESSED WOOD-CONCRETE COMPOSITE FLOOR SYSTEMS FOR LONG SPAN APPLICATIONS

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1. SUMMARY

It is a challenge for strucutral engineers and contractors to design and built long span floor systems indifferently of the materials used. This is primarily due to the combination of statical and dynamical issues which have to be considered in the design procedures.

Recent work in USA and Germany has indicated that continuous glued-in metal plates provide a highly rigid and ductile shear connection between wood and concrete in composite action. It is the degree of stiffness found in the following system that allows the suggesfull use of the semi prestressing technology. The developement and application of this continuous wood concrete composite system (hbv-system) has shown an efficient and reliable performance.

The system was tested in shear and bending. The shear tests were performed on a number of different shapes and under various climatic conditions. The bending tests were performend on full scale semi prestressed members with a maximum span of approx. 10 Meters. The testing was conducted at the Material Testing Laboratories MPA Wiesbaden as well as the MPA Munich.

The structural elements of the wood-concrete-composite system are shown by the following figure. The shear connector consists of a continuous steel mesh. One half of the connector is glued into a channel within the glue lam plate element. The other half is reaching into the concrete and acts as a support of the reinforcement.

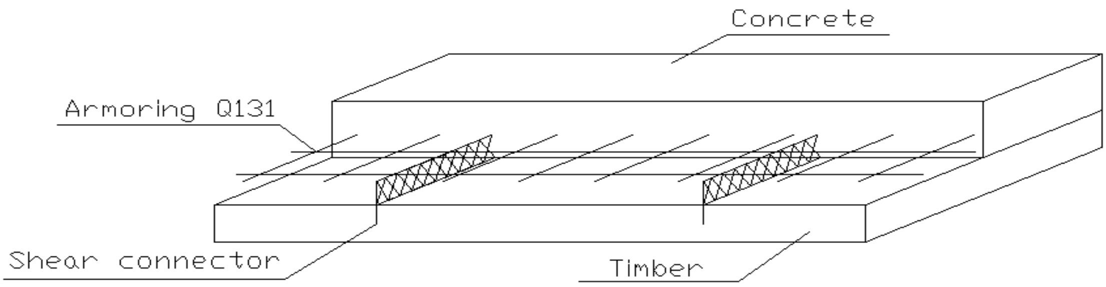

Fig. 1 Structural elements of the wood-concrete composite system.

The test results prove a tight fit with the predicted failure load and failure mechanism and prove therefore a reliable performance of the innovative composite system. The full scale member was testet to veryfy the application of the composite system in a pilot project. The test results were then transformed into an anaysis approach that uses the truss model methodoligy. The composite system was analysed based on prestressing, dead load, live load and thermal load. All stresses and defelctions were within the limits of DIN 1052.
The long span performance is in particular possible by the stiff continuous connector system. Its application potential can be found in floor systems of residential and commercial buildings as well as in bridge structures.

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2. INTRODUCTION

The success of a wood-concrete composite system depends solely on the performance of the shear connector. It is most advantageous from a structural standpoint to use a shear connector that provides 1) a stiff connection between the wood and the concrete while undergoing stresses in the elastic range and 2) a ductile response while undergoing stresses in the plastic range. Considering the relatively non-ductile failure modes of the concrete and wood in tension, it is most logical to design for failure to occur in the shear connector where improved stiffness and ductility can be achieved through an elastic perfectly-plastic steel failure. This design consideration was integral to the composite system developed in this study. Ensuring failure initiates in the steel component also improves system reliability due to the consistent nature of steel in comparison to wood or concrete.

Any slip at the interface of the two main components produces substantial deflection of the overall system and thereby reduces system performance. Slip can occur at one or more of the following slip plane locations: between the concrete and the connector, within the shear connector itself and/or between the connector and the wood. Many wood-concrete shear connector systems in use today are inherently soft in terms of the latter slip plane.

For example, high strength nails, screws and bolts are generally considered to be the least rigid of all connectors (Ceccotti 1995, Blaß and Schlager 1996, Bathon and Graf 2000, Avak and Glaser 2002) as they tend to split and crush the wood incurring slip under load. As demonstrated with numerous wood composite products (eg. glulam, I-joists and structural composite lumber), structural adhesives have the potential to provide extremely rigid connections. As such, adhesive was used to minimize interlayer slip between the connector and the wood in the composite system (hbv-system) developed in this study. Figure 2 shows load/displacement curves of four different connector types. All tests were done under equal boundry conditions coherent with 3.1 Shear Tests.

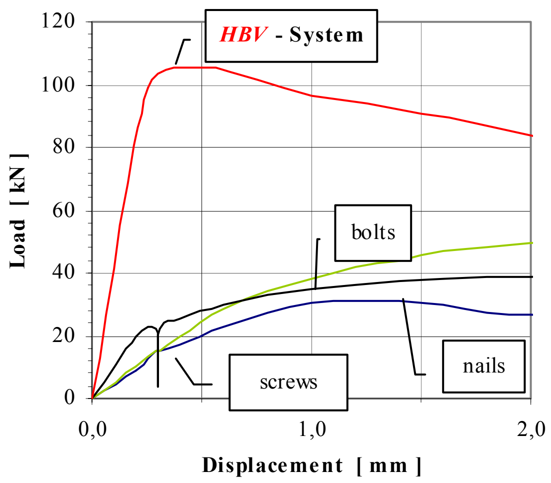


Fig 2 Comparison of load.displacement curves

3. TESTING PROGRAM

3.1. Shear Tests

The timber used was a European species; grade S11, with an allowable bending strength of 11 MPa. The moisture content of the timber was determined to be an average of 10% with minimal variation. The adhesive was a two component epoxy commonly used in Germany. The concrete was an average standardized concrete with a failure compression capacity of minimum 30 MPa. The shear connector consisted of a St 37 (comparable to an A 36) steel mesh.

Referencing Figure 3, specimens consisted of an 8x14x40 cm timber section conjoined to an 8x40x40 cm concrete slab through a 2 mm thick x 400 mm long steel mesh. The steel mesh was 100 mm high and reached 50 mm into the timber and 50 mm into the concrete. The connector rested in a 50 mm deep rout in the timber which was cut approximately 3 mm wide with a standard circular saw. Glue was then filled into the rout using a manufacturer approved dispensing system (ie. an applicator gun with a duo-pak cartridge and a mix nozzle). A continuous bead of glue was dispensed into the rout with several passes until full, ensuring uniform distribution of the glue. Shear connectors were then pressed slowly but firmly into the channel. It was common and desirable to observe glue overflow, which was simply removed. The premise to this approach is to provide adequate glue coverage such that the glue could flow into the voids in the steel lattice to provide mechanical interlocking. The adhesive was cured for a minimum of 16 hours. The timber sections were then placed upside-down on formwork in preparation for pouring the concrete. A moisture protection layer was installed between the timber and the concrete to prevent excessive wetting of the timber.

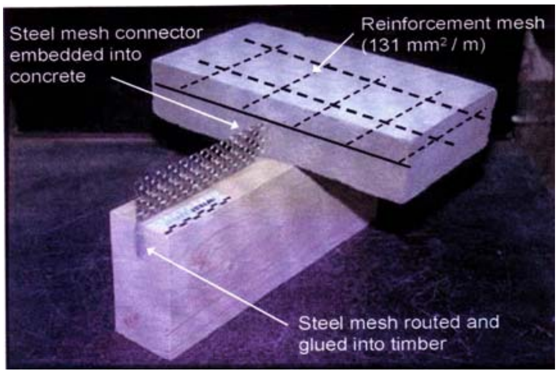


Fig 3 Shear test specimen

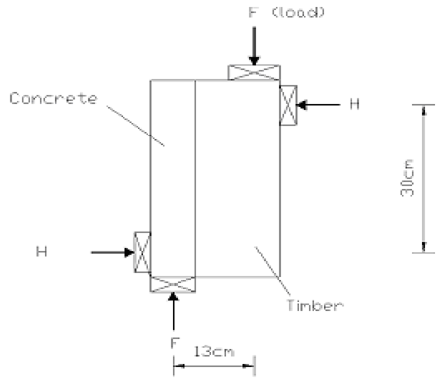


Fig 4 Shear test set-up

Specimens were subjected to a one-sided "push-out" test under ambient laboratory conditions. Loading and support conditions are illustrated in Figure 4. An inherent eccentricity of 13 cm exists in the setup resulting in a horizontal force couple that is linearly proportional to the applied shear force. The test was performed according to the DIN EN 26891 which requires a semi-cycling loading whereby loading is applied to 40% of the estimated failure load, paused, reduced to about 10 %, and then increased until failure.

3.1.1. Shear Test Results

Shear test results and corresponding descriptive statistics are shown in Table 1. They include ultimate failure load, corresponding displacement, corresponding shear stress in the connecting timber surface, and slip modulus as determined by the initial slope of the load-displacement curve.

The observed failure mode of shear specimens of this study was consistently steel failure. Figure 5 shows the resulting load/displacement curves from the push-out tests. A relatively close fit of all curves was observed with a rigid linear-elastic region and a well developed plastic region. The plastic behavior evident in the curves reaffirms that a steel failure occurred for each specimen.

The tests produced a minimum ultimate load of 102.53 kN, a maximum load of 120.97 kN and an average of 111.62 kN. The low coefficient of variation (COV) of 6.64% is highly desirable and particularly noteworthy for a composite system using 4 different materials (wood, steel, adhesive and concrete).

	Load	Deformation	Shear stress	Slip modulus
Test	F_{max} [KN]	v_{max} [mm]	τ [N/mm²]	C_e [KN/mm]
1	120,97	1,743	3,02	353,87
2	114,89	1,402	2,87	367,65
3	103,53	1,339	2,59	371,75
4	102,53	1,404	2,56	331,13
5	116,88	1,519	2,92	410,96
6	110,96	1,246	2,77	657,42
Ave	111,62	1,442	2,79	415,46
Var	7,41	0,172	0,19	121,38
COV [%]	6,64	11,9	6,81	29,22

Table 1 Results of the shear tests

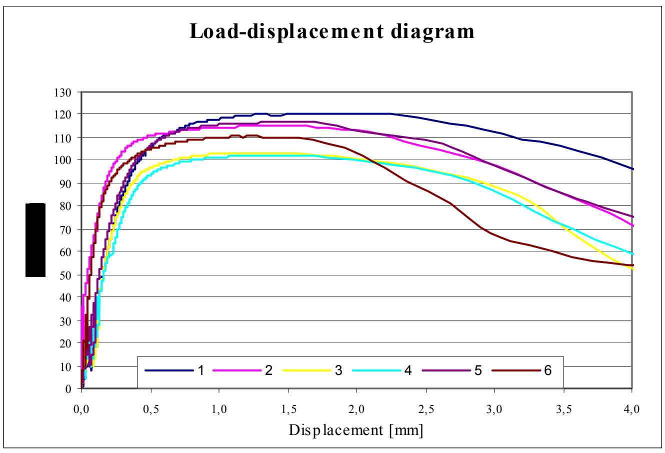


Fig 5 Load displacement curve of shear tests

The slip modulus varies between 331.1 kN/mm and 657.4 kN/mm with an average of 415.5 kN/mm. The variability is expectedly higher than that for ultimate load (29.22% vs 6.64%) since the slip modulus is influenced by slippage occurring in three different slip planes and can be accentuated by small variations in concrete porosity and glue spread as well as additional friction between the wood and concrete interface due to some geometircal discontinuities.

3.2. Bending Tests

In order to investigate the bending performance of the full scale wood concrete composite system as found in commercial applications, a 4 point bending test was conducted.

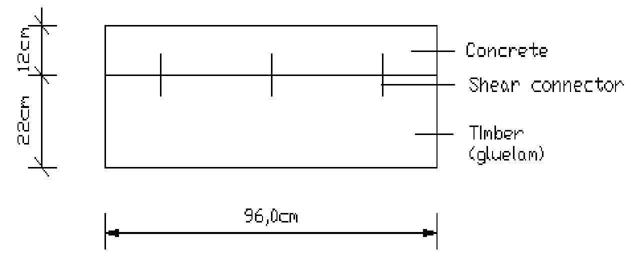


Fig 6 Bending test specimen cross section

As shown in Figure 6, the specimen consisted of a timber plate system (as opposed to a T-beam system, also compare: www.hbv-system.de) with a 22 x 96 cm solid glulam plate, a 12 x 96 cm concrete slab and a total of 3 rows of shear connectors in cross section. The shear connectors consisted of the same steel mesh material that was tested in the shear test with the exception that the connector length was 100 cm. As before, the steel mesh extended 50 mm into the glulam and 50 mm into the concrete.

Referencing Figure 7, the center-to-center span was 9.86 m with a bearing length of 96 cm at both supports. The glulam beam was prestressed by midspan before the concrete was applied. The prestressing was done through a camber of the wooden beam plate of 3.3 cm at mid-span. In contrary to prestressed concrete systems this procedure of prestressing is simple and cost neutral. Two load lines were applied 2.60 m apart centered about mid-span using a 2000 kN capacity hydraulic actuator mounted to a system of steel spreader beams. Vertical beam displacement was monitored at mid-span; horizontal slip between the concrete and timber was measured at mid-span, under load points and over bearings; and horizontal displacement of the beam at bearings was recorded.

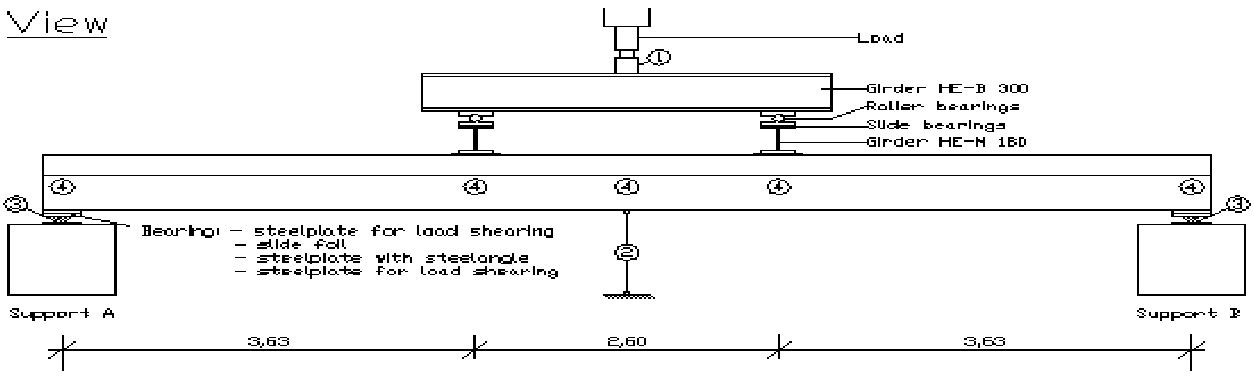


Fig 7 Beam specimen test setup

3.2.1. Bending Test Results

The load / mid-span displacement curve of the beam is shown in Figure 8. The only visible signs of failure at maximum load (291 kN) were slippage cracks in the concrete near the interface of the wood and concrete between the left end support and the neighboring load point - in a region of constant shear force. It was speculated (and later confirmed by sectioning the specimen) that shear failure occurred in the steel shear connectors on this end of the beam. Furthermore it was speculated that the three shear conntectors on one end of the beam did not fail at the same time. It was assumed (and later confirmed) that one row of the shear connector failed first and allowed a deformation of the composite plate structure out of plane. At yield of the steel connectors, the load apparatus tipped toward the broken end and side of the beam reducing mid-span deflection. As a result, the data curve indicates decreasing displacement (starting at approx. 250 kN, Fig. 8) upon failure. The predicted failure load based on the shear tests was approx. 300 kN. The failure of the bending test occured at 291 kN. Including the dead load based on the load application subsystems, the predicted load matches very closesly with the actual failure load.

The concrete was removed at the cracked locations to inspect the steel shear connectors beneath (Figure 9). As suspected, the shear connectors were deformed, partially torn or broken. The three shear connectors of the left end of the support showed different degrees of deformation indicating that the failure mechanism started and performed uniformly. Fig. 9 shows also that the largest deformation of the shear connector was at the far end indicating higher load transmission in that region. Adhesive failure was not visible at any location. The failure mode was confirmed to be plastic yielding of the steel mesh which was the same failure mode as in the shear tests.

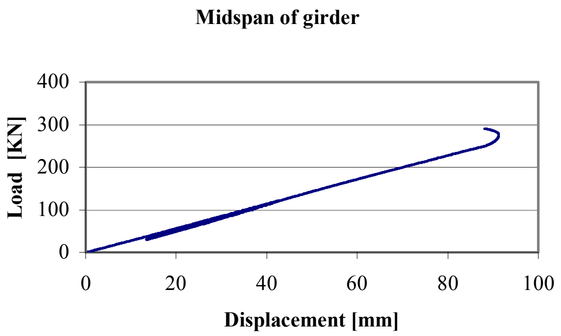


Fig 8 Load vs mid-span displacement

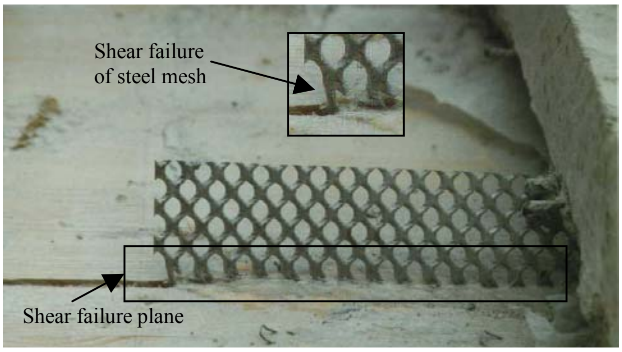


Fig 9 Steel failure of beam specimen

4. ANALYSIS AND DESIGN

The analysis of the wood concrete composite system was performed through a truss model. The model is shown in Figure 10. The truss model consists of a top and bottom member representing the concrete and wood respectively. The spring diagonals represent the shear connector based on the shear test of the steel mesh. The truss model provides both the prediction of the test perfomance as well as a design tool for the commercial application of the system.

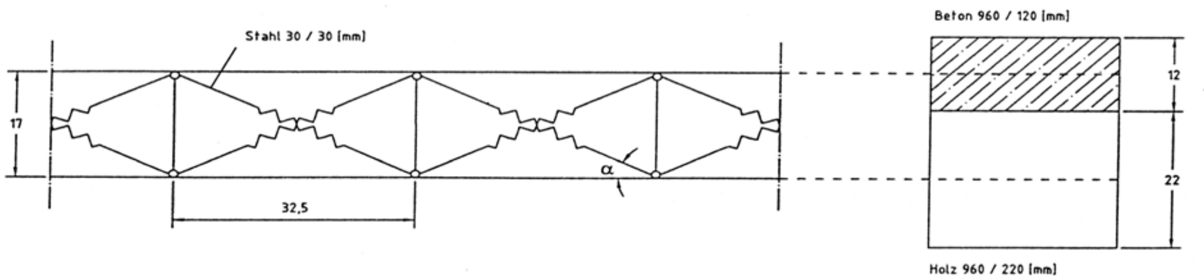


Fig 10 Truss model

The analysis showed that the wood concrete composite system produces a nearly fully composite action. Based on numerical values the hbv-system provides a 99% composite action. This means that in terms of mechanical properties it can be assumed that the concrete is rigidly connected to the wood. At the same time it allows for a full plastic performance in the range of ultimate load capacities due to the steel mesh (compare Figure 5). Figure 11 shows the stress distribution, the ultimate shear flow (t_u) and the deflection (f) of the composite cross section based on the various load applications. The analysis was done based on a single span member shown in Figure 7 (approx. 10 meter) using linear elastic truss modell behaviour. The addition of the first and last column shows that under prestress conditions the overall deflection under service load turns out to be 0,46 cm (4,78-4,32) and therefore approx. l/2000. At this point all stresses are within the boundries of DIN 1052. This study shows the tremedous advantages of semi prestressed continuous wood concrete composite systems.

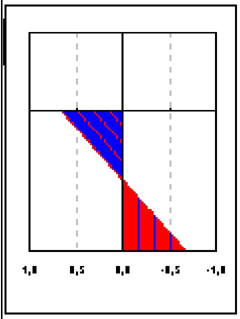
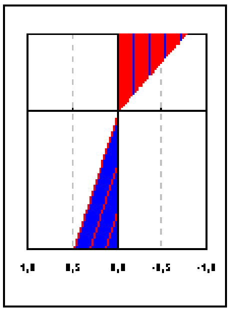
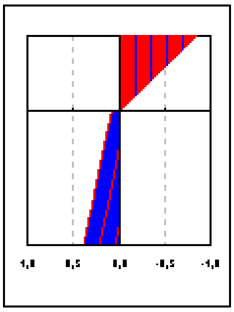
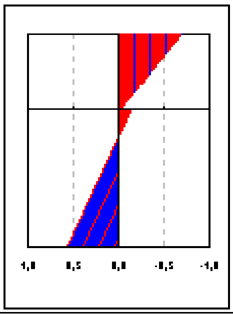
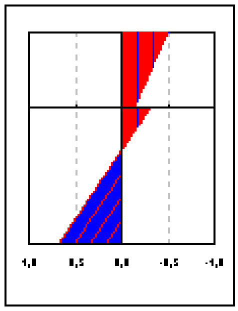
LA1	LA2 + LA3	LA2 + LA3 + LA4	LA2 + LA3 + LA5	LA6 + LA7 + LA9
t = 0 d	t = 28 d	t = 28 d	t = 28 d	t = ∞
prestressing	dead load + live load	dead load + live load + top side heating (+30°C)	dead load + live load + top side cooling (-30°C)	dead load + live load + top side cooling (-30°C)
				
f = -4,32 cm	f = 2,03 cm	f = 0,81 cm	f = 3,25 cm	f = 4,78 cm
	t_u = 0,58 kN/cm	t_u = 0,85 kN/cm	t_u = 0,67 kN/cm	t_u = 0,41 kN/cm

Fig 11 Results of analysis based on the linear elastic truss model

5. CONCLUSIONS

The objective of this work was to investigate the structural behaviour of an innovative semi prestressed continuous wood concrete composite system. The paper proves that the system is well suited for long span applications found in residential and commercial buildings. Due to the semi prestressing of the composite cross section, the hbv-system provides advantages in strength, deflection and cost.

The proposed system is not only well suited for new buildings – i.e. as an alternative to concrete floors, especially for curved applications - but is also ideal for use in upgrading of old buildings. The use in bridge design is also very promising, due to the overall advantages of the hbv-system over timber bridges in terms of durability, creep resistance, temperature and moisture fluctuations as well as dynamic response. Work in these areas is currently ongoing at the University of Applied Sciences Wiesbaden, Germany and at the University of Massachusetts, Amherst, MA, USA.

6. REFERENCES

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