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ADHESIVELY BONDED TIMBER-CONCRETE COMPOSITE CONSTRUCTION METHOD (ATCC) – PILOT APPLICATION IN A SCHOOL BUILDING IN GERMANY

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ABSTRACT: A pilot-application of adhesively bonded timber-concrete composite (ATCC) slab elements with prefabricated concrete parts in a school building in Germany is presented in this paper. Firstly, the concept and the relevant points of the planning process are outlined. The construction and the materials of the ATCC slab are then presented. After the introduction of a suitable calculation model for ATCC beams with discontinuous arrangement of the adhesive bond, a validation in the form of a full-scale bending test follows. Finally, the quality control concept which has been developed for this project is presented.

KEYWORDS: Adhesives, Timber-Concrete-Composite, Pilot Project, Full-Scale Testing, Quality Control, Monitoring

1 INTRODUCTION

The new building of the "Ernst-Leinius Schule" in Kassel, Germany (Figure 1), was planned as a timber construction. Due to the requirements to limit floor vibration, a hybrid timber-concrete composite (TCC) construction with notches as shear connections and cast-in-place concrete is to be used for the slab elements.

Figure 1: School building "Ernst-Leinius Schule Kassel" (From Baufrösche • Architekten und Stadtplaner GmbH)

Although TCC constructions with cast-in-place concrete offer great advantages as an end-product and contribute significantly to improving the competitiveness of timber construction in multi-storey construction, there are some disadvantages. The disruption of the construction process particularly plays a decisive role here: the assembly of the timber construction as a classic dry construction with surfaces that are largely ready for use (ceiling soffit, columns, walls) is considerably slowed down by the concrete work: reinforcement has to be laid, joints sealed, surfaces protected, and the concrete has to cure. All this takes time and delays the construction progress. In addition, the risk of water damage increases significantly during the time the reinforcement is being installed and the concrete is poured.

With that in mind, it appears astonishing that there have been comparatively few attempts to eliminate these disadvantages by using dry, prefabricated concrete parts. Apart from a method with plastic sleeves inserted in the precast reinforced concrete elements for subsequent screwing [1], using adhesives is an obvious solution for implementing the composite. The most important advantages of adhesively bonded timber-concrete composites (ATCC) are:

- full bond and optimized mechanical interaction,
- rapid construction progress,
- low moisture penetration into the building due to the use of precast reinforced concrete components and the quick assembly process,
- ready for load-bearing after one day of curing, fully loadable after approximately seven days,
- no contact pressure required when using epoxy resins,
- possibility of producing the floors on-site or in the factory,
- reduction of the influence from concrete shrinkage, and
- comparatively easy separation of components in terms of deconstruction and reuse.

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The client and the specialist planners involved in the project of the school building have created the framework conditions to apply the construction method of ATCC with prefabricated concrete parts for the first time out of the laboratory into the building industry. The pilot application represents the result of many years of development in which several members of the team of the University of Kassel have participated [2]-[8].

2 CONSTRUCTION

2.1 BASIC INFORMATION

The floor is characterised by a span of 7.68 m and design loads ($g_d + q_d$) of about 12.1 kN/m². The pilot project is located in an area of about 30 m², where the static system changes from a two-span to a single-span beam (see Figure 2).

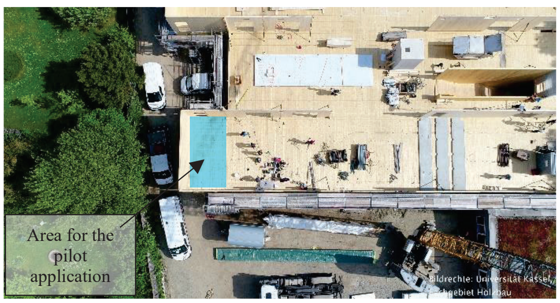

Figure 2: *Top view of the building with marked area for the pilot application*

The composite action is realised by applying the adhesive with a mortar sledge on the timber part and placing the concrete-prefab, which has a weigth of approximately two tons, on top with the help of a crane (see Figure 3 and Figure 4).

Figure 3: *Handling of precast concrete elements*

The adhesive is arranged in stripes perpendicular to the span (Figure 7) which are spaced closer together towards the support according to the shear force distribution. The notches along the edges of the prefabricated concrete parts (Figure 4) do not participate in the shear load transfer due to vertical loading. They are filled with concrete subsequently after bonding to create an in-plane diaphragm action of the slab.

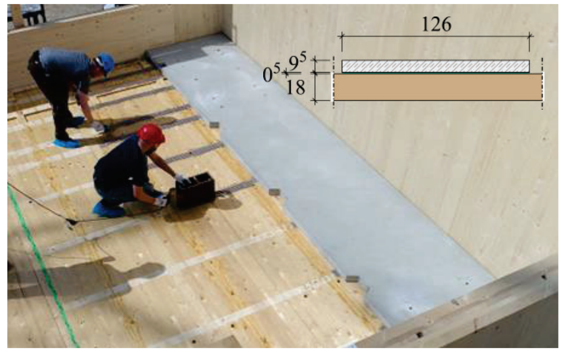

Figure 4: *Application of the adhesive on the timber part*

2.2 MATERIALS

Regarding the timber part, glulam of the quality GL28c with a height of 18 cm has been used throughout the entire slab area. The moisture content was tested at several measuring points on the floor, with values ranging from 13.0 to 15.4 %. Because the shear strength, which can be identified as the most relevant parameter regarding the determination of the bond strength, could not be determined on site, the surface tensile strength of the timber has been determined instead. The parameter was determined according to EN 311 [9] to $f_{\mathrm{ttm,surf}}$ = 2.3 N/mm² (n = 6, COV = 13 %).

The concrete parts were ordered with a thickness of 9.5 cm. According to the test certificates of the manufacturer, the concrete parts have a compressive strength $f_{\mathrm{cm,cube}}$ of 58.8 N/mm² and can, therefore, be assigned to the strength class C40/50. The underside of the slab has been sandblasted (see Figure 5).

Figure 5: *Sandblasted underside of the prefab concrete part*

The average surface tensile strength $f_{\mathrm{ctm,surf}}$ of the concrete has been determined as 3.4 N/mm² (n = 10, COV = 13 %), according to EN 1542 [10]. The moisture content of the concrete has been determined by weighting and drying (Darr drying-method) to about 0.9 %.

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The polymer mortar "Epument 130/2-14_B1" from RAMPF Group was used as an adhesive [11]. This product exhibits an average cylindrical compressive strength $f_{adh,c,mean}$ in the range of 140 N/mm², a flexural tensile strength $f_{adh,t,mean}$ of 28.7 N/mm² (n = 6, COV = 7 %) and an adhesion strength on a sandblasted steel plate of $f_{adh\text{-}steel,t,mean}$ = 13.8 N/mm² (n = 24, COV = 6 %). The mean thickness of the adhesive joint was set to 0.5 cm. The total height of the construction, therefore, was 28.0 cm.

2.3 EVENNESS OF THE SURFACES

The evenness of the surfaces plays a decisive role regarding the success of the bonding, as has been unanimously established in preliminary work on the adhesively bonded joint [5], [12]-[14]. With reference to the construction tolerances for planarity regulated by standards [15], a maximum deviation of ± 1 mm over a length of 0.20 m or ± 3 mm over a length of 1.00 m can be assumed for the flatness of the formwork side of the concrete part, according to DIN 18202 [16]. Regarding the timber, a construction tolerance of ± 4 mm per 2.00 m length can be assumed, according to DIN 18203-3 [17]. This leads to the conclusion that a maximum gap of 7 mm must be assumed in the case that the largest unevenness of timber and concrete are superimposed. In the course of the development of the adhesive system and the application technique, it was found that a gap of 7 mm can be bridged reliably if the adhesive is applied with a toothed spatula, with the height of each tooth of 12 mm (see Figure 6).

Figure 6: *Application of the adhesive with a toothed spatula, installed in a mortar sledge*

The evenness of the timber elements has been measured on-site with an aluminium batten of 2.0 m length in the range of 0.0 to 3.0 mm. After the concrete part has been placed on top of the timber, the actual gap at the edges of the precast concrete part was measured with a measuring-wedge in the range of 0.0 to 2.0 mm.

3 ANALYTICAL MODEL AND CALCULATION

3.1 PRINCIPLES

Due to the adhesive-bond, the connection between the timber and the concrete can be assumed as rigid, which means that the stresses can be determined analytically with basic, mechanic principles based on the theory of elasticity. This approach is commonly applied in literature [18], [19] and can also be used for TCC constructions with adhesives and cast-in-place concrete [13], as well as for TCC constructions with micro notches, for which, according to Müller and Frangi [20], a rigid bond can be assumed if the notches are arranged continuously over a large area of the span.

The basic relationships that are indispensable for understanding the calculation are briefly listed below. In a first step, the position of the stress zero line z_0 is calculated.

$$z_0 = \frac{\sum_{i=1}^{i} E_i \cdot A_i \cdot z_i}{\sum_{i=1}^{i} E_i \cdot A_i} \tag{1}$$

An effective bending stiffness $(EI)_{cal}$ is then calculated for the composite cross-section, taking into account the different Young's moduli E_i of the partial cross-sections A_i using Steiner's theorem. The geometrical parameter a_i is the distance between the neutral axis of the total cross-section and the neutral axis of the partial cross-sections.

$$(EI)_{cal} = \sum_{i=1}^{i} E_i \cdot I_i + E_i \cdot A_i \cdot a_i^2 \tag{2}$$

Knowing the effective bending stiffness, the bending stresses σ_i at each point of the composite section can be calculated.

$$\sigma_i = M \cdot z \cdot \frac{E_i}{(EI)_{cal}} \tag{3}$$

The maximum stress values at the top and bottom of the composite member are given by substituting the maximum distance between the neutral axis of the composite beam to the outer edges of the cross-section.

With knowledge of the bending stresses σ_i, the relevant criteria for the limit state design of the timber parts and the concrete according to Eurocode 2 [21] and Eurocode 5 [22] have to be fulfilled. For the latter, both bending and tensile strength should be considered.

Further guidelines regarding the long-term behaviour at time t = 3…7 a and t = ∞ are given in CEN TS 19103 [23]. Regarding the verifications in the serviceability limit state, the criteria of deformations and vibrations are of particular relevance, similar to with most other wide-span timber structures for residual use [26]. CEN TS 19103 recommends carrying out the design according to Eurocode 5.

3.2 STRESS CALCULATION FOR ATCC BEAMS WITH DISCONTINUOUS BOND

If the adhesive bond is not continuous along the entire length of the beam but discontinuous (e.g. lateral stripes) as in case of the pilot application, new questions arise with regard to the uniform transmission of shear stresses: How is the shear flow distributed into the adhesive areas and which bond stripe is decisive for the design?

Possible calculation methods to determine the shear flow T_b for a discontinuous bond arrangement are strut-and-tie models, two- or three-dimensional finite element models and analytical models. Because the analytical model offers advantages regarding its simplicity, which has currently only been applied to ATCC composites with a continuous bond, an extension is necessary. The geometric relationships are depicted in Figure 7.

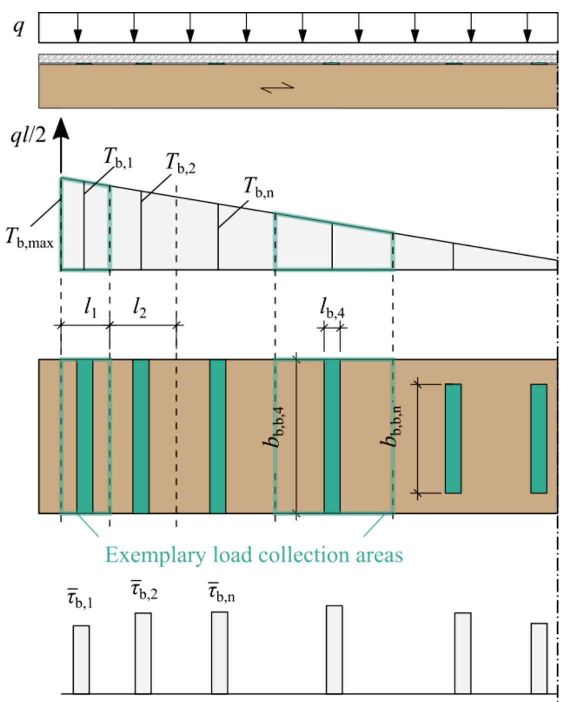

Figure 7: *Composite beam with discontinuous bond – geometric relationships for the analytical calculation model in case of a uniformly distributed load*

Firstly, the shear flow in the bondline $T_{b,i}$ at the stripe i is obtained considering the shear force $V_{n,i}$ at the corresponding stripe and the static moment in the bondline $S_{b,1}$.

$$T_{b,i} = V_{n,i} \cdot \frac{E_1 \cdot S_{b,1}}{(EI)_{cal}} \tag{4}$$

The shear stress in the bondline, which is transmitted at one strip, can then be determined by integration over the partial length. A medium value $\bar{\tau}_b$ can be calculated subsequently by referring the load-collection area to the area of the single strip n.

$$\bar{\tau}_{b,n} = \frac{T_n}{b_{b,n}} \cdot \frac{l_n}{l_{b,n}} \tag{5}$$

3.3 BOND STRENGTH

There are no generally applicable regulations for the verification of the adhesive bond between timber and concrete to date. However, comparable approaches can be found in the literature, whereby the bond failure could usually be attributed to a pure failure in the timber [1], [3]. However, if lower strength concrete, lightweight concrete or hardwood with a high shear strength is used, then the composite failure may be transferred into the top concrete layer [6], [13], [19].

It is generally concluded that the bond failure can be attributed to the substrates timber and concrete if a suitable adhesive is used where adhesion and cohesion failure can be excluded. In the case of the analytical model, where no stresses perpendicular to the joint occur, the bond strength f_b can be set as the minimum of the shear strength of the timber $f_{t,v}$ and the shear strength of the concrete $f_{c,v}$.

$$f_b = \min(f_{t,v}; f_{c,v}) \tag{6}$$

The characteristic value of the shear strength of the timber $f_{t,v,k}$ is defined in the respective product data sheet or the relevant standards of the wood-based material. In addition, according to EN 1995 [22], the modification coefficient k_{cr} should be used to take into account the increased shear stresses due to shrinkage. If k_{cr} is to be considered at the resistance level, the shear strength of GL28c is $f_{t,v,k} = 2.50$ N/mm².

The determination of the shear strength of the unreinforced concrete surface $f_{c,v,d}$ is less well-supported by systematic studies than it is with timber. Some characteristic values, however, can be found in the literature. They are in the range of $f_{v,c} = 3.3$ N/mm² for a concrete in the strength class C30/37 (according to the German Committee for Reinforced Concrete [DAfStb] in the guideline for post-reinforcing concrete with glued-on steel plates [25]; where $f_{v,c}$ is a function of the compressive strength and the surface tensile strength) to $f_{v,c} = 11{,}1$ N/mm² (according to CEN TS 19103 [23] assuming an angle θ of 45°). Based on own investigations [24], a clear correlation between bond strength and surface tensile strength could be found.

$$f_{c,v} = 2{,}0 \cdot f_{ct,surf} \tag{7}$$

The characteristic surface tensile strength is estimated to be $f_{ctk,surf} = 2.20$ N/mm², which results in a characteristic shear strength of $f_{c,v,k} = 4.40$ N/mm².

The design shear strength can be determined if the parameters k_{mod} for the timber and the parameter α_{ct} for the concrete are considered. Furthermore, the safety factor γ_M for the corresponding material is to be included.

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The resulting parameters are $f_{t,v,d}$ = 1.54 N/mm² and $f_{c,v,d}$ = 2.49 N/mm², respectively.

A consideration of the factors k_{b1} and k_{b2} is proposed for the last step of the verification of the adhesive bond. These parameters are recommended in accordance with the investigations on steel and CFRP laminates bonded to concrete [25], where comparable factors (e.g. k_{b1}-k_{b4}, k_{sys}) are proposed.

$$\frac{\tau_{b,max}}{k_{b1} \cdot k_{b2} \cdot f_{b,d}} \leq 1 \tag{8}$$

Regarding ATCCs, the coefficient k_{b1} considers possible degradation effects due to swelling and shrinkage depending on the adhesive used for bonding. With the coefficient k_{b2}, it is possible to consider more complex stress situations, for example, due to a varying bond width or stress peaks. Both coefficients are currently under investigation at the University of Kassel.

4 FULL-SCALE TEST

One full-scale test in the laboratory in a four-point bending configuration was carried out to validate the calculation model and the considerations regarding the bond strength. The test was designed as a single-span girder with a span of 7.68 m. The same materials were used as for the construction of the school building; the prefabricated concrete parts were manufactured in the same batch as the concrete parts for the construction site.

The test set-up is depicted in Figure 8. The force was measured with a load cell with a measuring range of up to 500 kN. In addition to the displacement of the hydraulic cylinder (S0), the deflections were measured with six displacement transducers: S1/S2 for the mid-span deflection and S3–S6 for the relative deflection between the concrete and timber. The deflection w at the mid-span of the composite beam was calculated as the average of transducers S1 and S2. Furthermore, the strains in the bondline were measured using fibre-optical sensors.

The specimens were loaded in a quasi-static procedure applying a constant displacement with a rate of 0.2 mm/s. The global failure of the ATCC beam occurred at a load level of $F_{u,exp}$ = 387 kN ($F_{u,exp}$ = sum of the load-bearing construction and machine load, without the self-weight of the specimen) as a combined bond failure in the timber and the concrete (see Figure 9).

Figure 9: *Bond failure in the timber and the concrete substrate, as predicted from the calculation.*

Before loading to failure, the specimen was, firstly, loaded up to 120 kN, which is approximately 30 % of the ultimate failure load, and then unloaded again up to 20 kN in order to visualise the hysteretic effects. The load was held for 30 seconds at each of these loading points. The full-scale test exhibited a quasi linear-elastic behaviour. No hysteresic behaviour was observed visible (see Figure 10).

The calculation of the full-scale specimen was carried out with the calculation model mentioned above. The prediction of the failure load was referred to mean material properties. The shear strength of the concrete $f_{c,v,m}$ was determined with reference to the experimentally determined surface tensile strength of the concrete ($f_{ctm,surf}$ = 3.0) as $f_{c,v,m}$ = 6.0 N/mm².

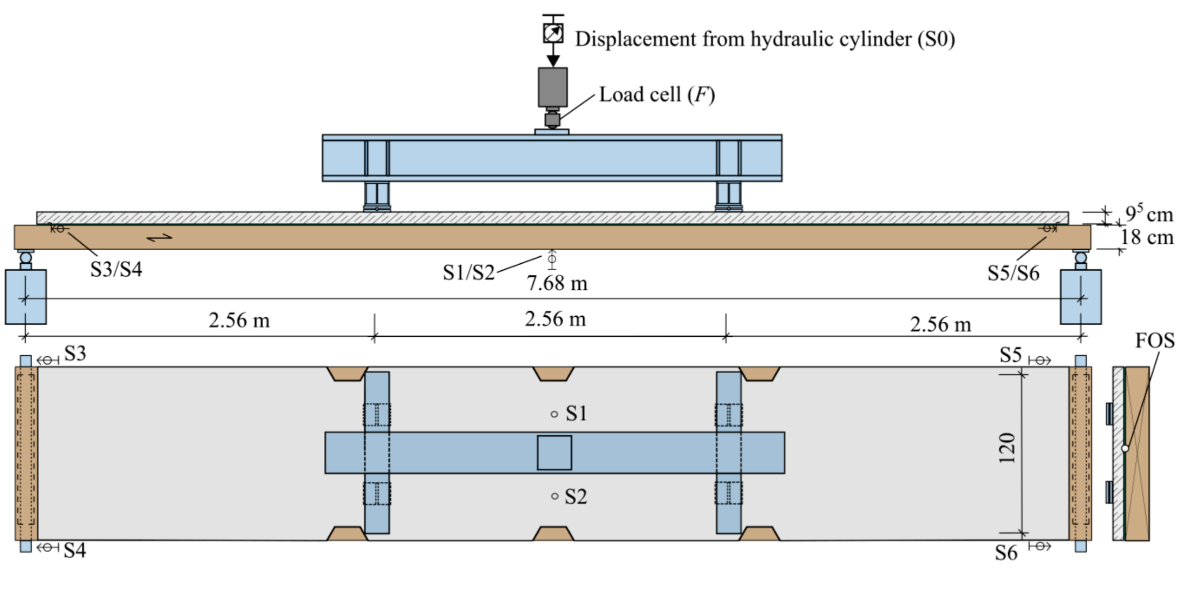

Figure 8: *Test set-up for the full-scale test: four-point bending configuration*

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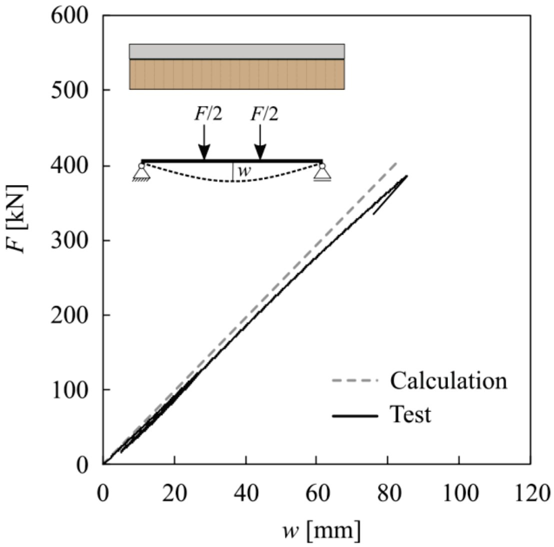

Figure 10: *Load-displacement behaviour of the full-scale test*

The shear strength of the timber was estimated according to Blaß and Krüger [27] as $f_{t,v,m}$(GL28c) = 4.2 N/mm². The resulting bond strength is the minimum of both $f_{b,mean}$ = min($f_{t,v,m,}$; $f_{c,v,m}$) = 4.2 N/mm².

As a result, the failure of the beam is expected to take place in the bondline at a load of $F_{u,cal}$ = 406 kN. The corresponding, predicted failure loads for a bending failure in the timber ($F_{u,cal,m+t}$ = 421 kN) and compression failure in the concrete ($F_{u,cal,c}$ = 438 kN) are higher and, therefore not expected to happen in the test.

The agreement between the test $F_{u,exp}$ = 387 kN and the calculation model is very good, for both the predicted failure mechanism (bond failure) and the failure load ($F_{u,exp}$ = 95 % of $F_{u,cal}$ = 406 kN).

5 QUALITY CONTROL

5.1 CONCEPT

The procedure of the construction work has been planned carefully and diligently to ensure successful bonding. In this context, a reliability concept has been implemented. The aim is to prevent the following potential defects:

- insufficient adhesion formation, or adhesion failure between the adhesive and joined part (due to insufficient surface preparation, too high or too low temperature, humidity or other inappropriate climatic conditions),
- insufficient cohesion strength of the adhesive due to a disturbed curing or an incorrect mixing ratio,
- insufficient load-bearing capacity of the concrete or timber surfaces, and
- contamination of the bonding surfaces.

5.2 PREPARATION

Some universal requirements for the components themselves and the weather and environmental conditions during the first 24 hours of adhesive curing on site were defined and checked before starting the execution process (see Tab. 1).

The requirements have been defined based on EN 14080 [28] and Part 3 of the DAfStb guideline on the bonding of concrete components [25]. Special attention has been paid to the surface tensile strength of the concrete because experience has shown that this particular parameter is a key factor for the success of the bond. Minimum requirements on the surface tensile strength in literature can be found in the range of $f_{ctm,surf}$ > 1.0 N/mm² [25]. A minimum value of 2.0 N/mm² has been defined in this project.

Table 1: *Requirements for the quality control of the pilot application*

Category	Criterion	Requirement
Weather conditions	Outdoor temp.	> 8 °C
	Rel. humidity	< 75 %
Concrete	moisture	< 4 %
	Surface temperature	3 K above the dew point
	Strength class (delivery receipt)	C30/37
	Surface tensile strength $f_{ctm,surf}$	≥ 2.0 N/mm²
Timber	Moisture	< 16 %
	Cleanliness of the surface	Free of dust and loose parts, free of grease
	Planing or grinding the surface	24 hours before starting the bonding
	Strength class (delivery receipt)	GL28c
Tolerance	Evenness timber	± 4 mm (on 2000 mm)
	Evenness concrete	± 1 m (on 200 mm) and ± 3 mm (on 1000 mm)
	Gap between timber and concrete	< 7.0 mm

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5.3 GLUING

The environmental conditions (temperature and moisture) can strongly influence the hardening of the adhesive, therefore, bond samples were manufactured in-situ under on-site conditions. After seven days, the samples were tested in the laboratory. The gluing was carried out on 18 May 2022. The weather that day was very sunny and over 25 °C warm. It had rained the previous day, and although the ceiling area was covered, some moisture had entered the timber elements. However, since the moisture content of the timber elements were in the range of 13.0 to 15.4 %, the works could still take place.

The work was carried out in such a manner that the timber elements were lifted by a crane and fixed against displacement. As soon as the surrounding walls were in place, the timber surfaces were checked for evenness using an aluminium batten. The precast concrete elements were then lifted in on a trial basis and the unevenness between the timber and concrete was checked again with a measuring wedge.

In a next step, the position of the subsequent adhesive strips was marked and then freshly planed with a planing depth of about 1 mm. After the gluing surfaces had been planed, careful attention was paid during the work to ensure that no dirt, dust or grease residues got onto the gluing surfaces. This was achieved by wearing disposable gloves and disposable shoe covers. After cleaning with a vacuum cleaner, the adhesive was mixed and applied area by area with a mortar sledge for one precast concrete part at a time.

The pot-life of the adhesive was controlled by a time measurement. The concrete slab was then placed and fixed to the timber part with 12 assembly screws per precast concrete part by means of holes which had been installed in the precast part before pouring.

5.4 SAMPLE MANUFACTURING DURING THE GLUING PROCESS

Accompanying the gluing work, selected test specimens of each adhesive batch were produced directly on-site (see Tab. 2).

Table 2: *Quality assurance – tests during the bonding process*

Category	**Criterion**	**Number of tests**
Adhesive	Flexural tensile strength	2 per batch
	Surface tensile strength on a sandblasted steel plate	3 per batch
Bond to concrete	Surface tensile strength of the concrete prefab on-site with polymer mortar as adhesive	3 per batch

The number of specimens produced for the bending tensile prisms were chosen according to the technical approval Z-10.7-282 [29] as a related adhesive construction method is regulated there. At least two specimens should be produced for each adhesive batch according to EN 12350-1 [30] and tested after seven days of curing, according to EN 12390-5 [31]. Since all adhesive containers were manufactured in one batch at the production factory, two test specimens would theoretically have been sufficient due to the relatively small surface area and the resulting small quantity of adhesive. However, it was decided in this case to take samples from each container which was opened and mixed.

A similar procedure was followed for the tensile adhesion tests on a sand-blasted steel plate, and three specimens were taken per mixture. The surface tensile strength of the concrete was also tested again on a separate concrete plate to verify whether the adhesive formed a sufficient bond to the concrete. The surface tensile strength of $f_{ctm,surf}$ = 3.4 N/mm² was above the value of 3.0 N/mm² determined previously in the laboratory and also larger than the value of 2.0 N/mm² required. All further tests which were conducted in-situ also show no loss of strength compared to the reference value taken in the laboratory (Table 3).

Table 3: *Comparison of strength parameters from laboratory and in-situ*

Parameter	Lab.	In-situ
Flexural tensile strength $f_{adh,t,mean}$	28.7	30.0
Surface tensile strength $f_{ctm,surf}$	3.0	3.4

6 CONCLUSIONS

The pilot application of the ATCC construction method under realistic conditions on the construction site has been proved to be successful.

The construction process could be significantly accelerated compared to the conventional construction method with in-situ concrete, as the gluing operations of the prefabricated concrete parts were executed quickly and efficiently. It can be seen that it is possible to integrate ATCC constructions into the planning and construction process with the combination of a validated calculation method, a diligent planning process and a solid quality control concept. The economic use of prefabricated concrete parts for use in TCCs opens up new, promising possibilities for the whole building industry.

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