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Snap-fits made of reinforced concrete: From advanced manufacturing to novel applications

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Abstract

In this paper, the functional capability and producibility of snap-fits made of reinforced concrete (RC) for a category of joints, commonly made from metal or polymers, are discussed. Based on theoretical considerations of a functional geometric design, investigations on suitable reinforcement strategies for strengthening the brittle concrete and the development of accurate molds achieved by AM technologies (Additive Manufacturing), a range of snap-fits made of RC was manufactured and tested. The paper shows an extensive design approach for possible geometries suitable for snap-fits made of RC. Here, the flexible clips of the "male" elements, the guiding surfaces of the "male" and the "female" element, as well as considerations for the transfer of tension and compression forces in the interlocked joint were defined. Three possible reinforcement elements of the clips were investigated: Carbon fibers, micro-steel fibers and steel rods. For optimizing those specimens reinforced by micro-steel fibers, their concentration and orientation in the clips were controlled during the casting process by magnetic forces. The most promising reinforcement strategies for the clips were implemented in the design of two different applications for those novel snap-fit connection: A slab-slab connection and a column-column connection.

Keywords: Snap-fits, Reinforced Concrete, Joints, Manufacturing, UHPC

Introduction

The development of particularly high-performance concrete and the progress in digital planning and high-precision production enable new construction methods in the field of concrete construction.

Due to the complex and precise manufacture, such load-bearing structures have to be erected from prefabricated parts, which places high demands on the elements connections. The component connection can be realized in different ways. On the one hand, it can be examined by using a bonding intermediate layer, so-called match-cast method, in addition by the subsequent installation of coupling elements or by dry joints with high evenness of the contact surfaces.

Dry joints realized with CNC technology were successfully used by the construction company Max Bögl in the serial production of precast high-strength segmental post-tensioned concrete towers for wind turbines [1]. Based on this experience, a pilot post-tensioned bridge made of ultra-high-strength concrete segments was built [2]. In both cases, the segments were produced conventionally and combined with grinded, smooth joints. Within DFG Priority Programme 1542, Prof. H. Kloft (ITE) and his research group developed precise dry-joint systems for thin-walled UHPC (Ultra-High Performance Concrete) elements, see Fig. 1(left). Pressing the elements during the assembly process and the resulting additional frictional connection between the contact surfaces could enhance the effect of geometric interlocking. Here, dry joints were realized using high-precision formwork made of CNC-milled plastic molds for cast UHPC elements and high-pressure water jet cutting of precast UHPC-plates [3].

The advantage of such dry form-fit dry joints based on mechanical principles lies in the good manufacturability and reproducibility, the fast and cost-effective construction of the elements and the possibility of dismantling. Post-tensioning the joined elements can prevent unintentional loosening of the positive locking in the mounting direction.

On the one hand, the feasibility of thin yet powerful elements made of high-performance concrete depends largely on the type of reinforcement. Therefore, carbon fibres and micro-steel fibers are used that significantly increase the ductility and tensile strength of the brittle concrete. An impressive example is DUCON, a micro-reinforced high-performance concrete, which is mixed with micro-reinforcement. The special material set-up allows very slim and ductile constructions at high load bearing capacity and high resistance against dynamic loading, see Fig. 1(centre).

On the other hand, the construction industry demands ever shorter construction times and thus sophisticated joining techniques for the individual components. Snap-fits as an alternative to conventional joining methods such as adhesives, screws or pressing have the advantages of speed and no loose parts and have long proven themselves in everyday products such as snap fasteners and pins [4]. In the construction industry today snap-fits are mainly used for interior fittings and façade cladding. On the level of the supporting structure, there are only few examples of snap-fit connections, such as ClipHut, a plug-in system with snap-fits milled into wood panels, see Fig. 1 (left).

Building on this state of research, snap-fits as a novel category of connection of concrete elements is now to be investigated. By combining the flexibility of reinforced UHPC with the principles of snap-fits, the first tests on the suitability of this connection method in concrete construction are presented in this paper.

The aim of the investigations is to develop form-fit and reversible connections that can be connected quickly and independently of weather conditions. Furthermore, they should not be unintentionally detachable in the mounting direction without the need of grouting mortar, adhesives or post-tensioning. These special features of this new construction method should therefore make it possible to quickly build a complete structure from individual prefabricated parts made of concrete.

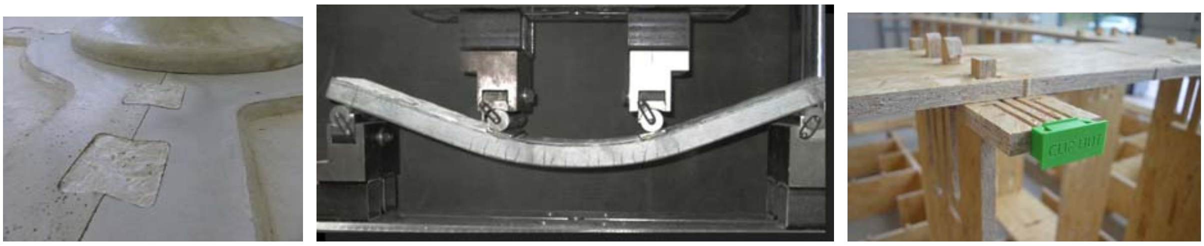

Figure 1: The demonstrator UNI-CON² [source: Ledderose] (left); specimen made of DUCON, [https://en.ducon.eu] (centre); detail of the plug-in system ClipHut [https://www.cliphut.org] (right)

Design planning

In a first step, comprehensive design approaches for possible geometries that could be suitable for snap-fits made of RC were examined. In general, there are three main types of snap-fits: annular, cantilever and torsional [5]. Most snap-fit joints have a common design of a protruding edge (“male”) and a snap-in area (”female”).The specific name of the snap-fit is usually named after the type of stress or strain it utilizes; the torsional snap-fit uses torque to hold parts in place, while the annular snap-fit utilizes hoop-strain to hold into place. The cantilever snap lock, as the most frequently used snap-fit of the three, was the subject of the investigation because of its properties as a connection element transmitting both compressive and tensile forces and also to function as a plane connection. Therefore, the flexible clips of the “male” elements, the guiding surfaces of the “male” and the “female” elements, as well as considerations for the transfer of tension and compression forces in the interlocked joint were of particular interest. Depending on the design of the snap-fit, the clips must absorb either pressure (cf. Fig. 5 (right)) or tension (cf. Fig. 7 (right)) when subjected to tensile stress between the two joined elements.

The production of the individual specimens presented here followed a digital process chain, starting with the creation of digital CAD-models, the generation of corresponding digital machine data sets, up to the digital production of the formwork using CNC-milling machines, CNC-lasers or FDM (Fused Deposition Modeling) 3D printers, see Fig 2(left to right).

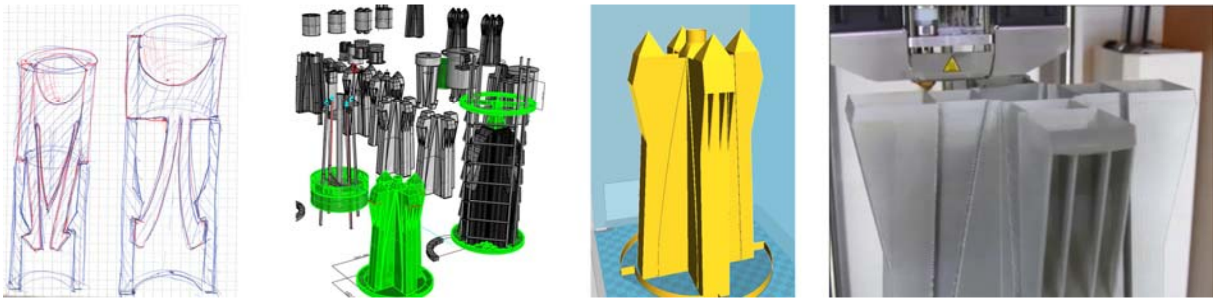

Figure 2: First sketches (left); CAD-Modeling (centre left); Generation of machine data sets (centre right); 3D printing of the mold (right) [sources: L. Ledderose]

Choice of materials

Highly stressed concrete components such as snap-fits, which are examined in this research work, require close manufacturing tolerances and high material utilization due to their low wall thickness and filigree properties. Therefore, not only the two components matrix and reinforcement of this hybrid material play a decisive role for this novel application, but in particular also their finely tuned interaction.

UHPC was exclusively used as matrix, see Table 1. It has been used by the authors in many experiments in the DFG Priority Programme 1542 and has proven to be high performing and user-friendly. It is characterized by high self-compacting properties, low viscosity when still liquid and high pressure stability when hardened (cylinder compressive strength (d/h = 80mm/160 mm) approx. 140 MPa), fine grained microstructure and thus fine crack distribution, as well as high impermeability that allows thin concrete covering with yet high corrosion protection of reinforcement members made of steel.

Table 1: UHPC concrete recipe

Ingredient	**Weight [kg/m^3]**
NANODUR® Compound 5941, grey	1100
Quartz sand H33	1012
Superplasticizer (GRACE ADVA® Flow 375)	21
Shrinkage reducer (GRACE Eclipse® Floor)	7
Water	159

By adding suitable reinforcement elements to the UHPC matrix, the tensile strength and ductility of the entire element can be significantly increased. For the investigations described here, it was essential that the used reinforcement was able to introduce a high flexibility to the clips of the snap-fits, so they could tolerate the relatively large elastic deflection required for assembly or disassembly. Further requirements for the reinforcement were an even crack distribution of the matrix with small crack widths in the clips, a high resilience of the reinforcement after bending and a strong bond with the matrix. Two basic materials for the reinforcement of the clips were mainly investigated: Carbon fibers and steel.

Carbon fibers were used both as prefabricated strands impregnated with epoxy resin and as rovings. After being fixed in position, the rovings were impregnated with epoxy resin and additionally sprinkled with fine quartz sand for better bonding to the concrete matrix.

Steel was used in the form of conventional reinforcing steel B500 (Ø 6mm and 8mm), as well as macro- and micro-steel fibres. The macro-steel fibers had a length of 40mm and a cross section of about 1mm x 2mm, the micro-steel fibers (tensile strength of about 2000 N/mm²) were 11mm long with a diameter of 0.17mm. In addition, various diameters (Ø 3mm, 4mm and 6 mm) of spring steel bars with smooth surfaces were tested.

Experimental research

The following is a description of the test series carried out. These are divided into A) experimental preliminary tests, B) a series to examine suitable clips, and the implementation of the most suitable movement strategy of these clips in C) slab-slab connections and D) column-column connections as application-oriented case studies.

A) Experimental preliminary tests

The aim of the experimental preliminary tests was to achieve a first approximation to a suitable geometric form of slab-slab connections and to achieve an assessment of the necessary manufacturing tolerances and the pre-selection of suitable reinforcement strategies. To ensure a high degree of comparability, a series of 24 slab-slab connections with uniform dimensions of the clips but different reinforcements as well as two complete slab-slab connections were cast and tested by joining them to a "female" counterpart manually. All the above-mentioned carbon and steel reinforcement elements were tested. Here, the evaluation criteria examined were limited to the crack distribution and crack width of the clips after joining. Fig. 3 (left and centre) shows one of the reinforcement plans and manufacturing methods of this series. Fig. 3 (right) shows the application of force flow optimized alignment of micro-steel fibres along the main tensile trajectories using magnetic fields of neodymium permanent magnets as described in [6] and [7]. The most frequent failure of the this series was the formation of a main crack at the base of the clips, which prevented the clips from resetting themselves after the joining process.

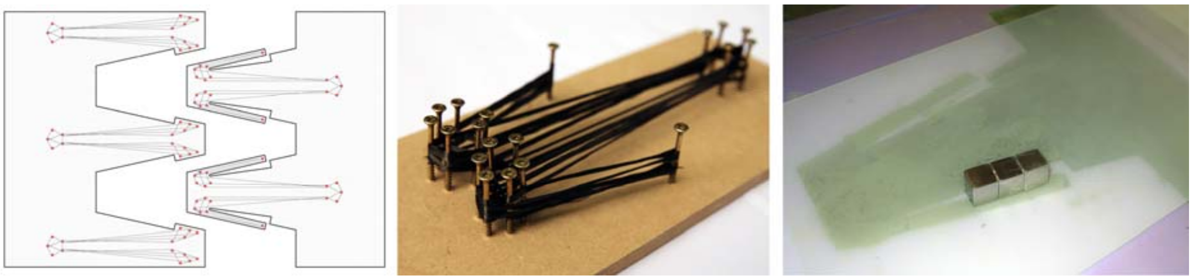

Figure 3: Reinforcement plan of a preliminary slab-slab-connection (left); Tailored reinforcement made of carbon fiber rovings (centre); Magnetic alignment of micro-steel fibers (right) [sources: L. Ledderose]

B) Suitable clips

Based on the findings of series A), a standardized geometric shape of the clips (250mm x 32mm x 16mm) were defined in series B). The height of the clips (16mm) was chosen slightly less than the necessary travel of bending the clips (17mm) in order to guarantee that the clips snap into the snap-in area in the "female" counterpart. The length - and thus the buckling length of the clips functioning as braces in the joined connection - was kept as short as possible. In addition, the bending line of the clip was calculated to design a bearing for the clips when deformed under load (Fig. 4 (bottom left)). This attempt had a clearly positive effect on the crack distribution of the examined clips. A total of 14 different reinforcement strategies were tested on 52 clips. The evaluation criteria were the return of the clips to their initial position after one, two and three loading cycles. Crack distribution and crack width were detected visually with a contrast agent. Fig.4 (top left) shows the set-up of the testing machine. Fig.4 (right) shows the three deformation states: before (a), during (b) and after bending (c).

A comprehensive evaluation of test series B) cannot be carried out in this paper. However, its evaluation according to the criterion of maximum flexibility, i.e. the ability to return the clips to the position before each loading cycle, showed that two reinforcement concepts in particular seem suitable for this special application: On the one hand, the use of reinforcing steel bars as the only reinforcement element; the high geometric rigidity of the rods played a particularly important role here. Secondly, the additional use of micro-steel fibers, especially when treated with the magnetic fiber alignment method, was responsible for an even finer crack distribution. However, the fibres did not have a significant influence on the flexibility when using concrete steel bars.

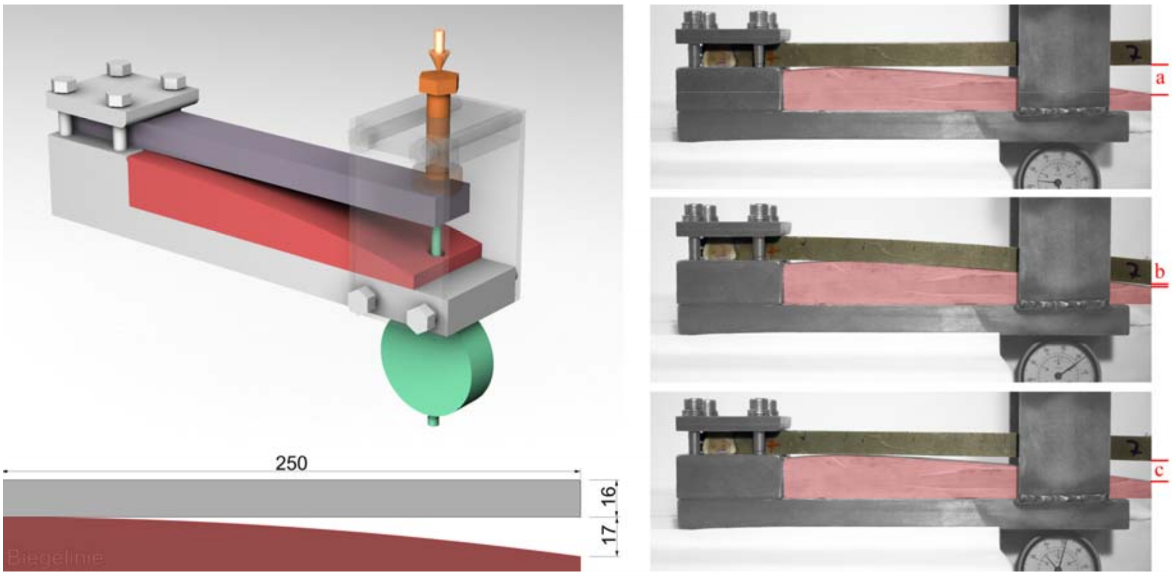

Figure 4: Experimental set-up for measuring the flexibility of RC clips (250mm x 32mm x 16mm) (top left); bearing according to the bending line (bottom left); Deflection of a clamped clip before (a), during (b) and after bending (c) (right) [sources: L. Ledderose]

C) Slab-slab connections

For the production of the two slab-slab connections, those two best rated reinforcement strategies were selected from the tests from series B). The same geometries from series B) were used for both the clips and the bearings. The total insertion depth of the connection was 520mm, the joining angle of the front and rear grooves was 0.8°, that of the middle part with the clips was 14°.

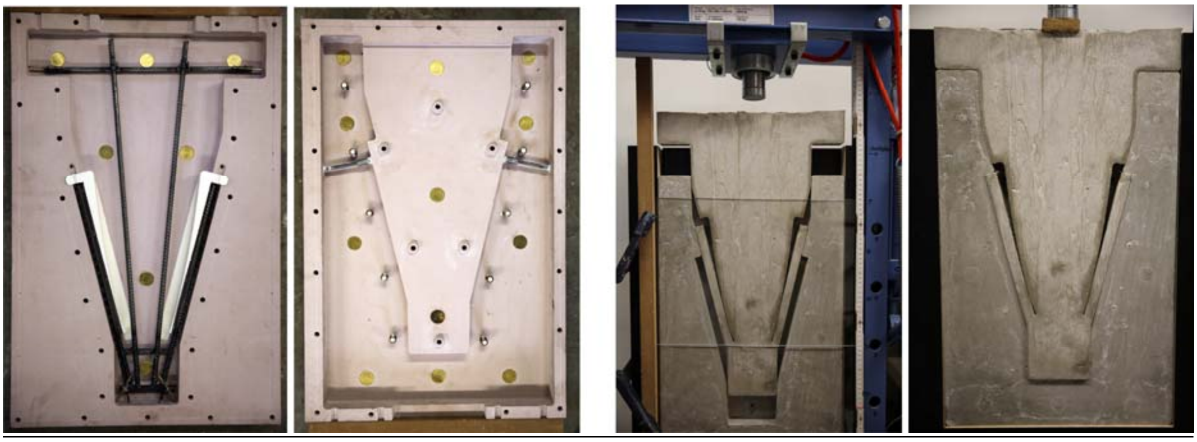

Figure 5: The two CNC-milled molds for a slab-slab connection (left); Joining of the cast connection in a testing machine (right) [sources: Ledderose]

The two-face formwork was made of polyurethane panels (obomodulan® with a density of 700 kg/m³) with a 3-axis CNC milling machine, see Fig. 5 (left). As placeholders between the clips and the body of the "male", milled wedges made of XPS rigid foam board or 3D-printed PLA (polylactide) using the FDM (Fused Deposition Modeling) method were inserted. The expected shrinkage of the UHPC used was taken into account when creating the formwork geometry. Furthermore, threads were concreted into the formwork of the "female", which made it possible to press the clips into their final position after the joining process. Slots were milled on the underside of the formwork of the "male" at a small distance from the outside flanks of the clips, which made it possible to treat the micro-steel fibre in the still liquid matrix using the magnetic fibre alignment method.

Both slab-slab-connections could basically be joined in a press without any problems, see Fig 5 (right). On one of the two connections, one clip could presumably not jump back into its snap-in area due to poor manufacturing tolerances or blocking spalling and had to be tracked manually.

D) Column-column connections

In order to test the application of snap-fits also for frame structures, a column-column connection was developed and produced twice. The same proven basic dimensions of the clips were used here. These were now arranged crosswise and form a head with four identical clips. In order to limit the space required by the snap-action mechanism and thus gain as much contact area as possible for the transfer of compressive forces, the geometry and function of the clips were changed: Hooks were attached to the ends of each of the four clips, by means of which the tensile forces that occur - for example when the support is subjected to bending load - can be transferred to the "female" counterpart, see Fig.6 (right). Again, the clips can be pulled into their final position through openings in the "female" element, whereby the entire connection can be prestressed by wedging the hooks in the snap-in area. Central internal channels were provided to carry out a post-tension strand or a tensioning element for the test setup.

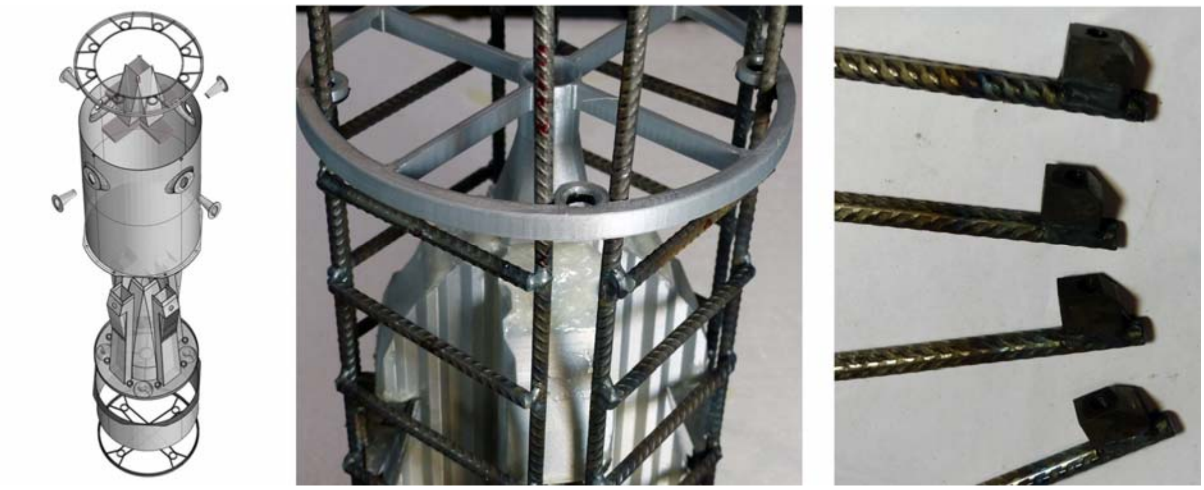

Figure 6: Illustration of a 3D printed mould for a column-column connection (left); reinforcement cage (centre); tig-welded flag plates on the clips (right) [sources: Ledderose]

The FDM 3-D printing process was chosen for the production of the formwork, as it has ideal prerequisites for this application of producing a precise, complex and yet cost-effective and rationally producible formwork for prototype construction, see Fig. 6 (left). The reinforcement concept included the arrangement of a reinforcement cage for the "female" and reinforcement steel rods (Ø 8mm) with welded flag plates on the tip of the clips for the "male", see Fig. 6 (centre). Furthermore, micro- steel fibers were used, which in the case of the clips were again treated and optimized with the method of magnetic fiber alignment.

The concreting was carried out in two steps and represented a variant of the match-cast method, see Fig.7 (left). 24 hours after concreting the "male" and its magnetic treatment, the "female" was cast directly around the "male´s" outer formwork. The common, 0.4 mm thick PLA separation layer was thus used twice. This procedure guaranteed a very simple and precise production of the two parts, which now fit exactly. The tolerance of 0.4 mm was taken into account when planning the geometries, so that the two contact surfaces in particular for transmitting the compressive forces are in close contact. Cavities were printed in the area of the snap mechanism that must not touch each other. After the UHPC had hardened, the formwork could be easily removed using hot air, see Fig 7(right).

Figure 7: Molds of a column-column connection before assembling including tig-welded reinforcement cages (left); column-column connection with a snap-fit made of UHPC (right) [sources: Ledderose]

Conclusion

The results of these investigations indicate that it is fundamentally possible to introduce the principle of snap-fits to the reinforced concrete building material if specific conditions are met. These are in particular an appropriate geometry of the snap-fits, which, despite the rather low flexibility of the clips, allows the necessary movement during the joining process, and a suitable material combination of fine-grained concrete (such as UHPC) and high-performing reinforcement. Of particular note in this regard are the use of precise formwork (i.e. CNC-machined, 3D printed). The use of magnetic forces during concreting showed a significant increase of the performance in particular of the clamps by a locally optimized alignment of the micro-steel fibres.

The expected application field of this joining technique is detachable connections between prefabricated concrete elements with each other as well as with elements made of different materials like wood or metal. However, this new type of joining is also conceivable as an assembly joint that can be finally fixed in a second operation using conventional joining techniques (casting, screwing of steel fixtures). Further benefits compared to, for exemple, exposed steel connections are the increased corrosion protection, wich is relevant in offshore application where higher exposure classes are required, and increased fire protection. The expected simplification of assemly and reduction of the erecting time may have great potence especially for joints that are difficult to access, for example in the case of large shells or wide-span spacial structures.

The implementation of this novel construction method requires a rethinking in conventional construction practice at different levels. The new approaches concern both the digital area of the production chain, such as the generation of the joining geometries, the automated generation of data sets for CNC machining and the fabrication, as well as standardized and preferably robot-assisted production methods. Snap-fits made of RC thus may offer the possibility of breaking new ground and pointing out future innovative construction methods.

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