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First Investigations on WAAM-Printed Adhesive Sockets for Reinforcement Connections

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Abstract. Additive manufacturing (AM) is attracting increasing interest in the construction sector due to its potential for automation and its ability to produce complex components. The potential of AM, particularly in the free-form design of concrete components such as beams, columns and force flow-optimised nodes, depends largely on solutions for their reinforcement. As a suitable solution for reinforcement integration, robot-assisted additive wire and arc manufacturing (WAAM) combines a high degree of automation and geometric freedom with a high deposition rate and tensile strength.

In this study, the WAAM process is investigated using the example of welded connection elements for reinforcing bars, accompanied by centric tensile tests on representative WAAM specimens and pull-out tests on reinforcing bars bonded into different sockets with two different injection mortars. In comparison to this novel approach of connecting steel components with reinforcing bars by bonding sockets produced using WAAM, comparable connection methods such as bolting and welding of the reinforcing bars are investigated.

The possible applications of the connection technology presented range from steel inserts in connecting elements and brackets to the connection of segmented rebars in AM concrete components.

Keywords: Additive Manufacturing Construction, WAAM, Concrete Components, Reinforcement, Injection Mortar

1. Introduction

Additive manufacturing or 3D printing is a disruptive technology that is emerging as a viable method of construction. Metal additive manufacturing is increasingly becoming the focus of development in the construction industry as a supplement to traditional methods of manufacturing metal components [1]. Directed Energy Deposition-arc (DED-arc) AM or Wire Arc Additive Manufacturing (WAAM) in particular is expected to play a prominent role, as the process combines high deposition rates with a comparatively simple and robust process [2,3,4]. Coupling this process with the precision and geometric freedom of robots enables reproducible and robust component manufacturing.

The most promising potential applications in practice are currently structural connections between building components, component reinforcements, and repairs that utilize the geometric freedom offered by AM [5].

Nodes play a central role in the field of structural components, where they can demonstrate the strengths of DED-arc processes, namely the rational production of complex, mechanically highly resistant, and force flow-optimized components that often function as individually manufactured adapters [6,7,8]. In a metal-only structure, the nodes can be connected by welding with predominantly linear components such as pipes or profiles. However, the connection with reinforced concrete components requires a detailed design solution for connecting the reinforcing bars in order to transfer the stresses through the node.

The approach presented here addresses the application of WAAM-printed steel sockets directly onto steel components and the bonding of conventional reinforcing bars into these sockets using injection mortar.

Two key questions arise: Can injection mortar—originally developed for anchoring bars in concrete—also provide a reliable bond in steel sockets, and do WAAM-printed sockets outperform sockets made from off-the-shelf pipes?

In the authors' estimation, this technique is particularly suitable where conventional screw connections or welded joints are not practical. Bolted joints often demand angled drilling and lack adequate bearing surfaces for nuts or washers when bars are not orthogonal, and WAAM parts frequently require additional milling to create flat contact areas. Welding, meanwhile, can be hindered by crowded reinforcement layouts and the uneven surfaces inherent to WAAM components, which destabilize the arc.

Where connection geometries are becoming increasingly complex and the number of reinforcement bars is increasing—especially in WAAM-printed steel elements—bonding bars into printed bases could prove to be a practical and technically robust solution. This novel approach is therefore currently being tested in initial trials for its feasibility and performance, and the initial results are presented here.

2. State of the Art

2.1 WAAM-printed reinforcement

In the context of 3D concrete printing, dot-on-dot welding using the WAAM process is becoming increasingly important, as it enables steel to be applied precisely and layer by layer. By selectively interrupting the arc at defined points, heat input and distortion can be better controlled and component accuracy significantly increased. This high process stability allows the production of complex reinforcement geometries with variable angles and cross-sectional designs, which can even be embedded directly during concrete printing. This can result in customized steel structures that are both mechanically optimized and integrated into the digital construction process.

Although point-to-point mode is interesting for small reinforcement structures, it also has a very low melting rate, long cooling times, and extensive idle times. This significantly reduces energy and material efficiency as well as the ecological and economic balance compared to conventional reinforcing steel. Therefore, it may not be suitable for large reinforcement structures. In Germany in particular, there has been research activity on this topic in recent years:

In 2018, Mechtcherine et al. presented a dot-on-dot 3D-printed steel reinforcement for digital concrete production and investigated its manufacture, mechanical properties, and composite behavior in concrete [9]. A year later, Müller et al. conducted a systematic design and parameter study on WAAM of steel bars and developed guidelines for the standardized production of WAAM-printed reinforcement [10]. Building on this, Kloft et al. analyzed various reinforcement strategies in 3D concrete printing in 2020 and derived design principles for the seamless integration of additively manufactured reinforcement [11]. Currently, Tischner et al. (2023) compared the composite behavior of WAAM-printed reinforcement with conventional steel bars and revealed advantages and disadvantages in terms of adhesion, failure mode, and crack formation [12].

2.2 Welded and bolted joints

Welded and bolted connections play a central role in steel construction in the building industry: welded seams allow components to be joined monolithically and form-fittingly in order to safely bear high loads, while bolted connections enable modular assembly and, if necessary, easy disassembly. The same processes are also used in the production of steel components for reinforced concrete structures, such as brackets, anchor plates, or built-in locks, which are pre-positioned precisely before concreting and then integrated. Adhesive bonds with injection mortars, on the other hand, are often used today for the subsequent anchoring of steel anchors or reinforcing bars.

In today's building construction and civil engineering, welding reinforcing steel is essential for making sure concrete structures are strong and last a long time. Resistance welding in accordance with DIN EN ISO 17660:2007 is now established as standard practice, precisely tailored to the requirements of reinforcing steel [13]. This standard specifies, among other things, limit values for current, welding pressure, and electrode diameter, as well as test procedures for quality assurance. Despite increasing automation, the manual effort remains high: welders must set the mechanical specifications precisely, change electrodes regularly, and perform visual and functional tests before each welding process. Uneven electrode wear, fluctuating material properties of the steel, or minimal deviations in the alignment of the reinforcing bars require careful readjustment. The qualification of welders is therefore of crucial importance. In accordance with the requirements of DIN EN ISO 9606 [14], they must not only have flawless welding tests, but also undergo regular further training in accordance with DIN EN ISO 14731 [15]. Only in this way can responsible tasks such as creating welding instructions, monitoring parameters, and documenting visual inspections be competently fulfilled. Of course, these measures also involve a significant amount of time and high employee qualification (*Fig. 1, left*).

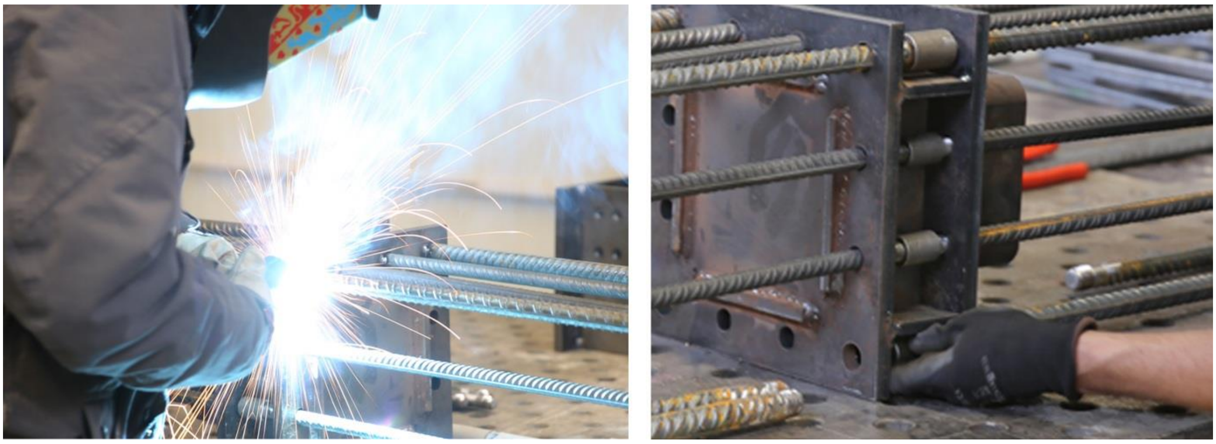

Figure 1. *Butt weld of reinforcing bars to a steel node (left), screw connection of reinforcing bars for reversible connections of steel components (right)*

Bolts –in contrast- enable fast, flexible, and highly resilient connections between components. Eurocodes and the associated product standards must be observed above all when designing and constructing. EN 1993-1-8 (Design and construction of connections) specifies the rules for the design of steel connections [16], while EN 1090-2 (Execution of steel structures) specifies the requirements for manufacturing, quality control, and marking [17].

There are basically two possible methods for bolting reinforcing bars into steel nodes or steel components: firstly, the bars can be threaded and pushed through a through hole in the node or steel component and bolted in place. A lock nut on the opposite side prevents the connection from loosening (*Fig. 1, right*). This method requires that sufficient space and accessibility be provided during the construction of the connection for assembly with wrenches or similar tools: Flange connections can be assembled from the outside and hollow components with assembly openings can be assembled from the inside.

Alternatively, the bars with corresponding external threads can be bolted into threaded holes arranged in the steel component. This method has the advantage that no nuts are required. However, for reasons of handling, only individual bars that are not part of reinforcement cages can be bolted in, and it should be noted that the production of threads on reinforcing bars requires a special method of thickening the ends by upsetting before the external threads can be cut, so that the cross-section of the rebars is not reduced.

2.3 Injection mortar

Nowadays, injection mortars enable the retrofitting of reinforcing bars in existing concrete components, ensuring a force-fit connection between old and new components and thus economical reinforcement or repair without costly demolition work. With this technique, drilled holes are first cleaned of dust, then the two-component or single-component mortar is systematically applied using a cartridge gun or pump, and immediately afterwards the reinforcing bar or threaded rod is screwed in – this creates a form-fitting anchorage that reliably transfers loads to the existing structure.

The most important standards for this are, on the one hand, the European Assessment Document EAD 330499-00-0601 (formerly ETAG 001) for chemical composite mortars, which specifies product properties, test methods, and application requirements [18], and DIN EN 1992-4 (Eurocode 2, Part 4), which defines the design and construction rules for retroactive anchoring in concrete [19]. To date, typical applications have been in the renovation of load-bearing structures, for example, to reinforce corrosion-damaged reinforced concrete ceilings and columns and to install concrete-on-concrete connectors. In addition, injection mortars are used in the preservation of historical monuments when historical load-bearing structures need to be maintained under load requirements.

Research into retrofitted reinforcement bars focuses primarily on load-bearing and anchoring mechanisms, design approaches, and durability aspects. Back in 2002, Spieth and Eligehausen laid the foundation for practical design formulas and safety verifications with extensive experimental and numerical investigations into load transfer [20]. Building on these findings, Feistel conducted a detailed investigation of the failure patterns of various connection variants in 2007 and derived recommendations for permissible embedment lengths in existing concrete [21]. Fuchs provides a compact overview of installation techniques, application limits, and current standardization approaches in his compilation published in 2023, in which he critically discusses optimization potential and design guidelines [22]. In parallel, Wörle et al. 2020 address the specific challenge of moment-carrying steel-concrete connections according to EOTA TR 069. The focus here is on bending moment transfer via post-installed stirrups and the application-oriented arrangement of composite dowels to ensure sufficient stiffness and load-bearing capacity [23]. A further addition to this topic is Blochwitz's dissertation from 2019, which investigates the long-term behavior of bonded anchor systems under permanent load. His work focuses on creep processes in the anchor bed, corrosive processes on the reinforcing bar and their influence on the verification over the entire service life [24].

3. Methods and materials

3.1 Test-Setup

Note that the initial investigations presented here on WAAM-printed adhesive sockets for reinforcement connections are limited to a proof of concept.

The forces for all tests were generated manually using a hydraulic jack and measured using a pressure transducer connected to a measuring amplifier. The values were recorded with a video camera and evaluated visually. Since these tests focused on the maximum force at failure, no measurement technology was used to determine the deformation during the tests. Further and more extensive investigations with qualified measuring tools are necessary in order to be able to make valid statements about the composite behavior. These investigations should include surface roughness, consideration of scattering, and validation of the transferability of the results to full-scale connection details.

3.2 WAAM-printed sockets

All WAAM-printed conical sockets for the examined pull-out tests were produced using a Fronius TPSi-600 welding system and the CMT welding process (Cold Metal Transfer). The welding filler material used was SUPRAMIG® ULTRA by Lincoln Electronics, a copper-coated solid wire electrode with increased manganese content (EN ISO 14341-A G46 3 C1 4Si1 / G50 5 M21 4Si1) with a specified yield strength of 500 MPa [25]. The shielding gas used was a mixture of 18% CO2 and 82% argon (EN ISO 14175: M21-ArC-18) and had a flow rate of 16 l/min. The travel speed of the torch was 4 m/min, the layer height was 1.1 mm, the average layer width was 7.5 mm . Due to the cone angle of 5°, the lower diameter of a 70 mm high socket was 32 mm at the base and 20 mm at the edge. Structural steel S355JR (thickness 15 mm) was used as the substrate. The interlayer temperature was between 200 °C and 300 °C (*Fig. 3, left*).

3.3 Reference sockets

The reference sockets used in the pull-out tests were made of seamless precision steel tubing (D=30 mm, wall thickness = 5 mm) made of S235JR with dimensions based on DIN-EN 10305-1. The sockets of different lengths were also welded onto a plate made of S235 with a thickness of 15 mm. The contact adhesive surfaces inside the sockets were radially ground with abrasive fleece corresponding to a grain size of 280 and then degreased. The contact adhesive surfaces inside the WAAM-printed sockets as well as those from seamless precision steel tubing were radially ground with abrasive fleece corresponding to a grain size of 280 (*Fig. 2, left*).

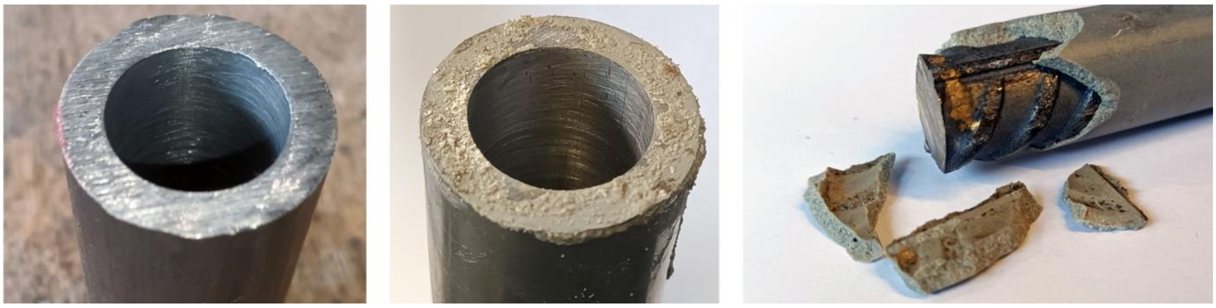

Figure 2. *Reference socket before the pull-out test (right), after the pull-out test (middle), reinforcing bar bonded with UPAT UPM after the pull-out test from the reference socket (right)*

3.4 Reinforcement bars

All reinforcement bars had a diameter of 16 mm and an M16 thread cut into one side by MAX Frank GmbH [26]. A special sleeve nut, also from Max Frank GmbH, was screwed onto this thread to absorb the tensile forces during the pull-out tests. The reinforcing steel was highly ductile B500B, which complies with EN ISO 17660 (material number 1.0439) and Swiss SIA 262 with a stated yield strength of 500 MPa. All steel surfaces were degreased before bonding.

3.5 Injection mortars

Two different injection mortars, A and B, were used in the experiments. The injection mortars were supplied in double cartridges, which were applied using a cartridge gun and mixing nozzles. The criteria for selecting the two mortars were ease of use and availability, comprehensive approvals for use in conventional bonding of reinforcement in concrete, and selection of two representatives of the two most important mortar systems. Both mortars are characterized in their original area of application, the subsequent grouting of reinforcing bars in concrete, by fairly short bond lengths of steel-mortar-concrete, which qualifies them for the steel-mortar-steel application investigated here.

3.5.1 Fischer FIS EM Plus (injection mortar A)

FIS EM Plus is a two-component, styrene-free epoxy resin mortar that can be used in dry, damp, or flooded drill holes. It has a very short curing time (from approx. 10 minutes at +20 °C) and achieves high adhesion and shear values shortly after installation. Due to its thixotropic consistency, it does not drip and enables clean working even in overhead installations. The mortar is approved for cracked and uncracked concrete, in some cases even for seismic applications (C1/C2), and achieves characteristic load values in accordance with ETA when used with suitable dowels [27, 28].

3.5.2 UPAT UPM 44 (injection mortar B)

UPM 44 is a viscous, two-component, styrene-free vinyl ester injection mortar that is characterized by curing of typically 8–12 minutes at +20 °C, thus allowing short construction processes. It adheres in dry, damp, and even submerged drill holes and does not drip when used for overhead or ceiling connections. It has European ETA approval for use in cracked and uncracked concrete, often with seismic evaluation [29, 30].

3.6 Reference adheasive

In addition to the two injection mortars, a commercially available two-component construction adhesive was tested in the centric tensile tests in order to better classify the results of the injection mortars. The product used was UHU plus endfest [31].

4. Experimental investigations

The experimental investigations include pull-out tests of reinforcing bars from two types of sockets, centric tensile tests, and tensile shear tests of the two injection mortars investigated on different surfaces.

4.1 Pull-out tests

The aim of the pull-out tests was to determine the bond strength of conventional reinforcing bars with a diameter of 16 mm in two different types of sockets: WAAM-printed sockets and reference sockets, which were sawn from off-the-shelf pipes. Six socket lengths (30, 50, 70, 90, 110, and 130 mm) were varied and both injection mortars A and B were examined, resulting in a total of 24 pull-out tests (*Fig. 3, right*).

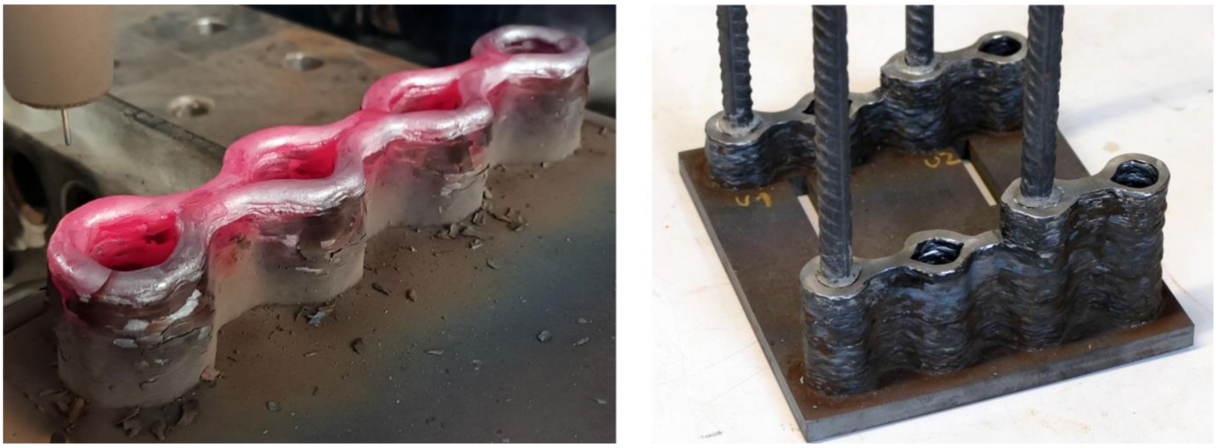

Figure 3. *WAAM printing of conical sleeves (left), sockets with bonded reinforcing bars prior to pull-out tests (right)*

Since these were initial exploratory tests, a complex testing procedure in a testing machine was dispensed with and a simple test setup was chosen. Note that no statement can be made about possible dispersion because only one pull-out test was performed per parameter combination.

The test setup essentially consisted of a manually operated hydraulic jack with a hollow cylinder, a load cell, and rubber buffers, which served to extend the stroke and thus improve dosing. The reinforcing bars were pulled out by the hydraulic jack, with the package consisting of the jack and the load cell at the bottom edge of the socket and at the top on a nut screwed onto the reinforcing bar. The reinforcing bars were pulled out by the hydraulic ram, with the package consisting of the ram and the load cell pressing down on the bottom edge of the socket and up on a nut screwed onto the reinforcing bar.

The results are shown in *Figure 4*. The dashed line at 180 kN tensile force represents the yield point of the reinforcing bar with a diameter of 16 mm. It can thus be seen that

- bond strength of the UPAT UPM 44 and Fischer FIS EM Plus samples in the WAAM-printed sockets is higher than the yield strength of the reinforcing bar from a bonding length of 70 mm.
- bond strength of the UPAT UPM 44 injection mortar with the reference pipe, on the other hand, was very low and the entire series did not show any plausible values (*Fig. 2, middle, right)*.
- bond strength of the UPAT UMP 44 with the WAAM-printed socket was significantly increased compared to the smooth reference socket. The reason for this is the irregular surface and conical shape of this socket, which achieves bond strength solely through the form fit.
- bond strength of Fischer FIS EM is highest in the reference tube, and a bond length of approx. 60 mm would already be sufficient to achieve a magnitude of 180 kN. Interestingly, the bond strength is even higher than with the WAAM-printed socket, despite its conical shape and irregular surface.

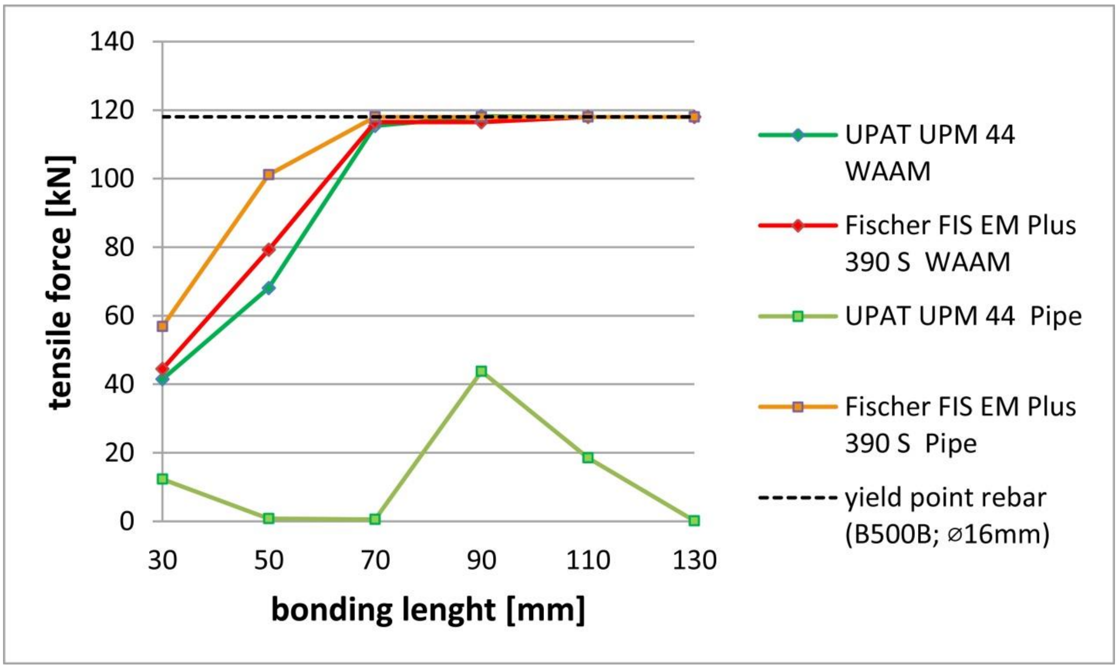

Figure 4. *Maximum tensile force of pulled-out reinforcing bars bonded with injection mortars in WAAM-printed or reference sockets of different lengths*

4.2 Centric tensile tests

To supplement the results of the pull-out tests described above, further investigations were carried out on the composite behavior of the two injection mortars on relevant surfaces. Since there are no standardized setups for these specific material combinations, a custom test specimen geometry was designed and manufactured using FDM printing from PLA (*Fig. 6, left*). This consisted of a rotationally symmetrical bell with an opening diameter of 11.5 mm. The injection mortar was pressed through the opening with a slight protrusion. A M6 screw was inserted through the bell, to the end of which an extension could be attached using a long nut in order to pull the bell centrically from the different surfaces after the maximum adhesive bond had been reached. These tensile tests were essentially carried out again using the combination of a hydraulic cylinder, load cell, and rubber buffers (*Fig. 5, left*).

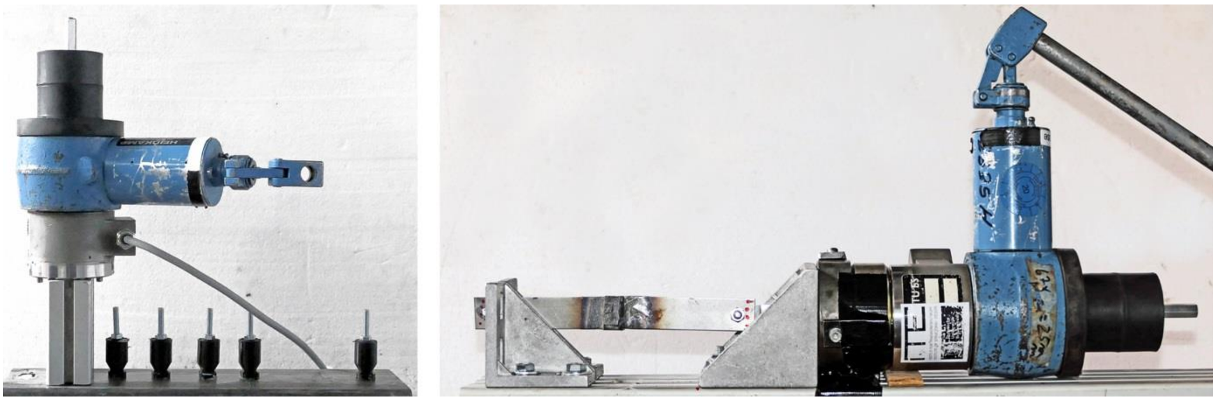

Figure 5. *Test setup for the centric tensile tests (left) and tensile shear tests (right)*

The results shown in *Table 1* are basically consistent with the pull-out tests. Here too, injection mortar A (Fischer FIS EM Plus) showed the highest bond strengths on ground and degreased S235 steel sheet, closely followed by the WAAM-printed surface, which was also ground and degreased (*Fig. 6, middle, right*). The bond of injection mortar B (UPAT UPM 44) was so low on both surfaces that no measurements could be taken. This confirmed the observations from the pull-out tests: The adhesion of injection mortar B is too low for the transfer of tensile or shear forces. Force transfer can only be achieved through a form fit, such as an irregular surface and, in particular, undercuts, which can be easily achieved with the WAAM process.

In order to gain a better understanding of the bonding mechanisms of these mortars with the materials for which they were developed, the adhesive forces were measured on two different types of concrete. The concretes regarded were a standard concrete C30/37 with a maximum grain size of 16 mm and Nafufill KM 250 from MC Bauchemie. The latter is a fiber-reinforced PCC/SPCC concrete substitute for repair work that can be used in the manufacture of components using the 3D shotcrete process. Here, too, the two injection mortars exhibited different types of failure: while the adhesive forces of mortar A were greater than the tensile strength of the concrete, leading to material failure due to the cement paste and aggregate, the test specimens filled with injection mortar B could be removed from the concrete surface almost without residue and without tearing the concrete. This result provides an indication of the bonding behavior of mortar B in the pull-out tests: Since this mortar exhibits very low adhesive forces to both steel and concrete, forces can only be transferred through the form-fit of the mortar joint.

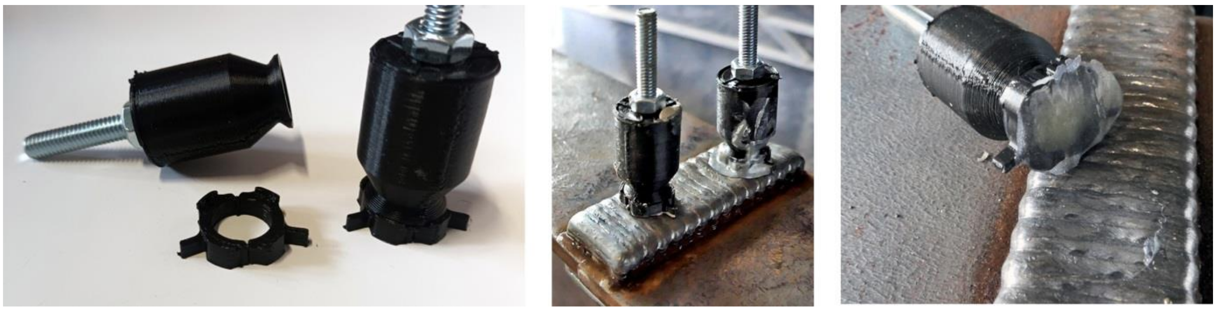

Figure 6. *Custom test specimen geometry (right), specimen bonded to a WAAM-printed surface before the centric tensile test (middle), and after the centric tensile test (right)*

The two-component adhesive UHU plus endfest, which was also tested, was only slightly above the tensile strength of injection mortar B in the tests on concrete surfaces and significantly below the tensile strength of injection mortar A in the tests on metal surfaces, showing comparatively poor performance in this regard.

Table 1. *Average tensile strengths [MPa] determined in centric tensile tests from 6 samples each; test speed 1 mm/min; round contact area (d=11.5 mm)*

Surfaces	**Fischer FIS EM Plus**	**UPAT UPM 44**	**UHU plus endfest**
concrete C 30/37 D16 gravel, sawn	8,52	3,83	5,73
MC Nafufill KM 250, SC3DP printed, sawn	11,71	4,44	5,82
WAAM-printed plate, brushed, degreased	18,98	*failed*	6,23
S235 sheet, ground K280, degreased	20,13	*failed*	7,19

4.3 Tensile shear strength tests

In a recent test, the tensile shear test was performed based on DIN EN 1465 [32] on the Fischer FIS EM Plus 390 S and UPAT UPM 44 injection mortars on S235 sheet metal and WAAM-printed sheet metal (*Fig. 7*). The thickness of the adhesive layer was 2 mm, which corresponded to the thickness from the pull-out tests, as the diameter of the reinforcing steel was 16 mm and the average inner diameter of the sleeves was 20 mm. The test setup consisted of the same core components as in the previous tests (*Fig. 5, right*). The results are shown in *Table 2.*

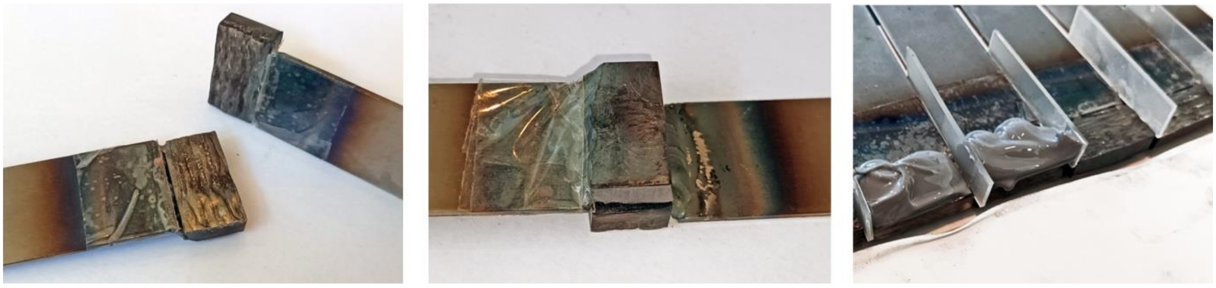

Figure 7. *Preparation (left, centre) and bonding (right) of a WAAM-printed specimen for the tensile shear test*

The results of injection mortar B (UPAT UPM 44) confirm the observations from the pull-out tests: The irregular surface resulted in a load-increasing form fit and thus an improved bond compared to the weak bond with the slightly roughened sheet metal made of S235. Here, simply mounting the samples in the test rig caused the bonds to tear. The results of injection mortar A (Fischer FIS EM Plus) contrast in some ways with the results of the pull-out tests and the centric tensile tests: While the trend in these two tests clearly showed better bonding of the mortar on smooth surfaces, the results of these tensile shear tests indicate better bonding on WAAM-printed surfaces. Possible causes for these inconsistent results could be inadequately prepared surfaces, damage to the specimens after fabrication, or an inherently different behavior of the adhesive joints in pull-out tests compared with tensile-shear tests. The authors intend to carry out further series of experiments to gain a deeper understanding of the bonding behavior.

Table 2*. Average tensile shear strengths [MPa] determined in tensile shear strength tests from six samples each; test speed 1 mm/min; contact area 12,5 x 25 mm*

Surfaces	**Fischer FIS EM Plus**	**UPAT UPM 44**
WAAM-printed plate, brushed, degreased	4,19	*2,21*
S235 sheet, ground K280, degreased	1,82	*failed*

5. Summary

This article examines a novel connection technique in which steel sleeves are applied directly to steel components using robot-assisted wire electrode welding (WAAM) and conventional reinforcing bars are bonded with injection mortar. The focus is on the bonding behavior of the reinforcing bars in the sleeves, determined in pull-out tests with two different mortar systems as well as centric tensile and tensile shear tests. In addition, established connection types—bolt and welded connections—are used for comparison.

The results show that WAAM-printed sockets offer a comparable or, in some cases, better bond to the reinforcing bars than conventional steel pipes, and their use is particularly suitable when complex geometries or confined installation situations make the use of bolts or welds difficult. The automated generation of the sleeves also allows a high degree of design freedom, and the low surface quality requirements save on post-processing, as hardly any mechanical processing steps are necessary. This opens up new fields of application for connecting conventional reinforcing bars in additively manufactured steel components such as nodes and steel inserts, but also for applications in the field of building renovation or modification.

6. Outlook

For further research, it is first recommended to systematically optimize the socket geometry—in terms of wall thickness, inner diameter and cone angle—to better adapt the force-flow behavior to different bar diameters. Additionally, durability investigations under corrosion, fatigue and temperature loads, as well as combined loading scenarios, should be carried out. In the long term, this approach would enable the development of flexible, force-flow-optimized connections that offer significant advantages over conventional connection types in both new-build and repair projects. In addition, large-scale tests are being carried out to investigate the new type of reinforcement connection on a real scale and in comparison with conventional reinforcement connections. Figure 8 shows a WAAM-printed node as an intermediate piece of a beam-to-beam connection before bonding the longitudinal reinforcement with injection mortar at the ITE of the TU Braunschweig.

Figure 8. *Real-scale test specimen for investigating the performance of WAAM-printed adhesive sockets for reinforcement connections*

Data availability statement

The data that support the findings of this study were generated at the Institute of Structural Design (ITE), TU Braunschweig (Germany) and are available on request from ite@tu-bs.de.

Author contributions

Conceptualization, L.L., H.K.; methodology, L.L., H.K.; validation, L.L.; formal analysis, L.L.; investigation, L.L.; resources, L.L., H.K.; data curation, L.L.; writing - original draft preparation, L.L.; writing - review and editing, L.L., H.K; visualization, L.L.; supervision, H.K.; project administration, L.L., H.K.; funding acquisition, H.K. Both authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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References

[1] Buchanan, C. and Gardner, L., “Metal 3D printing in construction: A review of methods, research, applications, opportunities and challenges,” *Engineering Structures*, vol. 180, pp. 332–348, 2019.

[2] Delgado Camacho, D., Clayton, P., O'Brien, W. J., Seepersad, C., Juenger, M., Ferron, R., and Salamone, S., “Applications of additive manufacturing in the construction industry – A forward-looking review,” *Automation in Construction*, vol. 89, pp. 110–119, 2018.

[3] Evans, S. I., Wang, J., Qin, J., He, Y., Shepherd, P., and Ding, J., “A review of WAAM for steel construction – Manufacturing, material and geometric properties, design, and future directions,” *Structures*, vol. 44, pp. 1506–1522, 2022.

[4] Kanyilmaz, A., Demir, A. G., Chierici, M., Berto, F., Gardner, L., Kandukuri, S. Y., Kassabian, P. et al., “Role of metal 3D printing to increase quality and resource-efficiency in the construction sector,” *Additive Manufacturing*, vol. 50, p. 102541, 2022.

[5] Gardner, L., “Metal additive manufacturing in structural engineering – review, advances, opportunities and outlook,” *Structures*, vol. 47, pp. 2178–2193, 2023.

[6] Reimann, J., Henckell, P., Ali, Y., Hammer, S., Rauch, A., Hildebrand, J., and Bergmann, J. P., “Production of Topology-optimised Structural Nodes Using Arc-based, Additive Manufacturing with GMAW Welding Process,” *J. Civ. Eng. Constr.*, vol. 10, no. 2, pp. 101–107, 2021.

[7] Feldmann, M., Kühne, R., Citarelli, S., Reisgen, U., Sharma, R., and Oster, L., “3D-Drucken im Stahlbau mit dem automatisierten Wire Arc Additive Manufacturing,” *Stahlbau*, vol. 88, no. 3, pp. 203–213, 2019.

[8] Laghi, V., Babovic, N., Benvenuti, E., and Kloft, H., “Blended structural optimization of steel joints for Wire-and-Arc Additive Manufacturing,” *Engineering Structures*, vol. 300, p. 117141, 2024

[9] V. Mechtcherine, J. Grafe, V. N. Nerella, E. Spaniol, M. Hertel, and U. Füssel, “3D-printed steel reinforcement for digital concrete construction – Manufacture, mechanical properties and bond behaviour,” Constr. Build. Mater., vol. 179, pp. 125–137,2018, doi: https://doi.org/10.1016/j.conbuildmat.2018.05.202.

[10] Müller, J., Grabowski, M., Müller, C., Hensel, J., Unglaub, J., Thiele, K., Kloft, H., and Dilger, K., “Design and Parameter Identification of Wire and Arc Additively Manufactured (WAAM) Steel Bars for Use in Construction,” Metals, vol. 9, no. 7, p. 725, 2019, doi: 10.3390/met9070725

[11] Kloft, H., Empelmann, M., Hack, N., Herrmann, E., and Lowke, D., “Reinforcement strategies for 3D-concrete-printing,” *Civil Engineering Design*, vol. 2, no. 4, pp. 131–139, 2020, doi: https://doi.org/10.1002/cend.202000022

[12] Tischner, K., Rappl, S., Riegger, F., Strasser, A., Osterminski, K., Kraenkel, T., Baehr, S., Zaeh, M. F., and Gehlen, C., “Bond Behavior of WAAM Reinforcements in Comparison to Conventional Steel Reinforcements,” Construction Materials, vol. 3, no. 2, pp. 217–232, 2023, doi: https://doi.org/10.3390/constrmater3020014

[13] Institut für Stahlbetonbewehrung e. V. (ISB), Schweißen von Betonstahl nach DIN EN ISO 17660:2007 und DVS RiLi 1708:2009. Berlin: Ernst & Sohn, 2022.

[14] DIN EN ISO 9606-1:2017-12, Prüfung von Schweißern_- Schmelzschweißen_- Teil_1: Stähle (ISO_9606-1:2012, einschließlich Cor_1:2012 und Cor_2:2013); Deutsche Fassung EN_ISO_9606-1:2017.
[15] DIN EN ISO 14731:2019-07, Schweißaufsicht_- Aufgaben und Verantwortung (ISO_14731:2019); Deutsche Fassung EN_ISO_14731:2019.
[16] DIN EN 1993-1-8:2025-04, Eurocode_3_- Bemessung und Konstruktion von Stahlbauten_- Teil_1-8: Anschlüsse; Deutsche Fassung EN_1993-1-8:2024.
[17] DIN EN 1090-2:2018-09, Ausführung von Stahltragwerken und Aluminiumtragwerken_- Teil_2: Technische Regeln für die Ausführung von Stahltragwerken; Deutsche Fassung EN_1090-2:2018.
[18] EAD 330499-00-0601, "Bonded Fasteners for Use in Concrete", European Organisation for Technical Assessment, 2017.
[19] DIN EN 1992-4:2019-04, Eurocode_2_- Bemessung und Konstruktion von Stahlbeton- und Spannbetontragwerken_- Teil_4: Bemessung der Verankerung von Befestigungen in Beton; Deutsche Fassung EN_1992-4:2018.
[20] Spieth, H. A. and Eligehausen, R., "Bewehrungsanschlüsse mit nachträglich eingemörtelten Bewehrungsstäben," Beton und Stahlbetonbau, vol. 97, no. 9, pp. 445–459, 2002, doi: 10.1002/best.200202130
[21] Feistel, G., "Bewehrungsanschlüsse mit nachträglich eingemörtelten Bewehrungsstäben," DIBT Mitteilungen, vol. 38, no. 6, pp. 174–178, 2007, doi: 10.1002/dibt.200730048
[22] Fuchs, W., "Nachträglich eingemörtelte Bewehrungsstäbe," 2023. In 2024 BetonKalender, ed. Konrad Bergmeister, Frank Fingerloos, and Johann Dietrich Wörner, 429–60: Wiley, doi: 10.1002/9783433611494.ch5
[23] Wörle, P., Appl, J., and Genesio, G., "Bewehrungsanschlüsse für momententragfähige Verbindungen nach EOTA TR 069," Beton und Stahlbetonbau, vol. 115, no. 11, pp. 887–896, 2020, doi: 10.1002/best.202000057
[24] Blochwitz, R., "Verbunddübelsysteme unter dauerhafter Lasteinwirkung," Dissertation, Univerität Stuttgart, 2019, doi: http://dx.doi.org/10.18419/opus-10337
[25] Lincoln Electric, *Supramig® Ultra*. https://ch-delivery.lincolnelectric.com/api/public/content/618bbd37e18d4adb9d7892001be5e00b?v=eeec56f9, (accessed July 31, 2025).
[26] Max Frank GmbH, *Max Frank Coupler: Schraubanschluss*. https://www.maxfrank.com/wAssets/docs/products/brochures/MAX-FRANK-coupler-schraubanschluss-BR-DEDE.pdf (accessed July 31, 2025).
[27] ICC Evaluation Service, L. L., *ICC-ES Evaluation Report: ESR-1990*, 2024. https://fiproductmedia.azureedge.net/media/Certification%20Documents/ICC%20Evaluation%20Report/fischer/ZD_ICC_01_FIS-EM-PLUS_EN_V3.pdf (accessed July 31, 2025).
[28] Deutsches Institut für Bautechnik (DIBt), *Allgemeine Bauartgenehmigung: fischer Injektionssystem FIS EM Plus zur Verwendung in unbeschichteten FD-/FDE- Betonflächen in LAU-Anlagen: Nummer Z-74.8-199*, 2020. https://fiproductmedia.azureedge.net/media/Certification%20Documents/Country%20Specific%20Approvals/fischer/ZD_Z_01_WHG-FIS-EM-PLUS_F_DE_V1.pdf (accessed July 31, 2025).
[29] Deutsches Institut für Bautechnik (DIBt), *Europäische Technische Bewertung: ETA-10/0388: Bewehrungsanschluss mit Upat UPM 44, Injektionssystem für nachträgliche Bewehrungsanschlüsse*, 2016. https://fiproductmedia.azureedge.net/media/Certification%20Documents/ETA%20European%20Technical%20Assessment/UPAT/ZD_ETAB_U_10-0388_SDE_AIP_V1.pdf (accessed July 31, 2025).
[30] MFPA Leipzig GmbH, *Gutachterliche Stellungnahme Nr. GS 3.2/18-297-1: Upat Injektionssystem UPM 44: Brandschutztechnische Bewertung der charakteristischen Stahlspannungen unter Zugbeanspruchung in Porenbeton in Anlehnung an Technical Report TR 020 „Evaluation of Anchorages in Concrete concerning Resistance to Fire"* https://fiproductmedia.azureedge.net/media/Certification%20Documents/Test%20Report%20Fire%20Protection/UPAT/ZD_B_04_UPM44_U_SDE_AIP_V1.pdf (accessed July 31, 2025).
[31] UHU GmbH, *Produktbeschreibung, Technische Spezifikationen*. https://www.uhu.com/de-de/produkte/uhu-plus-endfest-binder-harter-blister-33-g-d#Unterlagen (accessed July 31, 2025).

[32] DIN EN 1465:2009-07, Klebstoffe_- Bestimmung der Zugscherfestigkeit von Überlappungsklebungen; Deutsche Fassung EN_1465:2009.