

Identification of Potentials and Applications for Additively Manufactured Reinforcement (WAAM) in Bridge Construction

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Abstract:

This paper investigates the potential of additively manufactured reinforcement produced via Wire and Arc Additive Manufacturing (WAAM) for structural concrete applications in bridge construction. Mechanical tests and pull-out experiments confirm that WAAM reinforcement achieves bond behaviour comparable to conventional rebars. The WAAM reinforcement layout can be precisely adapted to the principal stress trajectories, enabling optimized force-flow-oriented detailing. Three application scenarios are examined: bearing pedestals, post-tensioning anchorage zones and bridge decks. Although further research is necessary, the current conclusions suggest improved crack behaviour, a reduction in required reinforcement quantities and enhanced constructability. Consequently, additive manufacturing emerges as a promising approach for the development of structurally optimized and digitally driven reinforced concrete systems.

Keywords: Force-Flow-Oriented Reinforcement, Additive Manufacturing, WAAM, Bridge Construction

1 Introduction

The development of reinforced concrete construction has historically been closely linked to a linear, truss-based understanding of structural behaviour. This perspective, which is embedded in traditional standards and structural design practice, has led for decades to the widespread use of orthogonal, grid-like reinforcement layouts, regardless of the actual force flow within the structure. In his discussion paper [1], Stefan Polónyi criticizes the resulting over-reinforcement, which not only leads to excessive material use and increased corrosion risk, but also fails to fully utilize the structural potential of reinforced concrete. In particular, the use of stirrups placed perpendicular to the principal tensile stress directions is seen as detrimental to durability [1]. With the increasing availability of additive manufacturing technologies, especially Wire and Arc Additive Manufacturing (WAAM), new opportunities arise for producing high-performance, force-flow-oriented reinforcement that can be precisely aligned with the principal tensile stress trajectories. This marks the first opportunity to translate Polónyi's concept of material-conscious reinforcement into practical and cost-effective structural applications. This paper investigates the potential of WAAM fabricated reinforcement elements in bridge construction, focusing on three typical application areas: force-flow-oriented reinforcement in bearing pedestals, crack width control reinforcement in the bridge deck, and optimized reinforcement layouts in the anchorage zones of post-tensioning systems.

2 Fundamentals of WAAM-Reinforcement

2.1 Manufacturing process

The Wire and Arc Additive Manufacturing (WAAM) process was employed to fabricate reinforcement bars with the specific aim of producing specimens featuring a deliberately roughened surface to enhance the bond behaviour between steel and concrete. An optimized surface roughness promotes mechanical interlocking and can significantly improve the bond performance in reinforced concrete. Various examples of WAAM-fabricated reinforcements can already be found in the scientific literature, including both individual bars and grid-like structures [2]. Previous studies have demonstrated the fundamental feasibility of producing slender reinforcement bars with diameters of up to approximately 10 mm using a point-by-point (dot-by-dot) manufacturing strategy. However, for larger cross-sections, particularly from a diameter of 10 mm upwards, a continuous deposition strategy has proven to be more advantageous [3]. For this example, a continuous manufacturing strategy with a meandering toolpath was therefore adopted to produce reinforcement elements with a nominal diameter of 16 mm. This approach enables the production of geometrically uniform bars with a defined roughness and a stable process for higher material volumes, making it especially suitable for the use in the construction sector. The geometries are either based on past literature [4] or manufacturability and process speed. The fabrication was performed using a Gefertec arc605 machine in combination with a Fronius TPS4000 CMT welding source. The resulting reinforcement specimens have already been tested to evaluate their bond behaviour when embedded in concrete. This contribution presents only selected results, whereas the complete experimental campaign is documented in [3].

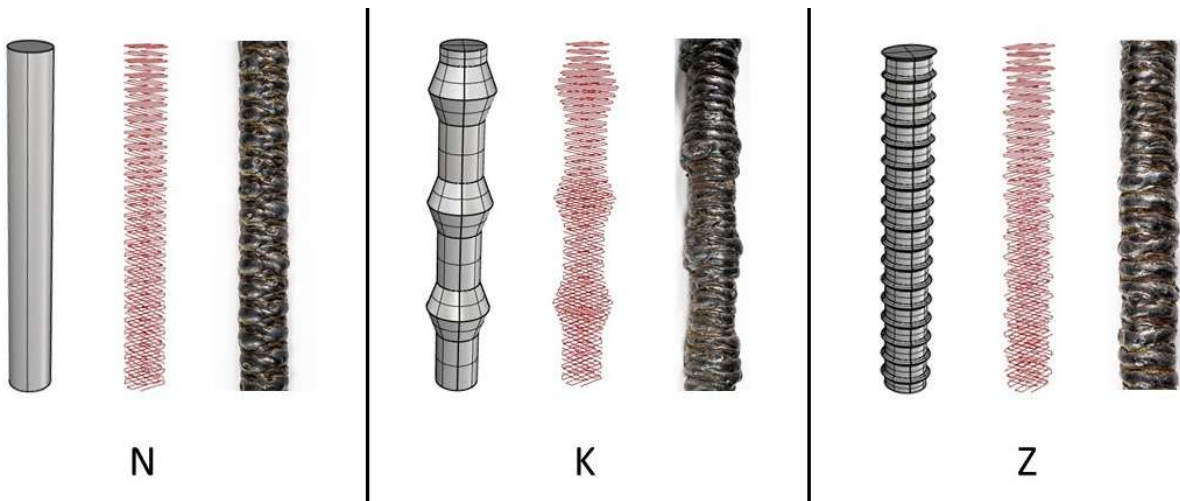


Figure1: CAD model with its designated toolpath and the corresponding specimen

2.2 Mechanical properties and bond behaviour

Tensile tests in accordance with DIN EN ISO 15630-1 [5] and pull-out tests based on the recommendations of RILEM [6] were performed to characterize the mechanical properties and bond behaviour of the additively manufactured reinforcement bars. The tensile tests provided key parameters such as yield strength and elongation at fracture, while the pull-out tests enabled an assessment of the bond performance between the WAAM reinforcement bars and the surrounding concrete matrix. It should be noted that the reinforcement bars were manufactured using a base material with a specified yield strength ≤ 420 MPa, which does not meet the minimum yield strength requirement of ≤ 500 MPa defined in Eurocode 2 [7]. By applying standardized test procedures, a direct comparison with conventional reinforcement bars becomes possible, forming a robust foundation for structural assessment. All results obtained from the additively manufactured reinforcement specimens (N, K, and Z series) are systematically benchmarked against those of the reference series produced from standard B500B (B series).

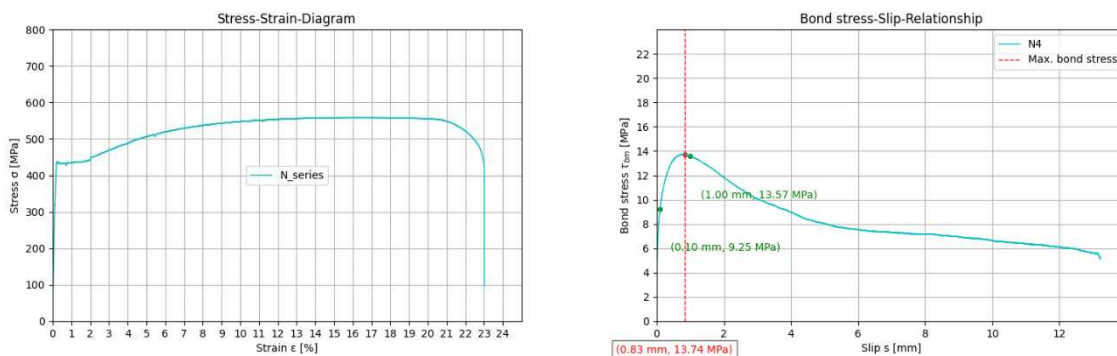


Figure 2: Selected Stress-Strain-Diagram (left) and Bond stress-Slip-Relationship (right) of Specimen N

The full test campaign, including tensile and pull-out tests, along with the corresponding results and evaluations, is documented in detail in a separate article [3]. This includes a comprehensive description of the testing procedures, material properties, and comparative analysis between the WAAM-fabricated specimens and conventional reinforcement.

Table 1: Mechanical properties of the WAAM specimens (N,Z and K_series and reference sample B_Series)

	Unit	B series	N series	Z series	K series
Young's Modulus E	MPa	208.500	199.500	163.000	195.000
Yield strength R_{eH}	MPa	582	438	338	427
Tensile strength R_m	MPa	687	558	446	546
Elongation at fracture A_{gt}	%	10,52	16,61	14,82	11,29
Tensile-to-yield-ratio		1,18	1,27	1,32	1,28
Weight	kg/m	1,58	1,61	1,53	1,61

3 Enhancing Efficiency and Durability with Force Flow aligned Reinforcement

If the reinforcement of structural elements is not aligned with the principal tensile stress directions, it significantly loses efficiency, which generally necessitates additional shear reinforcement. This intervention of the force flow may, under certain conditions, be detrimental to the structural element. In his critical paper [1] on reinforced concrete design, Polónyi points out that stirrups can negatively affect durability, as they are commonly placed orthogonal to the direction of the principal tensile stresses in practice. This disrupts the natural force flow and can lead to cracking, particularly in cases of insufficient concrete cover. In surface structures, especially in slabs, the principal tensile stresses must first be transformed into an orthogonal coordinate system in both the main and secondary directions to allow for a conventional reinforcement layout [8]. When examining this approach using the example of a bridge deck, it becomes evident that it may adversely affect crack development. In [9] Equation (7.15) from DIN EN 1992-1-1 [7] is critically reviewed and an alternative method is proposed. However, there is professional consensus that reinforcement aligned with the principal tensile stress trajectories not only reduces the required reinforcement content but also improves crack control [1], [9].

To conclude this section, a quotation from the authoritative German textbook *Vorlesungen über Massivbau – Teil 2: Sonderfälle der Bemessung im Stahlbetonbau* is presented.

“[...] reinforcement is most effective when the reinforcement bars follow the trajectories of the principal tensile stresses or principal moments. In doing so, they intersect the developing cracks perpendicularly and can directly take over the tensile forces from the concrete. However, in almost all structures, there are areas where this ideal reinforcement layout cannot be realized for practical reasons.”, translated from [10].

Additively manufactured reinforcement offers a promising solution to this challenge. Coupled with a stress adapted design strategy, it facilitates a deliberate reduction in reinforcement ratio. This approach leads to structurally optimized designs while simultaneously reducing material usage and associated CO₂ emissions.

4 Potentials and Applications in Bridge Construction – Review of Selected details from the Literature

A key advantage of additively manufactured reinforcement is its adaptability to be aligned along the principal force flow within a structure. This is exemplified by two application scenarios: a centrally loaded anchorage zone (Bearing pedestal and Post-tensioning Anchorage zones) and a bridge superstructure (Bridge deck).

4.1 Bearing pedestal

The superstructure of a bridge is typically supported on a pier via a bearing (e.g. calotte); which is typically located on a bearing pedestal. Due to the limited contact area, a high load concentration occurs in this region. The resulting load transfer induces a biaxial stress state within the prismatic bearing block, leading to compressive stress zones forming on all four sides. In current engineering practice, the corresponding splitting tensile reinforcement is commonly arranged orthogonally to the compressive stress directions in the form of conventional stirrups [11]. This traditional reinforcement layout can be replaced by a force-flow-oriented, additively manufactured reinforcement element specifically designed to accommodate the splitting tensile forces arising from the biaxial stress condition. The geometry of the reinforcement is optimized for the typically confined spatial conditions within the bearing pedestal and allows for a reduction in the required amount of reinforcement material.

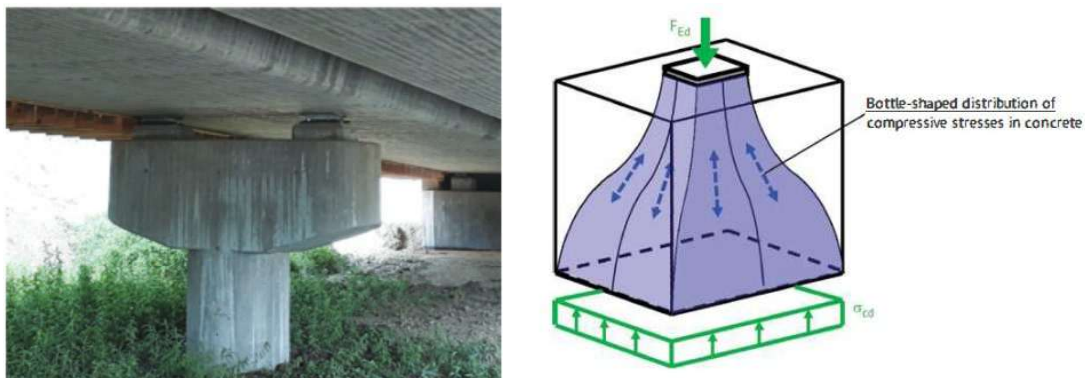


Figure 3: Bridge Pier and Bearing Pedestal (left) and distribution of compressive stress in concrete [11], edited.

4.2 Post-tensioning Anchorage Zones

Another relevant application in which the use of force-flow-optimized, additively manufactured reinforcement can lead to a more efficient and practical solution is the anchorage zone of post-tensioning systems. These regions involve the combination of anchor head, bearing plate, tendon, and duct, requiring the concentrated loads to be efficiently transferred into the concrete through suitable reinforcement detailing. In current practice, this is typically achieved using spiral reinforcement in combination with additional transverse stirrups [11]. However, due to the large number of embedded components and reinforcement elements, especially when tendons are arranged in multiple layers, significant space constraints can arise. This dense arrangement not only compromises clarity and execution quality but also makes the proper placement and compaction of concrete considerably more difficult. The application of a force-flow-aligned, geometrically adapted reinforcement layout can substantially alleviate this issue. By reducing the reinforcement volume at critical locations, additional working space is created, thereby facilitating concrete placement and compaction while simultaneously improving execution reliability.

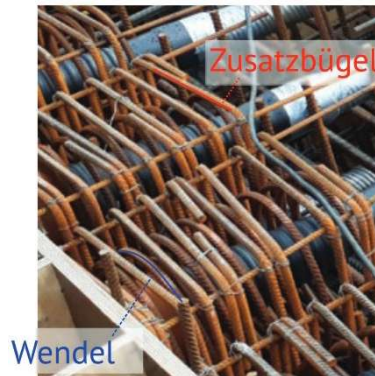


Figure 4: Detailing of reinforcement in Post-tensioning Anchorage Zones [11]

4.3 Bridge deck

As previously discussed in Section 3 *Enhancing Efficiency and Durability with Force-Flow-Aligned Reinforcement*, the alignment of reinforcement along the principal stress trajectories is considered beneficial in mitigating crack formation. In the work of Krakowski [9], a positive influence on crack behaviour is attributed primarily to the orientation angle of the reinforcement. If, however, the full path of the principal stresses is followed by a technically correct, force-flow-optimized reinforcement layout, a significantly more effective contribution to crack control can be expected. To substantiate this hypothesis with scientific evidence, a broad set of validated numerical and experimental investigations are still required. Nevertheless, additively manufactured reinforcement holds significant potential in this context, as it facilitates the implementation of complex, non-linear reinforcement trajectories that cannot be achieved with traditional fabrication techniques.

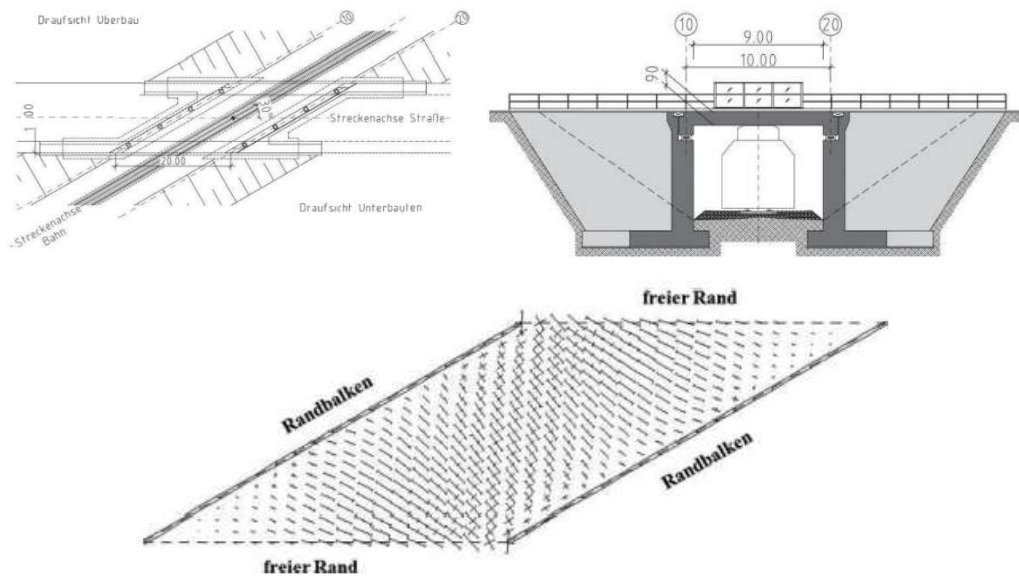


Figure 5: Top view, Side view and corresponding principal bending moment resulting from dead load [9]

5 Conclusion

The prerequisites and practical conditions for implementing force-flow-oriented, additively manufactured reinforcement are in place, both in terms of bond behaviour with concrete and material properties. This study has identified three specific application cases in bridge construction where the use of WAAM manufactured reinforcement offers clear advantages in terms of structural efficiency and construction practice. Nevertheless, further experimental investigations and systematic research are required to establish a reliable design basis for the structural application of additively manufactured reinforcement. The potential of this technology is evident. The key challenge now is its targeted implementation in practice. When applied to selected structural details, this approach enables the optimization of reinforcement layouts in terms of load transfer, material utilization, and long-term performance. Paving the way for a new generation of reinforced concrete structures aligned with digital fabrication and sustainable design.

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