

Structural Behavior of Topology Optimized Connectors for Steel Frames Structures

AMIR AHMED

`amir.ahmed@fsv.cvut.cz`

Czech technical University in Prague: Ceske Vysoke Ucení Technické v Praze <https://orcid.org/0009-0004-0334-2601>

Research Article

Keywords: Topology Optimization, Steel Connectors, Wire and Arc Additive Manufacturing (WAAM), Structural Behavior, Finite Element Analysis (FEA)

Posted Date: August 31st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10654634/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Amir Ahmed^{1*}

Department of Steel and Timber Structures, Faculty of Civil Engineering, Czech Technical university in Prague,
Thákurova 7, 166 29 Praha 6, Czech Republic

Abstract: This paper presents a finite element analysis (FEA) of a topology-optimized steel connector, comparing conventional welded connections with an optimized connector manufactured by Wire-and-Arc Additive Manufacturing (WAAM).

This study developed a structural benchmark case and an optimized connector case. The benchmark is presented as a conventional welded assembly of four IPE 360 beams welded to a central hollow steel column, and the second case is presented as a topology-optimized 3D-printed steel connectors, that connect central and lateral columns with IPE 360 beams through cylindrical pieces.

Both cases were modeled under the same boundary conditions and pressure-based loads in the software package ABAQUS CAE 2024 with detailed considerations of material nonlinearity, contact interactions, and load transfer paths.

The welded benchmark showed high initial stiffness and a uniform stress distribution, with maximum stress values remaining below the safe limit. The optimized connector case showed bitter stress gradients and lower stress concentrations.

Despite the occurrence of local plastic deformation, the optimized connector was stable and showed an acceptable service performance.

The results indicate that the topology-optimized connectors can significantly improve the load transfer paths efficiency, especially when a high interaction efficiency between the hollow column and the IPE beams is required and provide flexibility in architectural steel design.

Keywords: Topology Optimization, Steel Connectors, Wire and Arc Additive Manufacturing (WAAM), Structural Behavior, Finite Element Analysis (FEA).

1 INTRODUCTION

In recent decades, several revolutionary technologies have emerged, fundamentally transforming the processes and prospects of the engineering sector. With a focus on steel construction, this research paper examines additive manufacturing technology. [1]

Additive manufacturing (AM) is a rapidly transforming global manufacturing technology known as 3D printing, driven by advances in robotic control and programming. It is already widely used in both prototyping and final production in the aerospace, automotive, and biomedical industries [12, 13, 14]. Meanwhile, lower costs and increased availability of manufacturing equipment have enabled the more

* Corresponding Author E-mail: amir.ahmed@fsv.cvut.cz

price-sensitive construction sector to begin exploring its practical application. [28] In construction, although concrete printing has received considerable research attention and is increasingly being adopted [15, 16], research on metal additive manufacturing remains relatively limited.

Additive manufacturing (AM) refers to building parts layer-by-layer from raw materials, as opposed to traditional subtractive manufacturing. [2] AM is a promising technology for reducing parts costs by minimizing material waste and accelerating time to market. Furthermore, it allows for greater design flexibility, which can lead to weight savings and simplify the manufacturing of complex assemblies that were previously made from numerous sub-components. [6, 17]

2 LITERATURE REVIEW

2.1 WIRE-ARC-ADDITIVE-MANUFACTURING (WAAM)

Most famous category of AM, also known as Wire Arc Direct Energy Deposition (WADED) [3] is a type of direct energy deposition (DED) in which metal wire is fed into an electric arc and is then selectively deposited to form the part being manufactured [18]. Metal Inert Gas (MIG), Tungsten Inert Gas (TIG) or Plasma Arc (PA) technology can be used to produce the electric arc, and the motion can be controlled by either a robotic system or computer numerical controlled (CNC) gantries [23]. WAAM technology is identified as the more flexible category because it allows the development of structural components without theoretical dimensional constraints. [10]

Compared to other metallic AM methods, WAAM boasts several advantages: higher deposition rates (3–8 kg/h vs. 0.1–0.6 kg/h for powder-based systems) [17], lower capital costs, and greater flexibility in material compositions.[7] WAAM appears the most suitable for large metal structural elements with 50% reduction in CO₂ emissions. [5] WAAM is less expensive than other methods of metal AM since the equipment is off-the-shelf, the technology is more mature [26] and the feedstock costs 10 % that of powder [27].

However, the WAAM process has some limitations. It can suffer from geometric inaccuracy, some plane shapes cannot be deposited using WAAM, such as surface roughness which also causes variation in thickness of as-built specimens [22], sharp angles and curve shapes with large curvature. They play as the geometric limitation for forming path planning and geometric structure designing. [19] The surface quality and dimensional accuracy are inferior [24], meaning that subtractive postprocessing is often required to ensure the part meets the requirements for geometric accuracy [25].

The most challenging concerns that arise from the WAAM process are geometric distortions due to non-uniform expansion and contraction of the material during thermal cycles, resulting in large and anisotropic residual stresses. [8] Therefore, it is important to understand the thermomechanical performance during the WAAM process and improve the WAAM process to reduce the residual stress and distortion level.

2.2 Topology optimization (TO)

An advanced mathematical method that seeks to achieve the best performance for a structure while satisfying various constraints such as a given amount of material. Optimal structural design is becoming increasingly important due to the limited material resources, environmental impact and technological competition, all of which demand light weight, low-cost and high-performance structures. [4]

Topological optimization allows changes to be made not only in the geometry of the structure, but especially in its topology, modifying the number and connectivity of components and creating in the medium some boundaries, branches and holes. With topology optimization methods, the aim is for the optimal distribution of material and void regions inside a predefined design domain for a given set of loads and boundary conditions. [20]

2.3 Integrated framework

The scientific community put a lot of effort towards the implementation of WAAM in topology optimization tools to leverage the full potential of their combined use [9], the integration of TO and AM broadens the freedom in structural design and manufacturing of end-use components [21]. However, specific geometrical and mechanical features different for each set of printing parameters need to be properly accounted.

An integrated framework approach is proposed to integrate the capabilities of topology optimization with WAAM manufacturing constraints and structural design verification. The approach integrates a stiffness-based topology optimization approach with conceptual structural design principles to conceive an initial configuration, together with concepts of robustness and reliability to turn the solution toward practical designs. The optimized designs must comply with the manufacturing constraints of WAAM process, and then to be structurally verified through iterative nonlinear numerical simulations till the convergence to a final design is achieved. [9]

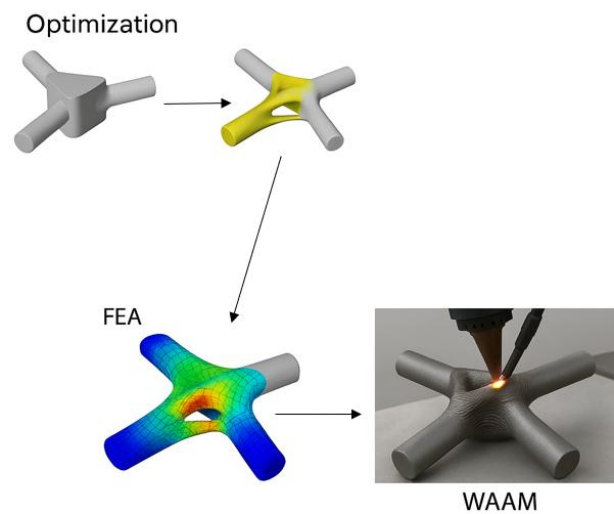


Figure 1: Integrated structural optimization framework

3 PAPER'S QUESTION

"How does a WAAM -fabricated topology -optimized steel connector behave within a steel frame, particularly welded to a hollow circular column and carrying an IPE360 beam via cylindrical pieces under a certain load and boundary conditions using finite element analysis as the principal validation tool?"

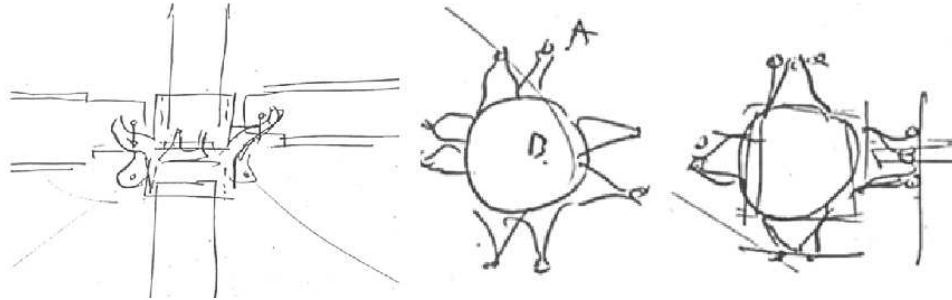


Figure 2: Initial conceptual 2D sketches for the optimized connector

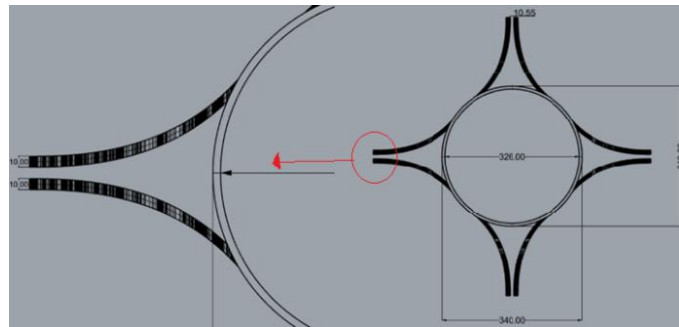


Figure 3: Dimensions of the optimized connector

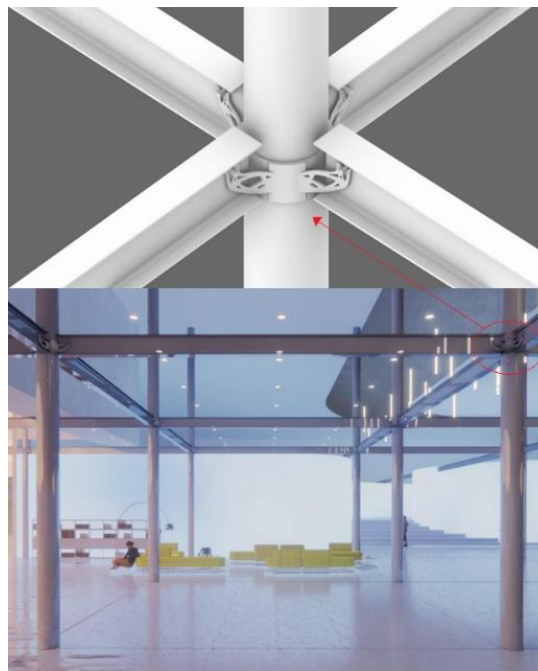


Figure 4: Realistic model with zoom up on the optimized connector

4 STRUCTURAL VERIFICATION THROUGH NON-LINEAR FEA:

A 3-dimensional finite element model (FEM) was developed using the software package ABAQUS to investigate the characteristics of 3D printed steel connections and the factors affecting their behavior to predict their structural behavior and failure mechanisms under working loads. [11]

The process begins by importing a pre-designed ACIS model of a fabricated steel connector designed through a 3D CAD model created in Rhino 3D [29], assembled in ABAQUS with hollow columns each with height of 4m and IPE 360 beams each with length of 6m. This setup is then compared to conventional welding to benchmark its performance.

For this simulation, linear hexagonal elements with incompatible mode(C3D8R) were employed to model the beams in the benchmark case and the columns in both cases.

Linear wedge elements with incompatible mode(C3D6) were employed to model the cylindrical pieces, quadratic tetrahedral elements with incompatible mode(C3D10) were employed to model the beams and connectors in the benchmark case.

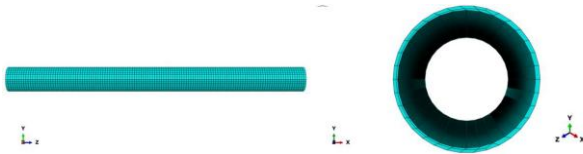


Figure 5: Column's mesh in both cases

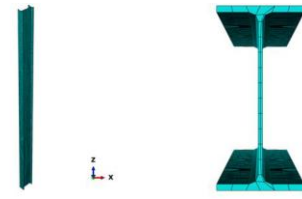


Figure 6: Beam's mesh in the benchmark case

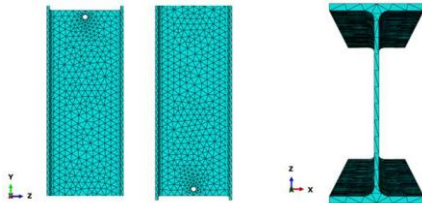


Figure 7: Beam's mesh in the connector case

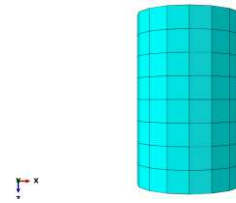


Figure 8: Cylindrical piece's mesh in the connector case

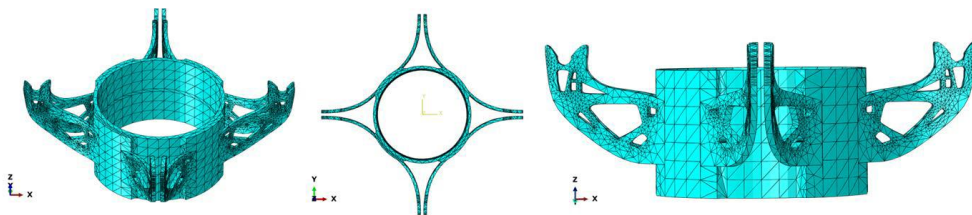


Figure 9: Connector's mesh in the connector case

Tie constraints were used between the beam ends and the column's surface in the benchmark case, and between the optimized connectors and the column's surface in the optimized connector's case. A surface-to-surface contact definition was used between the outer surface of the cylindrical pieces and the inner curve of the optimized connector's branches and between the internal surface of the beam's holes and the outer surface of the cylindrical pieces.

For both cases, the boundary conditions on the bottom of the columns were ENCASTRE, and the applied loads were the gravity load to simulate the self-weight of the structure and an external load with value of 20KN/m was applied as a vertical pressure load of value 0.11765 N/mm² on the IPE 360 beam's top flange.

The material used for all elements was steel S275 except for the connectors and the cylindrical pieces, the used material was high strength steel (HSS) E470.

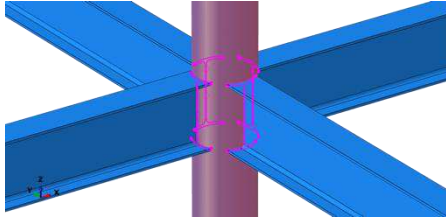


Figure 10: ABAQUS model for the benchmark case

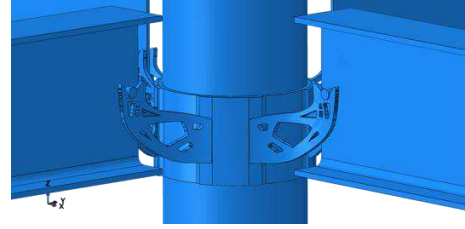


Figure 11: ABAQUS model for the connector's case

5 RESULTS:

The maximum values of stresses and displacements resulting from the FEA for both cases are summarized in the following table:

Table 1 - FEA results

Case	V.Mises Stresses	Vertical Displacement
	[MPa]	[mm]
Benchmark	222.9	3.3378
Optimized Connector	788.7	1.6120

The benchmark case showed typical stress distributions in the welded connection. Von Mises stress concentrations were the highest at the rigid joint between the beams ends column due to the transfer of moment and shear force.

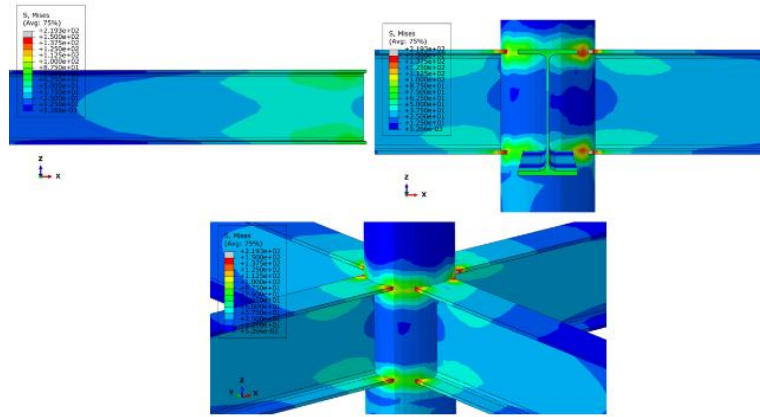


Figure 12: Maximum Von Mises stresses for the welding case 222.9 MPa

The optimized connector model showed a more distributed stress pattern across the topology-optimized branches, where the highest von Mises stress values were observed. The maximum von Mises stress of approximately 788.7 MPa (related to equivalent plastic strain of 0.102) was locally concentrated at the branch roots of the connector.

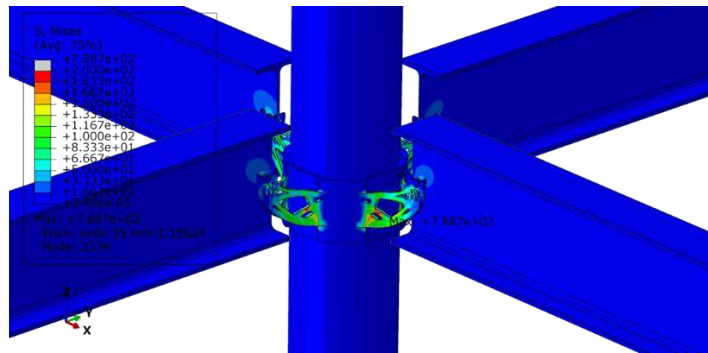


Figure 13: Maximum Von Mises stresses on the central connector 788.7 MPa

In both cases, the deformations followed the expected trends. Maximum vertical displacements occurred at the beam's mid-spans.

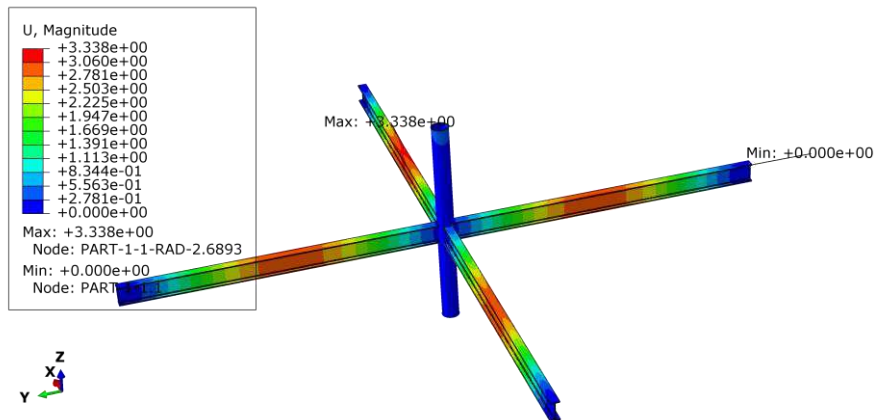


Figure 14: Maximum vertical displacements in the welding case 3.3378 mm

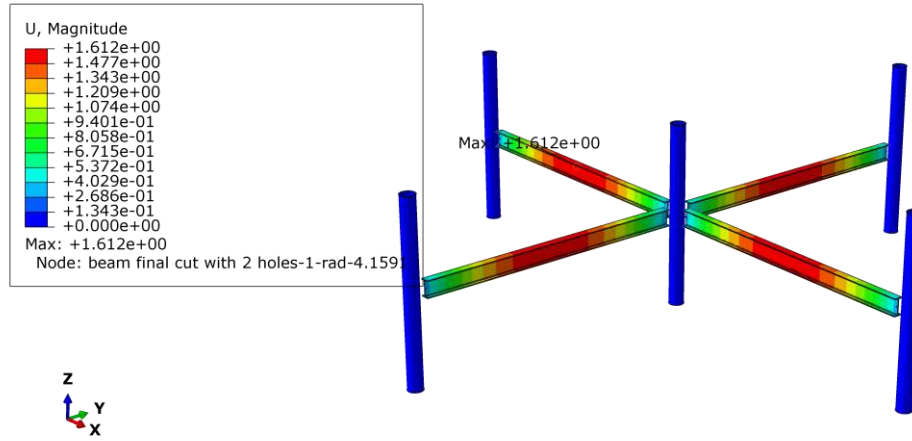


Figure 15: Maximum vertical displacements in the optimized connector case 1.6120 mm

6 CONCLUSIONS:

This paper presents a structural validation procedure of innovative steel connectors realized with WAAM. The integrated framework approach aims to integrate the capabilities of topology optimization with WAAM manufacturing constraints in an efficient way. The procedure is set on a maximum allowable deformation equal to $L/250$, according to Eurocodes provisions. The structural performances of the optimized connector are verified through FE-based numerical simulations.

The performed finite element analysis showed that the topology-optimized connectors provided effective load paths and improved deformation while enabling material savings. The maximum stress reached was within the plastic limits. The connector was deformed and structural integrity was maintained.

This paper confirms that optimized connector manufactured by WAAM offers better stress distribution and better load transfer the defined load paths. Topology optimization offers reduction in the used weight and less waste materials while maintaining stiffness.

7 RECOMMENDATIONS AND FUTURE WORK:

- Updating the connector's thickness, or even a part of the connector where the over-stressing occurs (at the branches).
- Minimizing the used material in the connectors body, since the stresses on it are quite low, additional voids for saving materials can be implemented.

8 DECLARATION:

Conflict of interest: The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9 REFERENCES:

- [1] Kyvelou, P., Buchanan, C., & Gardner, L. (2022). Numerical simulation and evaluation of the world's first metal additively manufactured bridge. *Structures*, 42, 405–416.
- [2] Haden, C. V., Zeng, G., Carter III, F. M., Ruhl, C., Krick, B. A., & Harlow, D. G. (2017). Wire and arc additive manufactured steel: tensile and wear properties. *Additive Manufacturing*, 16, 115–123.
- [3] Evans, S. I., Wang, J., Qin, J., He, Y., Shepherd, P., & Ding, J. (2022). A review of WAAM for steel construction – Manufacturing, material and geometric properties, design and future directions. *Structures*, 44, 1506–1522.
- [4] Huang, X., & Xie, Y. M. (2010). *Evolutionary Topology Optimization of Continuum Structures*. Wiley.
- [5] Priarone PC, Pagone E, Martina F, Catalano AR, Settineri L (2020) Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing. *CIRP Ann* 69:37–40
- [6] Laghi, V., Babovic, N., Benvenuti, E., & Kloft, H. (2024). Blended structural optimization of steel connectors for Wire-and-Arc Additive Manufacturing. *Engineering Structures*, 300, 117141. <https://doi.org/10.1016/j.engstruct.2023.117141>
- [7] Egiza, M., & Dekis, M. (2024). Unveiling the characteristics of ER70S-6 low carbon steel alloy produced by wire arc additive manufacturing at different travel speeds. *Metals and Materials International*. <https://doi.org/10.1007/s12540-024-01766-x>
- [8] Pires, M.M. Finite Element Analysis of Residual Stresses in Metallic Parts Produced Byadditive Manufacturing. Master's Thesis, University of Porto, Porto, Portugal, 2021.
- [9] Laghi, V., Palermo, M., Bruggi, M., Gasparini, G., & Trombetti, T. (2022). Blended structural optimization for wire-and-arc additively manufactured beams. *Progress in Additive Manufacturing*. <https://doi.org/10.1007/s40964-022-00335-1>
- [10] Dissanayake, M., Suntharalingam, T., Tsavdaridis, K. D., Poologanathan, K., & Perampalam, G. (2022). Informed finite element modelling for wire and arc additively manufactured metalics – a case study on modular building connections. *Buildings*, 12(5), 614.
- [11] Dassault Systèmes. (2019). *Abaqus 2019 User Manual*. Retrieved from <https://www.3ds.com/support/documentation/user-guides> [Software].
- [12] Leal R, Barreiros FM, Alves L, Romeiro F, Vasco JC, Santos M, et al. Additive manufacturing tooling for the automotive industry. *Int J Adv Manuf Technol* 2017; 92(5-8):1671–6.
- [13] Najmon JC, Raeisi S, Tovar A. Review of additive manufacturing technologies and applications in the aerospace industry. In: *Additive Manufacturing for the Aerospace Industry*. Elsevier; 2019. p. 7–31.
- [14] Sheoran AJ, Kumar H, Arora PK, Moona G. Bio-Medical applications of Additive Manufacturing: A Review. *Procedia Manuf* 2020;51:663-70.
- [15] Bos F, Wolfs R, Ahmed Z, Salet T. Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. *Virt Phys Prototyping* 2016;11(3):209–25.
- [16] Lim S, Buswell RA, Le TT, Austin SA, Gibb AGF, Thorpe T. Developments in construction-scale additive manufacturing processes. *Autom Constr* 2012;21: 262–8.

- [17] S.W. Williams, F. Martina, A.C. Addison, J. Ding, G. Pardal, P. Colegrove, Wire +Arc additive manufacturing, *Mater. Sci. Technol.* (2016) 1–7.
- [18] Buchanan C, Wan W, Gardner L. Testing of wire and arc additively manufactured stainless steel material and cross-sections. Ninth International Conference on Advances in Steel Structures. Hong Kong: China; 2018.
- [19] Geng H, Li J, Xiong J, Lin X, Zhang F. Geometric limitation and tensile properties of wire and arc additive manufacturing 5A06 aluminum alloy parts. *Journal of Materials Engineering and Performance* 2017;26(2):621–9.
- [20] Saadlaoui Y, Milan JL, Rossi JM, Chabrand P (2017) Topology optimization and additive manufacturing: comparison of conception methods using industrial codes. *J Manuf Syst.* <https://doi.org/10.1016/j.jmsy.2017.03.006>
- [21] Li S, Yuan S, Zhu J, Wang C, Li J, Zhang W (2020) Additive manufacturing-driven design optimization: building direction and structural topology. *Addit Manuf* 36:101406. <https://doi.org/10.1016/j.addma.2020.101406>
- [22] Laghi V, Palermo M, Gasparini G, Girelli VA, Trombetti T (2021) On the influence of the geometrical irregularities in the mechanical response of Wire-and-Arc Additively Manufactured planar elements. *J Constr Steel Res* 178:106490. <https://doi.org/10.1016/j.jcsr.2020.106490>
- [23] Laghi V, Palermo M, Gasparini G, Girelli V, Trombetti T. Geometrical characterization of wire-and-arc additive manufactured steel elements. *Advanced Materials Letters* 2019;10(10):695–9.
- [24] Khorasani A, Gibson I, Veetil JK, Ghasemi AH. A review of technological improvements in laser-based powder bed fusion of metal printers. *The International Journal of Advanced Manufacturing Technology* 2020;108: 191–209.
- [25] Careri F, Imbrogno S, Umbrello D, Attallah MM, Outeiro J, Batista AC. Machining and heat treatment as post-processing strategies for Ni-superalloys structures fabricated using direct energy deposition. *Journal of Manufacturing Processes* 2021;61:236–44.
- [26] Buchanan C, Wan W, Gardner L. Testing of wire and arc additively manufactured stainless steel material and cross-sections. Ninth International Conference on Advances in Steel Structures. Hong Kong: China; 2018.
- [27] Wang L, Xue J, Wang Q. Correlation between arc mode, microstructure, and mechanical properties during wire arc additive manufacturing of 316L stainless steel. *Materials Science and Engineering A* 2019;751:183–90.
- [28] Paolini A, Kollmannsberger S, Rank E. Additive manufacturing in construction: A review on processes, applications, and digital planning methods. *Addit Manuf* 2019;30:100894.
- [29] Rhinoceros 3D (2017) Rhino 3D computer-aided design software (Version 5 SR14 64-bit) [Software].