BRIDGING DIGITAL AND TRADITIONAL FABRICATION: ENHANCING PREFABRICATED METAL PANELS WITH ADDITIVE MANUFACTURING

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Additive Manufacturing (AM) is distinguished as a stand-alone production method, however, integrating AM into established industries presents a key opportunity to accelerate the transition toward more advanced, adaptable, and efficient fabrication systems. In the Architecture, Engineering, and Construction (AEC) sector, particularly in the manufacturing of prefabricated metal panels, production still relies on traditional techniques such as rolling, stamping, bending, and cutting. These methods impose geometric constraints, generate material waste, and require costly molds and manual adjustments. As a result, large-scale production of identical parts becomes necessary, where the efficiency of the established setup is justified by the high volume of repetition. The absence of AM within these workflows limits innovation and adaptability, slowing the industry's evolution toward digital and automated production.

Integrating AM into existing fabrication workflows transforms metal panels from static, prefabricated components into adaptable, performance-driven elements that optimize structural behavior and material efficiency. Rather than replacing conventional manufacturing, AM serves as a complementary tool, selectively enhancing prefabricated components through targeted reinforcement, geometric modifications, and multi-material hybridization. Instead of fabricating entire structures, AM is applied precisely where needed without disrupting established production chains.

Advancements in computational workflows, real-time scanning, and robotic automation further enhance the feasibility of integrating AM within industrialized fabrication. By embedding AM into prefabricated panel manufacturing, the transition toward more efficient, flexible, and high-performance construction becomes achievable. Bridging the gap between digital fabrication and traditional manufacturing unlocks new possibilities for efficiency, sustainability, and even design-for-disassembly strategies. The challenge lies not only in refining AM technologies but in reshaping industrial workflows and mindsets to integrate them as essential tools within large-scale production.

INTRODUCTION

Additive Manufacturing (AM) has emerged as a transformative technology across various industries, enabling the production of complex geometries, reducing material waste [1], and introducing new design possibilities [2]. As AM moves beyond prototyping and into large-scale fabrication, its potential to complement existing manufacturing systems becomes increasingly relevant [3]. However, most AM processes remain stand-alone production methods, primarily used to fabricate on an isolated workflow rather than integrating with conventional processes. This presents an opportunity to rethink AM not as a substitute for traditional manufacturing, but as a complementary strategy that enhances prefabricated components and introduces new material efficiencies, as shown in an AI-conceptualized scenario in Figure 1, where robotic fabrication synergistically enhances metal panels through the integration of additional structures produced by additive manufacturing techniques.

Metal panels, widely used in architecture, structural applications, and industrial enclosures, rely on conventional forming techniques that prioritize mass production and standardized geometries. These methods remain constrained by fixed tooling, excessive material use, and the

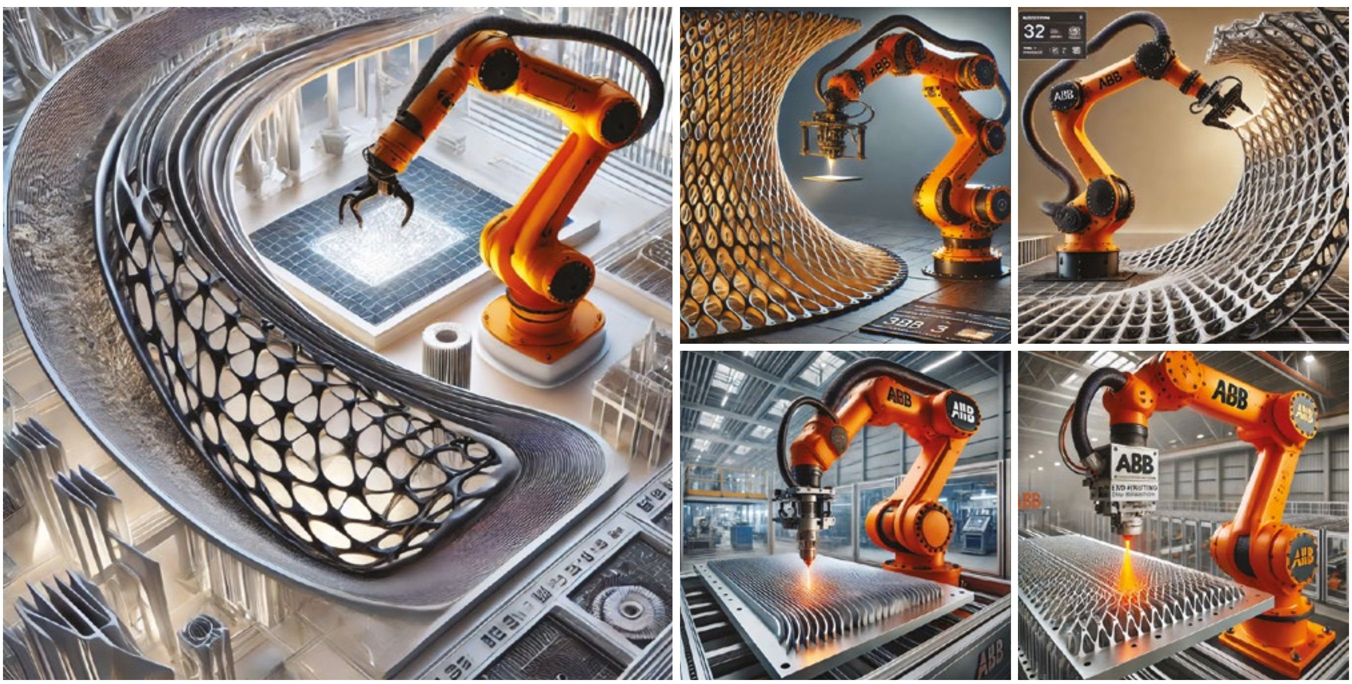

Figure 1: Conceptual AI visualization of robotic additive manufacturing reinforcing a freeform metal panel in an industrial environment. [OpenAI, 2024.]

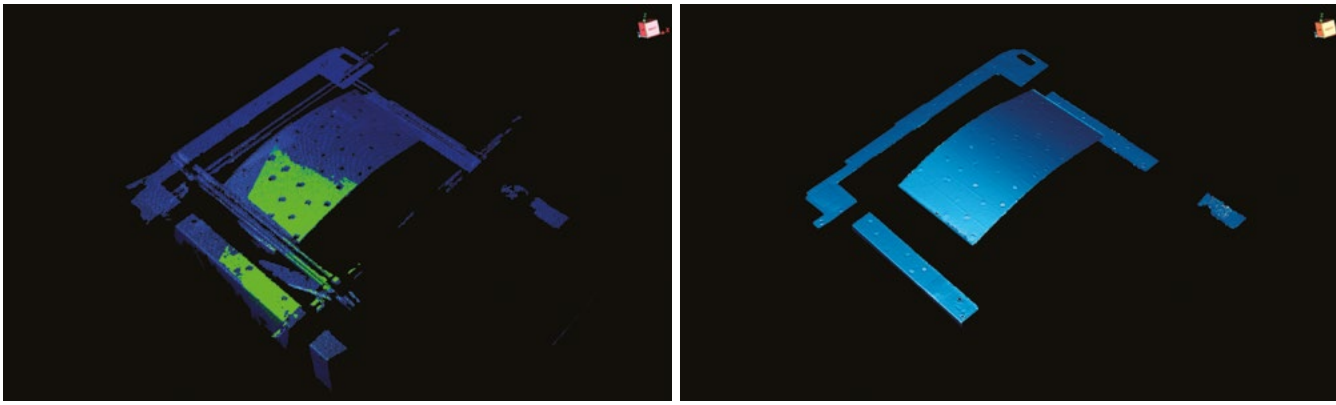

Figure 2: Sequence showing the process of using a 3D scanner to capture the geometry of a curved aluminum plate with scan markers (left), and the resulting mesh after post-processing and cleaning the point cloud (right).

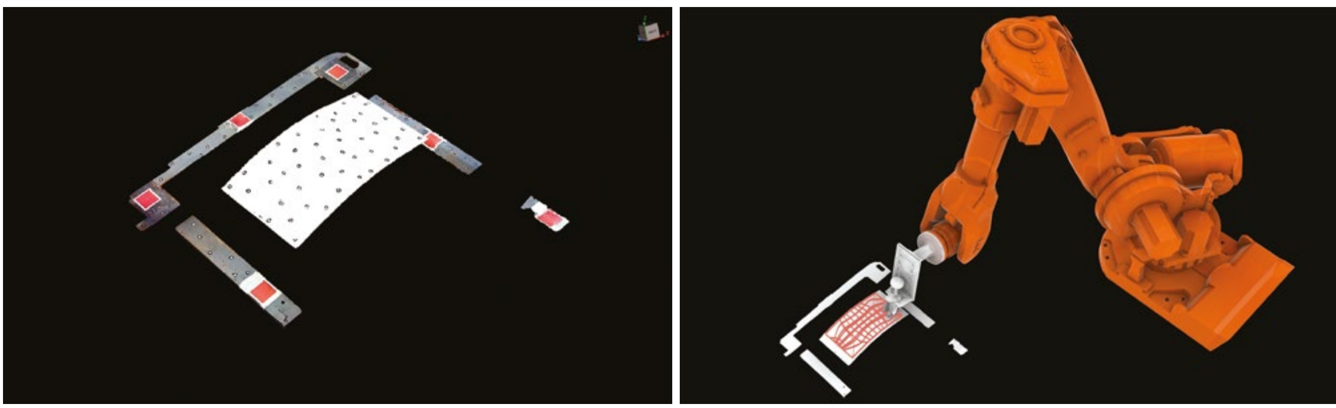

Figure 3: Texturized 3D mesh generated from the point cloud. Markers enable scanning reflective surfaces (left) and positioning the model relative to the robot's workspace (right).

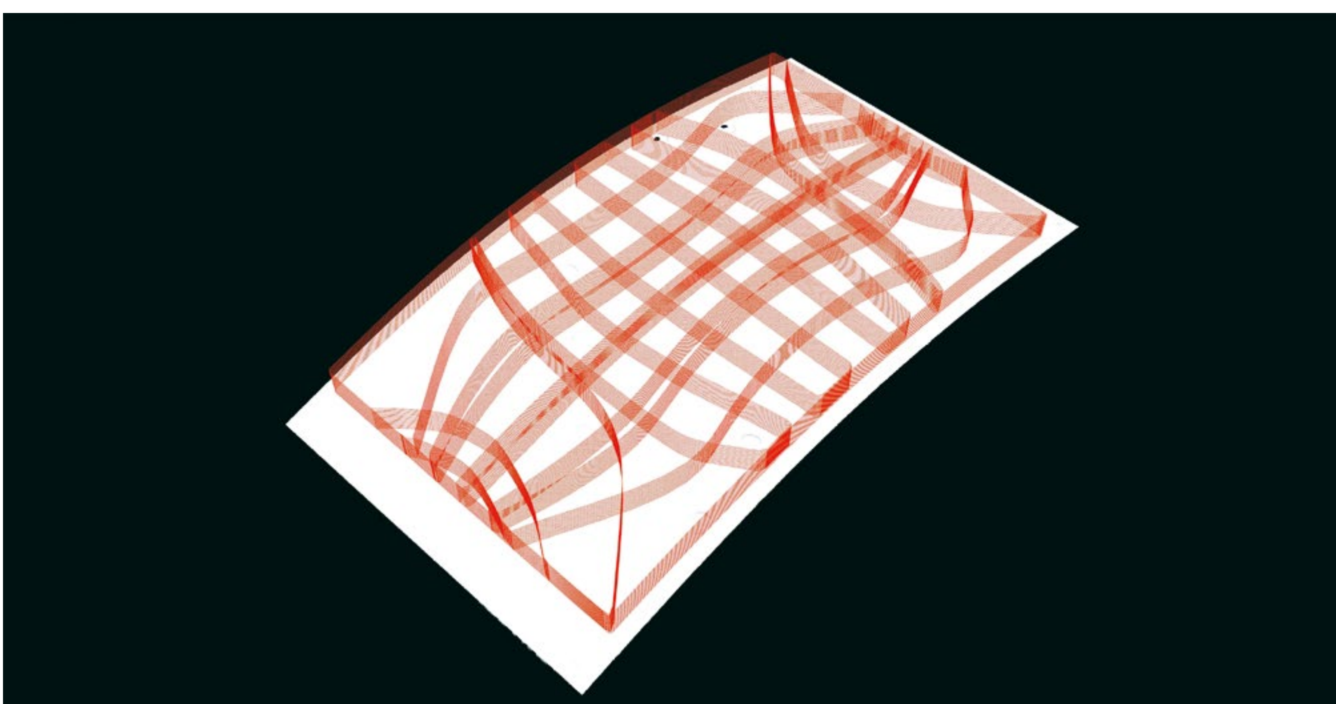

Figure 4: Example of a printing path of 20 layers, each 1 mm thick, over the aluminum surface.

high cost of molds, particularly when applied to complex freeform geometries. AM introduces a paradigm shift by treating prefabricated panels as adaptive substrates that can be selectively reinforced, modified, or optimized for specific performance criteria. Rather than requiring dedicated tooling for every geometric variation, AM enables a more flexible and dynamic approach, responding to material and structural requirements in real-time.

Despite these advantages, integrating AM into industrialized fabrication introduces technical challenges, particularly in geometry acquisition (Figure 2), process control, thermal management, and multi-material integration, among others. For example, when capturing the geometry of non-planar aluminum panels, advanced 3D scanning methods are used to generate detailed point clouds that accurately capture the surface geometry despite its reflective properties. These point clouds are subsequently processed into 3D meshes, which can be enhanced either by applying textures derived from the scanner's captured images or by applying color information directly from the point data (Figure 3). Additional computational steps are necessary to align the reconstructed mesh with the robot's working plane, allowing additive manufacturing paths to be precisely projected and adapted to the complex geometries of prefabricated components (Figure 4). Addressing these barriers is key to bridging the gap between digital fabrication and traditional metal forming, unlocking AM full potential as a scalable, performance-driven enhancement tool. By leveraging computational design workflows, robotic automation, and real-time scanning, AM offers a material-efficient alternative to conventional manufacture strategies. This integration represents a step toward a more adaptable, sustainable, and scalable approach to panel fabrication, aligning with the evolving demands of architectural and structural applications.

TRADITIONAL METAL PANEL FABRICATION AND ITS LIMITATIONS

The production of metal panels for architectural and structural applications relies on well-established forming techniques, each optimized for mass production but often inefficient when applied to customized or freeform designs. These panels generally fall into two primary categories, composite and monolithic panels, each follows different fabrication processes, facing design, cost, and material efficiency constraints. A common approach to achieving freeform facades while minimizing manufacturing complexity and cost is the triangulation of panels (Figure 5). By subdividing a curved surface into a series of flat triangular segments, fabricators can rely on standard cutting, bending, and assembly processes rather than expensive molds or complex double-curved forming techniques [4]. While this method reduces production costs and simplifies installation, it increases the number of individual components, leading to higher material waste, additional joints, and a fragmented visual appearance that may compromise the original design intent.

COMPOSITE METAL PANELS

Composite metal panels, widely used in building facades and lightweight enclosures [5], consist of thin metallic skins bonded to a core material such as aluminum honeycomb, polyethylene, or fire-resistant mineral cores. Their production process typically includes:

- Coil coating: metal sheets are pre-treated with protective and aesthetic finishes.
- Lamination: the metal skins are bonded to the core through adhesives, pressure bonding, or heat fusion.
- Cutting and shaping panels are resized and prepared for final installation.

While these panels achieve an excellent strength-to-weight ratio, they lack geometric flexibility. The rigid core structure makes it difficult to accommodate double-curved or free-form surfaces, leading to the common practice of faceting, where curved geometries are broken down into small, flat triangular segments for approximation [6] This increases material use, complicates assembly, and restricts the potential for continuous, structurally efficient panelization.

MONOLITHIC METAL PANELS

Monolithic metal panels, used in structural reinforcements, industrial enclosures, and roofing systems, are fabricated through bulk metal forming techniques such as:

- Rolling: produces continuous metal sheets of uniform thickness, ideal for flat and corrugated panel designs.
- Stamping (Figure 6) and deep drawing: uses rigid dies to shape panels into predefined forms, offering efficiency in high-volume production but at the cost of expensive molds and limited geometric flexibility [7].
- Incremental Sheet Forming (ISF) (Figure 7): a CNC-controlled process that deforms sheets incrementally, allowing for customized three-dimensional geometries without the need for dedicated molds [8] However, ISF remains constrained by process speed, thickness limitations, and challenges in achieving precise surface quality.

Both composite and monolithic panels require significant material use, particularly when structural stiffness needs to be improved. Traditional fabrication methods typically achieve this by increasing the material thickness uniformly or by relying on mechanical stiffeners, which require additional assembly and fastening.

This lack of localized reinforcement leads to material inefficiencies and limits structural optimization. Additionally, traditional forming techniques depend heavily on fixed molds and manual labor, restricting design freedom, scalability, and adaptability in highly customized projects [9].

As the demand for lightweight, geometrically complex, and material efficient solutions increases, these traditional manufacturing processes are struggling to keep pace. The reliance on standardized thicknesses, inefficient material distribution, and high setup costs highlights the need for a hybrid fabrication approach. One that combines precision, flexibility, and sustainability through computational and digital manufacturing strategies.

ADDITIVE MANUFACTURING AS AN ENHANCEMENT STRATEGY

Rather than replacing traditional manufacturing, AM provides an adaptive reinforcement method, transforming prefabricated metal panels into structurally optimized components [10]. Unlike conventional approaches that require uniform thickness increases or additional mechanical stiffeners, AM enables localized reinforcement and geometric modifications directly onto existing panels. This allows manufacturers to enhance performance without disrupting base fabrication processes, making AM a scalable enhancement tool rather than a disruptive alternative.

LOCALIZED MATERIAL DEPOSITION FOR STRUCTURAL REINFORCEMENT

One of AM key advantages is its ability to deposit material selectively, reinforcing only high-stress regions rather than applying uniform stiffening [11]. This technique, particularly useful for thin sheet applications, enables:

- Load-responsive reinforcements, where material is added in structurally necessary locations rather than across an entire panel.
- Anisotropic stiffness distribution, optimizing mechanical properties without excessive weight gain.
- Multi-material integration, allowing for metallic, polymeric, or composite reinforcement strategies based on specific functional requirements.

COMPUTATIONAL WORKFLOWS AND DIGITAL MANUFACTURING

AM's integration into industrialized fabrication relies on advanced computational workflows that enhance precision and adaptability. By leveraging Finite Element Analysis (FEA) and real-time scanning, reinforcement strategies can be dynamically adjusted to match specific stress distributions and fabrication tolerances (Figure 8). Key computational methods include:

The creation of a real-time virtual model of prefabricated panels enables precise geometry mapping, structural analysis, and process optimization [12]. This dynamic representation allows for continuous monitoring, simulation, and predictive analysis, ensuring fabrication adjustments can be made before physical production, reducing errors and improving material efficiency.

Digital Shadow: A high-resolution reconstruction of a 3D model that captures the current state of a prefabricated panel and serves as a basic reference for future workflow steps. Unlike a full digital twin that is continuously updated with live data, the digital shadow represents a static yet highly detailed snapshot of the geometry, enabling accurate pre-processing, path planning and robotic motion control before applying AM reinforcement. [13].

Parametric Optimization: applying algorithm-driven reinforcement placement based on load path analysis.

AI-Driven Process Control: adapting material deposition rates and toolpath generation in response to fabrication deviations.

EXPANDING THE POTENTIAL OF AM IN PREFABRICATION

Hybrid AM approaches introduce a new layer of design adaptability and performance optimization within prefabrication. Instead of producing fully 3D-printed components, AM techniques can be used to:

- Enhance existing structural elements, reducing material waste and excess mass (Figure 9).
- Integrate smart features, such as embedded sensors, thermal control layers, or acoustic insulation.
- Facilitate design for disassembly, enabling panel systems to be recyclable, reconfigurable, and adaptable over the long term.

Figure 5: Massimiliano and Doriana Fuksas (2007-2012). Georges-Freche School of Hotel Management. Montpellier, France.

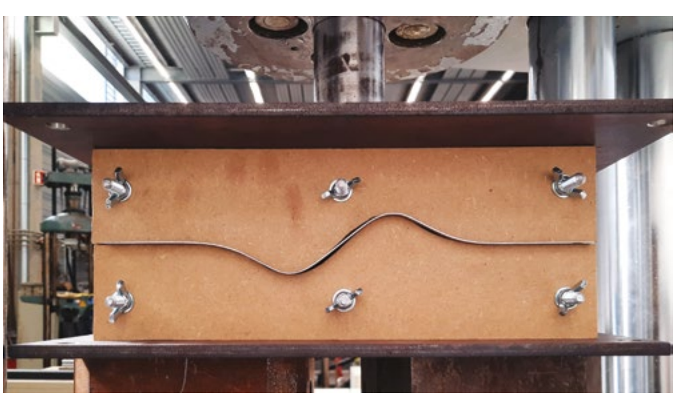

Figure 6: MDF dies for forming a 1mm steel plate. The stamping process requires a die design with a shape different from the desired part due to the spring back that occurs when the plate is released after deformation.

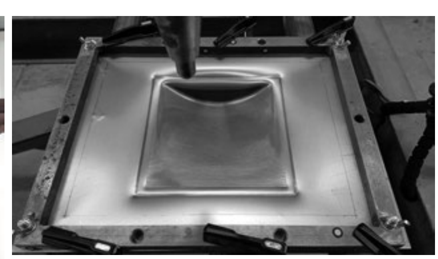

Figure 7: Robotic arm shaping a 0.4mm steel plate with Single Incremental Forming.

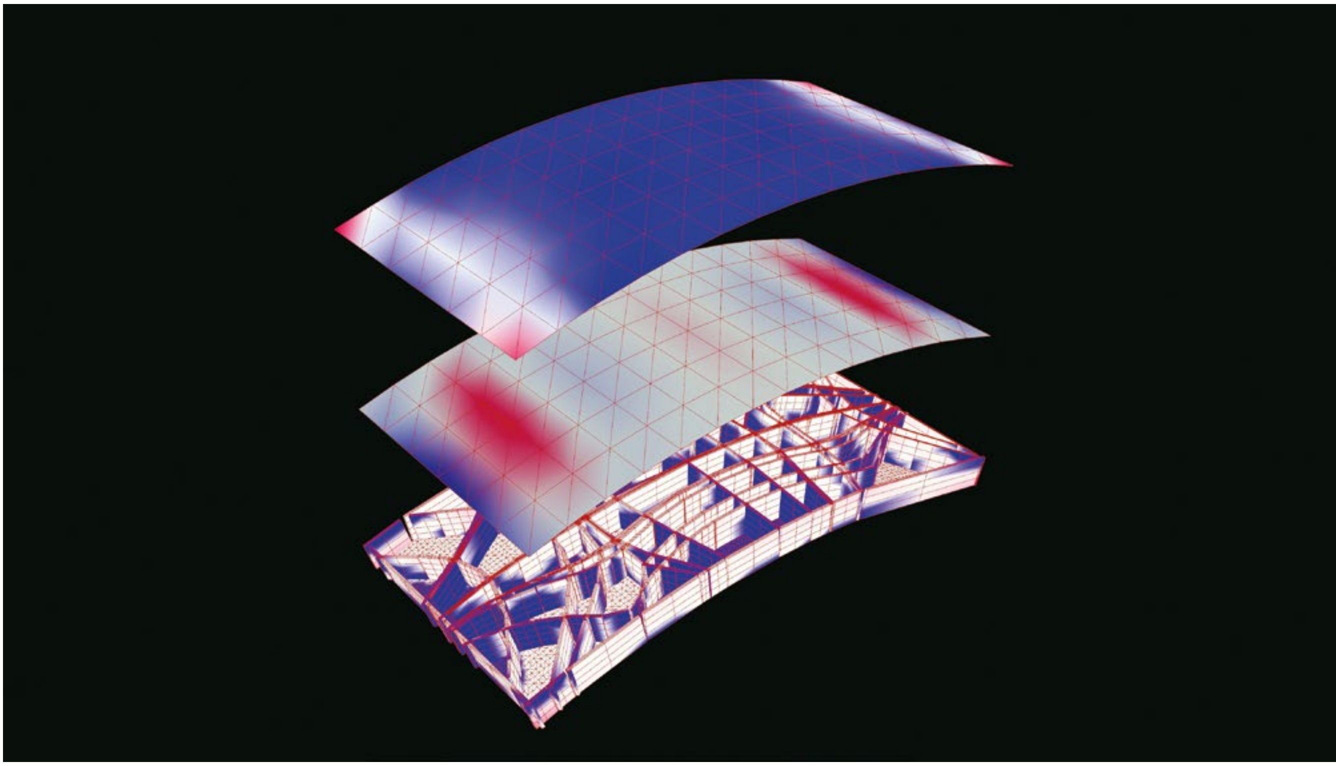

Figure 8: Using Karamba3D to analyze the stress lines used as guides to create 3D printed reinforcements, adding material in the most needed areas to reduce the overall thickness of the sheet that serves as the substrate.

Figure 9: 1 mm steel plate reinforced with 4 ribs of 6 layers of 0.95 mm printed with WAAM. The reinforcement in turn generates the plastic deformation of the plate which follows a unidirectional curve with a radius of approximately 4 meters.

BRIDGING THE GAP BETWEEN TRADITIONAL AND DIGITAL FABRICATION

The integration of AM into panel manufacturing represents a critical shift in industrialized construction. One that balances customization with production efficiency. As robotic automation and multi-material printing techniques continue to evolve, the potential for digitally augmented, performance-based fabrication becomes increasingly viable. AM offers an unprecedented level of precision, adaptability, and sustainability, ensuring that future architectural and structural systems are optimized for both form and function.

DISCUSSION

Technical Challenges in AM-Enhanced Panels

The integration of AM into prefabricated metal panel fabrication presents a technical challenge that extends beyond material deposition. Unlike traditional forming processes, which operate within well-defined mechanical behaviors and predictable tolerances, AM introduces thermal distortions, variable deposition rates, and material inconsistencies, complicating its seamless integration into industrial workflows.

One of the main obstacles in hybrid AM manufacturing is geometric accuracy and surface adaptation. Prefabricated metal panels formed by rolling, bending, stamping, or incremental forming, often have geometric deviations that must be addressed before AM can be applied. Real-time scanning and digital reconstruction are required to create an accurate 3D model of the existing surface. However, current scanning techniques have limitations in terms of time-resolution-post-processing, surface reflectivity, and computational processing speed, which affect the automation of the processes. Advances in machine vision, sensors, and adaptive path planning for robotic AM systems are needed to improve accuracy and efficiency.

Another critical technical challenge is thermal distortion and residual stress accumulation, particularly in metallic AM processes such as Wire Arc Additive Manufacturing (WAAM). Unlike traditional panel stiffening methods, that rely on mechanical deformation, WAAM deposits molten material layer by layer, leading to localized heating, cooling, and shrinkage effects. These inconsistencies can induce warping and internal stresses, making it difficult to achieve predictable mechanical properties. Current strategies, including preheating, interpass temperature control, path planning, and computational heat dissipation simulations, provide partial solutions but require further refinement for large-scale industrial use.

Thermoplastic-based reinforcements, such as Fused Deposition Modeling (FDM), face challenges in material adhesion and anisotropic performance. Unlike metallic bonding, where fusion occurs through melting, polymer-to-metal adhesion depends on surface treatment, chemical bonding agents, or mechanical interlocking. Ensuring long-term durability in outdoor applications remains an open question, as UV radiation, humidity, and temperature fluctuations that can degrade polymer inserts. Additionally, anisotropic material behavior in fiber-reinforced polymers must be carefully controlled to ensure structural reliability.

INDUSTRIAL INTEGRATION CHALLENGES

From an industrial perspective, AM integration faces challenges in scalability and production efficiency. Traditional panel production lines are designed for high-repetitive manufacturing, where each unit follows a fixed sequence of operations. AM, by contrast, introduces non-uniform material additions, requiring real-time process adjustments, making it difficult to integrate into automated production lines. Current robotic AM processes lack the speed and consistency required to match traditional manufacturing flow, making AM-enhanced panels more suitable for custom, high-performance applications rather than mass production.

Another critical barrier to widespread adoption is cost effectiveness. While AM offers material savings through localized reinforcement, it requires high-precision robotic systems, highly skilled operators [14], specialized deposition equipment, and computational infrastructure, all of which contribute to higher initial investment costs. The return on investment (ROI) for AM-enhanced manufacturing remains highly application-specific, favoring industries with high-performance demands (such as aerospace, advanced facade systems, and lightweight structural elements) rather than low-cost, high-volume manufacturing sectors. In addition, standardization and regulatory challenges present a major obstacle. Traditional prefabricated panels conform to established building codes and material performance standards, while AM-based reinforcements introduce new mechanical behaviors, bonding mechanisms, and failure modes that require rigorous validation. The lack of industry-wide standards creates hesitation in large-scale adoption, as manufacturers lack clear guidelines for quality control, testing, and certification of AM-enhanced products.

Despite these challenges, ongoing advances in real-time scanning, robotic automation, and computational design continue to improve the feasibility of AM integration. Addressing these technical and industrial barriers is essential for AM to transition from experimental workflows to standardized, scalable manufacturing techniques.

CONCLUSION

The use of AM in the production of prefabricated panels represents a fundamental shift in industrialized construction and material optimization. Rather than replacing traditional forming techniques, AM serves as a targeted reinforcement strategy, that enhances mechanical properties while maintaining compatibility with existing workflows. Hybrid approaches introduce performance-driven modifications, localized stiffening, and adaptive material distribution, to achieve structural efficiencies not possible with conventional methods.

Despite its technological promise, several barriers must be addressed to ensure scalability, economic feasibility, and regulatory acceptance. Overcoming thermal distortions, optimizing adhesion mechanisms, and implementing real-time process control will be critical for refining AM-enhanced panel fabrication for widespread industrial adoption. Furthermore, the cost-benefit ratio of AM integration requires deeper analysis, particularly in comparison to conventional reinforcement strategies. Future research should focus on multi-material hybridization, combining metallic and polymeric reinforcements within a single prefabricated panel. By integrating computational simulation, AI-driven process optimization, and sensor-based feedback loops, AM-enhanced fabrication could evolve into a fully adaptive, real-time controlled system, exceeding the static nature of manufacturing methods.

Beyond technical development, collaborative efforts between researchers, industry stakeholders, and regulatory bodies will be essential for establishing standardized guidelines for AM-enhanced panels. Developing certification protocols and defining clear performance benchmarks will accelerate industrial acceptance and enable scalable deployment across sectors such as architecture and advanced engineering applications.

Embedding AM within industrialized fabrication workflows represents a significant step toward a digitally integrated, high-performance, and resource-efficient manufacturing paradigm. This transition not only enhances structural optimization and sustainability but also paves the way for new material innovations, adaptive manufacturing systems, and intelligent fabrication strategies that will redefine the built environment.

REFERENCES

[1] Cabibihan, J.-J., Gaballa, A., Fadli, F., Irshidat, M., Mahdi, E., Biloria, N., Mansour, Z., & Abdulrazak, H. (2023). "A guided approach for utilizing concrete robotic 3D printing for the architecture, engineering, and construction industry". *Construction Robotics*, 7(3-4), 265–278. https://doi.org/10.1007/s41693-023-00103-9

[2] Pereira, T., Kennedy, J. V., & Potgieter, J. (2019). "A comparison of traditional manufacturing vs additive manufacturing, the best method for the job". *Procedia Manufacturing,* 30, 11–18. https://doi.org/10.1016/j.promfg.2019.02.003

[3] T. Wohlers, R. I. Campbell, O. Diegel, J. Kowen, N. Mostow, and I. Fidan, *Wohlers Report 2022: 3D Printing and Additive Manufacturing – Global State of the Industry*, D. L. Bourell and J. Van Rensburg, Eds. Fort Collins, CO: Wohlers Associates, 2022.

[4] Pottmann, H., Eigensatz, M., Vaxman, A., & Wallner, J. (2015). "Architectural geometry". *Computers & Graphics*, *47*, 145–164. https://doi.org/10.1016/j.cag.2014.11.002

[5] Selvakumar, M., James, D. J. D., & Thangadurai, K. R. (2021). "A Deep Study on Aluminum Composite Panel: Applications, Merits, and Demerits". *International Journal of Mechanical Engineering, 6*(Special Issue), 358–365.

[6] Pottmann, H., Liu, Y., Wallner, J., Bobenko, A., & Wang, W. (2007). "Geometry of multi-layer freeform structures for architecture". *ACM Transactions on Graphics*, 26(3), 65–es.

[7] Groover, M. P. (2010). *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems* (4th ed.). Hoboken, NJ: John Wiley & Sons.

[8] P. Nicholas, M. Zwierzycki, E. C. Nørgaard, S. Leinweber, D. Stasiuk, M. R. Thomsen, and C. Hutchinson, "Adaptive robotic fabrication for conditions of material inconsistency: Increasing the geometric accuracy of incrementally formed panels," in *Fabricate 2017*, London, UK: UCL Press, 2017, pp. 114–121.

[9] Pellis, D., Kilian, M., Wang, H., Jiang, C., Müller, C., & Pottmann, H. (2020). "Architectural freeform surfaces designed for cost-effective paneling mold re-use". *In Advances in Architectural Geometry 2020* (pp. 1–14). Paris, France: Ecole des Ponts ParisTech and Université Gustave Eiffel.

[10] Houda, M., & Reinhardt, D. (2018). "Structural Optimisation for 3D Printing Bespoke Geometries". In T. Fukuda, W. Huang, P. Janssen, K. Crolla, & S. Alhadidi (Eds.), *Learning, Adapting and Prototyping - Proceedings of the 23rd CAADRIA Conference - Volume 1* (pp. 235–244). Tsinghua University, Beijing, China.

[11] C. Borg Costanzi, *Reinforcing and Detailing of Thin Sheet Metal Using Wire Arc Additive Manufacturing as an Application in Facades*, vol. 68. Wiesbaden, Germany: Springer Fachmedien Wiesbaden, 2023.

[12] Ojeda, J., Knaack, U. and Rosendahl, P. L., "Geometry Acquisition with Computer Vision Applied to WAAM," in *AM Perspectives 1. Research in Additive Manufacturing for Architecture and Construction*, P. L. Rosendahl, B. Figueiredo, M. Turin, U. Knaack and P. J. S. Cruz, Eds., vol. 1, Guimarães: Lab2PT, 2024, pp. 157–166.

[13] Ojeda, J., Knaack, U., & Rosendahl, P. "3D Scanning Workflow Applied for Robotic 3D Printing on Complex Surfaces: Taking Advantage of a Digital Shadow for Robot Motion Path Generation and Geometric Control". In A. Estevez & D. Torreblanca-Diaz (Eds.), *SIGraDi 2024: Proceedings of the 28th Conference of the Ibero-American Society of Digital Graphics, 2024*, pp. 1117–1128. ISBN: 978-9915-9635-2-5.

[14] Wolf, A., *Applied Additively Manufactured Ceramics for the Built Environment*, Ph.D. dissertation, Technische Universität Darmstadt, Darmstadt, 2025.

FIGURES

1. Conceptual AI visualization of robotic additive manufacturing reinforcing a freeform metal panel in an industrial environment. Prompt: *A robotic arm using additive manufacturing to reinforce a freeform metal panel in an advanced industrial setting. The robotic arm features a 3D printing nozzle end effector, precisely extruding filament onto the panel to enhance its structural integrity. The background showcases an industrial workspace equipped with metal panels, high-tech fabrication equipment, and digital monitoring interfaces. The scene emphasizes precision engineering, automation, and the seamless integration of AM technology into metal panel fabrication* [OpenAI, 2024.]
2. Sequence showing the process of using a 3D scanner to capture the geometry of a curved aluminum plate with scan markers (left), and the resulting mesh after post-processing and cleaning the point cloud (right).
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