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Design to manufacture of fully stressed curved structures through elastic deformation of thin steel sheets with interlocking connections

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Abstract:

The research project presents the development of a fully digital design to manufacture process chain for high-performance curved steel elements produced by laser cutting thin steel sheets and assembled through elastic deformation. Although there have been developments in industrial robotic setups to automate steel beam bending, these processes rely on an iterative approach and are time-consuming and costly when there is a need for high accuracy.

The paper shows how the production of tailor-made geometric parts with interlocking connections enables the design of free-form structure as well as the complete integration of secondary functions such as façade and mounting positions. The research is based on an integrated co-development of the construction system, structural FEA analysis, as well as manufacturing and assembly methods. A computational tool was developed to combine geometric studies and structural analysis and to automate fabrication data. This project is situated in an industrial context to test the potential for upscaling the system and detailing techniques for the assembly of curved geometries. The potential of the system is demonstrated through the design and fabrication of a 1:1 scale canopy.

Keywords:

curved steel structures, steel laser cutting, bending active, interlocking connection, Façade integration, ETFE façade; FEA analysis, computational design, welding

1 Introduction

1.1 Context

Steel is a highly energy-intensive material commonly used in building construction, and it has a significant market share of around 67% in Germany [1]. In this sector, the construction industry accounts for approximately 35% of total steel consumption, with the majority (60%) used in primary structures [2]. Given the industry's potential impact on energy consumption and the European Union's goal of achieving sustainable energy, reducing steel usage in primary structures would be a critical step in conserving resources [3] [4]. In this context, optimizing the shape and cross-section of supporting structures, bears a great potential for steel structures to be planned in a more resource-efficient way [5].

The lightweight principal of a 'fully stressed design' may be one of the most effective ways to reduce mass in a structure. Following this principal, the geometry of the structure as well as the cross section are optimized in such a way, that every part of the structure is loaded to its maximum load bearing capacity in at least one load case. As a result, the structural geometry often includes curved members and uses varying cross-sections for and within each member. Although curved geometries have structural advantage both in overall structural geometry and the individual building components, the geometric complexity poses a challenge for manufacturers using conventional production lines and machinery[6]. The steel construction industry has developed different methods for bending conventional cross-sections to create curved members, including rolling, incremental bending, hot bending, rotary draw bending, and induction bending, as described by Todd A. Alwood [7]. Certain bending methods are more commonly used in the steel construction industry, while others are used for parts in automobile, piping, and other industries. Curved members can be made from a variety of shapes, including rolled open shapes, welded built-up shapes, and closed shapes. The trend in steel construction is moving towards complex profile structures that consider the mechanical-geometric requirements of load-optimized structural components [8]. Although both robot-

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assisted welding processes and new bending technologies are developing around manufacturing techniques such as Rotary Draw Bending (RDB) and Three Roll Push Bending (TRPB) [9], manufacturing three-dimensionally bent parts from rolled standardized profiles without shape deviations to the target geometry is a complex task, since the bending contour is mainly influenced by geometry, process and tool-related parameters [10]. Currently, the transition zones in the forming process are not considered in the design process, resulting in a geometric shape deviation between the CAD model and the bent part. Another significant challenge in creating curved members is cutting and drilling mounting positions for secondary functions after the forming process, which can result in an inconsistent and imprecise process. Therefore, developing a new method to plan and build free form geometries with varying cross sections can open new fields for design and engineering.

In an industrial context, modern laser cutting (LCT) has significant benefits to create custom geometries in a cost effective and highly accurate way [11]. This manufacturing technique allows to not only engrave assembly information and reduce the need for blueprints, but also the geometry can be designed in a way that it is possible to have a predefined assembly sequence [12]. In the Intermeshed steel connection (ISC) project, the fundamental concept is to replace the existing steel connections with conventional standardized profiles (e.g. I-Beams) with interlocking connections [13]. Projects such as the Mitoseum [14] and Adidas Herzogenaurach membrane facade showcased the combination of digital detailing and laser cutting technology for designing adaptive joint system in gridshell structures.

In the context of freeform building envelopes, designing with ETFE cladding offers several advantages such as its transparency, lightness, and durability. It also allows for flexibility in creating complex shapes and forms, while still maintaining a high level of thermal insulation and energy efficiency. This can also be seen in the environmental aspects and life cycle analysis of ETFE cushions compared to normal glazing panels [15]. The construction includes ETFE foil cushions, aluminum extrusions and supported by substructure which is attach to primary structure. [16]. This results in a noticeable increase in weight for the primary structure, as well as impacts the fabrication process involving welding and coating [17]. Mounting profiles and individual connections are time consuming especially when assembled on a curved geometry, therefore, developing a method to detail the structure and deal with this complexity before the deformation process would save time and energy during fabrication and assembling of the secondary function.

Bending-active structures have been used as a way to simplify the production of curved elements in a cost-effective way [18]. Projects such as Asymptotic Grid shell [19] and Point. One *Solarladestation* in BMW utilized laser cutting and elastic deformation of thin sheets to create shell structures. However, in steel construction little research has been addressed to generating stiff curved elements through elastic deformation and the integration of the secondary function.

1.2 Research objectives

The main objective of the presented research is to demonstrate through a proof-of concept 1:1 scale prototype, the feasibility of creating fully stressed curved geometries through assembling bending active laser cut plates with an integration of secondary functions within primary structure. The research questions are oriented towards two fields i) design and engineering, ii) manufacturing:

- How much material can be saved through complex member shapes and differentiated cross sections for the primary structure and an integration of the substructure?
- What is the geometric accuracy of the fabricated geometry compared to the digital model considering spring back and tolerance?
- What is the impact of the residual stress of elastic deformation in the load bearing capacity of the beam?
- How does integrating connection detailing improve the assembly process? And how does it impact the structural design.
- How does the bending active impact the manufacturing process?

By addressing these research questions, this project aims to apply the developed methodology in an industrial context to test the potential for upscaling the system and detailing techniques for assembly of curved geometries.

Figure 1. Preassembly of fabricated curved geometries

2 Research Methodology

The research methodology is structured into three main areas: construction system development, structural analysis, and manufacturing and assembly methods. The construction system development involves top-down design approach to design a canopy and its elements, as well as a bottom-up design approach for elements and cross-section design. Detailing strategies, including interlocking connections and tolerances, are also considered. The structural analysis focuses on the development of a computational workflow and digital modeling strategies for bending active plates, along with global and local structural analysis. The manufacturing methods encompass preassembly considerations such as tolerances, jig development, and welding, as well as assembly measures such as protective coatings.

2.1 Development of integrated construction system with secondary function

The study aimed to develop tailored design elements using a combination of bottom-up and top-down approaches. The global study focused on designing an underlying surface and defining the typology and geometric properties of the design elements, including load-bearing capacity and forces involved in the system. This provided information for the local study, which focused on designing the cross section and bespoke interlocking connections for curved elements. The physical modelling and digital modeling investigations were then used to create a feedback loop between the studies. A computational tool was developed to combine the geometric studies and structural analysis and automate fabrication data generation. (Figure 2)

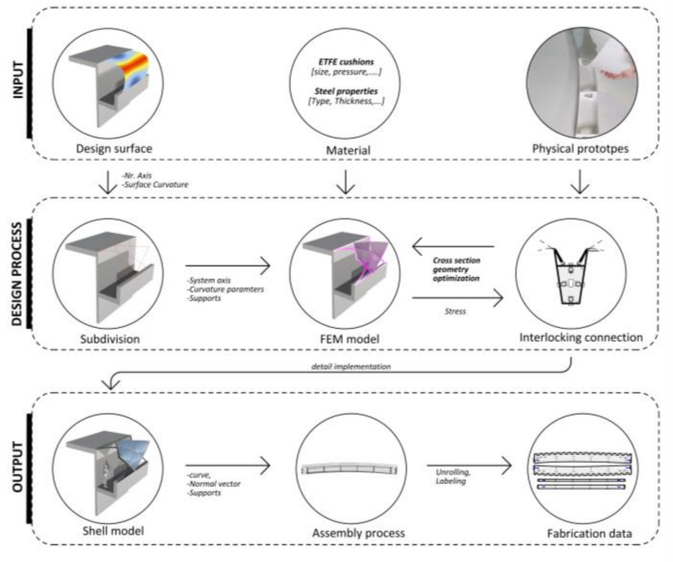

Figure 2. Digital workflow

2.1.1 Global model

A global design study was conducted to determine the overall design surface and its segmentation for the canopy. Early design concepts were developed, and an anticlastic hyperbolic geometry was selected to create space for the balcony, with the symmetric property of the surface reducing complexity and element variation (Figure 3.a). Various segmentation techniques were examined and evaluated, and ultimately, the geodesic method was selected as the optimal approach due to its ability to generate tangential developable surfaces as straight elements, which minimize material wastage. (Figure 3.b)

A key aspect of the segmentation is maintaining the principle bending axis of the curved geometry parallel to the surface normal. The underlying surface defines the curvature parameters for the components such as Normal curvature k_n, Geodesic torsion t_g and Geodesic curvature k_g, as described by Schling [19] . Physical investigation was carried out to determine suitable component typologies. Initial attempts to connect the beams directly were unsuccessful due to insufficient connection stiffness. As a result, a prototype with discrete geometry as nodes was built to provide stiffness in the connections. Two discrete typologies were considered: (i) beams made from long plates to create long spans, and (ii) nodes with stiff connections capable of accommodating varying numbers of beams. The resulting structure comprised 20 beams and 11 nodes, each of which consisted of 5 beam types (5 unique types + 15 mirrored ones), with fabrication possible using only 5 different formwork sets (Figure 3.c).

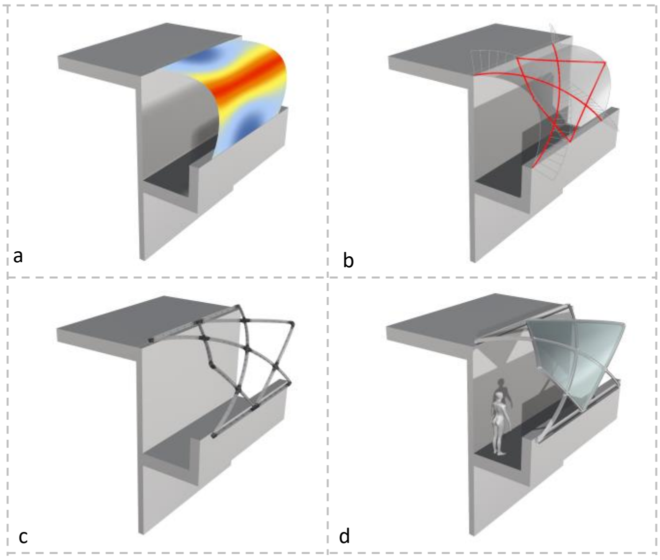

Figure 3: Global model study. a) Target surface curvature, b) Geodesic segmentation, c) Component typologies, d) ETFE cladding system

2.1.2 Local design

The local design study utilizes a construction principle to create curved components using developable bending active plates and stiffeners from previous work [20]. By unrolling the bent surfaces and applying the interlocking connections, the final geometry can be assembled by inner stiffeners deforming the flat surface into target position and interlocking connection aligning the developable surfaces. The system's properties are defined by a 3-dimensional curve as the system axis including curvature properties and custom cross-section geometry(-ies).

To determine the geometric parameters of the stiffeners, various cross section studies were carried out. The cross-section study aimed to optimize the material utilization and enhance structural capacity. Geometric properties were then defined based on the number of segments, and material characteristics and integrating secondary function were considered.

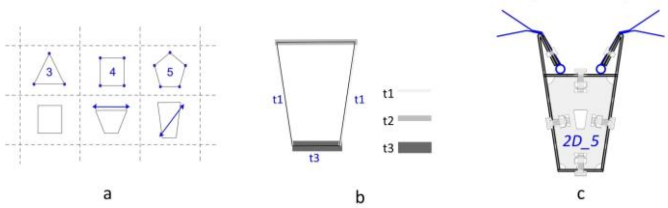

Figure 4: Cross section study. a) Geometry variation, b) Material thickness, c) Secondary function integration)

Geometric optimization was achieved by selecting a quad shape over pentagon or hexagon due to its structural advantages for bending and axial forces. The trapezoid shape of the quad cross section was preferred over a square shape due to its geometric versatility, providing greater design flexibility (figure4.a). Furthermore, the material properties of each web and flange were selected to meet the structural performance requirements. (figure4.b). The extension edge of the webs is considered for the integrating the secondary function (figure4.c).

The system axis is determined by a NURB (Non-Uniform Rational B-Spline) curve from the global model segmentation. The flanges modelled as tangential developable surface along the geodesic curves with a constant vanishing geodesic curvature as kg. Therefore, the unrolled geometry results as straight strip (figure 5. a). The webs are developable surfaces with rulings parallel to kg. (Figure 5.b). Their geodesic torsion correlates directly with the gaussian curvature of the underlying surface. The number and spacing of stiffeners are determined based on a global loading factor.

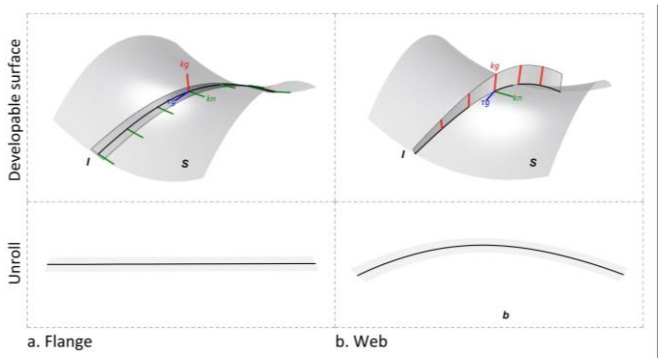

Figure 5: Surface unrolling. a) Flange, b) Web. *(Target surface S and curvature parameters normal curvature kn, Geodesic torsion tg and Geodesic curvature kg)*

2.1.3 Interlocking connection detailing

The interlocking connections were developed to provide attachment details for ETFE framing and to facilitate the component assembly. To develop ETFE attachment, extending the top edges of the webs and folding it provides clamping surface for the ETFE. This can be achieved by adding dash lines through laser cutting. To ensure waterproofing and protection of the connection, EPDM gaskets, known as beading, are added on top of the folded edge, effectively safeguarding the ETFE material from sharp edges of the steel. Steel strips clamp the ETFE and EPDM to the folded edge using self-threading bolts. The detail has been drawn in comparison to Mitoseum project to highlight the material efficiency as seen in Figure 6.

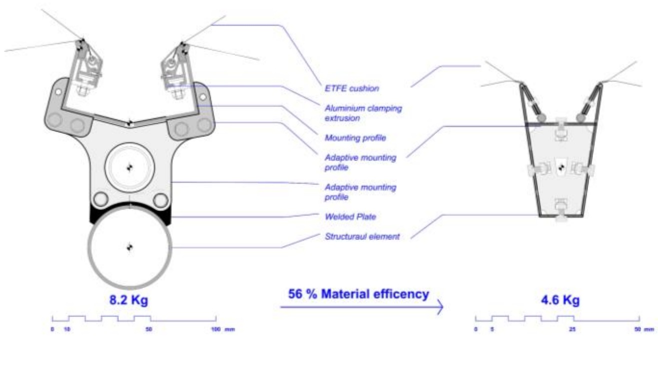

Figure 6: Material efficiency through the integrated construction system

Interlocking connections were also developed to be used in the assembly process in two positions: i) plate to plate connection, which position and aligns the plates, ii) stiffener to plate connection, which holds a nut to lock the bending elements to the stiffeners. The plate-to-plate connections are positioned along the long outline edges of web and flange plates to align them together. The stiffeners to plate connections were designed as finger to pocket connection which clamp the plates to stiffeners by screws. A small thin edge designed within the stiffener, which after bending holds a threated screw in plate, pulls the plates.

Another important parameter involved in dimensioning interlocking is tolerance definition. The finger joint can only generate resistance after the contact takes place. There are positive t (in direction of curve) and negative tolerances -t (opposite direction curve). The positive tolerance allows for large adjustability for assembly process without significant impacting the structural performance, corrosion protection layer. The negative tolerance adjusts the spring back of the geometry with extra rotation around system axis. This rotation value (Δk_g) correlates to start normal vector and end normal vector of the beam. After the assembly, this connection mainly carries shear force in the system through compression on one side as soon as the contact happens.

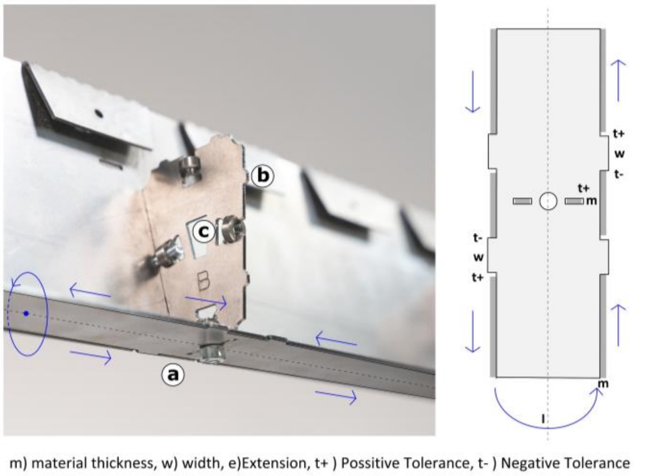

Figure 7: Interlocking connection parameters. a) plate to plate finger joint parameters, b) plate to stiffener parameters, c) not holder detail

The interlocking connections were then applied to the shell model to provide the fabrication data. Figure 8 shows the detail 3D model and unroll fabrication data for the node and beam components.

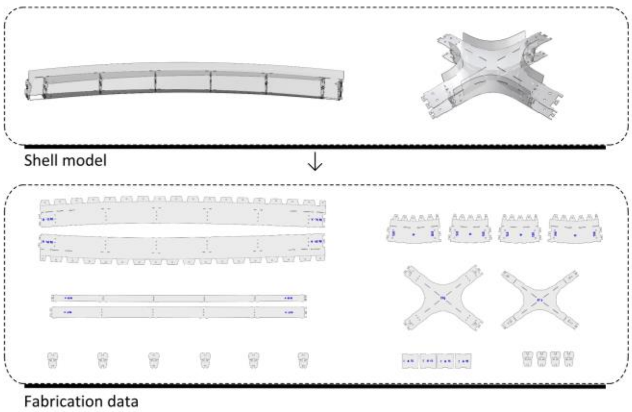

Figure 8: Fabrication data generation (Unrolling, detailing and labeling)

2.2 Structural analysis

The structural analysis was carried out through developing an FE model to integrate material properties and loads to optimize the cross-section geometry and material within the system. The structural analysis was divided into component and global scale. The analysis was carried out using the commercial FEM software SOFiSTiK®, which offers custom programming in the parametric interface Teddy.

At the component scale, the studies were carried out to determine the loading capacity, as elastic assembly process results in residual stress. The FE model simulates the deformation process with adaptive incremental load steps, which contract cable elements between the matching edges of the beam from its 2D flat to the 3D bent configuration [18]. After form-finding, residual van misses stress determines the load-bearing capacity in the global model [20]. The simulation was carried out on the component with highest geodesic torsion from the global model, revealing that the residual stress did not surpass 40% of the material properties. Local buckling is another critical factor that must be taken into consideration when designing cross sections with thin plates. Based on the Eurocode 3, the c/t value was calculated for web and flange as internal elements and the top folded edges of webs as outstand element. The calculation indicates that the webs in bending and the top and bottom flange in compression fall into category 1. Top outstand edges of web alone are in category 4, with c/t=19 (which is close to 14 for category 3). Considering the constraint from the folded edges and the pretensioned cushions, local buckling of these parts is not expected.

On the global scale, the curved geometry was modeled using beam elements in SOFiSTiK with adapted strong bending axis according to the surface. The loads, including self-weight, wind, and membrane pre-stress, were then applied.

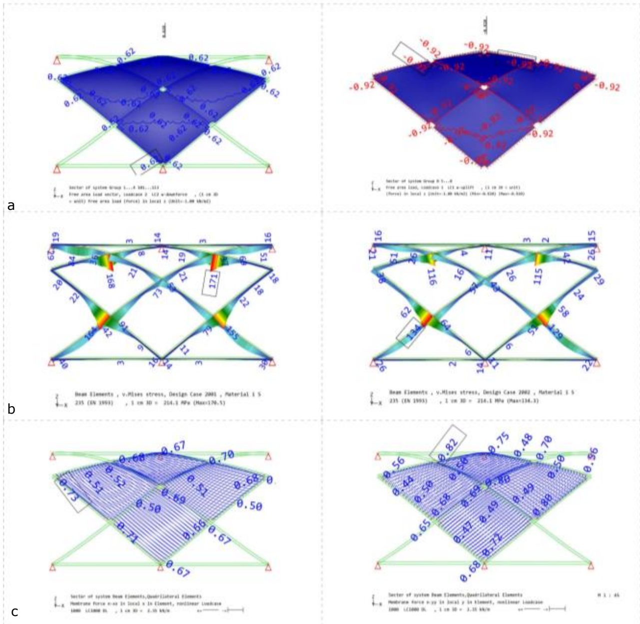

Figure 9 a) Wind force, b) Residual van misses stress, c) ETFE cushion force

For the wind load, Eurocode 1991-1-4 was followed to determine the design wind pressure, resulting in -1.39 kPa wind suction and +0.92 kPa wind pressure. The form-finding process of ETFE cushions was carried out using an internal pressure of 0.5 kPa and an initial volume of 0.25 m³ based, resulting in a line load of about 0.8 kN/m on the supporting edge beams (figure 9.c). Figure 9.b demonstrates the v. Mises stress for ULS wind uplift and downforce load cases, which is below 80 MPa.

2.3 Manufacturing process

In the manufacturing process, there are strategies for dealing with components and global assembly. The manufacturing development aim is to maximize the production efficiency and geometric accuracy. The manufacturing process of the realization prototype was conducted at the Hahner Technik steel workshop in accordance with industry standards, with support from Alpaka GmbH.

The selected material for the product was 1.5 mm S235 black steel, and parts were cut using a Sprint Pro laser cutting system with a laser power of 4000 watts, achieving a thermal cutting shrinkage tolerance of ±0.1 mm. After laser cutting, the parts were identified and sorted based on engraved information on the plates, followed by orientation and edge folding (Figure 11. a, b). The preassembly of parts was carried out using bolts and nuts to align geometries, which were then fixed in formwork to provide the working space for subsequent MIG spot welding (Figure 11.c, d). Beam components had higher spring back effect compared to node components, therefore, a solid formwork was designed to precisely adjust the geometric accuracy. The formwork comprises of two vertical plates and a single horizontal timber plate. The cut-out of cross-section geometry in the vertical plates is determined based on the coordinates (x, y) and rotation angle (r°). This can be calculated by aligning the normal vector of the start and end beams with the YZ planes of the vertical plates. The horizontal plate is positioned at a distance between the vertical plates corresponding to the length of the beam.

Figure 10: Assembly form work. a) start vertical plate, b) end vertical plate, c) horizontal plate

Metal inert gas (MIG) welding was performed at the finger joints to securely fix the geometry in its final position. Welding step increases the stiffness of the beam which serves to minimize the spring back effect and plate buckling. Post-weld cleaning was then carried out with grinder to smoothen the weld points (Figure 11.e, f). Despite the environmental impact of hot dip galvanizing was selected for corrosion protection mainly to assess the viability for system application in construction industry.

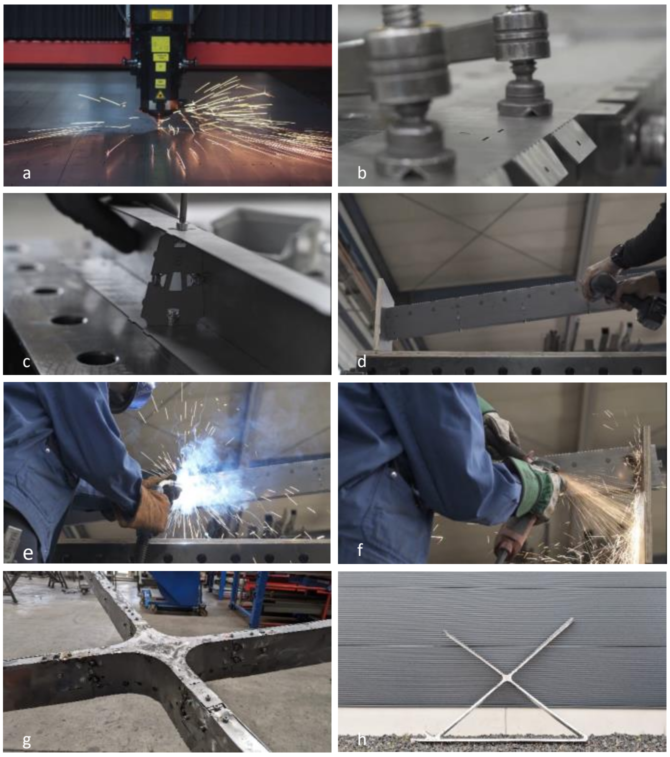

Figure 11 Manufacturing Process. a) Laser cutting, b) Sorting and edge folding for ETFE, c) Preassembly using bolts and nuts, d) Fixation in formwork, e) MIG spot welding, f) Post-weld cleaning, g) Alignment of beams to node element using finger joints, h) Assembled components for zinkbath

Figure 12: a) Hot dip galvanized 4 sets, b) Off-site assembly.

In the global scale, the assembly process involves both off-site and on-site methods. During the off-site assembly, the associated beams are connected to their corresponding node to create larger components due to zinc bath dimension requirements. The four main components underwent a hot-dip galvanizing process to enhance corrosion resistance, followed by thorough examination to ensure assembly accuracy (Figure 12.a). The off-site assembly was carried out by aligning the interlocking connections between the main parts (Figure 12.b), facilitating a robust assembly process.

Discussion and conclusion

The research presented introduces a novel methodology for the design and fabrication of an integrated structural system for roof or façade structures made of laser-cut flat material with interlocking connection. The computational workflow shows the potential for integrating geometric modelling, FEM simulation, optimization and fabrication in a closed loop. The manufacturing development shows that laser cutting of flat material enables a more efficient and precise process. The FEM structural analysis also illustrates that the individual arrangement of the plates has an influence on the primary load-bearing capacity and that the geometric stability is based on in-plane shear forces and the transmission of these together with the interlocked connections at the plate edges. The development of an integrated design system improves both material efficiency and the manufacturing process.

The digital modelling method has demonstrated the flexibility of designing and creating manufacturing files for curved elements within a calculation pipeline. From the design aspect, the beams were designed based on one constant cross-section to reduce manufacturing complexity and focus on exploring the manufacturing and assembly parameters; however, in the future design, more various optimized cross-sections will be explored in the design phase [21]. From the structural analysis aspect, two models were built to deal with the complexity of manufacturing and assembling deformed elements. The global model uses beam analysis to define cross-section and material thickness based on dead-external load. However, in future developments, to understand the structural behavior more precisely, FEM analysis of the entire geometry based on individual plates will be necessary. Future research on structural behavior will focus on developing 3-point bending tests to validate the calculation for buckling of the structure.

In the assembly process, the design of formwork increased the manufacturing efficiency and precision of the beam significantly. On the other hand, although the built geometry of the nodes was precise, the cold forming process of the side plates was time-consuming due to manual work. Another assembly issue was the unpredicted galvanization protection thickness. In the project, the design tolerance for laser cutting and assembly was set to 0.1 mm. However, due to extra layers of the hot dip galvanization, an extra thickness of 0.1-0.15 mm Zink and a weight of 3-5 Kg was added to geometries, which creates a challenge to assemble the 4 main parts together on-site. The canopy was designed to be placed for 4 weeks on the balcony of a building, however, due to the concrete quality of the balcony and difficult working conditions, the final roof form was initially only exhibited as a single component. Therefore, the structure will be assembled in front of the library of the university of Kassel summer of 2023 as a bike station.

In conclusion, the research project promotes the use of laser cutting in the construction industry to create free-form and highly precise curved elements. This design to manufacturing methodology may therefore be recommended as an alternative to the conventional complex fabrication process, which requires less energy consumption and provides higher structural integrity.

5 Acknowledgment

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