Design for Manufacturing of a Digital Hollow Section Beam Using Interlocking Connection

Seyed Mobin Moussavi, Felix Kallwies, Arnold Walz, Philipp Rumpf, Stefan Böhm, Niklas Sommer, Stephan Völkers and Julian Lienhard

September 4, 2021

Proceedings of the IASS Annual Symposium 2020/21 and the 7th International Conference on Spatial Structures
Inspiring the Next Generation
23 – 27 August 2021, Guilford, UK
S.A. Behnejad, G.A.R. Parke and O.A. Samavati (eds.)

Design for Manufacturing of a Digital Hollow Section Beam using Interlocking Connection

Seyed Mobin MOUSSAVI [a,*], Felix KALLWIES [a], Arnold WALZ [b], Philipp RUMPF [b], Stefan BÖHM [c], Niklas SOMMER [c], Stephan VÖLKERS [c], Julian LIENHARD [a]

*Tragwerksentwurf (TWE), Universität Kassel
Universitätsplatz 9, 34127 Kassel (Germany)
Moussavi@uni-kassel.de

[a] Tragwerksentwurf (TWE), Universität Kassel
[b] Design-to-Production GmbH, Stuttgart
[c] Trennende und Fügende Fertigungsverfahren (TFF), Universität Kassel

Abstract

This paper presents a computational design strategy and manufacturing technique for a curved steel beam using interlocking connections. 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. A shift from bending a whole section to 2D steel laser cutting and bending during assembly simplifies the fabrication processes, as well as reduces the weight of the structure.

This work presents a novel methodology to create a three-dimensionally curved beam that is elastically pulled into position from discrete laser-cut sheets. The surfaces of the double curved beam are generated by defining the stiffener's geometry and an axial curve through geometric modeling. The interlocking connection details are then applied to the edges of unrolled plates based on graph connectivity. Finite Element Method (FEM) form-finding simulates the deformation process of plates using contracting cable elements. Structural analysis and optimization are also performed to evaluate the residual stress under external loads to reduce the thickness of individual plates. The physical prototyping demonstrates geometric accuracy and laser-cut tolerance. The uniaxial tensile tests highlight the impact of welding on structural performance at the interlocking connection.

Keywords: steel construction; active-bending; elastic deformation; FEM form-finding; structural analysis; optimization; manufacturing tolerances; welding; interlocking connections; steel laser cutting

1.Introduction

This research presents the development of a computational design and manufacturing methodology that explores the capacity of digital modeling and fabrication technologies for designing a three-dimensional curved steel beam.

In today's steel construction industry, the construction and production of a single or double curved beam is a challenge for manufacturers. Although there have been developments in industrial robotic setup to automate this process, these processes still rely on an iterative approach and are time-consuming and costly when there is a need for high accuracy. One of the fabrication techniques for manufacturing spatially bent parts is three-roll-push bending, which is a kinematic forming process. However, producing parts out of cut standardized profiles without shape deviations to the target geometry is a nontrivial task as the bending contour is mainly influenced by geometry-, process- and tool-related parameters (Growth *et al.* [1]). Due to this inaccuracy, in order to create fabrication data, it is necessary to calculate the amount of the spring back and consider the corresponding correction values for each point of the bending geometry. Another significant challenge is cutting and drilling mounting positions for connecting elements on the beam after the forming process, which requires scanning tools that make the process inconsistent and imprecise (Industrie Anzeiger [2]).

1.1 Laser Cutting Technology

Modern laser cutting technology (LCT) is typically used for industrial manufacturing applications and it dominates other metal-cutting processes due to the significant benefits in both cost and accuracy (BLM Group [3]) which improves the manufacturing productivity by 70% to 80% [4]. This technology leverages the potential of full automation through CAD programming and eliminating the intervention of operators, which leads to important financial savings and a great increase in quality. The traditional fixed costs determined by punches, clamps, tools, templates, and dies are eliminated by CAD programming, and the laser beam can be used as a universal tool (Kanyilmaz [4]).

The following projects employed LCT to create a structural system by interlocking connections. 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 (Al-Sabah et al [5]). The geometrical arrangement of interlocking pieces involves simultaneous, bi-directional meshing and load transfer within the system. The *Point. One Solarladestation* in BMW Welt Munich, LAVA Architects and Design to Production (dtp) designed and manufactured a shell structure using thin metal sheets as the substructure for solar panels. The free form surface was achieved through elastic deformation of CNC milled aluminum parts (Walz [6]). A Similar project at Innovations Festival in Bozen 2013 uses the same principle to create a shingle shell, in which the panels are mounted on predefined slots on the main structures (Walz [7]). Projects such as *Mitoseum* steel grid-shell and the membrane facade of Adidas Herzogenaurach showcase the combination of the digital detailing concept and laser cutting technology in designing complex three-dimensional joints for grid-shell structures. The joints are assembled from 2D laser cut parts and fixed together through interlocking connections. This geometric information, saved within the cutting pattern of a detail's parts, enables the manufacturing, joining, and erection of complex freeform geometries without the need for costly and time-consuming templates (Lienhard *et al* [8]). The *Asymptotic Gridshell (Inside out)* built at the central campus of the TUM is a single-layer grid shell constructed from flat straight lamellas. The strips are elastically bent and twisted into the asymptotic networks on the target minimal surface and fixed by a universal identical and orthogonal joint system (Schling [9]).

1.2 Design and Manufacturing of Computationally Controlled Beams using Interlocking Connections

The state-of-the-art projects have shown that methods to rationalize the design of structural elements using bending-active properties of thin sheet metal reduce the fabrication and assembly time while increasing the structural performance. The LCT manufacturing method enables the possibilities to integrate the interlocking connections and defines the mounting positions to other structural elements as well as engraving manufacturing data which eliminates the need for costly and time-consuming templates as well as shop and assembly drawings.

The current project investigates computational strategies to design and manufacture a curved steel beam using interlocking connections. The three-dimensionally curved beam is assembled from flat laser cut parts. The final geometry is achieved by elastically deforming the plates and locking them into their positions using inner stiffener plates. This research follows an integrated computational methodology in which an integral form-finding approach integrates the geometric and material characteristics in the deformation process, to inform the design of connection details as well as structural performance (Lienhard *et al* [10]). The project scope covers the development of a digital modeling strategy and some physical prototypes to validate the developments. It also calls into question the conventional industrial fabrication methods for bending the standardized cross-sections.

2 Methodology

The research follows a two-fold methodology of design to fabrication development and physical prototyping. Digital development consists of strategies for geometric modeling, FEM form-finding, analysis, and manufacturing (Figure 1). Within the digital development, geometric modeling consists of strategies to extract principles from physical tectonic studies to approximate digital surfaces. FEM simulation validates the geometry through form-finding and determines the residual stresses and structural performance as well as load-bearing capacity of the beam. Digital manufacturing deals with the development of assembly information and plate joining methods. The physical prototyping evaluates both the geometric accuracy of the form-finding and the structural load-bearing performance of interlocking connections. The following chapters will describe the method development for a three-dimensional curved beam.

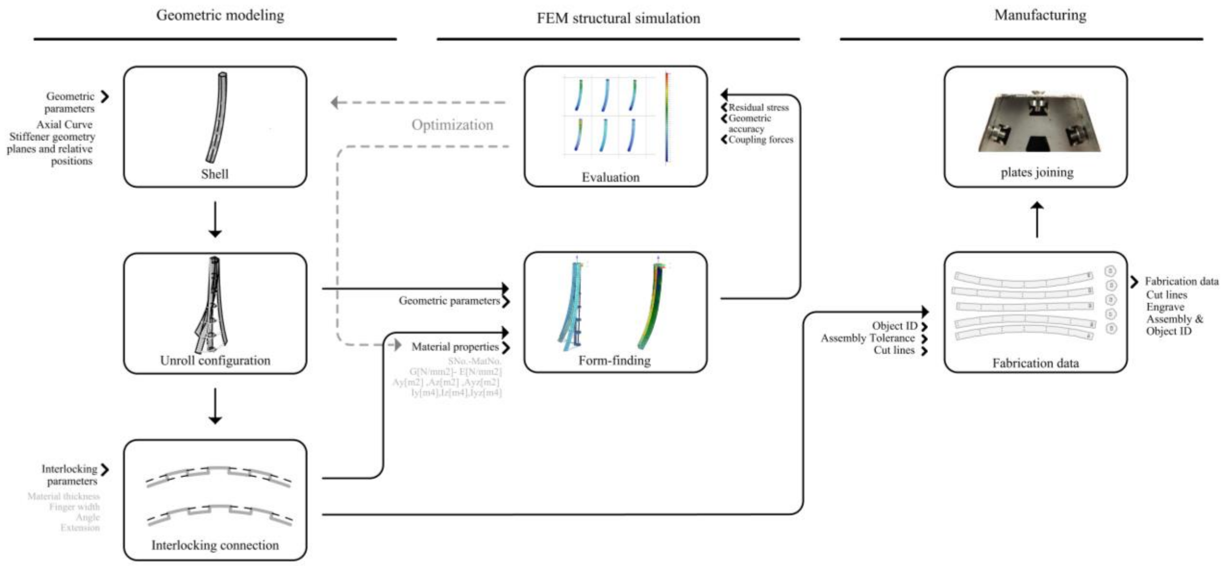

Figure 1: Digital workflow

2.1. Geometric modeling

The geometric studies and computational modeling developments for designing a double-curved beam follow several consecutive steps. As a first step, a series of physical tectonic studies was carried out to determine geometric parameters and relationships between parts. Next, the abstracted construction principles translate into the digital environment (Figure 2). The system is comprised of bent slender plates pulled into their target position. The final geometry is defined by inner stiffener plates and interlocking connections at the plate edges. The interlocking connection system includes finger joint connections between the bent plates, which carry the shear forces, and the cog connection between the stiffeners and plates. A computational workflow mainly deals with creating developable surfaces from an axial curve and inner stiffeners geometries, to unroll them for applying the interlocking connection details, as well as providing data for the manufacturing process. The workflow has been developed within Rhino® and Grasshopper visual scripting environment and custom scripts using Kangaroo solver (Piker [11]).

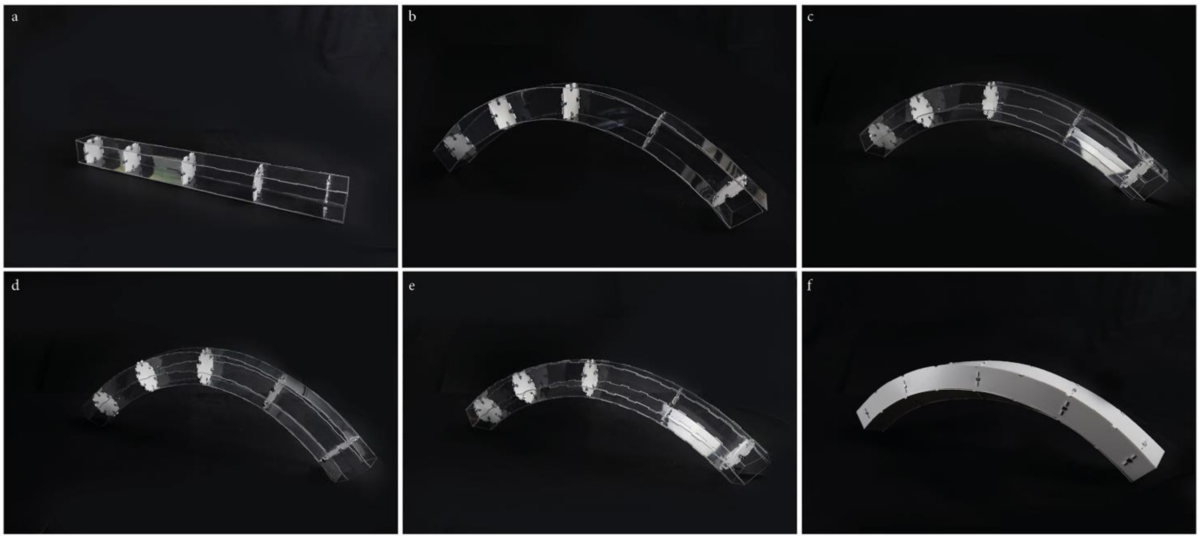

Figure 2: Tectonic study

The inputs for geometric modeling are a primary axial NURBS curve and the stiffeners geometries (Figure 3.a). The plane associated with each stiffener defines the local curvature of the beam by its orientation around the axial curve and relative position on the curve. The ruled surfaces are generated by sweeping the edge of the stiffener plate along the axial curve as a directrix (Anastas *et al* [10]). To ensure that the surfaces are developable and have a constant of nearly zero (< 0.01 mm) Gaussian curvature, a spring-based relaxation script was used to approximate the surfaces (Piker [11]). The script adjusts the local curvature based on the *discrete orthogonal geodesic nets* model with angle constraints (Figure 3.b) (Rabinovich [12]).

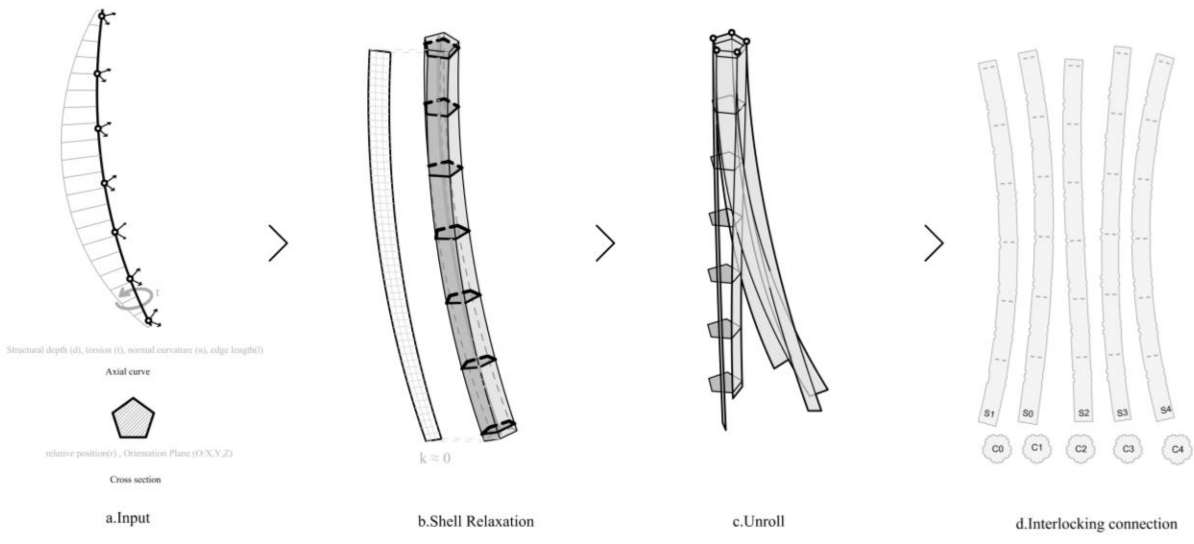

Figure 3. Geometric modeling process

A connectivity graph (Schwartzburg and Pauly [13]) is generated based on the surface intersections, which determines the number and type of connectivity between the individual parts in the system. This allows to apply the interlocking connection details in the 2D unroll configuration without any further 3D information (Figure 3.c). The final geometry of each plate provides fabrication data for the assembly process (Figure 3.d).

A special focus in the development of the two-dimensional finger joints lies in the construction, structural performance, and assembly details; Therefore, several factors were considered in designing the interlocking connections (Figure 04.a). The connections of stiffeners adjust the curvature of the bent plates by clamping them to their final positions. The edge connections of the bent plate align the plates together and carry shear forces. Other parameters such as number and width and depth of the finger joints are determined based on edge length and material thickness respectively. A similar method was suggested by Schwinn *et al* [14] and Schwartzburg and Pauly [13].

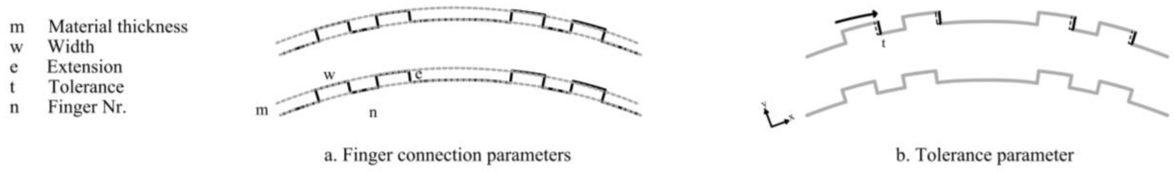

Figure 4: Interlocking connection parameters

A crucial parameter of designing the interlocking connection is the correct definition of tolerances. Besides different aspects of production and corrosion protection, which need to be considered in calculating the tolerances, the geometric modeling determines the tolerance which impacts the assembly process. Due to the curvature in the beam, the gap parameter along the local -x direction of each connection is crucial for the assembly process (Figure 04.b). The finger joint can only generate resistances after the contact takes place. This gap allows for larger adjustability without significantly impacting the structural performance during the assembly process. This method was adopted from Knippers *et al* [15]. To fill the gaps and increase the stiffness of the plate, torsioning the stiffeners along the axial curve of the beam locks the plates in the opposite direction of the tolerance.

2.2 FEM Simulation

The necessity of using the Finite Element Method (FEM) for generating the final position, based on the geometric modeling parameters, lies in integrating the complete mechanical description of the material system including its deformation process. The obtained information on residual stress and tension forces necessary for assembly allows evaluation of the feasibility and gives crucial information for further optimization of the system. The FEM numeric results are used to determine the structural performance for additional stress as well as assembly forces required to pull the plates to their final positions. The optimization process closes the loop between the design and analysis by sorting numeric values based on the evaluation criteria to trigger a new set of design parameters. The digital workflow was carried out using the commercial FEM software Sofistik®, which offers custom programming in the parametric interface Teddy. A custom script within Teddy uses adaptive incremental load steps (Lienhard *et al* [16]) which contract cable elements between the matching edges of the beam from its 2D flat to the 3D bent configuration.

2.2.1 Form finding and Analysis

The contracting elastic cable approach has proven to be a reliable technique for the form-finding of bending active structures (Lienhard [17]). The contracting cable elements are defined as one single element which does not contain further internal nodes to avoid sagging and other collateral phenomena associated with the simulation of cable elements.

In the preprocessing step, the unrolled geometries and their corresponding mechanical properties are the inputs for generating a FE model in Sofistik (Figure 5.a). The cables connect the stiffener nodes to predefined positions on the' plates' edges. The simulation process starts by assigning a pre-stress value to the cables, which is later translated into a connection force acting on coupling elements between the plates. The cable elements work with a temporary reduction of elastic stiffness which enables large deformations under increasing pre-stress (Figure 5.b). The pre-stress that is independent of the change in element length also allows the simultaneous use of several cable elements in the different positions of the system.

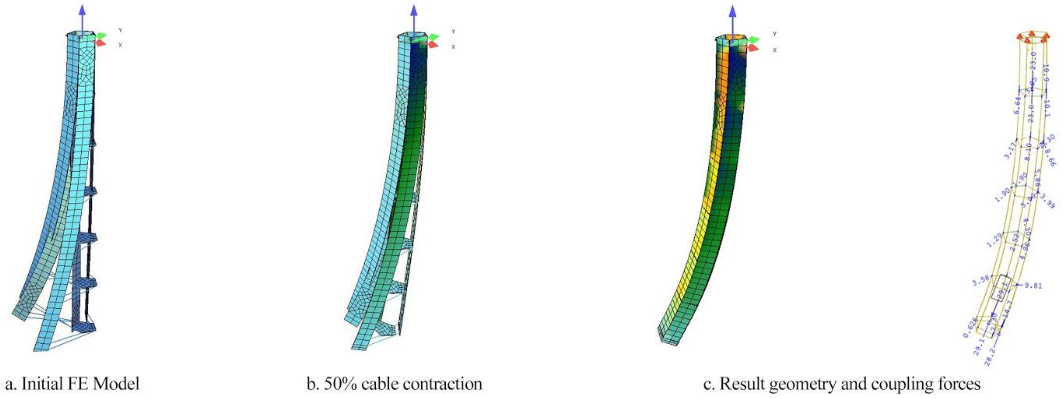

Figure 5: form-finding process

The results of the from-finding process are the final position and corresponding residual stress of each plate. As the post-process step to determine the structural behavior of the beam, the contracted cables with zero-length are replaced by coupling elements. Residual van misses stress is analyzed to determine the load-bearing capacity of the beam under the external loads. The coupling forces in the joints indicate the assembly forces of the beam (Figure 5.c).

2.2.2 Optimization

To reduce the self-weight and residual stress in the beam, an optimization loop was initiated to assess the impact of geometric parameters on the FEM analysis. This integration allows to set up a generative model, in which each set of numeric values gets rated and triggers the next generation.

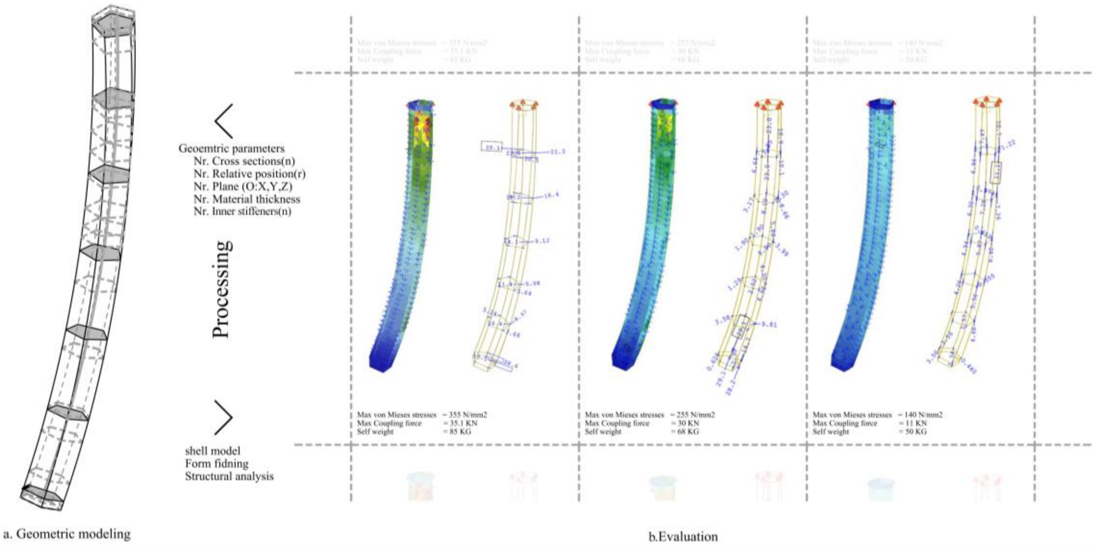

Figure 6: Optimization of the geometric parameters based on the FEM numeric values

Optimization of the multiple evaluation criteria is performed by looping the relative positions of the inner stiffeners and material thickness of the individual plates. Due to residual stress, the utilization is initially limited to 60 %.

The higher-rated solutions indicate that the higher material thickness is only needed near the supports where double curvature may be reduced to zero. Some maximum van Mieses stresses are singularities near the clamping point which can be reduced by positioning the stiffeners in the high curvature area of the axial curve. It was observed that assembly forces increase drastically with the plate thickness and curvature. Figure 6.b demonstrates the drop of residual stress from the initial model from 355 N/mm2 to 164 N/mm2.

2.3 Manufacturing

Manufacturing development consists of strategies to deal with the fabrication, assembly processes, and plate joining. The manufacturing process is as follows: first, the parts are cut from a flat plate using a corresponding power QCW laser based on manufacturing data. The plates are then pulled together for assembly, followed by a welding step to permanently fix the parts in the final position. The fabrication model includes the cutting data of geometry and interlocking connection details as well as the element ID to define the orientation of plates. This coding organizes the on-site assembly process without the need for templates, shop drawings, or auxiliary constructions as seen in Lienhard *et al* [8].

Two strategies have been explored for plate joining: the bolting method allows for an orthogonal reversible joint between the stiffener and bent plates, which leads to the implementation of assembly-related functionalities such as screw and nut pockets. To generate the cutting geometry data, the standard dimension of the screws and nuts are extracted from the manufacturer (Figure 6.a), and by determining the relative position of the nut on the screw (Figure 6.b), the outline geometry can be output (Figure 6.c). The geometry can be integrated within the stiffeners cutting pattern, the circular hole is based on the dimension of the screw and is positioned in the bent plates (Figure 06.a). Laser fusion welding can increase the structural strength and reliability of the edge joint by creating a strong and durable bond through a localized fusion of the two materials. The welding parameters depend on the fusion welding process used and are adjusted according to the material properties and sheet thickness (Figure 06.b) [16].

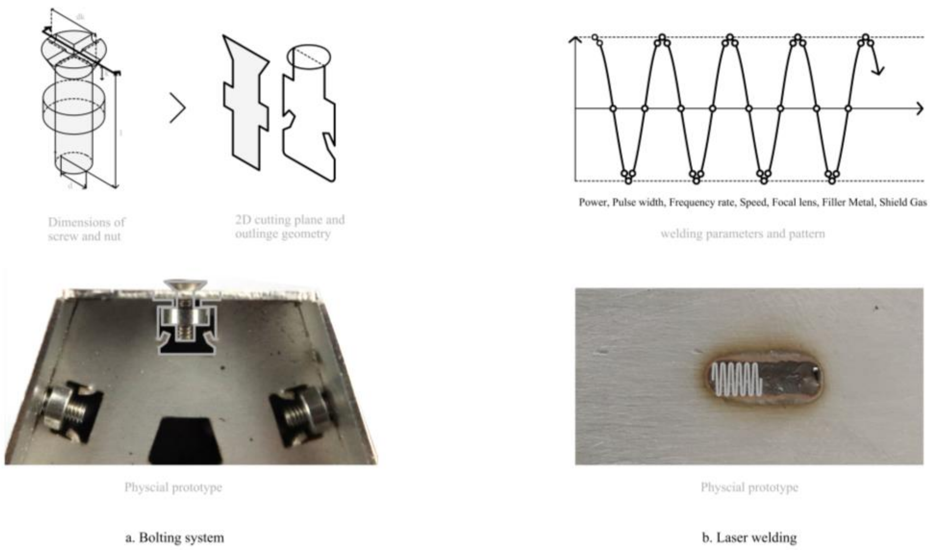

Figure 7: Joining methods (a. Bolting system; b. Laser welding)

3 Physical Prototypes

In the presented research the developed computational methodology was tested on a double curved beam with a pentagon stiffener. The physical prototypes aim to evaluate the accuracy of the resulting geometry and the structural performance of the interlocking connection. The material used for this experiment is 1 mm stainless steel 1.4305. The manufacturing process was carried out at the TFF laboratory. An *Lmts IR* from *Dr.Kieburg GmbH* laser cut machine was used to cut parts with 600 watts and ±0.013 mm thermal cutting shrinkage tolerance.

3.1 Geometric Accuracy

The aim of the first steel physical prototyping is to compare the geometric accuracy between the steel manufactured model and the computational model. The laser-cut parts assembled using a bolting system. The comparison shows a strong correlation which indicates the simulation model has a predictive capacity (figure 07). However, there were some small deviations observed in the free end of the beam. This deviation results from the rest length of the contracting cables in the form-finding where the plates are not 100% pulled together.

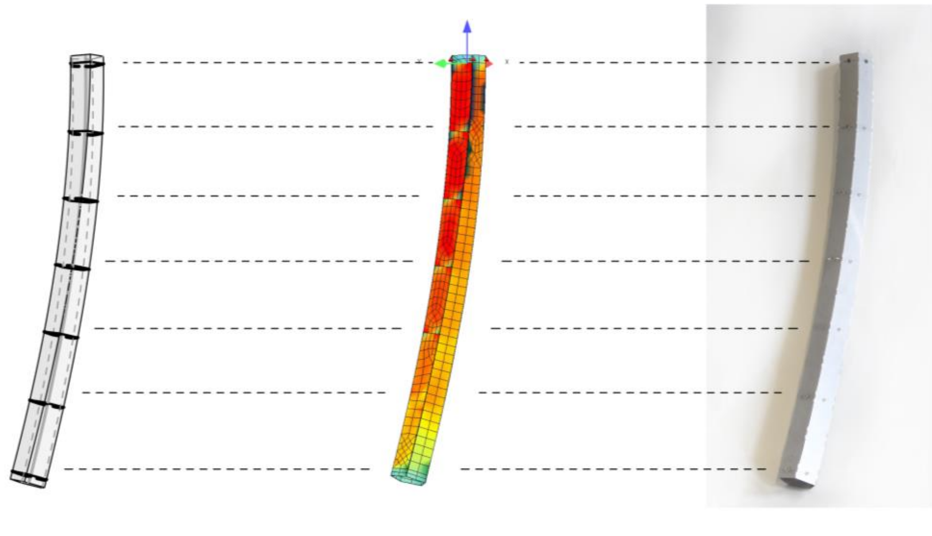

Figure 8. Overlay of FEM form-finding result and built beam

3.2 Structural Performance of the Interlocking Connection

The objective of the structural test is to determine the load-bearing capacity of the interlocking connections and analyze the shear force behavior in the edge connection. A simple model was abstracted for the uniaxial test, in which the maximum mechanical tensile force and elongation for each specimen measured. Different specimens with different placement and amounts of weld were fabricated to measure the impact of welding on structural performance (Figure 09). A laser fusion welding processes TIG and a laser beam (fiber laser) were used for welding, whereby the TIG process was also used for tacking the laser beam welds. The welds were made in three different ways. One-sided welding, i.e. only one side of the gap was welded, two-sided welding, i.e. both sides of the gap were welded, and complete welding, i.e. the laser beam has oscillated sinusoidally over the entire gap and the finger. Sinusoidal welding was used only for laser beam welding and not for TIG welding. A *zwickroell* structural testing machine at the TWE laboratory was used to perform the tests.

Figure 9: Structural specimen

Figure 10.a shows how welding can improve structural performance drastically. Focusing on the linear elongation of the steel material in the force range of 100-1400N demonstrates the impact (Figure 10.b). Although the full edge welding has the highest impact, single point welding series already provides double the stiffness compared to no weld connection and at the same time has the advantage of less heat input to the beam, which is a key factor to maintain accuracy within the complexly curved geometry.

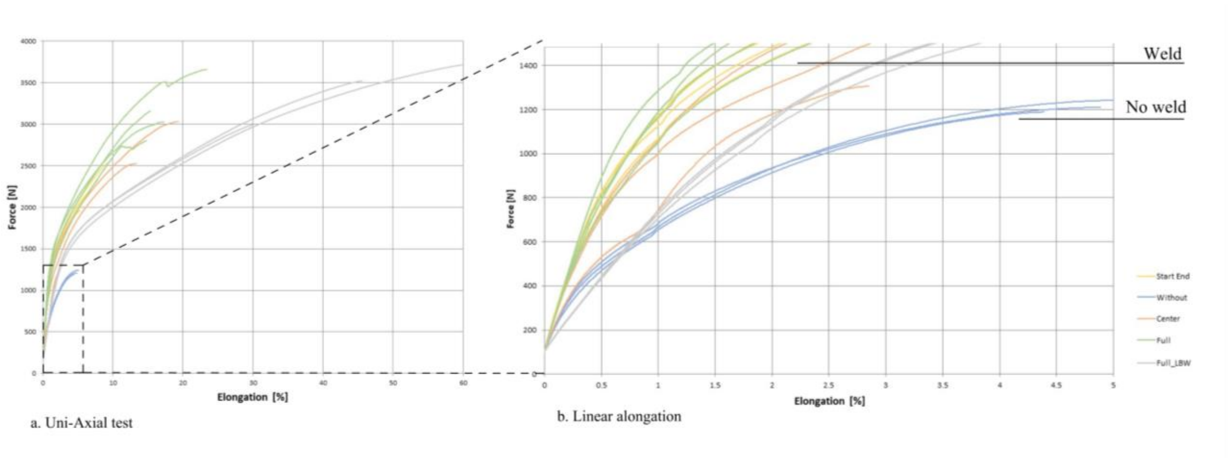

Figure 10: Structural test results

4 Conclusion

The presented research introduces a novel methodology to design and manufacture a digitally controlled beam from flat laser-cut material using interlocking connections. The computational workflow shows the potential to integrate geometric modeling, FEM simulation, optimization, and manufacturing within one closed loop. Although the digital modeling method has demonstrated the possibility of creating double-curved beams with one single inner stiffener, future development will expand the parametric framework to provide the opportunity of designing a beam with various stiffener geometries. The FEM structural analysis indicates not only that the individual arrangement of plates has an impact on the primary load-bearing capacity, but also that the structural stability is based on in-plane shear forces and the transfer of shear along with the interlocking connections at the plate edges. Nonetheless, due to the deformed and pre-stressed geometry, analyzing the dead load and external load is necessary to understand the structural reliability of the beam, which can be further implemented and physically tested. In the optimization loop, the alternatives were generated manually to test the methodology. As further development, a generative algorithm development will enable the inclusion of larger parameters and objective spaces such as manufacturing details.

The physical prototyping results demonstrate that the digital beam performs well in both structural capacity and geometrical accuracy. The physical models were jointed using bolting systems. However, this joinery technique can be replaced with welding, which requires a temporary clamping system. The laser welding method shows potential for providing ultimately more precision and less heat input to the desired area with narrow full penetration weld which makes an aesthetic final result with close to zero welding oxidation. Another advantage of laser cutting individual plates is integrating the attachments to join different types of structural elements, which impact the aesthetic and improve global structural integrity. Therefore, future works will extend the design methodology to create a building system for double curved facades and shell structures.

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

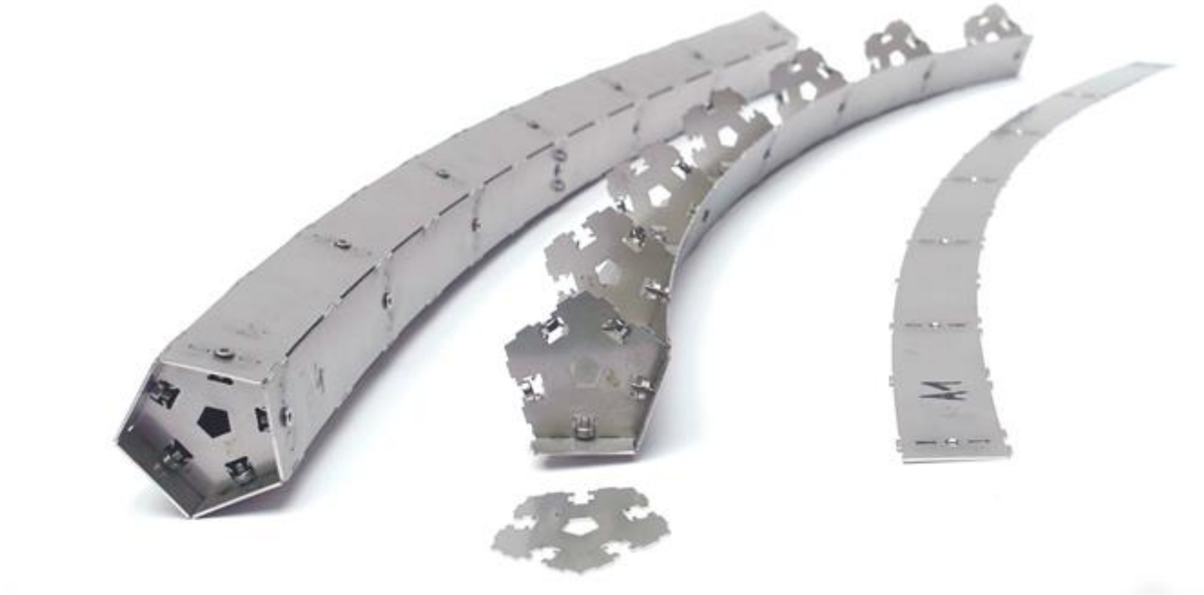

Figure 11: fabricated physical model

References

[1] S. Groth, P. Frohn, and B. Engel, "Product planning system for manufacture-oriented modeling of freeform bend tubes produced by three-roll-push-bending," *Procedia Manufacturing*, vol. 34, pp. 10–18, 2019.

[2] Volker Albrecht Fachjournalist in Bamberg, *Biegen ohne Grenzen: Rohrbearbeitung: Freiformbiegen ermöglicht individuelle Geometrien.* [Online]. Available: https://industrieanzeiger.industrie.de/technik/fertigung/biegen-ohne-grenzen/#slider-intro-3 (accessed: 2020).

[3] *Inspired for tube*, BLM group, London, 2015. [Online]. Available: https://www.blmgroup.com/inspired-for-tube-magazine

[4] A. Kanyilmaz, "The problematic nature of steel hollow section joint fabrication, and a remedy using laser cutting technology: A review of research, applications, opportunities," *Engineering Structures*, vol. 183, pp. 1027–1048, 2019, doi: 10.1016/j.engstruct.2018.12.080.

[5] S. Al-Sabah *et al.*, "Introduction of the Intermeshed Steel Connection—A New Universal Steel Connection," *Buildings*, vol. 10, no. 3, p. 37, 2020, doi: 10.3390/buildings10030037.

[6] A. Walz, *Koeln Digitale Details Digitalisierung im Bauwesen.* [Online]. Available: https://www.detail.de/fileadmin/uploads/10-PDFs/ZdB-2019-Koeln-Digitale-Details-Digitalisierung-im_Bauwesen-Arnold-Walz-Design-To-Production.pdf

[7] A. Walz, *Analogue and Digital: New Processes in the Planning and Execution of Buildings*, 2015th ed.: Detail Magazine, 2015. Accessed: 2020.

[8] J. Lienhard, O. Kaertkemeyer, P. Rumpf, S. Schoene, and A. Walz, "Design and Engineering of form-fit steel connections for complex grid-shell structures," IASS Annual Symposium, 2017.

[9] E. Schling, "Repetitive Structures," Technical University of Munich, PhD Dissertation, Technical University of Munich, 2018.

[10] Y. Anastas, M. Gillet, L. Rowenczyn, and O. Baverel, "Complex Surface Approximation with Developable Strips," *Journal IASS*, vol. 57, no. 2, pp. 133–143, 2016, doi: 10.20898/j.iass.2016.188.732.

[11] D. Piker, "Kangaroo: Form Finding with Computational Physics," *Archit Design*, vol. 83, no. 2, pp. 136–137, 2013, doi: 10.1002/ad.1569.

[12] M. Rabinovich, T. Hoffmann, and O. Sorkine-Hornung, "Discrete Geodesic Nets for Modeling Developable Surfaces," *ACM Trans. Graph.*, vol. 37, no. 2, pp. 1–17, 2018.

[13] Y. Schwartzburg and M. Pauly, "Fabrication-aware Design with Intersecting Planar Pieces," *Computer Graphics Forum*, vol. 32, 2pt3, pp. 317–326, 2013, doi: 10.1111/cgf.12051.

[14] T. Schwinn, O. D. Krieg, and A. Menges, "Synthesizing design computation and robotic fabrication of lightweight timber plate structures: Design agency : proceedings of the 34th Annual Conference of the Association for Computer Aided Design in Architecture, October 23-25, 2014, Los Angeles, California," 177-188, 2014.

[15] J.-M. Li and J. Knippers, "Segmental Timber Plate Shell for the Landesgartenschau Exhibition Hall in Schwäbisch Gmünd—the Application of Finger Joints in Plate Structures," *International Journal of Space Structures*, vol. 30, no. 2, pp. 123–139, 2015, doi: 10.1260/0266-3511.30.2.123.

[16] J. Lienhard and J. Knippers, "Journal of the international association for shell and spatial structure,"

[17] J. Lienhard, R. La Magna, and J. Knippers, "Form-finding bending-active structures with temporary ultra-elastic contraction elements," in *Mobile and Rapidly Assembled Structures IV*, Ostend, Belgium, 2014, pp. 107–115.