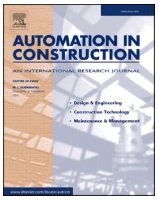
Automation in Construction 127 (2021) 103710

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon



Developing a mold-free approach for complex glulam production with the assist of computer vision technologies

Hua Chai [a], Zhixian Guo [b], Philip F. Yuan [a,*]

[a] College of Architecture and Urban Planning, Tongji University, Shanghai, China
[b] Shanghai Fab-Union Technology Co., Ltd, China

ARTICLE INFO

Keywords:
Glulam
Curvature
Computer vision
Digital simulation
Fabrication

ABSTRACT

With the increasing use of glulam in construction industry, low efficiency of material and time in complex glulam production process has been widely recognized. While single curved glulam components are normally achieved with the aid of heavy molds, double curved ones are difficult to be produced directly without massive subtractive fabrication. In this context, a mold-free approach for complex glulam production is proposed, which consists of a mechanical system that spatially shapes the curved beam, and a vision system to inform the fabrication directly with design model. Through the integration of digital design, simulation and physical process, different types of curved glulam could be produced following the same workflow. This approach could eliminate the use of complex molds in curved glulam production, greatly reduce wastes in post-processing process. With the feasibility initially verified through fabrication experiments, the system will be further developed so as to be transferred to industrial practice.

1. Introduction

Wood has been regarded as one of the most promising building materials for the future due to its many excellent features such as sustainability, lightweight and high strength [1]. Recent years has witnessed the increasing use of wood in a variety of building types, especially large-span and multi-tall buildings. One of the most important wood products in construction industry is Glue-Laminated Timber, or glulam, which is made from layers of dimension lumbers bonded together with durable structural adhesives. With timber grain running parallel to the length direction, glulam is allowed to be produced as large scale components with almost no limit in length, depth and width. Glulam has been widely used in a variety of structural applications due to its high strength-to-weight ratio and large dimensions [2]. However, along with the expansion of the application scope, complexity in timber structures are gradually becoming more prominent, posing great challenges for production and processing of complex glulam with high accuracy and efficiency.

Complex glulam structures such as Centre-Pompidou Metz [3], French Expo-Pavilion Milan [4] and La Seine Musicale [5] could only be realized with the technical support of advancing consulting firms and contractors, not only in the design and optimization process, but also in the fabrication process of complex structures, components and connectors. In such buildings, single curved glulam components are normally achieved with the aid of heavy molds, while double curved ones are mostly milled with Computer-Aided Manufacturing (CAM) machines like wood machining centers. However, great cost of time, materials and money in both mold making and glulam milling process is hard to ignore, since double curved components need to be milled from linear or single curve components. At the same time, the damage of the wood grain during the milling process also severely reduces the load-bearing performance of the wood. The necessity has been widely recognized to explore new approaches for producing complex glulam [6].

The main challenge here is how to produce complex glulam directly so as to reduce the immense material waste and time consumption in mold making and subsequent subtraction process. A straightforward mode of glulam production could not only conducive to simplifying the production process, but also significantly improve the material efficiency in glulam construction. Response to this challenge is of particular importance for sustainable use of wood resources in such environmental challenges that construction industry is facing.

Rapidly developing digital technologies are constantly re-shaping the way that buildings are conceived and produced. In this research, a mold-free approach for complex glulam production is developed with

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* Corresponding author.
E-mail addresses: chaihua@tongji.edu.cn (H. Chai), guozhixian@fab-union.com (Z. Guo), philipyuan007@tongji.edu.cn (P.F. Yuan).

https://doi.org/10.1016/j.autcon.2021.103710
Received 10 April 2020; Received in revised form 9 April 2021; Accepted 11 April 2021

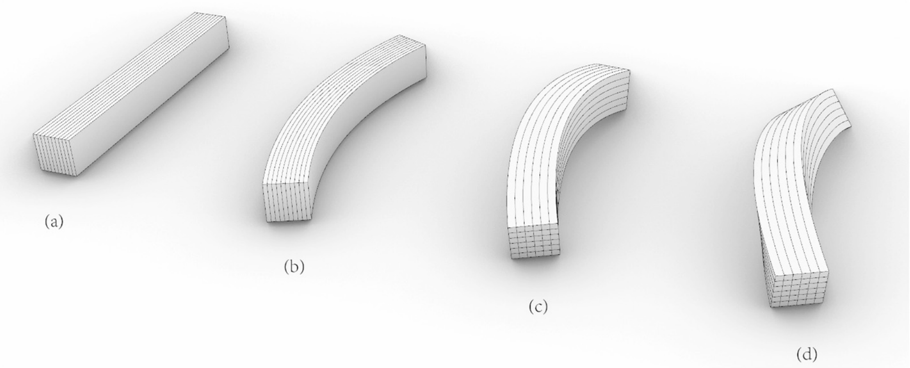

Fig. 1. Four glulam categories according to curvature: (a) Straight; (b) Single curved, (c) Double curved with no torsion; (d) Double curved with torsion.

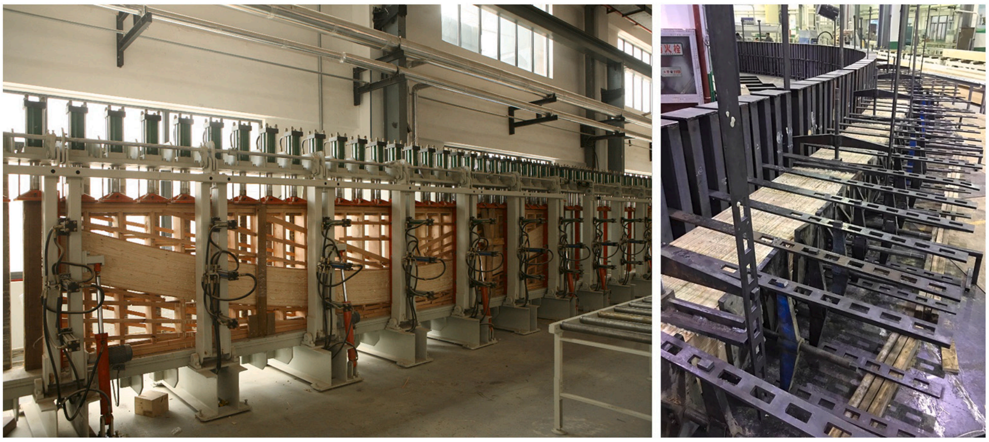

Fig. 2. Two approaches to produce single curved glulam, the left uses press bed for straight components and complex mold, and the right makes a mold with steel posts.

the aid of computer vision technologies. In order to avoid the use of molds, a mechanical equipment is designed to spatially shape the double curved glulam, with computer vision system employed to inform the fabrication process with digital design directly.

This paper is structured as follow: The second section summarizes the current research status of complex glulam production technologies and digital fabrication related computer vision technologies; The third section describes the aim and methods of this research; The fourth section introduces the proposed mold-free production technology from three aspects: equipment, vision system and digital integrated system; The fifth section presents the production process and experiments conducted with different vision systems; The meaning and importance of this approach are analyzed, and future steps are proposed in conclusion.

2. Background

The curvature of Glulam components could be divided into four categories, say Straight, Single curved, Double curved with no torsion and Double curved with torsion, with increasing degree of complexity [7](Fig. 1). For the production of ordinary straight glulam components, a mature production process in factory has long been formed from strength grading, finger jointing, gluing, laminating to finishing [8]. There are already specialized equipment for each process, forming an efficient production line through rational planning and logistics [9,10]. However, when it comes to curved beams, part of the production line would be no longer applicable, as curved components cannot be produced on ordinary presses for straight glulam without the help of customized molds, as in the very first curved glulam prototypes in Otto Hetzer's patent in 1905 [11]. Although there has already been equipment on the market for automatic laminating of single curved components [12], which allows for high efficiency and accuracy, the production process remains manual in most parts of the world. During the manual laminating process, a customized mold is necessary in most cases to determine the shape of curved members (Fig. 2). For example, a series of steel posts often act as molds during the laminating process through temporarily welded to a base plate along the beam curve with a certain distance in between. With the steel posts as template, thin lumbers with glue applied will be attached to the steel posts in sequence, and then bonded by a series of steel jigs with air impact wrench manually. The whole process is significantly labor-intensive, which constitutes an important reason for the basic fact that curved glulam is normally more expensive than straight ones [7].

2.1. Complex glulam production through digital fabrication

While the shape control of single curved components can still be achieved with molds, double curved components, with or without torsion, are difficult to be accurately produced with the same technology, whether manually or mechanically, due to the difficulty in positioning the double curved beams in place. Remains of traditional craftsmanship in double curved timber making can still be found in the field of furniture and installation art, such as the works of Richard deacon [13] and Joseph Walsh [14]. The production process often employs techniques like steam bending which is labor-intense and time-consuming, making it difficult to be applied in large scale structures in the construction industry.

Today, as in most cases, double curved glulam can be cut from straight or single curved components through CAM technology, mainly referring to milling with 3-axis or 5-axis Computer Numeric Control (CNC) machines. In recent years, there have also been researches on robotic band saw, which combines industrial robot with woodworking band saw to cut ruled surfaces in timber blanks, as an alternative to CNC in producing double curved glulam [15]. Although CAM machines could efficiently produce curved glulam with any curvature, as well as ones with torsion, both material waste and strength loss in the subtractive manufacturing make it a material-inefficient process. The material waste could be several times the required volume in the manufacturing of complexity components, resulting in sharp cost increase.

Recently, the needs and challenges in double curved glulam production have promoted researches that try to explore new solutions through the employment of advanced digital technology. Svilans et al. [6] propose four free-form glue-laminated prototypes. While two of the prototypes address the possibilities to laminate double curved blanks directly through subdivision at the cost of a certain amount of loss in strength, the other two explore more complex forms of glulam, however, without shaking off the need for complex molds. Robotic fabrication also opens up new approaches for double curved glulam through bending and twisting the laminas in three dimensional space [16]. But robot fails to provide sufficient anchor points to stabilize the laminas in place. Also limited by the reach and payload of industrial robots, it is more of a concept for small elements than a solution that can be used in construction industry.

2.2. *Computer vision aided fabrication*

It has been widely researched that computer vision technology could be used to inform the construction process in a variety of construction fields. Computer vision such as RGBD camera can assist humans or machines to accurately “see”, acquire and react to spatial information in real time, which could well meet the requirements for precise localization in complex construction tasks. Computer vision has been widely used in robotic construction to localizing the robot at the construction site [17] and monitoring materials during the fabrication process [18]. One of the most widely explored technologies in the field of digital fabrication is Augmented Reality (AR), which shows great potentials in assisting workers in building complex structures like brick wall by overlapping the virtual bricks layout with the construction site [19]. With the advent of software specialized in connecting computational design software with augmented reality devices, AR has been tested later on various construction tasks like steel rod bending [20]. The combination of AR with robotic fabrication also suggests Human Robot Collaboration through superimposing digital information in real time to on-site robot through an augmented reality interface [21]. Computer vision’s capabilities in fusing the virtual and physical could also been used to inform the making and constructing of complex timber structures [22]. In this research, computer vision provides a new perspective for the production of complex glulam by offering a feasible solution for component positioning.

3. Methods

The technical challenges faced by the current double curved glulam production technology are mainly two aspects: how to accurately locate the virtual design in physical space, how to spatially bend, twist, and finally stabilize the laminas in place during the fabrication process. In response to the current challenges, this research is dedicated to developing a mold-free approach for double curved glulam production, addressing existing issues from three aspects:

- a mechanical system is designed as form controller and material stabilizer to control the position and twist angle of the laminas in space through a series of specially designed fixtures;
- corresponding to the requirements in spatial localization, different computer vision technologies are introduced to establish a direct connection between virtual model and physical process, so as to inform the operation with digital information;
- furthermore, a digital integration system is to synthesize the former parts as an integrate workflow by simulating the equipment and material performance during the fabrication process. The integration process happens solely inside Rhinoceros 5.0 and Grasshopper.

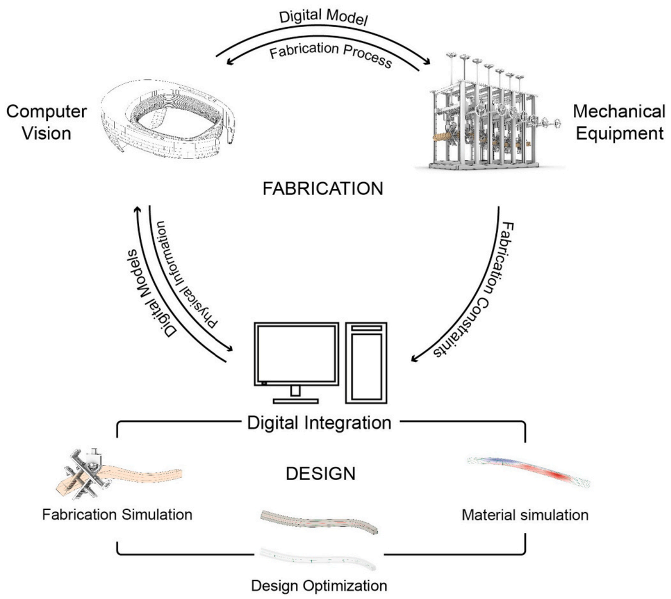

Fig. 3. Diagram of the manufacturing system.

The relationship of these three aspects is illustrated in Fig. 3. Computer vision is mainly employed as the intermediary between digital process and physical process, which takes the digital models to inform the fabrication process and feed the information in the physical world back to the digital environment. Making full use of the advantages of vision technology in real-time communication and feedback, this system allows the interaction of physical processes and digital processes through design adjustment in real time according to physical material behavior, thus integrate design, simulation and fabrication process as a whole.

In order to test its feasibility, a prototype of the mechanical equipment was built to carry out small scale glulam production experiments. Both depth camera and AR technologies were tested and evaluated using Microsoft Kinect V2 and HoloLens respectively.

4. Mold-free glulam production system

4.1. *Mold-free glulam production equipment*

The way to produce curved timber could be analogous to that of a draftsman to create a Spline curves with a wood strip. A series of nodes, which could prevent translational movements while allow rotation, act as boundary conditions to hold the strip, resulting in a natural curve with minimal strain energy [10]. In this sense, the logic of single curve glulam production could be understood as shaping the laminas by controlling the location and angle of each press point on a plane. To extend this approach to the production of double curved glulam, two more aspects of controlling forces need to be introduced in addition to that in the single curved glulam production: firstly, a vertical force needs to be added so that the global shape of the double curved glulam could be freely manipulated in space; secondly, twisting forces need to be introduced to adjust the twist angle of the glulam at each controlling points (Fig. 4).

Based on the analysis above, a spatial positioning equipment for

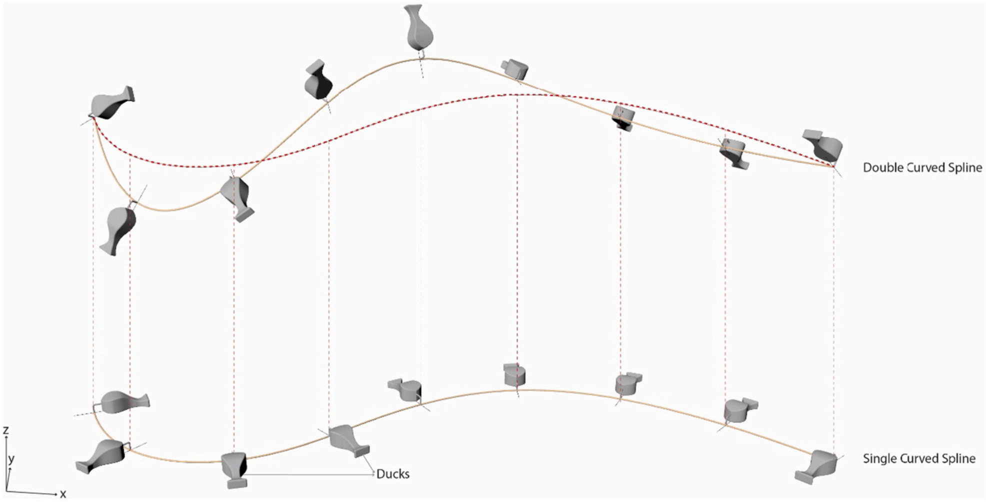

Fig. 4. Single and double curved spline presented in the manner of draftsman's spline.

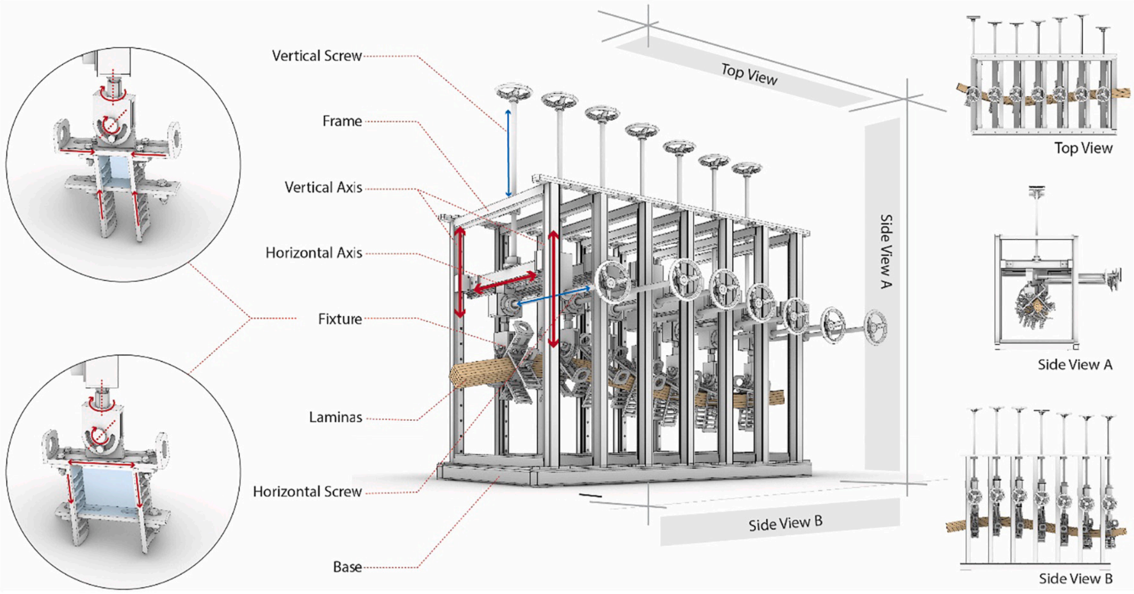

Fig. 5. The composition of the Equipment.

double curved glulam is proposed in this research (Fig. 5). The equipment consists of a planar base and a row of vertical frames mounted on the common base in parallel, forming a cubic area inside for glulam production. Each vertical frame contains a fixture, acting as positioning point in the laminating process, mounted on a two-axis motion system with two linear sliding rails. The motion systems are driven through guide screws, leading the fixtures to move freely in corresponding plane of the frames. The clamping size of the fixture can be adjusted according to the cross-sectional sizes of the target members. The bottom plate of the fixture can also be removed to facilitate the placement and removal of materials. Each fixture has two rotation axes, which is designed mainly to meet the needs in two aspects: On the one hand, without any intervention, the positioning fixture can rotate freely while holding the material, so the angle is changing with the global shape of the glulam during the adjustment; On the other hand, the angle of the fixture can also be fixed through mechanical fastening, thereby allowing the local angle of the fix point to be manually adjusted according to the design. Thus, the global shape of the curved glulam could be achieved as desired with this system.

Multiple equipment combinations are also supported to meet the needs of large scale curved components production without excessively increasing the equipment size. With each set of equipment installed on a movable base, different sets of equipment could be connected with joints at the corners. In this way, long length components with higher degree of curvature are allowed to be produced through adjusting the angle between each set of equipment (Fig. 6). Theoretically, curved glulam with unlimited lengths and radians can be achieved this way.

4.2. Vision system

In order to guide the operation towards the final state, it's necessary to monitor the global shape of the laminas during the production process of curved glulam. In this research, computer vision is introduced to establish a direct connection between the virtual design of double curved glulam with the physical process, which could be achieved in two ways: bring the physical objects into the virtual environment through virtualization, or project the virtual design into the physical scene. The former is typically represented by 3D reconstruction technology with depth camera, while the latter often refers to augmented reality technology. Both the possibilities of using depth camera and augmented

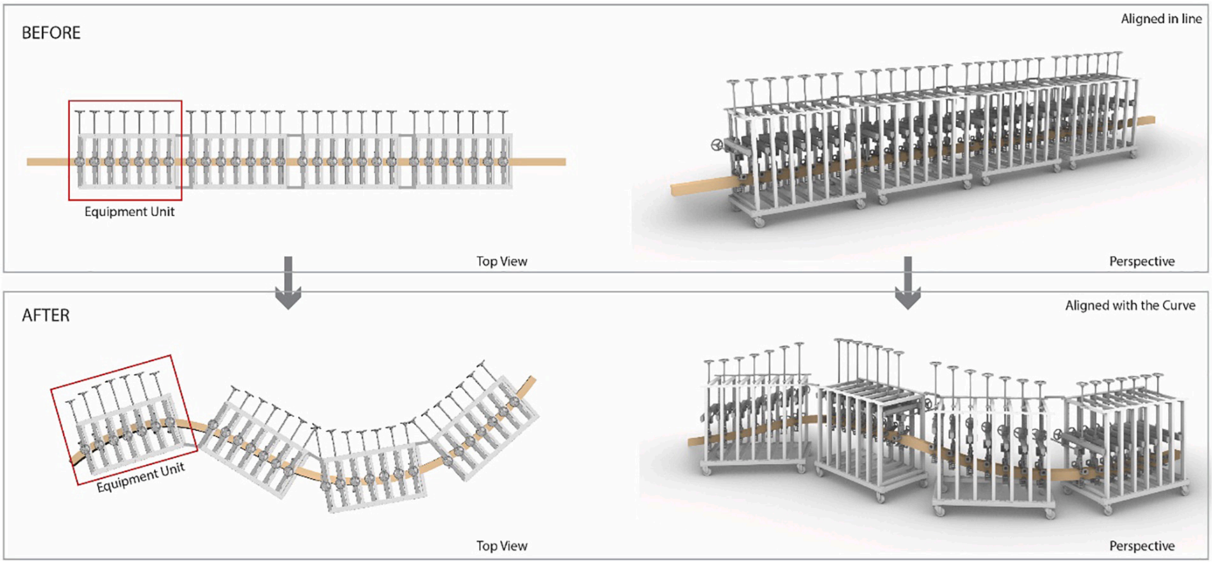

Fig. 6. Multiple equipment combinations for unlimited length.

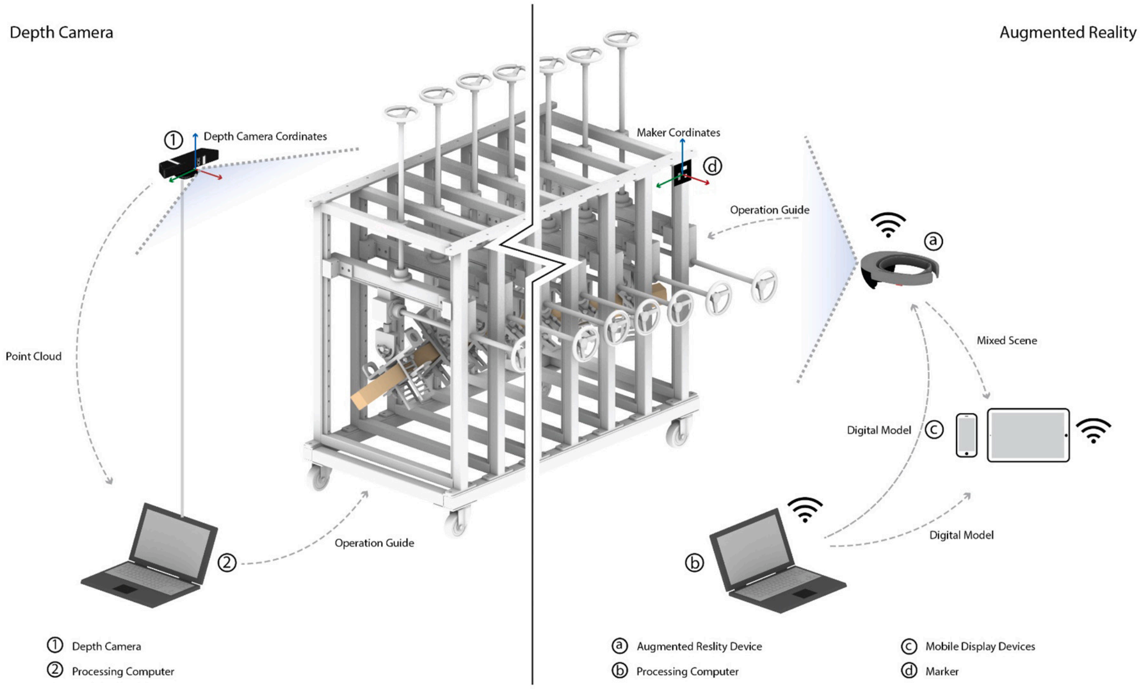

Fig. 7. Vision system design.

reality to assist double curved glulam production are explored in this research (Fig. 7).

For depth camera, a Microsoft Kinect V2 are used in this case, which incorporates RGB cameras, infrared projectors and detectors, and allows depth calculation through time of flight [23]. Based on the RGB and depth images from Kinect, a 3D point cloud of the fabrication scene could be generated in real-time. Through an interface that communicates Kinect with Grasshopper, the 3D point clouds are allowed to be generated in the computational design and modeling environment. Inside Grasshopper a plug-in called Tarsier is used to communicate with Kinect and stream the scanned point clouds in real-time. In addition to the feature that obtains the point cloud from Kinect, two other functions of Tarsier are used in sequence to process and optimize the resulting point clouds. Firstly, "Clip Point Cloud" function is used to crop the point cloud with the workspace volume of the equipment, extracting the point cloud of the workpiece and fixtures for easier observation during the production process. Secondly, "Voxellize" function is called to rationalize and reduce the point cloud based on a persistent decay grid. [24] The process could effectively reduce the amount of calculation, and also improve the visual effect of the point cloud, which could facilitate subsequent observation, as well as error calculation process. Through matching the design modeling with the real time point cloud inside Grasshopper, operators can monitor the deviation of the component from the target shape any time to make decisions for subsequent operations. The point cloud of the final state can be stored as a reference for subsequent post-processing.

Augmented reality, through blending the digital model into one's perception of the real world, provides an alternative option to locate the

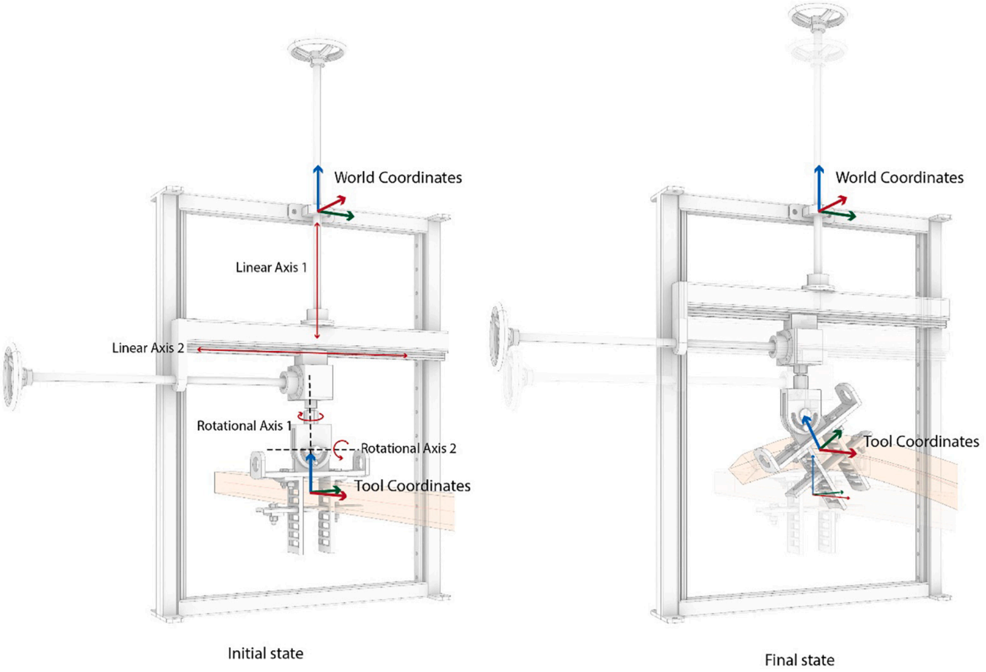

Fig. 8. Coordinates system in the Inverse kinematics simulation.

double curved glulam design in the fabrication area in a more intuitive way. AR device HoloLens as a representative is used in this study, in conjunction with Grasshopper as a modeling and data exchange platform. Apps are developed for HoloLens and mobile devices with Unity3D to bring Grasshopper geometries into view in HoloLens in real time. Inside Grasshopper, a plug-in called gHowl [25] allows the connection between Grasshopper and Unity3D (the apps in this case) based on User Datagram Protocol(UDP), transferring 3d models and related parameters to HoloLens and mobile devices. A UDP interface is developed in Unity3d to receive information from Grasshopper via LAN. HoloLens development environment is setup in Unity3D using Universal Windows Platform(UWP). Microsoft Visual Studio is employed as script editor. HoloLens Emulator is used to test the functionality of app on the computer, which is based on a Hyper-V virtual machine with RemoteFx for hardware acceleration. HoloToolkit for Unity is employed which provided a collection of scripts and components for AR app developments. After creating a new scene in Unity3D with digital models imported, gaze gesture control system is designed to define the interaction between users and models. World anchor is also defined to ensure that the digital model could be fixed in a certain position in the physical space. The imported models are recompiled in Unity3D so that and the model could share the same layers and material settings with that in Rhino and Grasshopper. Once the project is ready in Unity3D, Visual Studio will be used to debug the app and deploy the app to HoloLens. With the app, HoloLens could communicate with the hosting computer of Grasshopper via LAN by connecting to the same router. Android apps have also been developed using a similar process in Unity3D.

The system developed here allows the setting of layers and materials for different objects. Therefore, in the operation process, visual disturbance could be minimized through temporarily hiding the irrelevant layers in each stage or adjusting the display material for objects that need to be highlighted or weakened. After uploaded onto HoloLens, the model could be located in physical space by aligning the models to the physical equipment. Then the layer of the equipment model can be turned off, leaving only the layer of glulam in view to guide the laminating process. During the operation, users could observe the state directly through the augmented reality glasses. The scene observed by the glasses can also be showed in real time within Android devices like mobile phones or pads installed with corresponding apps.

4.3. Digital integration system

Digital integration system is dedicated to simulating and optimizing the fabrication process in the modeling environment. This system tries to simulate the behaviors of the equipment and materials in the fabrication process, and optimize the design through comprehensive consideration of different constrains. While digital design is used to guide the fabrication, it also obtains feedback from the fabrication process such as material locations to guide subsequent operations. The errors caused by the instability of equipment and vision system could be well compensated in the integration. In this research, digital integration system consists of three parts: equipment simulation, design optimization, and material simulation.

4.4. Equipment simulation

During the fabrication process, it could be helpful to simulate the final position and angle of each fixture on the equipment in advance to inform the operation. As a result of the complex spatial rotation of the fixtures, the final positions of the fixtures will deviate from the plane defined by the vertical frames, which makes it difficult to predict the distribution of the fixture on the equipment.

Since the position of each fixture is determined by the shape of the target component, an iterative method is developed to find the contact point between the fixture and the component, and further estimate the final position of the fixture (Fig. 8). The simulation first takes the intersection point of the frame plane and the glulam axis as the initial fixture location A_0. Then the fixture will be generated on the component section plane at A_0. The spatial rotation of the fixture around A_0 will inevitably cause the connection between the fixture and the slide rail to deviate from the initial location, in other words, the fixture and the frame will be misaligned. So in the next step, the fixture will be reconnected to the frame with the current posture. A_0 is moved to A_0' in this process. The vertical plane at A_0' will intersect with the component to create a new intersection point A_1. Based on the new intersection point, the fixture position will be recalculated. The loop will be repeated until

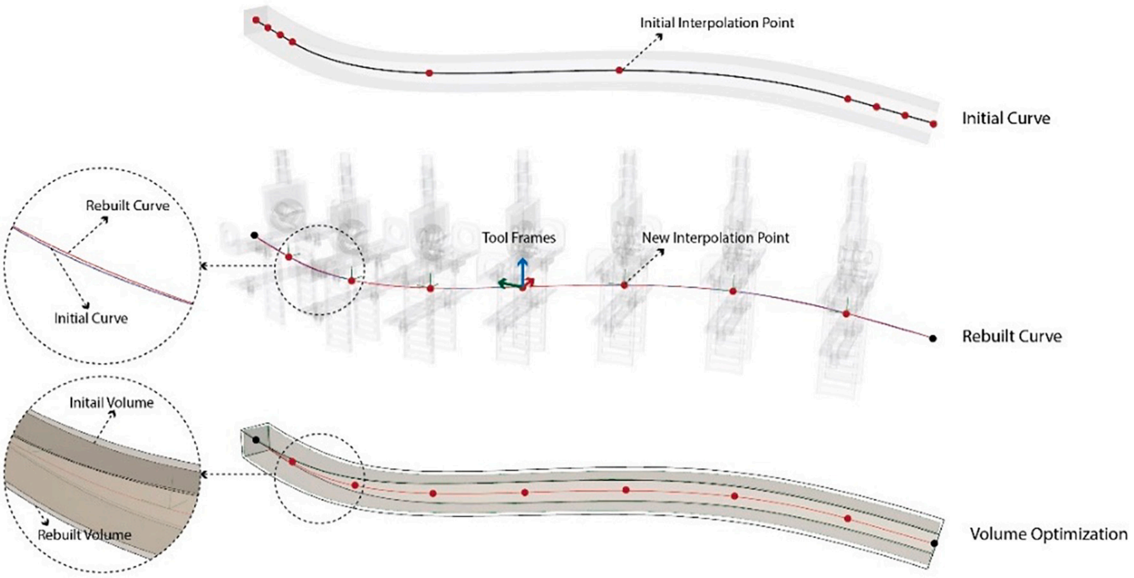

Fig. 9. Design optimization according to fabrication simulation.

the error at the connection of fixture and the frame is controlled within an acceptable range. The fixture posture could be updated in real time with the adjustments of component geometry. Combined with the real-time information from the vision system, equipment simulation also provides the possibility of real-time interaction between virtual design and physical process. In addition, the position and vertical distance of each fixture are also obtained in the simulation process, which will be used for the geometry optimization of the target component in the next section.

4.5. Design optimization

As said before, the shape of the final product of this equipment is defined by the fixtures as a series of control points in a similar way to the definition of Spline by draftsman. Since the positions of the fixtures are not arranged according to the controlling points of the curve, the resulting component geometry is a new curve which is generated taking the positions of the fixture as interpolate points (Fig. 9). This new curve is also a producible curve which follow the fabrication constraints of the equipment. Even when the fixtures are arranged densely enough, the resulting shape may still deviate slightly from the design curve. The solution here is to find the best fit of the design curve with the curve generated from the series of fixture points which are derived from equipment simulation. Due to the slight difference between the new curve and the design curve, the new component should have larger section so as to cover the designed component. The margin required for the cross section could be calculated based on the deviation to ensure that the finished product can be processed into the designed shape afterward. By converting the design curve into a producible curve during the design phase, the design optimization process could effectively reduce certain errors in the physical fabrication process.

4.6. Material simulation

Material properties are also critical for glulam production, especially when both bending and twisting are included in the laminating process. Therefore, to ensure that the design geometry is allowed by the material, this research tries to simulate the material behaviors through structural analysis. A structural simulation program is designed to simulate and monitor the structural performance of the component during the bending process from the initial state to the final shape to avoid excessive local stress. Using the structural simulation software Karamba3D

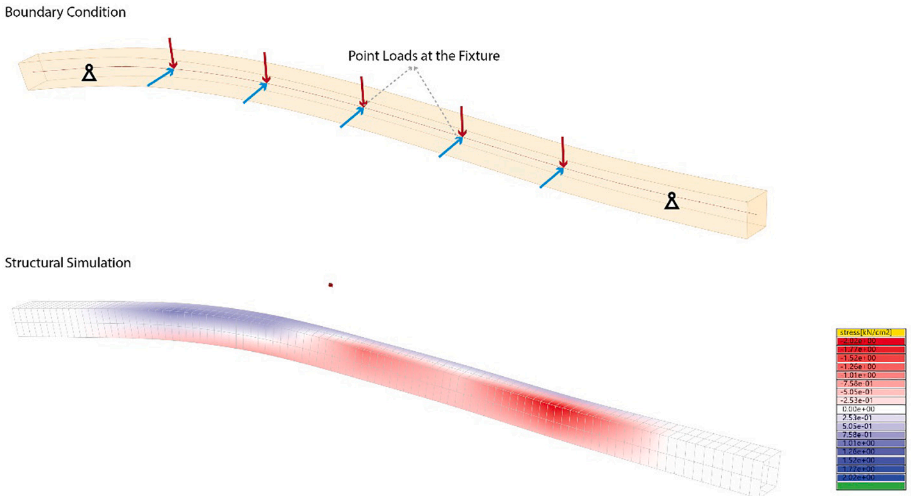

Fig. 10. Structural simulation with Karamba3D.

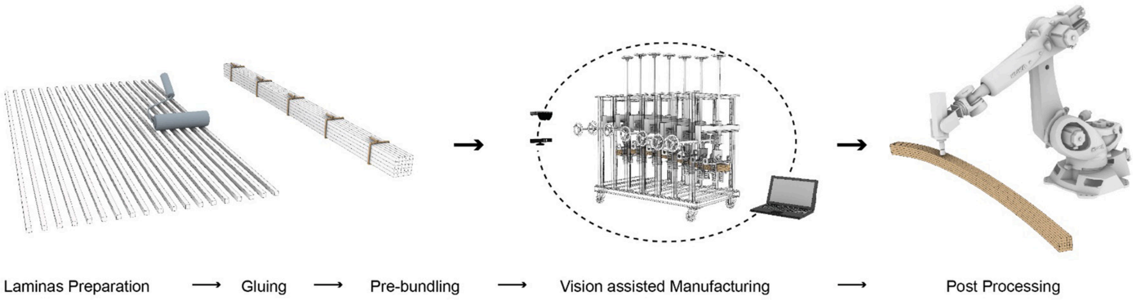

Fig. 11. The process of vision assisted glulam manufacture.

within Grasshopper [26], a simulation program is developed based on the Single Span Beam Tutorials of Karamba3D [27]. In the simulation, the first and last fixtures are defined as supports, while the other fixtures are regarded as point forces (Fig. 10). The program could output different stress values at different positions of the component, visualized through mesh. If the output stress value exceeds a threshold, the area of the output mesh could be easily extracted for subsequent design optimization.

This simulation is designed to simulate the bending performance of timber before the actual bending process. By simulating the movement of all the fixtures from the initial state to the final state at a constant speed simultaneously, this program could predict all the situations that may occur during the bending process. The simulation program also allowed changing the fixture location manually. By moving the fixture points in the way that actually happens in the physical world, a "real-time" simulation can be realized in a manual way. Nevertheless, it needs to be clear that this is just a timely imitation, not a real-time simulation. It is worth noting that, as it seems to be impossible to simulate the friction between layers of laminas with Karamba3D, the simulation considers the component as a solid glulam at the current stage, which also means that the current simulation results can only be used as a reference for design decision.

4.7. Integration method

In order to integrate information from different sources, including design models, simulation results, and feedback from physical process, this system uses an intuitive way to collect, visualize and communicate different information on a common software platform. As mentioned before, the entire integration process is carried out inside Rhino and Grasshopper. Since the software platform is commonly used for computational design, it provides plug-ins with different functions to allow the simultaneous running and interaction of different aspects in the same program through the sharing of common parameters. In this case, taking a fixed equipment model as the position reference, different information is integrated in the corresponding position in the same spatial coordinate system. By locating the information of design, simulation, and physical process in the same position, different information can be freely superimposed, switched, and displayed in a layer-like manner, thereby allowing intuitive and computational comparison between different processes. An example is shown in the following experiment in Fig. 13. The grey frames of the equipment model are the positioning reference, while the green part shows the simulation of the final state of the fabrication process. Fig. 13 also shows the superposition between point cloud collected by Kinect and the digital model of the equipment and component.

5. Experiments of curved glulam production

A series of double curved glulam production experiments were carried out to verify the feasibility of the system proposed in this study. A scaled prototype of the mold-free equipment was developed for the experiments. The external dimension of the equipment is 1320*740*1160 mm, maximum clamping size of fixture is 160*160 mm, and moving range of the two-axis system is 400*350 mm. As mentioned before, Kinect V2 and HoloLens, as a representative of depth cameras and AR respectively, were used as vision systems. The digital integration part took place in Grasshopper where the computational design and modeling happen.

5.1. Laminas

Normally straight and single curved glulam is made up from layers of thin boards stacked in one direction. However, the thin wood boards could only be bent in one direction. When twisted, misalignment will occur between layers, turning the cross section into a diamond shape. In response to this problem, smaller laminas with square sections, or rectangular sections that are approximately square, are needed to produce double curved glulam. The small laminas have similar bending capacity in both directions, which shows a higher degree of freedom in forming all kinds of linear shapes. It worth noting that, smaller lamellas also means finer subdivision of the component, which inevitable results in a more labor-intensive process.

5.2. Experimental procedure

The production follows a similar process with the general glulam production, which starts from design subdivision, followed by material preparation, gluing, vision system aided laminating, and finally post-processing (Fig. 11). The detailed workflow is as follows:

The model of target component is first isolated from the design model and oriented into the working area of the equipment model. Equipment simulation is then carried out to find the final locations and postures of the fixtures. A producible shape that most closely matches the target component will then be calculated based on the distribution of the fixtures. The cross-section of the producible component is adjusted so that the target component is completely covered, with a certain margin added to absorb errors in the later production process. Structural simulation will then be carried out to verify that the maximum stress of the material is not exceeded during the bending process. After all the simulation, the component will be subdivided into laminas according to available materials.

The laminas with required length will be prepared for gluing. Finger jointing is not included in this research due to technical limitations of the laboratory. The LOCTITE HB S309 PURBOND glue from Henkel Adhesives is used in this research. After gluing, the laminas would be assembled and simply bundled into a linear blank, and then put into the fixtures for laminating. At the same time, the vision device will be prepared to align the digital model with the physical equipment. Following the instructions of the visual system, the straight component is then pressed into the desired shape, through iteratively driving the manual operated screws. Once the desired state is reached, a series of additional clamps will be applied to the glulam to provide the required pressure for laminating. The component will be held under pressure for

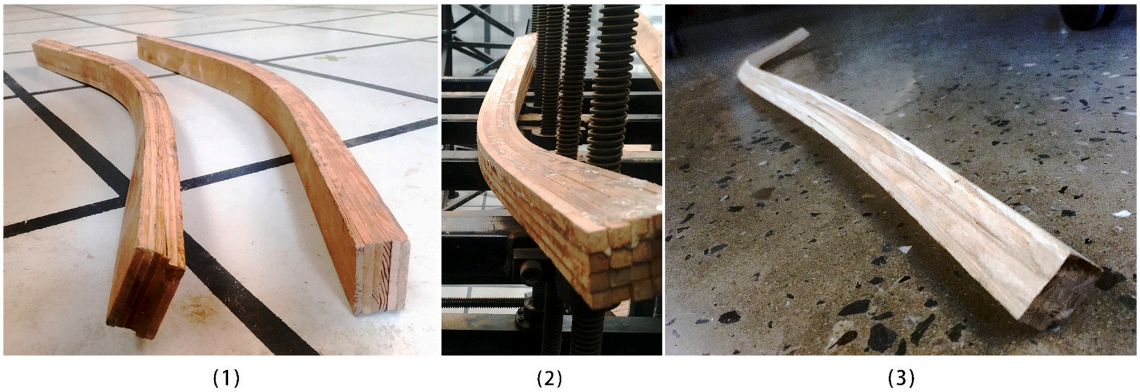

Fig. 12. Different types of Glulam prototype produced using the proposed system.

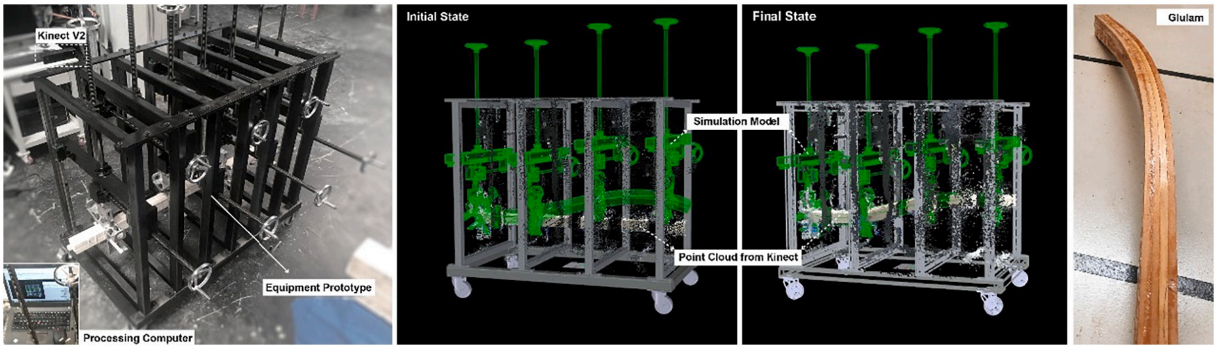

Fig. 13. Experiment with Kinect v2.

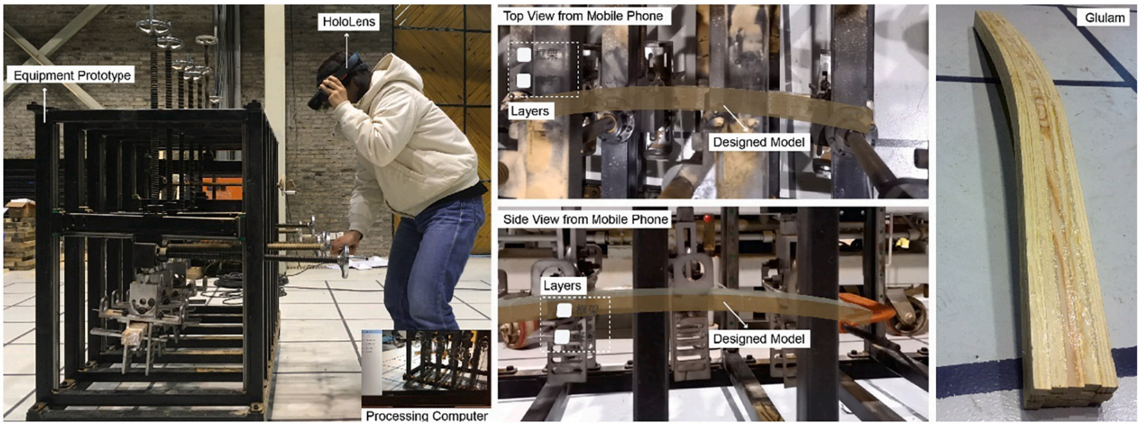

Fig. 14. Experiment with HoloLens.

4 h before removal. The desired shape will be finally obtained through further processing with CNC or robots to remove the margins. The error in the production process could be well compensated through milling, that is also to say, the final accuracy of the component depends mostly on the post-processing process.

5.3. *Experiments and discussion*

Following the procedure above, different kinds of components were tested, including single curved with- and without torsion (see Fig. 12-(1)), double curved without torsion (see Fig. 12-(2)) and double curved with torsion (see Fig. 12-(3)). While the former two types were laminated with both board laminas and square laminas, the last was tested with square laminas only. The material used in the experiment is *Pinus sylvestris* var.mongolica, the cross section of the board laminas was 55 *8 mm, and the cross section of the square laminas was 10*10 mm. The materials were ordered before experiments directly from a timber construction company specializing in the production of glulam. The moisture content of the material ordered is below 13%, and stored indoor at room temperature. As the environmental conditions were not recorded, the date and location that the experiments happened is provided here as a reference: Jan 7th to Jan 10th 2020, Yangpu District, Shanghai.

It can be observed from the experiment that the overall rigidity of the equipment prototype is slightly insufficient for glulam production. However, errors can be well compensated by the accuracy of the vision system. With the aid of the vision system, whether AR or depth camera, the overall deviation between the physical component and the model can be controlled within 5 mm, regardless of scale. Offsets between different layers will occur as expected when using board laminas to make torsions. Square laminas did cost more labor that boards laminas, but only in gluing process.

An important purpose of the experiments is to test the feasibility of the two vision systems, AR and depth camera (Fig. 13-14). The experiments show that, the advantage of depth camera is that the final state of the materials could be recorded as point clouds, which could be used to analyze errors and passed on to subsequent processing stages. However, the large amount of point cloud data output by the depth camera, with a large amount of interference information, had a negligible effect on the running speed of the program. As the camera need to be fixed at a point, it is also worth pointing out that the depth camera can only output point clouds with a specific perspective, and the rough point clouds captured from one perspective is especially disadvantageous for determining the angle of each fixture precisely. Augmented Reality has shown better accuracy, flexibility and operability in the experimental process. AR is more intuitive, and allows to observe three-dimensional models from multiple perspectives. Giving full play to the advantages of both, these two technologies can be integrated to achieve a more optimized workflow, with AR used to guide the production, and depth camera to record the results.

6. Conclusion

This paper presents a mold free approach for curved glulam production with the aid of computer vision technologies. Compared with the current approaches that rely on molds and subtractive processing, the approach proposed in this paper is more straightforward, which provides a universal mold system that adapts to different geometries and tasks. The intuitive benefit is that the consumption of materials, time and labor in complex mold making and material subtractive fabrication process could be greatly reduced. Compared with another approach, bending and shaping the laminas with industrial robot arms, this approach allows more freedom in the shape design of the glulam by providing more fixtures as control points. More importantly, this approach has greater potential to be further developed for large-scale components production, and then transferred to industrial practice. Currently this approach is still conceptual to some extent, which is expected to be improved in several aspects in the follow-up research. Once transferred from the laboratory to industry, the wood utilization rate in the glulam production could be effectively improved, leading to considerable economic benefits. From an architect's point of view, this approach lowers the barriers and cost of complex glulam production, which will also help to promote the application and innovation of complex glulam buildings. In addition to acting as a production method, this approach also provides a new perspective for construction through the interaction between virtual design and physical process, which could be used as an inspiration for dealing with other challenges in different sections of the building industry.

Declaration of Competing Interest

None.

Acknowledgment

The work was supported by the National Key R&D Program of China (Grant No. 2018YFB1306903), and Science and Technology Commission of Shanghai Municipality (Grant No. 16dz2250500, Grant No.17dz1203405).

We'd like to thank Gang Liu from Shanghai Fab-Union Technology Co., Ltd. for his support on the platform development. We would also like to thank Chunpong So from Tongji University for his assistance on the experiments.

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