Smart Structure: Designs with Rapid Prototyping

Ching-Shun Tang
Graduate Institute of Architecture, National Chiao Tung University, Hsinchu, Taiwan

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Abstract: This research presents the new orientation of the combination of digital modelling with generative programming and joint method of traditional wood structure for manipulating Rapid Prototyping to explore the assembling of free form objects. The presenting of the example indicates that the edition of Maya scripts defines the purpose of design. Through the discussion on scripts developing the assembly of the free-form objects of frames and surfaces and through the achievement that RP produces and examines objects, we bring out the possibilities of the new form developed from the old structure and illustrate how to develop our hypothesis. The developed result could provide the possible new way for free-form assembly. We expatiate our research process and final achievement and provide a new thinking direction in the education field.

1. INTRODUCTION

The digital era has influenced the practice of contemporary architecture. Digital technology has fundamentally changed the idea, design and production of buildings. The change in the digital trend and the effect on the practice of actual cases are discussed. At the same time, contemplation is conducted on the general effect and in the distant future, idea under different background will be presented in regard to the practice of architecture of today and the recent rising digital era. With the aid of current CAD systems, wild designing concepts have been unconstrained. Architects use computer motion simulation and automatic generation systems to aid design brainstorming, disintegrating conventional architectural pattern and
transcending traditional perpendicular structuring behavior (Luca and Nardin, 2002).

Digital fabrication is like selection of display of design and the utilization of the problem occurred in the process of design in regard to the enlightening topic generated in the course of perception of design of artifact (Kores, 2002). The range of discussion about experimental free-form objects in terms of building methods, aesthetics and structure has been expanded and become much greater than the one about traditional architecture. In order to have such complicated forms built, we need to rely on the techniques of CAM. In recent years, 3D Rapid Prototyping (RP), 2.5D and 3D Milling and computer aided Shape Cutting have been broadly discussed by the fields of architectural and industrial design, and have also become a useful tool in assisting designers nowadays on thinking and application (Mitchell 2004; Kolarevic, 2003b).

In the course of design, RP device for model production provides new aiding function. Besides solving complex form production, it can be utilized to check the design through 1:1 physical model output precisely from the computer model. Compared with traditional handwork model that is not accurate and manpower and time consuming, RP provides precise output that can breakthrough the constraint of perpendicular traditional model. Designers will find it easier to feel the space of the complex form or it can be utilized as test for complex form structure (Sass, 2004a, 2004c). In regard to the defect of RP, the time spent in the production in the course of creation is too long so that between display of model and design, it cannot be linked. In addition, in respect of output model, there is also the problem of dimension. Larger model would require cutting apart and assembly and therefore in respect of time, it is quite consuming (Sass, 2004b).

In the past, for the way of thinking by many designers on the liberation of space form, they are forced to abandon as such production is impossible due to traditional work method resulting that there is really a big difference between design imagination and reality. Now it can be achieved through CAD/CAM technology and it can serve as actual method to display the concept of the architectural design (Ryder et al., 2002).

2. PROBLEM AREAS

Nowadays CAD/CAM provides many new possibilities for the development of industrial manufacturing and architectural education for designers and scholars. It also generates many new media tools other than traditional ones for discussing structural issues (Kolarevic, 2003a). Therefore, many scholars
start the research on digital fabrication, especially in methods of building up various free-shape form structures (Kolarevic, 2004).

In the architectural field, Joints are the key factors in keeping the structure continuous and in making forms. In the east, wood architecture is one of the most primitive building structure types. The types of structure systems are various. They differentiate from each other with different sorts of jointing methods (King, 1996). From this research we discovered that mortise and tenon joint, dovetail joint, tongue joint, finger joint, dowelled joint etc. (table 1) are very interesting and functional joint methods (Breyer et al, 1998; Jau, 2005; Zwerger, 1997). We found that traditional technology limits the joint form of wood. However, is it impossible to create any new form? Can it be linked up to the free form assembly structure method? Based on the joint methods of traditional wood structure, we intend to use CAD/CAM tools to regenerate and combine the joint methods of traditional wood structure to develop various forms. By using new structuring ways derived from the traditional techniques, we could meet different kinds of functional demand and generate a newly refined and integrated designing mechanism (figure 1).

![Figure 1. PROCESS: The framework of generative mechanism.](image)

3. RELATED WORK

In the beginning when RP is applied in architecture, it is utilized as the method to transform 3D model that displays the process from CAD to NC (Streich, 1991). Following this, it becomes the display of fabricated architecture conceptual idea (Ryder et al, 2002). For example, the method of physical architecture design concept and in regard to rapid production, seven different rapid building device categories are utilized from stereo lithography, SLA to selective Laser Sintering 3D printing etc.

In respect of actual case, in the year 2000, Mark Burry(2004) completed Sagrada Familia church which has been suspended after Gaudi’s death in 1926 with the new media tool of CAD/CAM. He applied a parametric software – CADDSS5, which is used in ship making industry, combined with
RP technology to re-design and build the 35m-tall rose-window at the wing of the church. This case also reveals the potential and power of influence in design aid by RP technology on the complex form design in the course of design and real fabrication.

In the research sector, a few other researchers went through rule application as the design method and combined with the research process of the RP operation automation. For example, research by Sass (2004a, 2004b, 2004b) displayed a few artifact fabrication and through utilization of RP, it became the part of creative design process. He presented three topics including change of light and shade, production of complex form and assembly form to discuss that the method of improving design was to utilize RP and the digitized design production function. In his research, Kilian (2003) explained how to link generative design script written in AutoLisp with a 2D RP device. The AutoLisp scripting is like using a schematic tool to make surface joining points. The diversity of external form displayed by joining points will respond to the geometry of the sketch surface. The surface design and the accompanying joining points acquisition are based on the unique advantage of the 2D RP device. Wang and Duarte (2002) introduced a production method to design and fabricate an assembly model and the method is to use shape grammars to obtain the generated model. In the utilization of 3D printer fabrication and assembly, it is deemed as presentation of the early stage of design. This essay is an inspection of the course and some methods utilized in architecture. Compared with the above research, the structure of this paper presented is new and it emphasizes on relevant programming and RP combination. In addition, the standard of practice is based on the design background. Moreover, the acquisition of conclusion is based on the recording of actual examples and the course of practice, reaction and verification on questions presented.

4. ANALYSIS OF TRADITIONAL WOOD JOINTS

In the architecture sector, the joining point is the viewpoint clarification of design and it can really reflect the principle of system function and is the best vocabulary of combining design and technology into one. Looking from the evolution of history, the reform of wood architecture form and the structural system and joining point method breakthrough have a very close relationship. The evolution of structural joining point can reflect the development progress of wood architecture.

The compression resistance of wood structure means the ability to resist the upper and lower perpendicular external force of the structure and is the most utilized characteristic of all traditional architecture. In ancient wood
architecture in the orient, mortise-and-tenon joint is a common technique in Chinese traditional architecture just like the spirit hidden between two pieces of wood. At that time, after the craftsman chipped off the unnecessary part, the two pieces of wood would be held tightly and would not separate. In ancient architecture or temple, very often one can discover that with proper utilization, the entire structure can be combined together very tightly and there is no need for any pin or nail. The development of joining point is more complex like the dovetail point that can resist pulling and various finger joints and joining points have torsion resistance and that can unfold the strong creative idea and craft.

4.1 Wood joints

(a) Mortise and Tenon Joint - due to its higher strength, it is one of best joints in fabricating wood structure. Its main function is in the joining point of each frame of the wood structure. Diversifed assembly methods of Mortise and Tenon Joint joining point include keyed, doweled, blind and doweled. (b) Dovetail Joint - it is being used for combining the tails of two pieces of wood. If you place your two hands together and cross your fingers on the joints and more or less you can see the dovetail joint. Dovetail joint is being applied in traditional wood structure and is the strongest in all joining points. Normally dovetail joint is used to increase the wood structure fabrication value.

(c) Lap Joint - mainly it is used in combining two pieces of wood. Between mutual connection between wood and wood, each will remove half of the area. On the edge of the wood and the along the depth of the raised joint, it will establish the width and depth of the indenture. (d) Tongue and Groove Joint - it is a good joining method for preventing momentary separation of internal and external part and this can provide a simple form of joint to connect with linking surface. Through the raised joint along the wood edge, it is designed that it can tightly grasp the corresponding groove. (e) Dowelled Joint - Many joining points will be reinforced by dowelled joint. Dowelled joint will reinforce the joining point of mortise and tenon joint. Pegged mortise-and-tenon means to butt-join larger pieces edge to edge. By fixing the joining point of mortise and tenon Joint, the piercing through mortise and tenon by dowelled joint can prevent the tenon to be separated from the mortise.

(f) Butt Joint - it is the joining point of opposite edge of two pieces. Following this method, the checked patterns on the two wood surfaces on the two pieces of wood are joined. Then a gap with similar size is drilled and the enforced gap structure of the joining two ends of the dowelled joint is being inserted like using glue to fix it on the surface of broad and large form.
Table 1. Type of wood structure joint.

<table>
<thead>
<tr>
<th>Description</th>
<th>Figure</th>
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<tbody>
<tr>
<td>Mortise-and-Tenon Joint</td>
<td><img src="image1" alt="Mortise-and-Tenon Joint" /></td>
<td>The basic mortise and tenon comprises of a tongue(tenon) cut into one rail and a mortise cut all the way through the other rail.</td>
<td><img src="image2" alt="Mortise-and-Tenon Joint" /></td>
</tr>
<tr>
<td>Dovetail Joint</td>
<td><img src="image3" alt="Dovetail Joint" /></td>
<td>This popular notch is commonly used in true timber framing to join smaller members such as joists and purlins.</td>
<td><img src="image4" alt="Dovetail Joint" /></td>
</tr>
<tr>
<td>Lap Joint</td>
<td><img src="image5" alt="Lap Joint" /></td>
<td>Half lap joints are used extensively in construction and cabinetry for framing.</td>
<td><img src="image6" alt="Lap Joint" /></td>
</tr>
<tr>
<td>Tongue and Groove Joint</td>
<td><img src="image7" alt="Tongue and Groove Joint" /></td>
<td>Tongue and groove joint. A classic way of jointing two board together.</td>
<td><img src="image8" alt="Tongue and Groove Joint" /></td>
</tr>
<tr>
<td>Dowelled Joint.</td>
<td><img src="image9" alt="Dowelled Joint" /></td>
<td>In a doweled joint, small holes are cut in each of two pieces of wood at equal distances.</td>
<td><img src="image10" alt="Dowelled Joint" /></td>
</tr>
<tr>
<td>Butt Joints</td>
<td><img src="image11" alt="Butt Joints" /></td>
<td>A butt joint is a simple method of connecting two pieces of wood with the square end of one piece being placed against the side of another.</td>
<td><img src="image12" alt="Butt Joints" /></td>
</tr>
<tr>
<td>Finger joint.</td>
<td><img src="image13" alt="Finger joint" /></td>
<td>Finger joints on all sides of a project make a box that is very nice.</td>
<td><img src="image14" alt="Finger joint" /></td>
</tr>
<tr>
<td>Mitre Joint</td>
<td><img src="image15" alt="Mitre Joint" /></td>
<td>Tongued Mitre. A separate 'Tongue' is inserted into a groove in the mitre for stability.</td>
<td><img src="image16" alt="Mitre Joint" /></td>
</tr>
</tbody>
</table>

(g) Finger joint - it is the technique used in joining the top of two pieces of wood. Besides that it is more like a dovetail joint, the square tip and knocked-off corner are normally equal distance allocation. The crisscross
joining point method replaces the function of glue but it does not have detail effect of dovetail joint. (h) The mitre joint is formed by the top of the tenon so as to prevent cracking and the offensive look caused by concealed tenon protruded object (Chen and Jang, 2003; Graubner, 1992; Korn, 1993; Wuang, 2003).

This research will summarize the traditional wood structure joining point based on its function and provide examples as in table 1.

After analysis and summarization of the traditional wood structure joints, we discover that there are many complex joining methods. Its forms include simple to extremely complex joints. In addition, different joint has different function and different ability to take up external force. The maximum limitation of traditional wood structure is that its fabrication methods adopts perpendicular joining, yet on its joint, it has considerable important consideration and it is still being used. For example, the Mortise and Tenon Joint is very commonly used on desks and chairs.

5. GENERATIVE FABRICATION

At this stage we will concentrate in the study on how to redefine the original wood structure joint of the traditional wood structure joining rules through the aid of CAD system. In the CAD environment design, not only it can breakthrough the constraint of the fabrication method of traditional wood structure perpendicular means, in addition, this research also starts the new assembly method with three dimensional thinking to advance to a more challenging free form structure. Through the course of design of two examples, this chapter shall describe how to apply the new assembly method on the free form frame and the topic of surface assembly.

5.1 Designing joints

Hindered by the constraint in tool, traditional wood structure cannot be developed that is different from perpendicular fabrication. Under digital aid, the constraint of wood structure is no longer a problem. During assembly, it is not necessary to consider the constraint of angle and we can output the physical model precisely through CAD/CAM.

During the start of designing joint, we set three rules so as to retain the original function of wood structure joint. (a) During assembly, any hardware or metal piece and glue will not be used. (b) After assembly, there will be no trace mark of joint from the outer appearance of the form. (c) After assembly, the joining place will be tightly fixed. Through the setting of these rules, not
only clear direction can be seen during the design of joints, in addition, part of the traditional joint type are excluded under the constraint of rule.

Under the setting of rules, this chapter has decided to develop Mortise and Tenon Joint, Dovetail Joint, Lap Joint and Tongue and Groove Joint in the traditional wood structure joint as the key elements. Joints are developed and designed under the 3d CAD environment and assembly test is conducted on the physical model output through RP device (figure 2).

The purpose of development of joint in this chapter is to provide an assembly method required during free form fabrication. The joining method can be separated into two basic prototypes that are Point Joint (figure 3) and Edge Joint (figure 4).

The joint design concept of Point Joint comes from the Mortise and Tenon Joint, Tongue and Groove Joint and Dowelled groove in the traditional wood structure joint. The functions of these three joints are combined together that can conform to the development of joints of multiple angle developed under the self-established rules. It can be provided to complex free form frame assembly. Through the physical model of 4*3 sq. in. output through RP, the result of the joint detail can be examined especially on the dowelled groove. In order to determine the depth of dowelled groove, this chapter utilizes models with three different thickness that are output from the RP device and the thickness is 2mm, 1mm, 0.5mm respectively. After test, it is discovered that the surface structure of 1mm model output from the RP device is more intact. When the thickness is 0.5mm, there will be damage on the surface and the RP device material cannot be output correctly. Finally, the depth of the dowelled groove is set as 1mm and during joint test assembly, dowelled groove with that thickness can also provide its effect that means the joint can be tightly fixed.

The joint concept of Edge Joint comes from the Dovetail Joint, Mortise-and-Tenon Joint in the traditional wood structure joint. By combining the function of these four joints, it can provide a continuous joint type along the
edge during assembly of complex curve free form on the surface. The purpose is to add a dovetail joint in the continuous joint to provide the function of entire surface structure. Through the 8*8 sq. in. physical model assembly test output through RP, continuous joint can actually secure the structure of free form so that it will not be affected by the perpendicular external force.

Figure 3. Production process: Point Joint.

Figure 4. Production process: Edge Joint.
5.2 Digital design fabrication

The two examples mainly focus on the study on how to assemble when the free form frame is joined in multiple angles and when the surface curve is complex and a joining method can be derived through the traditional wood structure joint. The example will base on MEL (Maya embedded language) Script to write a method with productivity that can create unique form structure. The assembly form method shall combine with the Point Joint and Edge Joint developed in the above stage and then a physical model is output through RP device to check and test the assembly of model.

5.2.1 Design of assembly – structure

First example: During conceptual design of the free form, how to fabricate structural object with complex angle is presented. The designer will utilize control of Script parameter to create and revise the structure of form. This chapter will name it as “Duplicate Script” and its operation method is as what is described below. First, one object is set as a basic module and Script is executed to decide on the quantity of duplicating that object. The object parameters duplicated will be synchronously controlled in the original object. Through the x, y, z coordinates of the operation space, the design will move, rotate, miniaturize and magnify the size to induce the growth form of the object. Each object will be equally placed in the space and the objects are joined together with a clever angle to generate a complex and trigonometrically structural object (figure 5).

![Figure 5. Design process: duplicate script.](image)

Each frame of the final result structural object will be joined at different angle. Sometimes, part of the frame may have three to four joining points and will join with other frame in different angle. Therefore, during setting of joints on the frame of the structural object, the operation process is very complex. As part of the process of setting joints is all along a repetitive procedure, in order to simply the procedure the repetitive part can adopt script method that is recorded as simple press button. For example, during
setting of the depth of joint, use "move -r 0 -0.25 0 ;". To cope with different depth and angle, appropriate script can be set. This method can solve many complex operations and can also save time spent in the setting of joints.

### 5.2.2 Design of assembly - surface

Second example: During the conceptual design of the free form, how to fabricate large angle turn over and inside turning on the surface generated during excessive complexity is presented. The generation of form is by means of the control of Script and this chapter shall name it as “Dynamic Script” and the operation method is described as below. First the designer will establish basic curve to select curve execution “Loft” command to generate surface. Then the curve execution Script is selected to set the affected parameter of the cv point on the curve. The Script controls the x, y, z coordinate of cv point of each curve in the space. Part of cv points can be selected as group. Through parameter setting, designer can control the random shifting and rotation of cv point. The surface will operate following the cv point. The setting of parameter will allow the surface to generate random motion change. The larger the number of the surface is, the more the change will be. Finally it will display surface full of large angle and inside turning (figure 6).

![Figure 6. Design process: dynamic script.](image)

On the surface of the final result form, there will be many protruding objects. Each protruding object will face different angle and will rise up and down and pull each other forming a water wave form. During assembly of form, a single protruding object shall be a module. During establishment of edge point on the form, it is almost very smooth. Only there will be problem when the operation step is too complex and similarly simple script can be utilized to reduce work time.
5.2.3 Assembly Production

Upon completion of the design of the structural object in the 3d environment, we can check whether the structure can be assembled through the physical model output through the RP device. In this chapter, the Insight 4.0 software is adopted to calculate the digital model and then it is input into the RP device and then the physical model is the output. Model format supported by Insight software is stl file and in Maya the stl file cannot be output. It is necessary to go through external program Polytrans or other software such as 3ds max, Formz, Autocad. Finally we select 3ds max and transform the obj file output from Maya as stl file. During this process, it is necessary to pay attention to the setting of inch in order to avoid error in ratio during the output of model.

The final output dimension of the structure object (figure 7) of example 1 is 6*6*20 cubic inch. The minimum unit block frame cross section is 1*1 cm². After test, this dimension ratio is the bottom limit that detail joint can bring its function into full play. During assembly of frame, as the quantity of frame is as high as 32 sets of block and in order to consider the convenience in assembly, number is indicated on the bottom of each set of frame in order to facilitate identification of the assembly sequence. The final output dimension of the structural object of example 2 (figure 8) is 8*8*6 cubic inch. As the structural object is based on the protruding object as one module and the total number is 35 sets, the average dimension of the module is 1.3*1.3 sq. inch.

![Figure 7. Example 1: assembly production.](image1)

![Figure 8. Example 2: assembly production.](image2)
When the RP device has completed the output of the physical model, in the course of model assembly, it is discovered that the groove of part of the joint is too small and cannot be joined smoothly. Aiming at that joint and after repeated and re-output test, the result is the part of the re-output model can be matched. After arrangement, two possible effect results are presented (a) the number of the surface of the digital model is too low resulting that the level of fineness of the model falls. (b) The inclining vertical placement of the digital model in the RP device: as the RP material ABS plastic output method is stacking up towards the top layer by layer horizontally, if it inclines vertically, it may result in inaccurate output of model.

6. CONCLUSION

After this research has conducted integration of traditional wood structure joint and its analysis, once again people can obtain an understanding on the long forgotten ancient craft. In addition, under the aid of CAD/CAM, the traditional wood structure joint can now have a new form. The purpose of the design of point joint and edge joint is to provide a new direction in the assembly of free form frame and surface. Through the three rules in the process of this design, the original function of the traditional wood structure form is retained so that the direction of development can be clearer. The presentation of the two examples can clearly describe the process from digital design to assembly test of the physical model. The purpose of writing two mels scripts is to provide a new design method to create a unique form. In addition, it can respond during multiple angle joining of frames of the free form and how to assemble when the surface curve becomes complex. In addition, a method to solve the writing of simple script is provided. During the assembly stage, it explains clearly the produced model dimension and the purpose is that there will be problem in assembly due to models of different ratio. Through the location of the test verification problem, two factors that may affect the inaccuracy of the physical model output are presented.

This research utilizes diagrammatic explanation to explain how to develop our hypothesis. The result developed can provide a possible new method to assemble free form. We have clearly explained and described the course of research and presented the final results that can be provided as a new idea of contemplation in the design in architecture education.

Based on the variety of traditional wooden joints, it is suggested that the next research could be concentrated in the field of productivity, such as shape grammar and the line and model generated from genetic algorithms,
the rule of its form is established based on computing coding. This computer program and the purpose of the production method are to create many optional ideas and the best design plan can be selected from these.

7. ACKNOWLEDGEMENT

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8. REFERENCES


