DIGITAL FABRICATION AS A LEARNING MEDIA FOR LIGHTWEIGHT STRUCTURE WITH CASE STUDY OF SHELL STRUCTURE

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Abstract

The lightweight structure system is an effort to optimize the structure to distribute the load efficiently. Unfortunately, students often have difficulty imagining the learning outcomes application in the real world when studying light structural systems. However, the use of the scalar model can still explain several essential aspects of a lightweight structural system, one of which is the effect of connection and formation of material components on the structural capability. Therefore, this paper aims to bridge the learning process by utilizing digital devices from the concept stage of structural modeling with the help of software (Rhinoceros, Grasshopper, and Kangaroo) to the realization process using laser cutting. The method used is a semi-experimental method that applies Hooke's law principle, which produces a shell structure system with a digital fabrication approach that utilizes a lightweight material, namely, corrugated paper board, as the primary material. This paper concludes that digital technology and digital fabrication processes can help students understand the concept of lightweight structures because they can use computer simulations, cut them using laser cutting, and assemble them in the field in a series of simultaneous processes.

***Keywords**: Lightweight Structure; Hooke's Law; shell structure system; digital fabrication; corrugated paper board*

BACKGROUND AND AIMS

The process of studying structure so far is mainly under civil engineering. However, along with the times, architects are also required to understand the concept of a deeper structure to support the design understanding, a very light structural system. Students often have difficulty imagining processes and applications in studying light structural systems. The scalar model has not been able to explain several essential aspects of a lightweight structural system. One of which is the influence of connections and the formation of material component compositions on the structural capability. Therefore, this paper aims to accommodate the need for understanding structures using digital fabrication principles. This principle aims to explain the principle of division and arrangement of structural components as a whole. This process also uses Rhinoceros, Grasshopper, and Kangaroo software as digital simulation media. Then, with a laser cutting machine and assemble it in the field for the production stage itself.

LITERATURE STUDY

In planning the structural system, there are live loads and dead loads that need to be considered by the architect. The live load can be managed relatively easily by adjusting the functional requirements, the number of occupants, and the equipment. The live load is relatively easy to adjust by adjusting the functional requirements, the number of occupants, and equipment. However, in the early stages, architects also need to take into account dead loads. In buildings with wide spans, beam thickness is often a significant problem, especially concerning the dimensions and weight of the structure; Therefore, architects need an understanding of lightweight structures

Lightweight Structure

Lightweight structure (LS) is a concept for optimizing structures through effective load delivery and critical loading.(Lightweight Structure Association of Australasia Inc, 2020) . This type of lightweight structure generally uses materials that are relatively light but have high structural capabilities. Therefore, the area of discussion of lightweight structures is often related to the themes of advanced materials. The light structure type is cable structure: cable structures, membranes, shells, and folding structures or can be categorized as active form, vector active, active section, and surface-active (Engel, 2013). The description in figure 1 shows the force mechanism as follows:

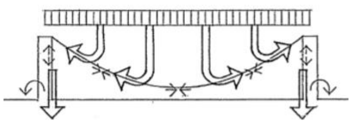
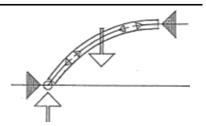
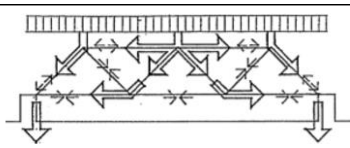
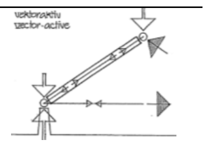
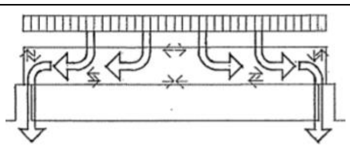
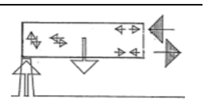
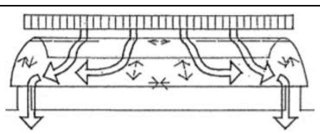
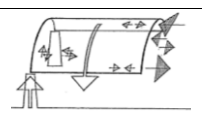
No.	Structure System	Mechanical
1.	 Form Active	
2.	 Vector Active	
3.	 Section Active	
4.	 Surface Active	

Figure 1. Structure System and mechanical
Source : (Engel, 2013)

Digital fabrication

Digital fabrication is a design process that involves the use of computers and all digital machines connected to computers as a whole, from the data management modeling stage to the production stage (Indrawan, 2017). The Rapid Prototyping Laboratory, which was popular in 1990, became a digital fabrication laboratory concept today(Celani, 2012) . In the Bauhaus era, in 1923 and 1928, László Moholy-Nagy presented a concept of design education, namely integrating art, science, and technology in the learning experience of his students. He is a teacher interested in material processing through tangible activities such as processing plastic formations and creating objects with good tectonic quality using tools and machines. Experiences like this cannot be achieved by simply reading books and lectures in the classroom(Moholy-Nagy & Bauhaus, 2005). A few years later, architectural learning developed with scientific content, which triggered the emergence of The Design Method Movement in the 1960s(Langrish, n.d.).This need arises because of the demands for the complexity of the space program, engineering science in architecture to research activities, artificial intelligence, and the involvement of computers in the architectural process.

The purpose of this change is first to understand the procedures in the second design process involving various disciplines; The third is using computers to complete repetitive design work (Maria & Caffarena, 2002). Designers can parse a design object into specific components through the use of software and machines that are connected directly to the computer. According to Iwamoto, there are five concepts in the digital fabrication process: sectioning, tessellating, folding, contouring, and forming (Iwamoto, 2010) This research will use the tesselation approach.

Tesselation

A tesselation is a group of components and panels of an object arranged to cover a surface. This method can be a strategy to form a 3-dimensional object. Tessellation itself is a drawing method practiced by the mathematician M.C. Escher is known for his geometric works of art (Iwamoto, 2010). His work shows the formation of fragments. The digitally based design process makes it possible to explore this method and apply it to the surface of organisms, such as the surface of shell structures.

Shell Structures

According to the style of formation, this structure is a structure that has a membrane-like shape with the principle of inverted structural forces. The membrane and the tent structure are structures formed due to tensile forces, while the shell structures are the opposite due to compressive forces(Adriaenssens, 2014).Based on the formation curve, the shell structure is composed of 2 ways: the first cylindrical shell formation is like a tunnel. This structure has a longitudinal span, and the direction of curvature is perpendicular to the cross-sectional diameter. This structure has a longitudinal span, and the direction of curvature is perpendicular to the cross-sectional diameter. In general, a series of forming structures forms rigid materials such as composite concrete or steel. The two shells of the dome shape are like a ball. This structure has a bidirectional longitudinal span or is considered a revolving curve on the object axis. In general, this structure's material consists of a series of rigid structural materials such as composite concrete or steel. However, the structural advantage is a series of rigid line elements or a repeating pattern arrangement such as a geodesic dome (Engel, 2013).

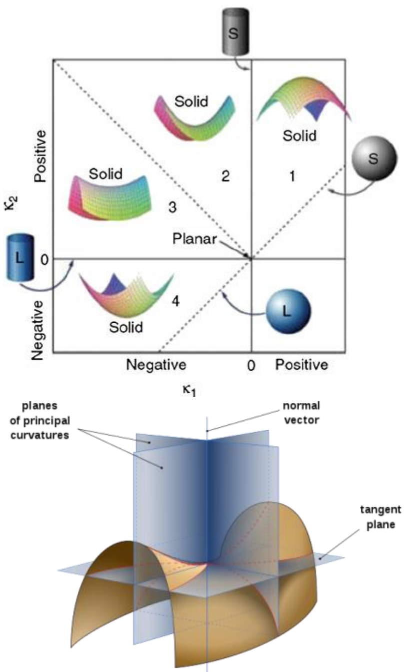


Figure 2. Gaussian Curvature
Source : (Gupta & Saxena, 2012)

From a mathematical point of view, identify the shell structure's shape through the Gaussian curve formula. K1 and K2 denote the two planes that intersect the surface. Both are called the principal curvature of the surface. The two primary curvatures produce an algebraic quantity, namely K=K1 x K2. If K2=0, K0, then the surface is said to have a single or zero Gaussian curvature. If K > 0, the surface is said to have positive Gaussian curvature; if K < 0, the surface has a negative Gaussian curvature. If K is more significant than zero (K>0), it is a positive Gaussian curvature, and if K is less than zero (K<0), the surface has negative Gaussian curvature. The definition of Gaussian curvature explains the classification of the surface (figure 2) . Depending on whether the quantity K = K1 X K2 is positive, negative, or zero at a point, the surface is, respectively, called a synclastic surface, an anticlastic surface, or a surface with zero Gaussian curvature at that point (Farshad, 1992).

Form Exploration Process

To explore formations, this study refers to several past experiments that used physical models to carry out structural and architectural planning. During the Renaissance, Gaudi used a series of hanging chains to form a collection of arcs or funicular curves which became the basis for drawing architectural designs (Célia Regina Moretti Meirelles et al., 2019). Through this test, Gaudi has clarified how the force is exchanged through the averaging arrangement. Until today, architects depend on 3-dimensional arrangements to reenact tensile compression capabilities, both digitally and manually. Within the chronicled improvement of engineering, there are many methods to require into consideration physical structures and models created by modelers, civil engineers, and contractors to realize wide-spanning scope structures, such as shell structures (Indrawan et al., 2020). During the pre-digital era, the form-follow-force rule was regularly utilized by architects to decide and reenact building mechanical standards utilizing adaptable layer materials such as latex cloth. The physical show's investigation strategy is partitioned into 3 categories based on creation necessities: Hanging Apparatus, Pressure Model and Pneumatic Model.

Material

CPB material made from polypropylene was chosen because it is widely used as billboards and packaging. According to one producer, apart from being used for billboards, promotional materials are also used for agricultural and construction needs. In sufficient thickness, this material is also used for construction needs such as foundation formwork. The following table 1 and 2 are material specifications that are commonly on the market:

Thickness (mm)	2	3	4	5	6	8	10
Grammage (gram/M^2)	400	500	700	900	1250	1800	2000
Width	Custom						
Length	Custom						

Table 1. Size and Weight
Source : Impraboard material spesification

Item	Test Method	Unit	TS		TS		TS	
			MD	TD	MD	TD	MD	TD
Modulus Elasticity	ASTM D 882	MPa	874	1107	612	661	824	956
Yield Stress		MPa	18.5	20.7	13.1	14.0	18.8	20.4
Yield Stress		%	12.2	11.5	12.6	8.3	10.3	5.1
Stress at Break		MPa	5	19.8	9.2	12.8	13.4	16.4
Surface Tension	ASTM D 2578	Dyne /cm			45			
Maximal Load	ASTM D 256	N	27.1	7.4	11.6		8.6	164

Table 2. Characteristics of Materials
Source: The results of material test

The advantages of this material are water and weather resistance, able to withstand more than cardboard, easy to clean, printable surface, resistant to chemicals, and easy to process such as cutting, bending, sewing, gluing, and so on (PT Kreasi Dasatama, 2020). CPB material is also included in the type of sandwich panel consisting of 2 thin layers and a thin vertical layer in the middle. This formation is the basic principle for reducing material loads and maintaining its structural capabilities. Corrugated core serves to keep the outer layers separate while stabilizing the components by resisting vertical forces. This design of figure 3 allows it to act as a single thick plate (Rejab & Cantwell, 2013).

Figure 3. Application of CPB
Source: Impraboard

METHODS

This study uses a pre-experimental method to determine the effect of specific treatments on one or more research objects under controlled conditions. However, there are still external variables that affect the research(Sugiyono, 2017). For example,) in a simple form in a non-scaled pavilion by utilizing corrugated plastic board (CPB) material. The selected material was light and flexible. However, it is not a material that has the potential as a construction material in general (e.g., wood, cement, iron, and others). The pavilion is an experimental medium to show forms, materials, and techniques. For example, the Barcelona Pavilion in 1929, which was the work of Mies van der Rohe, was a pavilion that was used not only as an experimental medium but as a real architectural masterpiece and caused much discussion from the experts of its time(Zimmerman, 2006). Another example is the Serpentine Pavilion in London, which curated architects attend almost every year(Arch Daily, n.d.). In this research, CPB material is common for billboards and product packaging to create a scope measuring 2.5 meters x 2.2 meters x 2.7 meters in the form of a dome or shell.

DESIGN PROCESS

This design process begins with the process of determining the effective area of space that will be accommodated by the pavilion and then continues by applying a hexagonal motif (figure 4). This motif was chosen because it has the ability to connect the force vector to its closest component (Birch et al., 2007) so that the force transfer that occurs will be faster which is in accordance with the rules for effective structural planning (Engel, 2013).

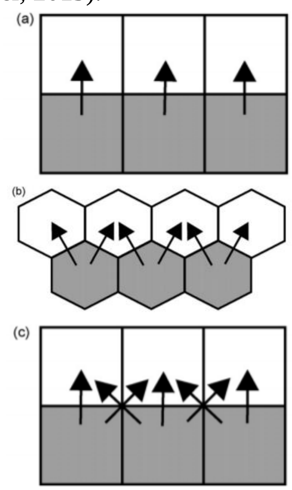


Figure 4. An overview of the potential interactions between components
Source : (Birch et al., 2007)

After the pattern is selected, it is followed by an exploration process of forms or form-finding. This process refers to the experiments conducted by Antonio Gaudi in the past in designing the Colònia Güell and Sagrada Família Churches which used a string with a weighted hanger (figure 5&6) .

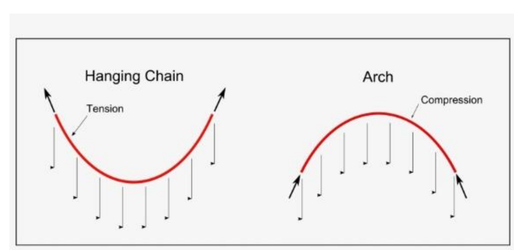


Figure 5. Hanging Chain Principles
Source : (Liu & Chen, 2015)z

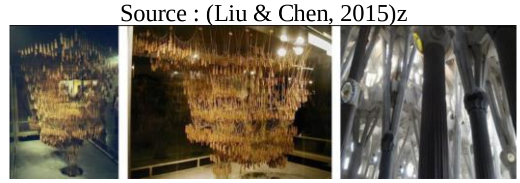


Figure 6. Gaudi’s Sagrada Familia Structure Study Model
Source: (De Luca, 2018)

Through a digital approach using the Rhinoceros, Grasshopper and Kangaroo software, the following can be applied as figure 7&8:

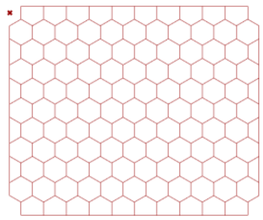


Figure 7. Hexagonal pattern application in floor plans
Source : Author

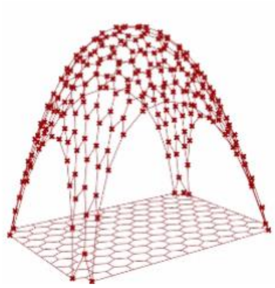


Figure 8. The simulation adopts the hanging chain principle
Source : Author

Corrugated Paper Board material is a sheet or planar material. So that the modeling that is made needs to be divided into mesh or into small pieces in the form of small straight sheets (not curved). In the figure 9 and 10 below, you can see the mesh concept that will be applied.

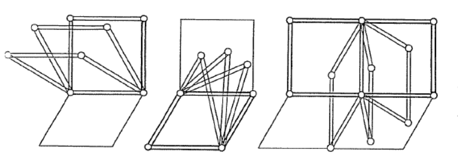


Figure 9. The principle of the component unit of the mesh
Source : (Engel, 2013)

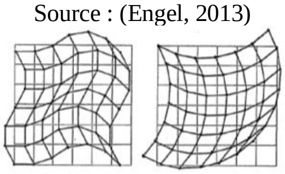


Figure 10. Field flexibility with mesh concept
Source : (Engel, 2013)

In this research, a Hooke's Law simulation process was also carried out which became the basis for distinguishing continuous curves (without fractures) in grasshoppers, known as interpolate curves with broken curves known as polygons. This process is then followed by the process of determining the degree of tilt of each panel. After the angle has been calculated, it can be sure that each straight panel can reach the shape according to the model made on the computer (figure 11). In this process, the material cutting process uses a laser cutting machine of 80cm x 160cm. Therefore, to optimize the use of material, a panel pattern arrangement process is carried out. This process is called Nesting, a process that is often used in modern industries, especially those related to optimizing material sheets (Lutters et al., 2012).

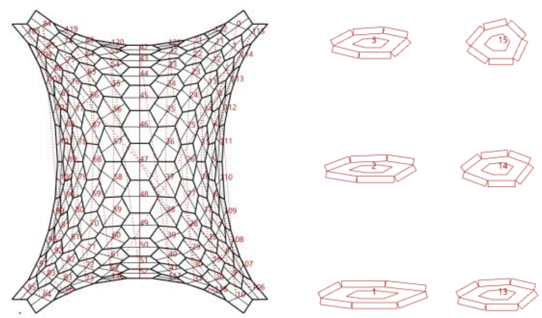


Figure 11. Panel numbering as a reference for the assembling process
Source : Author

In the assembly process, the use of 3-dimensional models plays a more important role than working drawings, this is due to the non-conventional shapes of objects that make it easier for workers to see and interact with the virtual model.

Parameter	Type of Scope Structure	Number of Polygon	Type of Curve	Degrees	Number of Panels (sheet)	Number of materials (sheet)
Structure System	Catenary	-	-	-	-	-
Polygon	-	6	-	-	-	-
Curve	-	-	Polygon	-	-	-
Planarity	-	-	-	<4 degrees	-	-
Panel	-	-	-	-	132	-
Material	-	-	-	-	-	40

Table 3. Control parameters in design
Source: The authors' documentation

The following figure 12 until 15 show the process of assembling objects in the workshop. Each panel is arranged sequentially based on the panel number that has been made in the computer process and then connected using cable ties which are easily found in building shops around the project site. The dome formation occurs automatically based on deformed hexagonal patterns during the simulation process carried out through the Kangaroo software. This CPB material is a material that tends to be lightweight, so it is easy to carry using a small pickup truck and re-installed on site.

Figure 12. Panel joining process

Figure 13. The result of joining the panels to form a shell

Figure 14. Object mobilization process

Figure 15. Object assembled with simple tools
Source : Author

CONCLUSION

Through the aforementioned experiments, it can be concluded that the Corrugated Plastic Board material can be used as the building scope. Although the model made is not large enough in size, it is sufficient as a shade space for humans.The fully digital fabrication process with software that allows formation exploration, structure simulation and material optimization can reduce the planning stages and thus shorten time. A parametric based design approach also allows planners to change the size and basic shape of the dome based on parameters that have been prepared through computer devices (figure 16). The principle of tessellation that is applied also proves that this principle can form a stable structural capability. The use of laser cutting machines can also shorten the material cutting process and can be done by a machine operator who is only assisted by 1-2 people collecting the cutting results of the machine and entering new material.

Figure 16. Dome of the Muqarnas Mosque in Iran
Source : (Goudarzi et al., 2020)

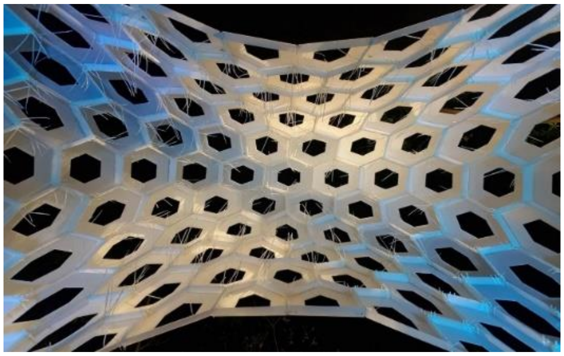


Figure 17. Shell structure with CPB material
Source : Author

However, this process is the initial stage of research on the potential of CPB material (figure 17) . For further stage, it is necessary to study the structure of external forces that will affect the object such as the effect of wind loads, rainwater and new possibilities to make the use of this material even more practical in the assembly process including the use of CPB material for an even larger scale

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