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A Case Study on Capstone Design Education in the Construction Field Using 3D Printer : Focusing on the Concrete Form Liner

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Abstract: Capstone design courses that aim to nurture field-oriented talent and respond to industrial demand are exhibiting various problems. In the construction field, the post-COVID-19 pandemic environment is accelerating changes in businesses centered on off-site production methods and digital data, thereby requiring changes in the direction and process of capstone design education urgently. This study suggests a direction from the new perspective of fostering convergence talents that can guide the future industries that companies must prepare for, presents challenging content and development goals that can converge building information modeling (BIM) and 3D printing technology with construction items, and conducts a case study to assess the problem-solving method. An education curriculum based on design thinking to enable creative problem-solving is presented, high-quality prototypes were printed by applying a step-by-step process, including BIM modeling, 3D printing output, and prototype production and review, and educational experience and completion of technology were verified through demonstrations on concrete members to evaluate the practicality and scalability of the proposed course. This study presents a new perspective of fostering convergence talents who will lead the technology of the future industry that companies must prepare for in the direction of capstone design education, and conducted a case study to introduce digital modeling and 3D printers, which are cutting-edge technologies for enhancing the productivity in the construction field.

Keywords: Capstone Design, 3D-Printing, Design Thinking, Concrete Form Liner, BIM Modeling

1. Introduction

Since 2012, the Korea Ministry of Education has been recommending the establishment of industry-academic cooperation subjects to foster field-oriented talents required by industries such as the Leaders in Industry-University Cooperation, as a measure to resolve the decrease in the educational population and employment oppotunities[1]. The emphasis on “smooth transition from school to field”[2] according to a 2017 press release by the Korea Ministry of Education, capstone design education has become common in various academic fields, including engineering and nonengineering fields, such as design and management. Existing engineering education is biased toward theoretical education and results in a lack of practical knowledge on design and tool application, problem-solving ability, weak adaptability, and communication and collaboration skills[3], leading to immense expenditure for additional education

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in the industrial world. Therefore, while many universities are conducting capstone design courses, the composition of the courses meant to fulfill industrial demand is considered as major courses that are merely an extension of courses that lack creativity[4]. The issues of capstone design education are dealt with based on research that pointed out problems such as the operation type of mono-disciplinary, the selection of tasks due to closeness with team members, and the professor's own experience or industry experience. Furthermore, no guidelines have been proposed for task derivation, team composition, and teaching methods, and research is being conducted to suggest guidelines. However, most studies on capstone design education in the engineering field focuses on the development of standardized educational methods or models based on the comprehensive design of the major field, the application of educational tools, and the proposal and evaluation of the curriculum[5].

In the post-COVID-19 pandemic era, construction industry is experiencing considerable changes at construction sites in terms of workers and materials suitable for the new normal era; furthermore, the innovation in production technology based on digital data and the development of OSC production methods are accelerating[6]. Yet, the capstone design curriculum, which focuses on enhancing practical skills to fulfill industrial requirements, has the restriction that it is limited in operating effective classes by changing the perception that it is an extension of major courses and lacks creativity. In reality, companies are eager to foster convergence talents that will lead the future society such as the 4th industrial revolution amid global competition in response to the rapidly changing industrial environment.

Therefore, this study suggests a direction from a new perspective of fostering convergence talents that can guide the future industry that companies must prepare for, presents challenging contents and goals of current technology in the construction field reflecting the rapidly changing market conditions, and conducts a case study on the methods for solving the problems in the present capstone design courses. The following research scope and methods were established to guide the future society by introducing digital modeling and 3D printing application for enhancing the productivity of capstone design education in the construction field.

- The curriculum of the capstone design education is presented for each week based on an appropriate methodology that allows production of prototypes and practicing the testing process.
- The development and application status of 3D printing-related technology introduced in the construction field was reviewed, a disposable pattern mold for practice was applied for each step of the class content during the class period, and a development process was suggested.
- The development process for prototype production through BIM modeling, 3D printing, and postprocessing was presented, and the optimization and usability of the output was evaluated through field application. In addition, unlike the existing teaching method of presenting a general capstone design curriculum such as team problem presentation, idea extraction, problem-solving method, prototype production, and results' analysis, a study for presenting a systematic process analyzing and evaluating the results of problem-solving up to the design stage through design thinking and practicing prototype production and its application on actual structures was conducted.

The results of this study will not only contribute to the employment and entrepreneurship of students who have experienced convergence research amid the rapidly developing digital-centered societal changes but also be used as basic data for the development of various curriculum tailored for fostering industry-leading talent.

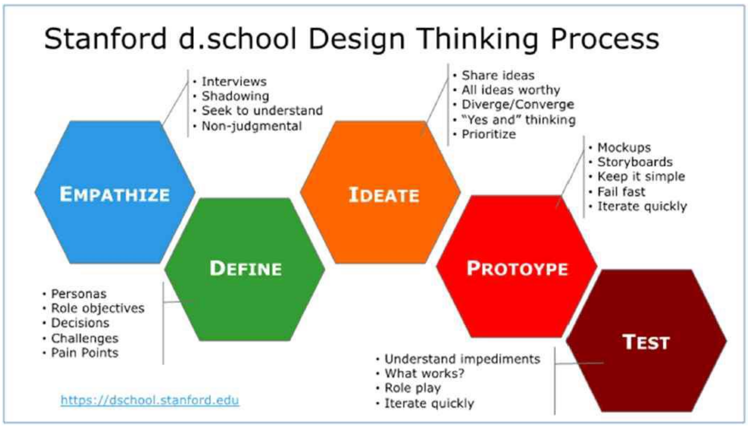
2. Curriculum Composition and Design Thinking

Design thinking refers to a process of finding problems and deriving solutions based on human observation and empathy. It is applied by summarizing and changing the consulting method employed by IDEO, an American design company, according to each situation to procedurally derive innovation.

As shown in [Fig. 1], the Stanford University Model comprise five steps in their design thinking process: empathy, define, ideate, prototype, and test[7]. In engineering, the general development process proceeds through analysis-design-implementation-test, and although long and comprehensive items are extracted when analyzing development requirements, design thinking defines empathy for the end user with concepts, such as personal and schedule.

A case study where the creative problem-solving ability was enhanced because of a capstone design course based on design thinking for engineering students, demonstrated that students experience insight, ideation, and execution of new ideas through the process of divergence and convergence of user problem situations in the design thinking process. This study suggests an education curriculum based on design thinking so that prototype production and field applicability review can be performed beyond the general development process, instead of limiting to deriving creative designs in existing capstone design courses, to ensure that the final product meets consumer requirements.

At the beginning of the course, design thinking process theory education based on creativity enhancement and team building was conducted, and a case study was carried out through a series or processes in which students implemented creative problem-solving by applying each step-by-step process to create a high-quality prototype.



[Fig. 1] Stanford d-school Design Thinking Process

The existing classes for senior consisted in the order of deriving unlimited ideas through discussion, selection and materialization of ideas, deriving design products, discussion, and evaluation. Therefore, the 16-week curriculum of the design thinking concept considering five steps, namely, empathy, problem definition, imagination, prototype, test, was designed to present convergence topics related to the 4th industrial revolution and technological innovation, solve problems and enable practice, and a capstone design curriculum for each week applying design thinking to the courses comprising BIM modeling, 3D printing output, prototype production, and review was suggested. This study is characterized by planning to go further than the concept of design and actually producing a prototype and applying it to the field.

3. 3D Printing Technology in Construction

3.1 Trends Reviews

The UK Ministry of Education conducted a project using 3D printers in several schools for about a year from 2012 for education and design learning in the fields of science, technology, engineering and mathematics, and successfully improved learning motivation and high satisfaction[8]. 3D printer is a tool that facilitates easy and cost-effective prototyping and production of prototypes. In Korea, the Ministry of Science and ICT has been conducting a pilot education program since 2014 in the elementary and secondary education curriculum to understand and practice 3D printing; furthermore, with the announcement of the 3D printing industry implementation plan, manpower training and education have been initiated since 2019[9]. The performance and value of education using 3D printing can be confirmed through various studies and can be summarized using few features. First, the concept of understanding and knowledge are promoted through physical expression of abstract and conceptual knowledge. Then, information and scientific thinking are promoted through the coordination of input values and coding in the process of modeling the imagined ideas.

Research in the 3D printing field related to enhanced productivity in the construction field is broadly divided as 3D printing of concrete materials, production of atypical formwork, and form liner design. Concrete 3D printing includes the binder jetting method, where depending on the lamination method and material, liquid adhesive is sprayed onto fine sand powder material according to input information, and the material extrusion method, which extrudes materials such as cement mixtures, plastic, and metals[10]. As a representative example, Apis Cor, a robot architecture company, constructed a two-story building in Dubai [Fig.2] using its own 3D printing technology. Increasing demand for atypical structures with superior landscape as well as design and construction technologies to reduce construction period and costs are being realized through the development of materials and equipment[11].

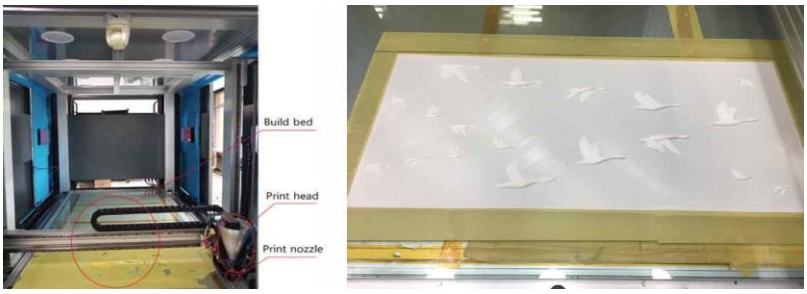
Generally, the production of atypical members consumes a large amount of time and manpower and is difficult to recycle. In the past, various materials, including steel, wood, styrofoam, and textiles, have been used, and research on casting technology of three types of methods (grouting, press, and plaster) and production management is in progress[12]. While the method of CNC machining EPS and installing it inside the existing formwork is economic, it has problems such as distortion from lateral pressure of concrete; therefore, research on foam liner printing and quality control using 3D printers has been recently conducted[13]. Research for the application of laminated object manufacturing (LOM) which enables fused deposition modeling (FDM), a representative 3D printing method, and rapid prototyping is underway, and verification of its safety and usability is in progress as shown in [Fig. 3] and [Fig. 4][14].

Among form liners, in case of the disposable pattern molds, 3D printing has a great effect on cost reduction as reuse does not need to be considered for the production of symbolic patterns or shapes. As basic research for the development of pattern molds, there is a study conducted using silicone, which can withstand lateral pressure of concrete, has a simple processing method, and has low initial investment cost, and another that is conducted on materials and experiments that maximize design effect for sophisticated exterior finishing. Another study that presented a design plan using variable modeling of the 3D design program to add regional characteristics or design elements to the existing sample repeating pattern mold, produced the mold, and applied and verified it on the field has been conducted as well[15].

This study, which aims to educate engineering students on 3D printing, was planned to secure durability and economic efficiency of concrete surfaces by using high-cost disposable form molds, which are used to exhibit aesthetics or symbolism of concrete, that were printed with a 3D printer, and was conducted to achieve experience in the planning and production process.

[Fig. 2] 3D Printed Wall Structure for an Administrative Building in Dubai[11]

[Fig. 3] Form Liner Manufactured by LOM[13]



[Fig. 4] Form Liner Manufactured by FDM[14]

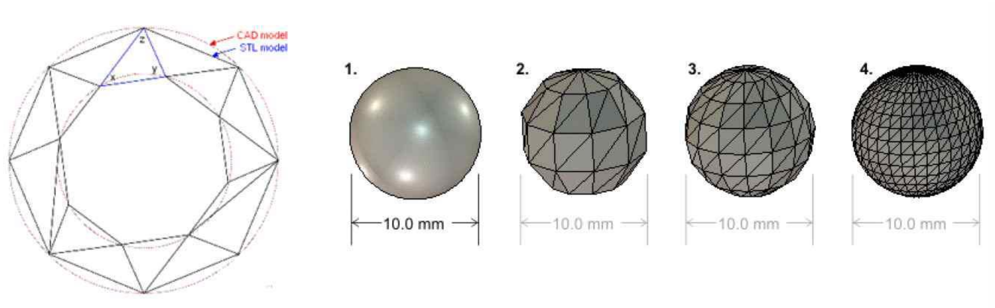
3.2 3D Modeling

3D printing is a process of stacking layers to create a three-dimensional shape, and the overall flow is shown in [Fig. 5]. First, after 3-dimensional designing through modeling, the process of producing a 3-dimensional object, STL (stereolithography) file format is mainly used to save modeling data as the standard format file. STL is a recognizable extension in the slicing stage, and as shown in [Fig. 6], the model surface is split into countless triangles and the location data of each vertex is saved. A smoother surface can be created with smaller triangle size[16]. The next step is the slicing step, which is the process of converting the STL file into G-code (general code) for the 3D printer to understand, and various types of software can be used. After printing the 3D object, the final step is the postprocessing step, which consists of smoothing and cleaning the surface, and color treatment to complete the object.

Generally, modeling work is classified into two types: the reverse engineering technique that converts an existing object into a digital model, and another where the designer creates a new shape using his/her own ideas. In case of an existing object, modeling can be done through a specific equipment that can measure the 3-dimensional structure or an image-based modeling approach, and in case of designing an imaginary object, tools such as paper sketching, model making, and CAD are used. Regardless of the modeling method, a digital model of the object must be completed before output in order to be connected with 3D printing.

Methods that can reproduce an existing object as a digital model include 3D Scanning, a method that convers surface area depth information of a target object into data through scanning from various angles to obtain morphological data, and Video Trace technology, which creates a 3D polygon mesh by creating the contour of the object as polygon data and converting it to a surface.

[Fig. 5] 3D Printing Process Followed by Digital Modeling



[Fig. 6] Conceptual Model for STL File Format[16]

In case of designing new objects, various digital tools such as 3DMax, Maya, and Catia are used. Research and development on designing using AR/VR technology is under progress. In the construction field, innovation in the design method using building information modeling (BIM) from the traditional method of designing with 2D CAD is in progress, and commercial software such as Revit, Archicad, and Rhinoceros are being used.

4. Prior Review and Modeling

4.1 Parametric Study

For the development of disposable pattern molds, establishing the research scope for manufacturing method using a general low-end 3D printer, setting the appropriate thickness for intaglio or embossing, and depth of pattern production on the concrete exposed surface is necessary. As developing a thin skin type with the FDM method is difficult, and applying curves with rigid materials is impossible, the selection of a material with high ductility for split fabrication and bending, and the possibility of using permanent mold were reviewed in advance.

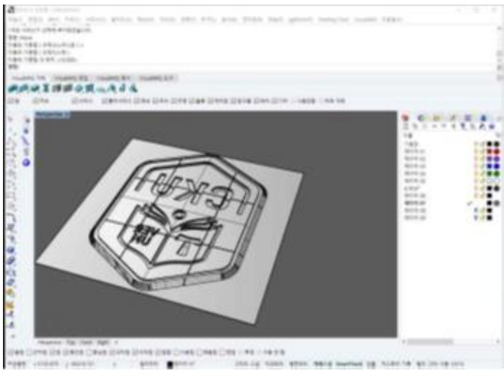
During modeling, the thickness and depth of the bed were established by considering the pre-segmentation work and the minimum particle unit, and variables were eliminated step-by-step through various experiments and pre-printing after split production for joining. The thickness of the skin to be attacked to the wooden form mold was determined to be 1 mm thick to minimize adhesion and step difference, but for the corners, where the protrusion and flat section meet at a 90-degree angle, various modeling and output tests were carried out in consideration of preventing concrete dropping during demolding, precision at the time of printing, and the applicability of TPU.

As a result of analyzing various modeling and output results for different variables, the range of the fillet was limited to a maximum of 0.7 mm, and when the depth of intaglio was greater than the width, problems such as concrete dropout and durability occurred, thus the depth was set to 5 mm based on 12 mm width of the linear line to produce the protrusion depth, and the width and depth of prototype production specifications were set at a ratio of 1:2.4.

4.2 Information Modeling

For The 3D printing modeling subject for student practice was selected as an environmentally friendly eco-pillar four-way dam for preventing landslides in the absence of concrete, and the hollow track-type column cross-section side was chosen for the performance test. To create a symbolic pattern on the surface of the column, the Catholic Kwandong University logo was borrowed, and a commercial BIM tool was used to model the pattern form mold. The size of the hollow track-type column made by precast was 1,500 mm in width and 1,000 mm in length, and the side of the column without curves was 500 mm wide, and the vertical size of the logo was limited to 600 mm; the width was determined according the accumulation and finally, the form liner to be printed was modeled to be divided into nine pieces of 200 mm in length and 200 mm in size.

As student experience and experimental data were insufficient to successfully produce a form liner in one process, the final product was planned to be printed through a multiple prototyping by producing BIM modeling in the form of a library while changing the specific dimensions. Since the creation of a new library in the commercial BIM tool is only possible with professional programming skills, the difficulty was adjusted to produce a prototype within the limited class time. Visual programming provides users with improved intuition and greatly reduces programming time and supports easy use for even beginners lacking coding skills[17]. Students were educated with minimal BIM modeling and visual programming techniques and given the form liner design mission.



[Fig. 7] Vidual Modeling using BIM tool

To create the pattern line of the form liner, the flat image file of the logo is set to scale after the import command. After converting the logo plane image to a face, the embossing depth is set and created into a solid object, removed from the intaglio solid to complete the model, and after saving, the process was finished after exporting it as an STL file. Modeling was done using Rhino and converted to STL extension using CADIAN 3D software. [Fig. 7] shows the programming and modeling execution screen.

5. Prototype Printing and Field Application

5.1 3D Printing

The 3D printer that will print prototypes based on BIM model data is the FB-Z420 model that is for professionals that can use various materials such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and thermoplastic polyurethane (TPU), and equipment supplied in the 3D printing education center at the university was used.

The representative materials used in 3D printers include ABS, PLA, and TPU. In case of ABS, while it has superior secondary processability, cracks or warping may occur during printing; in case of PLA, it contains few harmful elements in the raw materials, has low shrinkage due to thermal deformation, but has the disadvantage of weak durability and difficult secondary processing. In case of TPU, it has excellent elasticity, mechanical strength, abrasion resistance and transparency[18]. In this study, PLA was used for the output of the variables’ study, and TPY material was applied to the final prototype to be applied to the curved part. As shown in [Fig. 8], the final part to which the TPU material is applied was printed and bonded to complete the form liner after the final modeling was adjusted through the temporary output and matching test using the residual material.

[Fig. 8] Disposable Form Liner Printed by 3D Printer

5.2 Field Application

The form liner (disposable pattern form mold) that was finally printed with the 3D printer was applied to the side of the real model manufactured for the performance test of the concrete eco-pillar dam to review the installation process of the mold interior, and the degree of pattern production and applicability after demolding. As shown in [Fig. 9], the remaining form liner was removed after demolding of the concrete mold, and the final complete logo can be seen.

Improvement points and characteristics obtained through the demonstration process are: First, in the process of installing the form liner to the mold, the thickness of the base support surface of 1 mm may drop off after curing the concrete, thus a thickness greater than 1 mm must be reviewed and step difference must be considered. Also, there is a high possibility of concrete peeling where each part of the 9-divisions is connected, so enhancing the precision of output and connection work is necessary to improve the visual sense of disconnection. The selection of TPU material not only allowed to demold concrete without any damage without applying a separator but also prevented cracks by absorbing dry shrinkage stress generated during the curing process due to ductility of material and is expected to show great effect in securing durability of the exposed concrete. On the other hand, according to the size of the structure, variable studies on height difference of intaglio and embossing must be conducted considering the material characteristics to minimize trial and error, and observation of long-term wear after demolding is necessary to improve durability. In case of producing a disposable pattern mold is expensive but is expected that using a 3D printer will be able to economically produce symbolic products.

[Fig. 9] Final Logo Clearly Engraved on Concrete Face

By directly constructing and demonstrating prototypes produced through the compressed curriculum of advanced 3D modeling and printing on concrete structures, students can obtain quantitative educational effects as well as experience in using and applying advanced technologies from a macroscopic perspective and be given the opportunity to gain confidence.

Student interest was high in all courses, and the project was carried out in teams even outside of class time. In particular, the provision of direct on-site experience gave students confidence that this could be actually used in the field and be expandable, and it is judged that the direction of capstone design education of construction field converged with innovative technology will have a great educational effect.

6. Conclusions

Results of this study contribute to the employment and entrepreneurship of students who have experienced convergence research in a rapidly developing digital-centered future society; furthermore, these results are expected to be used as basic data for the development of various curriculums tailored for fostering convergence talent, and obtained the following results:

- The current status of development and application of 3D printing-related technology being introduced in the construction field is reviewed, and the required development process limited to disposable patterned molds for practice within the class period were introduced and reflected in the class contents.
- Development processes such as BIM modeling, 3D printing, and postprocessing for prototype production were presented, and optimization and usability were verified through field application of the printed results.
- If the curriculum of capstone design education is directed at educating advanced technologies that will lead the future, it is expected to develop into a subject that can achieve both educational effect and R&D results as shown in the results of this study. It is believed that this study will not only contribute to the employment and entrepreneurship of students who have experienced convergence research amid the rapidly developing digital-centered societal changes, but can also be used as basic data for the development of various curriculums tailored to fostering industry-leading talent.

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