Integrated Off-Site Construction Design Process

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Off-site construction (OSC) offers a promising means to improve the efficiency of construction projects. However, the lack of experience and knowledge regarding its use results in errors in design owing to conflicts and omissions of considerations for OSC projects. To mitigate these problems, the design for manufacturing and assembly (DfMA) is widely used to include the considerations in the OSC design process.

offsite construction (OSC) precast concrete (PC) design process

1. Introduction

Offsite construction (OSC) methods have many benefits, such as a decrease in construction waste, duration, project cost by standardization, and cost variation, in addition to reduced effect on the construction site, as the building elements are produced in factories [1][2][3][4]. Despite its benefits, OSC has yet to become a mainstream technique, even in countries that have successfully implemented it [5][6][7]. Many studies have been conducted to identify the factors hindering the widespread use of OSC, and the problems related to lack of experience and knowledge of the project stakeholders have been identified as the major barriers and constraints [7][8][9][10][11]. These problems caused errors such as omission and conflict in design and the absence of early interventions for essential decision-making [10]. To mitigate these problems, the need for design guidelines related to the OSC process has been emphasized [5][11][12][13]. The design for manufacturing and assembly (DfMA) principle is widely considered to include manufacturing and assembly considerations in the OSC design process, and several studies have been conducted to incorporate the same in the downstream design processes. However, the fragmented results of the previous studies do not facilitate the development of a comprehensive design process to mitigate the problems encountered in the OSC industry.

2. Considerations in Design Phase for OSC Project

2.1. Considerations in Structural Design

The considerations reported in the publications identified through the search criteria were classified as considerations related to (1) structural design or (2) architectural design. In OSC projects, the size of the prefabricated elements is limited because the size should satisfy the traffic law for transportation and the element should be designed considering the efficiency of lifting and assembly. After transportation, the discrete elements are assembled onsite to construct the building structure; therefore, the structural performance of the assembled elements as the whole building structure should be ensured. To evaluate the performance, many studies have focused on various performance criteria. The origin of anti-seismic research focusing on precast concrete elements can be traced back to the early 1990s [14]. Englekirk [15] investigated the seismic performance of PC buildings and the effect of the connection design between components on the seismic performance. The assembled elements are vulnerable to lateral loads such as seismic loads, and securing the structural performance is a major consideration in OSC projects. Therefore, many studies related to the seismic behavior of an element, performance evaluation of structures obtained by the assembly of the elements, and the connections between the elements have been conducted [14]. Gu and Dong [14] suggested an assembled rebar lap splice and tested the precast and cast in situ shear walls, where the suggested splice was applied by changing the position of the splice and length of the rebar lap in PC shear walls. The test results showed that the seismic performance of the PC shear walls was equivalent to that of cast in situ shear walls. Ding and Ye [16] investigated the seismic performance of a joint between a PC column and girder by using a bolt-connecting system. The experimental results demonstrated that the joint system with bolt connection satisfied the structural requirements and improved the resistance to seismic loading. Feng and Xiong [17] suggested a numerical simulation method for the assessment of the seismic performance of dry connected PC beams and slab assemblies. Wu, Xia [18] investigated the flexural behavior of PC walls and steel shoe composite assemblies with various dry connections. The flexural behavior tests were conducted under five different scenarios, and the results showed that the performance satisfied the requirements regardless of the connection arrangement. In summary, the design of the connection system in prefabricated buildings is a major consideration in structural design because the assembled prefabricated elements are subject to brittle shear failure during earthquakes and are more sensitive to seismic loading when compared with conventional reinforced concrete (RC) structures.

In addition to lateral loads, connection systems should meet other performance criteria. In the study by Jiang and Zhang [19], the out-of-plane bending performance of a PC hollow core slab with a suggested lateral joint was tested. From the test results, the relationships between the performance and effects of the rib of the slab and the number of joints on the crack of the slab were identified. While assembling the elements onsite, the temporarily connected elements should resist the loads generated during onsite construction. Araújo and Prado [20] focused on the temporary beam-to-column connection during onsite assembly to ensure construction safety. A beam-to-column connection was suggested, where the U-shaped steel corbel was embedded in the column to support the cantilevered steel tube at the beam extremity. The suggested connection system showed 60% of the theoretical strength of the corbel in the assembly phase, which ensured safety during construction.

In addition to the studies related to the structural performance of element connection systems, studies have been conducted to improve the comprehensive structural performance of whole building structures consisting of prefabricated elements. Dal Lago and Biondini [21] suggested a framework for the structural conception and seismic behavior assessment of PC structures with a cladding panel. The suggested PC structure with a cladding panel showed improved seismic behavior owing to the flexibility of the PC frame and stiffness of the panel. Vertical and horizontal wall connections are considered vital in the PC shear wall structure (PCSW). Horizontal wall connections usually ensure the normal functioning of the PCSW, and the development of a horizontal wall considering constructability and high structural performance is important for the PCSW structures. Wang, Li [22] investigated the seismic performance of precast shear wall structures with suggested horizontal wall connections, and the test results indicated a performance similar to that of the cast in situ concrete shear wall.

In the connection of a 3D volumetric modular unit, the connection system should ensure constructability in addition to satisfying the structural requirements. The lifting and assembly of units at the construction site are considered critical tasks. Therefore, the project efficiency is related to the assembly of large and heavy units. Sharafi and Mortazavi [23] suggested an interlocking system to connect the modular units and tested the structural performance of the proposed system. In addition to satisfactory structural performance, the constructability during onsite assembly was improved by automatically interlocking the units. Liew and Chua [24] suggested a connection system for a high-rise modular building and connected the units via a vertical rod and horizontal tie plate. The system was used to connect the building to an external unit. Lacey and Chen [25] suggested a connection system for modular steel units consisting of structural bolts with interlocking elements. The shear force–slip behavior of the suggested connection was improved when compared with that of the previous interlocking system. In addition to the structural performance, the limitation of small allowable tolerance was mitigated, and the constructability was improved by using bolt connections. Luo and Ding [26] investigated the mechanical performance of beam-to-column connections for steel-framed modular units. The proposed end-plate stiffener connection showed better performance than the other connection types.

In the structural design of an OSC project, discrete elements are assembled to construct a building structure. Owing to the nature of the discrete elements, it is necessary to ensure the following in the structural design phase: (1) the integrity of the elements for the composite behavior to resist various types of loads such as lateral and vertical loads, (2) meeting the structural requirements of the comprehensive building structure after element assembly, and (3) the constructability of the elements during onsite assembly.

2.2. Considerations in Architectural Design

The building design for OSC projects should be separated into elements for transportation and onsite assembly. The constraints related to the nature of the OSC project need to be included in the design. In modular construction, the building structure consists of 3D-volumetric units and the spaces for the facilities are generated by combining one or more units. However, it has constraints such as heavy weight of the concrete modular units and larger size than the materials used in conventional construction methods. In the study by Liew and Chua [24], the design guidelines for steel–concrete composite high-rise modular buildings were suggested to address these constraints. The steel–concrete composite units have long span, design flexibility owing to the open space framing system, and ease of assembly when compared with concrete units that require in situ grouted joints. Moreover, by using lightweight aggregate concrete, the issues related to heavy weight and fire resistance were mitigated. A high-capacity mobile or tower crane is used to assemble the modular units onsite. Hyun and Park [27] suggested an optimization model for tower crane location by considering the distance between the destination of the units and the locations of the tower crane and trailer at the construction site.

Prefabricated elements are usually transported by a trailer. Vibrations during transportation damage the prefabricated elements. The cost of restoring the damage is higher than that of rework in conventional construction methods [28][29]. Therefore, the need for a design procedure to consider non-traditional loads, such as transportation, lifting, and other pre-installation loads, has emerged [30]. In modular construction projects, the effects of vibration are different depending on variables such as speed, road condition, and structural type of the elements and the components of the furnished units. Innella and Bai [29] conducted an experimental study to quantify the acceleration affecting the modular units during transportation. The accelerations of the trailer and units were measured using triaxial accelerometers. Based on the results, the power spectral density, which characterizes the random vibration, was presented according to the speed and road conditions. The mechanical responses of the units during transportation can be calculated using the presented spectra. In a follow-up study, Innella and Bai [30] ascertained that the damage occurrence probability was high in the non-structural elements of modular units such as plaster board and their connections, which are subjected to long cyclic accelerations during transportation. A framework was developed to evaluate the damage levels of non-structural elements during transportation according to different parameters such as stress probability, accelerometer position, speed range, and road roughness.

The amount of dynamic loading during transportation depends on parameters such as the amount of load on the trailer, location of the center of mass, trailer suspension type, and level of damping of the vibrating part. Godbole and Lam [31] mentioned that the response behavior of buildings to the loads caused by an earthquake is similar to the behavior of the loads during transportation and investigated the effect of the parameters on the vertical motion of the trailer chassis. Researchers suggested the specific vertical acceleration that the mount and its connection to the trailer should withstand and estimated the vertical accelerations that damage the components attached to the unit. In a follow-up study, Godbole and Lam [32] investigated the pounding on trailers caused by the accidental uplifting of a unit during transportation. A methodology to estimate the impact acceleration resulting from the pounding of a unit on a wooden mount and the response accelerations of the components attached to the unit at the mid-span location were predicted. The prediction results showed that a typical steel unit amplified the component acceleration response up to three times. Previous studies related to unit transportation implied that the design of prefabricated elements such as modular units should consider assembly-related constraints such as weight and size, transportation-related issues such as the deformation of structural components caused by dynamic loads, damage to the non-structural components attached to the unit caused by the transformation, and amplified impact transferred from the structural components. This is in agreement with the study by Bogue [33], who suggested a guideline to reduce damage during transportation and recommended the minimization of the use of fragile parts. These studies indicate the importance of considering assembly and transportation in the design stage of OSC projects.

In OSC projects, the work of enveloping the building structures affects the project performance because the assembled building elements are integrated through the building envelopment. Therefore, novel technologies for envelopment of prefabricated buildings are required. PC panels and cladding have been used to enclose prefabricated and conventional buildings. A prefabricated building envelope is required to be waterproof because the joints of both the prefabricated envelope and building structure, which are connected onsite, are more vulnerable to water problems than cast in situ concrete envelopment. Gorrell [34] investigated the condensation problems that caused damage to the finished materials such as insulation and gypsum boards. Orlowski and Shanaka [35] suggested a methodology for designing waterproof seals for prefabricated buildings. They conducted a theoretical research of the generation and transfer of moisture, such as the capillary action of moisture in narrow gaps on the building surface. Then, the considerations for the application of the waterproof seal for prefabricated buildings were identified, such as fast erection time and omission of scaffolding.

To achieve the goal of design in OSC projects, it is necessary to facilitate collaboration between the project stakeholders. Chen and Lu [36] presented a case study of a curtain wall system designed using a DfMA-oriented approach to meet the requirements of stakeholders such as clients, manufacturers, and contractors, and a multidisciplinary team was organized for the integration of knowledge and experience. Researchers recommended that the project delivery method to integrate the team, such as design–build, should be selected, and the stakeholders involved in the design phase need to be identified depending on the project objective. Yuan and Sun [37] argued that although BIM can facilitate information exchange between stakeholders, the existing BIM tools do not fully account for the prefabrication of building elements, such as element production and transportation. The DfMA approach for prefabricated buildings was integrated with a parametric design method using BIM, and researchers suggested a DfMA-oriented design team, prefabricated element manufacturing process, and a DfMA-based BIM model development and optimization process.

In summary, the design of prefabricated buildings should consider an intermediate process owing to the nature of the OSC project. Many researchers have focused on the transportation aspects of prefabricated units, such as element size limitation set by traffic laws, vibration during transportation, and the use of impact-resistant materials. This means that the space in a building can be separated using the prefabricated elements, and the elements must be able to cope with vibration and deformation during transportation and lifting. Moreover, to consider the assembly at the construction site, the weight of the elements and site layout for facilitating the entry of the trailer should be included in the architectural design. Finally, project delivery methods or information-sharing tools to facilitate OSC project progress are required. Therefore, to support the design process of OSC projects, design guidelines that allocate the considerations for each sub-design phase are required.

3. OSC Design Process

The objective of the OSC design process is to support the OSC project stakeholders by sharing the identified considerations for the sub-design process; thus, this process can be used as a design guideline. To develop the process, it is necessary to allocate the considerations to the appropriate design phase to prevent errors such as omissions and conflicts caused by not including the essential considerations. The process is based on the conventional design process of the American Institute of Architects (AIA). AIA provides a checklist consisting of the tasks that should be conducted in each sub-design phase based on the standard form of agreement between the project stakeholders. The scope of the checklist is from the pre-design to construction documentation phase, and the checklist specifies the stakeholders who should be consulted by the designers to conduct the specific tasks in the design phase [38]. For example, in the project programing of the pre-design phase, the architect collaborates with the consultants to determine the preliminary structural, mechanical, and electrical systems. In this phase, the decision making to determine whether the OSC method will be applied can be included by allocating the considerations related to the decision-making process. The suggested process is based on the assumption that the OSC method is considered in the pre-design phase; if it is decided to apply the OSC approach, the project stakeholders will cooperate with the architect to provide consultation for the design, production, transportation, and onsite assembly of the prefabricated elements.

Because many studies have argued the importance of the early involvement of the OSC method, the suitability of the OSC method is evaluated in this phase to maximize project efficiency. If the program is suitable for the OSC construction of buildings, such as dormitories and apartments, comprising residential units that can be standardized, the architect supports the decision-making process of the owner based on the identified benefits and constraints [5][8][10][39][40][41][42][43]. After deciding to adopt the OSC method, the architect organizes the design team, including consultants, such as structural, MEP, and special engineers. In the OSC project, the manufacturers and engineers who have experience in or knowledge of OSC are included in the special engineering group to provide advice in the early project phase [44]. At the end of the pre-design phase, the preliminary building systems are determined, and the specific method of OSC (e.g., MiC, PC) is selected based on the consultation. Before the schematic design phase, site analysis is conducted and all consulting staff visit the construction site. In this phase, the information for transportation and onsite assembly, such as regulations related to traffic laws, road conditions for transport from potential manufacturing factories, pathways for trailers to approach the site, and potential location of the crane, is collected [27][28].

In the schematic design phase, laws, codes, and regulations applicable to the service of architects and necessary information for the OSC method. A preliminary design is presented for the owner’s approval. After obtaining approval, the tasks in the schematic design are initiated. In this phase, the major building systems to be used in the project, such as structural and MEP systems, are selected through analysis of the comparative systems, and the space and location of the systems are determined based on the requirements. The structural form and design load are determined, and the materials for the interior, exterior, and structure are studied [38]. Therefore, the load caused by transportation, lifting, and assembly should be considered in this phase [31][32][45]. Then a schematic design is prepared, which includes the features of the OSC method, such as repetitive production of elements and allowable span of space [24]. Materials that cannot resist vibrations and shocks during transportation should be excluded from the design [29][30]. In addition to consulting structural and MEP engineers, the architect draws the architectural design in collaboration with the engineers in the manufacturing unit by considering manufacturability and constructability.

In the design development phase, an approved schematic design is developed. The design documents in this phase include the typical construction details and layouts of the building systems, and they describe the size and features of the architectural, structural, mechanical, electrical, and other elements. The building design is separated into prefabricated elements, which are designed independently to determine their specifications, such as length, width, and height. In the separation process, the building parts to be prefabricated first are identified considering standardization and economic feasibility. For example, certain zones or floors in the architectural program may be excluded from prefabrication. In general, the architectural designs are for prefabrication of all structural elements. However, if some members are irregular or if the quantity is too small to be prefabricated, it can be evaluated whether the elements are to be constructed using the cast in situ concrete method, whereas non-structural elements, such as the building cladding, can be prefabricated [21]. After identifying the building parts that qualify for prefabrication, the elements of building design, such as beams, slabs, and columns, are split for prefabrication considering their transportation and assembly. Yuan and Sun [37] have recommended that the element-split designers, including the manufacturer and assembly technicians, from the construction company be included during the separation process. These personnel should cooperate with the architectural and structural designers. Additionally, appropriate communication channels must be established between these designers to obtain timely feedback from the stakeholders. The individual elements are assembled onsite; therefore, the constructability of OSC indicates the ease of assembly. In this phase, the details of the connecting system for the elements are prepared.

In the construction document development phase, drawings and specifications are prepared to describe in detail the quality level, performance criteria of materials and systems, and other requirements for the construction. In terms of structural design, the dimensions of the individual elements, such as width, height, and cross-sectional area, are determined. In addition to the size of the elements, the design and performance of the joint connecting the prefabricated elements of the PC structure should also be considered, because the structure is more sensitive to lateral loads, unlike the joint of a traditional reinforced structure. Therefore, in this phase, it should be ensured that the selected joint design can resist lateral loads such as the earthquake loads specified in the structural requirements. At the construction site, the prefabricated elements are assembled according to the joint design. The efficiency of the onsite assembly can be improved by considering the constructability when designing the joint. For example, the PC structural elements are assembled by connecting the rebar of the elements using sleeves or grouting non-shrinkage mortar to the joint, although the connection method differs depending on the joint design. Therefore, it is helpful to improve the constructability to reduce the number of rebars in the elements while preserving the structural performance [46]. After the construction documentation is complete, the manufacturer prepares the drawings for the prefabrication of the elements, and contractors prepare the shop drawings for element assembly based on the construction documentation.

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