

# Digital engineering models for prefabricated bridge piers

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**Abstract.** Data-driven engineering is crucial for information delivery between design, fabrication, assembly, and maintenance of prefabricated structures. Design for manufacturing and assembly (DfMA) is a critical methodology for prefabricated bridge structures. In this study, a novel concept of digital engineering model that combined existing knowledge of DfMA with object-oriented parametric modeling technologies was developed. Three-dimensional (3D) geometry models and their data models for each phase of a construction project were defined for information delivery. Digital design models were used for conceptual design, including aesthetic consideration and possible variation during fabrication and assembly. The seismic performance of a bridge pier was evaluated by linking the design parameters to the calculated moment–curvature curves. Control parameters were selected to consider the tolerance control and revision of the digital models. Digitalized fabrication of the prefabricated members was realized using the digital fabrication model with G-code for a concrete printer or a robot. The fabrication error was evaluated and the design digital models were updated. The revised fabrication models were used in the preassembly simulation to guarantee constructability. For the maintenance of the bridge, the as-built information was defined for the prefabricated bridge piers. The results of this process revealed that data-driven information delivery is crucial for lifecycle management of prefabricated bridge piers.

**Keywords:** DfMA; digital engineering model; parametric modelling; prefabricated bridge pier; tolerance

## 1. Introduction

A novel data-driven design paradigm has emerged in the construction industry. The design indicates that domain knowledge should be digitalized for digital transformation of construction. Building information modeling (BIM) is widely used in construction projects and provides well-organized data from each construction stage. BIM functions as a platform of information delivery only in the construction industry and is mostly used for design check, simulation, and estimation (Lee *et al.* 2012, Shim *et al.* 2012, Shim *et al.* 2018). Digital models with appropriate data can improve the design quality and support digital fabrication. Level-3 BIM requires considerable effort to generate knowledge data, and its uses beyond the construction industry include robotic field and data science (HM Government 2015). For the digital economy and sustainable development of infrastructures, construction engineers should expand information exchange with other industries. Through the digitalization of infrastructures, data-driven engineering can be realized for national assets (Bryden Wood Technology Limited 2017).

To enhance the productivity of the construction industry, prefabricated bridge elements and systems have been developed in several countries (Shim *et al.* 2010, Kim *et al.* 2016, Koem *et al.* 2016). The main objective of this study is

to enhance the connections of prefabricated systems. When prestressing is required to integrate individual members, geometry control should be strictly managed using the match-casting method. If the tolerance is higher than the allowance, the assembly works can be delayed and required additional temporary work on construction site. For example, accurate geometry control during fabrication is critical for bridge columns; otherwise, vertical cracks may occur during prestressing because of uneven compression to the section.

Among design parameters of bridge piers, seismic requirements regarding details and ductility are critical for standardized design of prefabricated column segments. Numerous experimental programs have concluded that prestressing forces and relevant design values are critical (Shim *et al.* 2008, 2017b, Wang *et al.* 2014, Sideris *et al.* 2015, Koem *et al.* 2016). P–M diagrams are calculated for static loads from superstructures to evaluate safety. Moment–curvature curves are used for evaluating seismic requirements (Koem *et al.* 2016). When typical column sections and seismic requirements occur, fabrication and assembly consideration can be automatically performed.

Design for manufacturing and assembly (DfMA), which originates from the manufacturing industry, is critical for prefabricated structural members in civil engineering. DfMA is an engineering methodology to reduce the delivery time and total costs through easing of manufacturing of the prefabricated structural members and systematic assembly of these members into the final structure. DfMA requires integration of production and assembly experience. Typically, a feedback loop between design, manufacturing,

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and assembly is required in prefabricated member DfMA to identify any potential problems or wastage and reduce project delivery time, cost, material use, pollution, and workers' injuries (BCA 2016, Gao *et al.* 2018). The process of bridge construction may eventually be automated through the digitalization of the design, digital fabrication, and automatic machine guidance.

Object-driven tool and an integrated collaborative environment are critical for optimizing the design of prefabricated components through DfMA (BCA 2016). Digital models for DfMA of prefabricated components should be developed and standardized to streamline the process (Yuan *et al.* 2018, Alfieri *et al.* 2020, Gbadamosi *et al.* 2020). These studies focused on building components. By using BIM, DfMA for prefabricated bridge members can integrate data throughout the project cycle. This result is the foundation for current engineering processes to minimize waste and inefficiency. Digital models for prefabricated members can be produced through 3D concrete extraction printing (3DCP) for automatic fabrication in a factory (Anton *et al.* 2021).

The digital model accumulates domain knowledge and data for DfMA of prefabricated members, which results in the development of digital twin model including performance history during operation and the maintenance period. Shim *et al.* (2017a, 2019) developed a BIM-based maintenance system for prestressed concrete members and cable-supported bridges. Federated digital models with data from design to construction can be imported to a maintenance system through database-to-database transfer (UK BIM Alliance 2019). Therefore, defining digital models and their data for prefabricated members is essential.

In this study, the theoretical digital engineering models for prefabricated bridge piers were proposed to enable data-driven engineering through the information of design-fabrication-assembly. Previous findings regarding development of precast bridge columns were considered to define the digital models and their uses. For each phase of a construction project, digital models and data were defined and revised through construction management.

## 2. Digital engineering models for prefabricated bridge piers

### 2.1 Digital engineering models

Prefabricated members exhibit various characteristics from common precast members. As displayed in Fig. 1, all the information for design, fabrication, and assembly should be federated for the ease of fabrication and assembly. Therefore, DfMA is a basic approach and should be digitally defined as data models for data-driven information delivery between each phase. Among bridge members, bridge piers belong to critical path of any bridge construction project. During the development of the precast bridge columns, critical design parameters for safety, serviceability, and seismic performance were determined (Shim *et al.* 2008, 2017a, b, Koem *et al.* 2016).

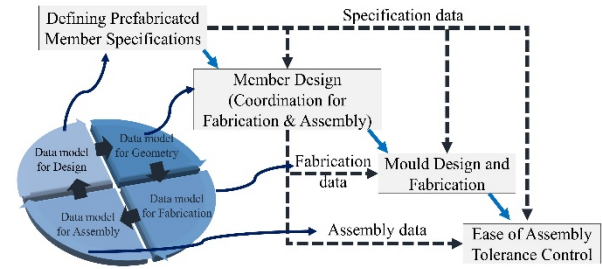


Fig. 1 DfMA for prefabricated members

To create the digital engineering model, this study first defines the prefabricated member specifications for the digital design model which provides datasets for design and geometric data. The next step is to develop the digital fabrication model from the needed datasets for 3D concrete printing, robot milling, and assembly elements through parametric modelling algorithms. Finally, the digital assembly model consists of datasets and algorithms for assembly tolerance control. Although the use of BIM can result in superior quality control for the construction of bridge piers (Shim *et al.* 2018), match-casting method was inevitable for assembly of the segmental columns. The bottom steel formwork was manufactured through a computer numerical control (CNC) milling machine for accurate surface fabrication. However, the top surface was finished manually. The match-casting process, as illustrated in Fig. 2, delays the fabrication schedule and requires a crane at every activity, which increases fabrication cost. For the prefabricated bridge pier, two alternative fabrication processes were proposed. In one process, three-dimensional printers are used for permanent concrete formwork with aesthetic design. In the other method, the CNC machine is used to mill the top surface of the column using the same surface definition for the steel formwork. For variable height of a bridge pier, the first segment of the pier has variable height. Through this improvement, multiple column segments can be fabricated simultaneously without the match-casting method.

Digital engineering models (DEMs) for prefabricated bridge members were proposed to support DfMA by defining geometry models and their data model for each phase, as shown in Fig. 3. The crucial requirements of the developed digital engineering model are the ease of tolerance management through the seamless data exchange between design, fabrication, and assembly based on the predefined data model and parametric algorithms. From the design calculation to satisfy design requirements in terms of strength, serviceability, durability, and seismic performance, data can be extracted for defining geometry of the bridge pier segments. A visual programming algorithm are developed to generate the prefabricated members. In the modeling algorithm, possible error components in geometry during fabrication and assembly were considered for easy update of the digital models. When the definition of DEM for a prefabricated member was agreed by project participants, information delivery was performed only through the data models. For digital fabrication and machine guidance of the assembly equipment, G-code was

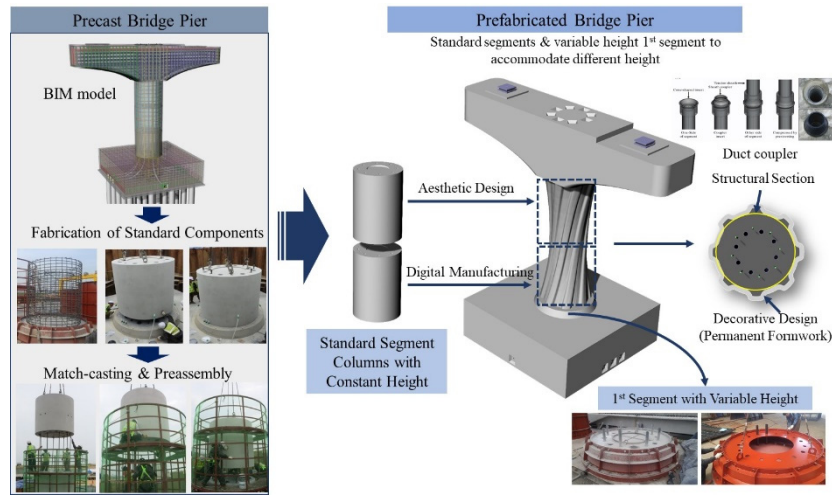


Fig. 2 Characteristics of the prefabricated bridge pier

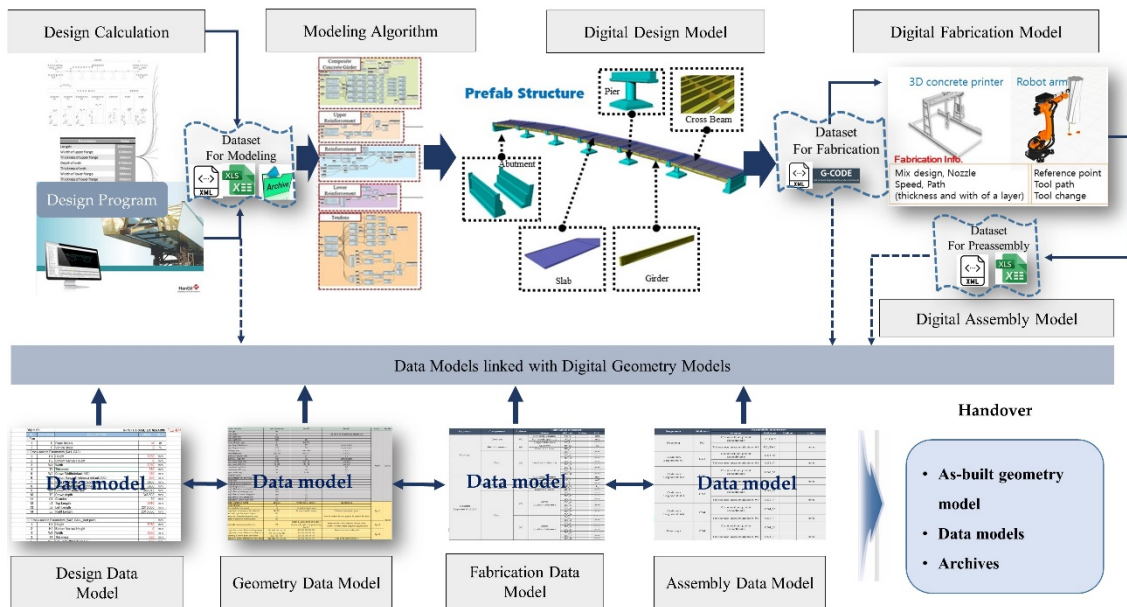


Fig. 3 Digital engineering model for prefabricated bridges

defined and linked as the data model. Each participant has their own knowledge as the data model and delivers necessary information for the next phase.

DEM can enable accumulation of information through the lifecycle of prefabricated members and bridge systems by collecting data. The designer can use digital models for easier fabrication and assembly and minimize design error. The bridge components have relative positions and rules to satisfy design codes. The reference points are defined through bridge alignment and positions of bearings, and connections are defined through relative coordinates. The substructure geometry is defined from the superstructure geometry. For bridge piers, the control positions are defined at the bearings. Therefore, the segment height and verticality control should be considered for allowable tolerance of the control positions (Culmo *et al.* 2018). As-built geometry models and their data models are delivered to bridge owners and stored in a bridge maintenance system

(Shim *et al.* 2017a, 2019). As specified in the report by UK BIM Alliance (2019), three deliverables, namely models, data, and documents are ready for the handover at the closure of the bridge construction without any loss of information.

When the DEM for a prefabricated bridge is defined, individual DEM for prefabricated members can be defined considering the constraints of bridge modeling. The geometry of each column component has a control point, and the points are used for digital manufacturing and virtual assembly simulation. Standardized digital models for the prefabricated bridge components are assembled using the alignment and control points. Each component has its own design checks and results so that a designer can report the complete design calculation. Allowable tolerance for each member or assembly is derived by this virtual assembly process in the design stage.

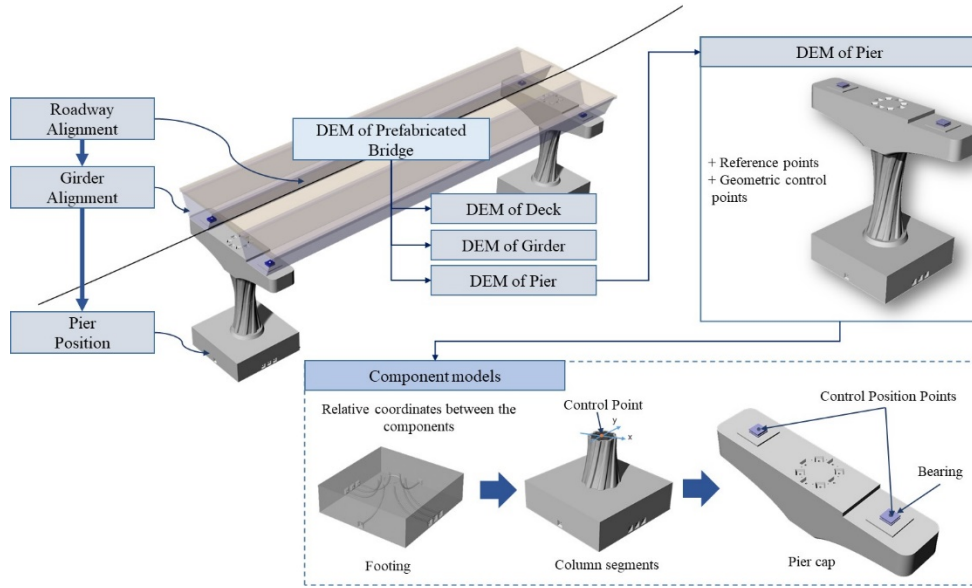


Fig. 4 Rules for digital modeling of prefabricated bridges

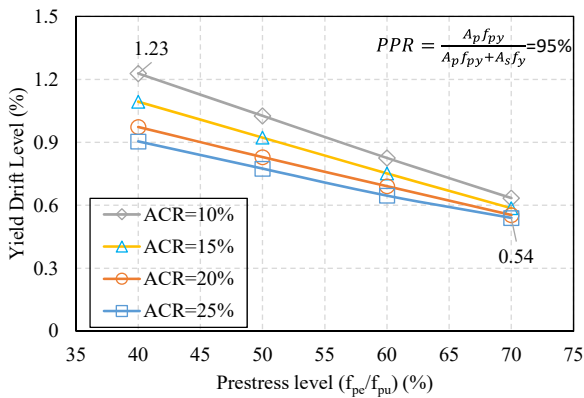


Fig. 5 Yield drift level of post-tensioned columns (Koem 2020)

### 2.2 Digital design models

In the design of prefabricated bridge piers, the main critical design parameters are prestressing force and tendons to satisfy design requirements on strength (P-M diagram) and seismic performance. The dimensions of the column section were determined to calculate the appropriate axial compression ratio. The axial compression ratio (ACR) is the ratio between the axial loads to the sectional compression resistance, as shown in Eq. (1). From the design calculation during the development of the prefabricated columns prestressing and axial prestressing levels revealed a considerable influence on the yield drift level, as shown in Fig. 5.

The yield drift level was decreased when the magnitude of prestressing level, axial compressive ratio, and partial

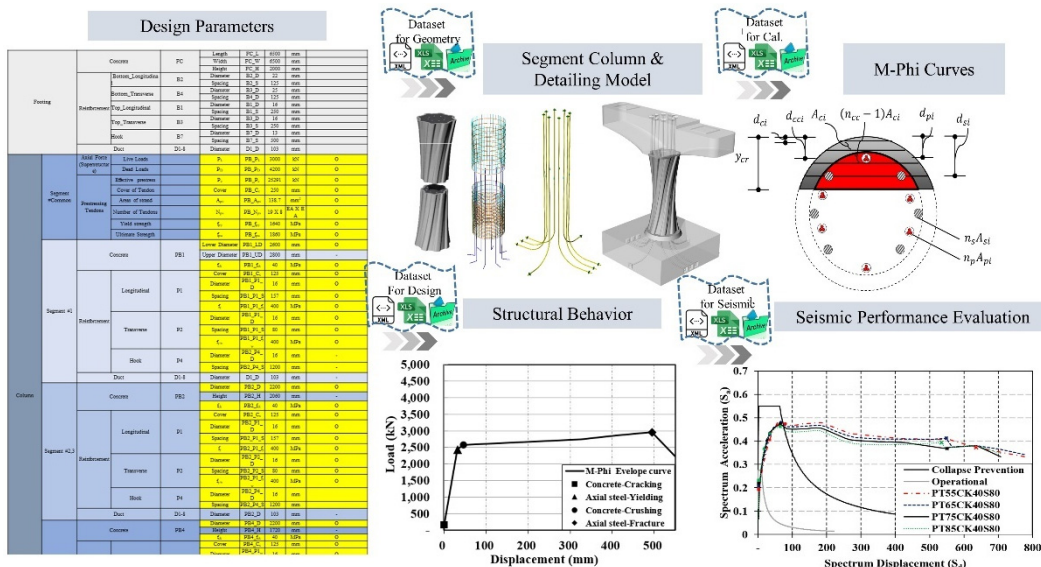


Fig. 6 Design process to derive a data model for geometry

prestressing ratio increased. In the range of design parameters, the post-tensioned precast columns yielded at 0.54%–1.3% drift level (Koem 2020). These calculated data on the performance of the prefabricated columns are used as data model for design. When the design conditions and requirements are given, designers can directly determine the appropriate design parameters to satisfy the design requirements from the previously defined results of the members.

$$ACR = \frac{A_p f_{pe} + P_{axial}}{(A_{core} f'_{c_{core}} + A_{cover} f'_{c_{cover}})} \quad (1)$$

where  $A_p$  is total area of prestressing steel;  $f_{pe}$  is effective prestress;  $P_{axial}$  is axial force;  $A_{core}$  and  $A_{cover}$  are the area of core and cover concrete;  $f'_{c_{core}}$  and  $f'_{c_{cover}}$  are unconfined concrete strength for core and cover concrete, respectively.

From the design calculation, design parameters are derived as displayed in Fig. 6. A data model for 3D geometry of the pier is extracted from the design parameters. By using an algorithm to generate digital models, a digital engineering model for design is defined using structural performance information. The prestressing force is determined to prevent tension across the segmental joints under service loadings. The moment–curvature curves are derived using the strain compatibility method (Park *et al.* 2020). The details of reinforcement and prestressing tendons are included in the digital models by considering specification requirements. The spreadsheet file is generated and converted into the XML format for data delivery. Variable parameters exist during fabrication and assembly. Section dimensions and prestressing-related values are defined as variables so that the modeling algorithm consider these values for model update only by changing the variables. This process can minimize the effort of engineers for using DEM.

Digital geometry modeling of the prefabricated pier consists of a footing, column segments, and pier cap as illustrated in Fig. 7. Three-dimensional (3D) digital models

have a set of data model for geometry and an algorithm. In rule modeling, the concrete cover, minimum and maximum spacing of reinforcing bars, and relative positions between each part were considered. The detail requirements of design codes are satisfied when this algorithm is used to generate a digital model. Among the input data for the modeling algorithm, some values originate from design calculation and the others from designer’s decision. For DfMA, variable parameters are defined as control parameters to update the digital models during fabrication and assembly. The modeling algorithm is developed based on an object-oriented modeling approach. Each component of the member has design parameters, constraints, and master–slave relations. The automatic revision of the model can be achieved by changing the geometric data. Tolerance inspection can be performed by a comparison of dimensions between design models and fabrication models. The level of development for the digital model is basically defined as LOD400.

Fabrication and quality control procedure exists for prefabricated bridge members. However, the footing is commonly constructed using the cast-in-place method. The first column segment is fabricated in a factory and delivered to the site and placed on the footing reinforcement before casting concrete. To match the exact locations of the ducts, a steel frame is added in the footing reinforcement and a target level is also controlled by the frame adjustment, as shown in Fig. 8. One control point for the assembly is defined and each center point of the duct has relative coordinates in the modeling. To guarantee the insertion of prestressing tendons, duct holes and their verticality should have tight tolerance. As recommended in NCHRP 12-98 project report (Culmo *et al.* 2017), horizontal location and elevation of final bridge bearings seats have tolerance limits of 6.35 and 3.18 mm, respectively. The tolerance of the duct locations from the control point is considered to be 3.175 mm. As displayed in Fig. 2, duct couplers are used in the prefabricated pier for the ease of assembly and insertion of prestressing steel. Therefore, the actual fabrication error is smaller than the specified location tolerance because all the ducts should be matched together. In the modeling

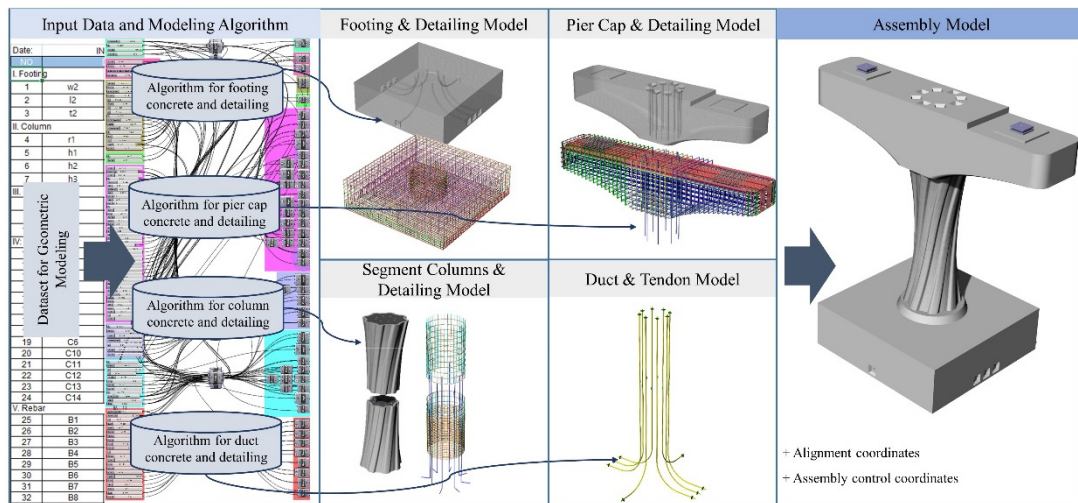


Fig. 7 Algorithm of digital modeling using a design data model

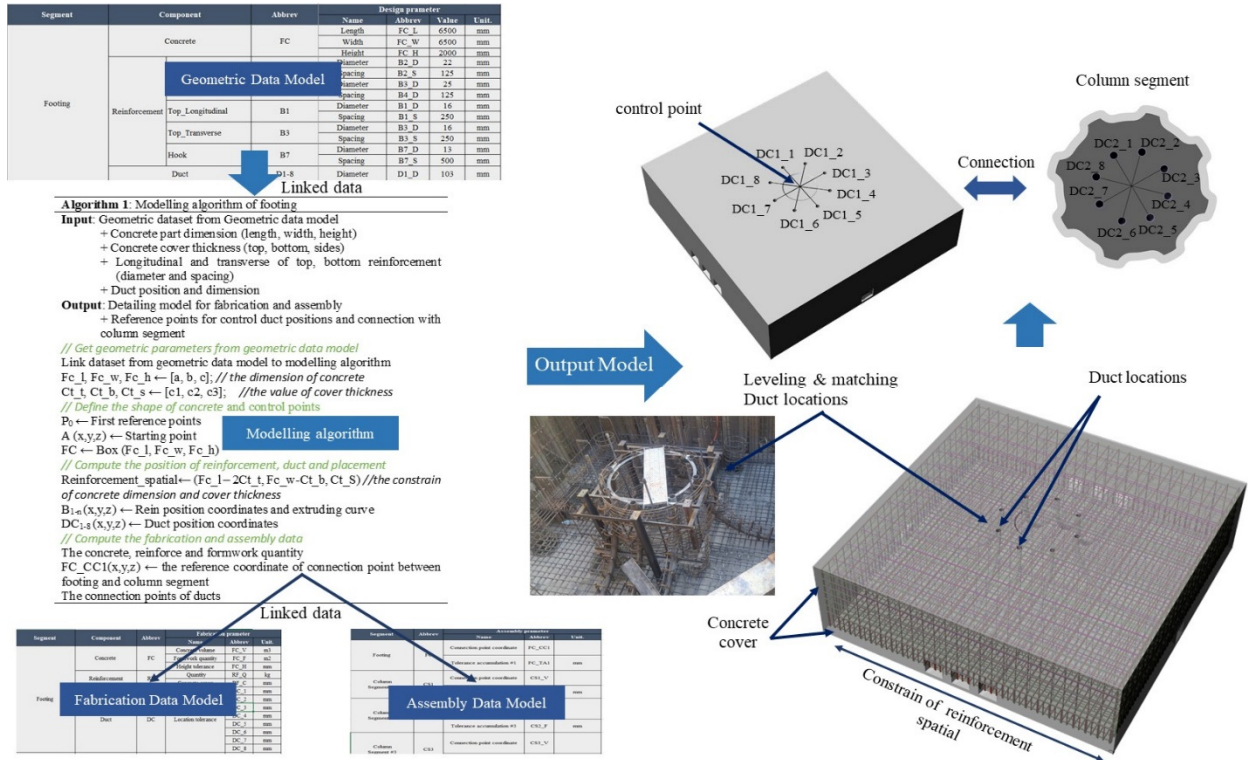


Fig. 8 Algorithm of a footing modeling through DEM procedures

algorithm, reference coordinates are considered for the geometry control.

Bridge columns commonly have various height resulting in the demand of multiple steel forms. Automated and digital fabrication of column segments should be used to remove this constraint. When the bridge column has a variable section, the cost of fabrication increases considerably. In DfMA of the prefabricated column, an alternative fabrication strategy based on digital fabrication technologies is required for the ease of fabrication. According to the designed height of the bridge piers, segmentation can be performed to minimize the number of forms. In this study, a conceptual digital fabrication procedures and essential considerations were proposed, and

a virtual implementation to a highway bridge was performed. Instead of precast bridge columns, prefabricated columns were fabricated using a 3D concrete printer and robot milling to facilitate the designer freedom of aesthetic design. A general contractor can achieve fast, superior, and cheap prefabrication and assembly.

### 2.3 Digital fabrication models

Digital fabrication can be realized using a robot or a 3D concrete printer. The aesthetic design of the pier column is developed in the new context of the printed concrete formwork implementation. The geometric freeform provided by 3D concrete printing (3DCP) is used to liberate

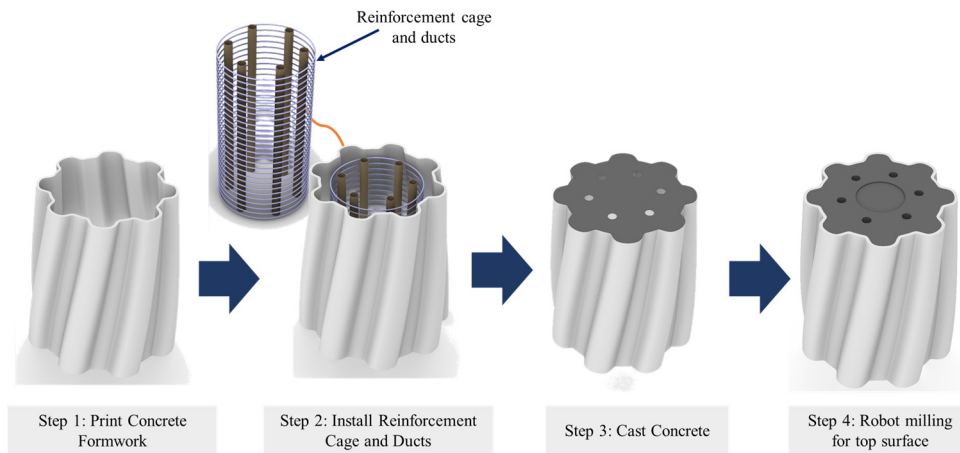


Fig. 9 Fabrication procedure for a prefabricated column segment

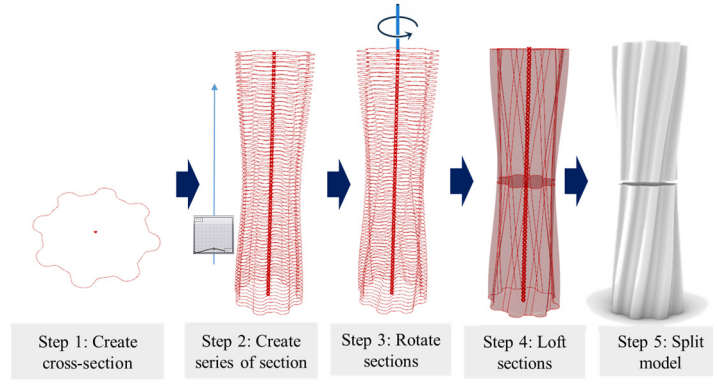


Fig.10 Process to create a digital model for the permanent formwork using 3D printing

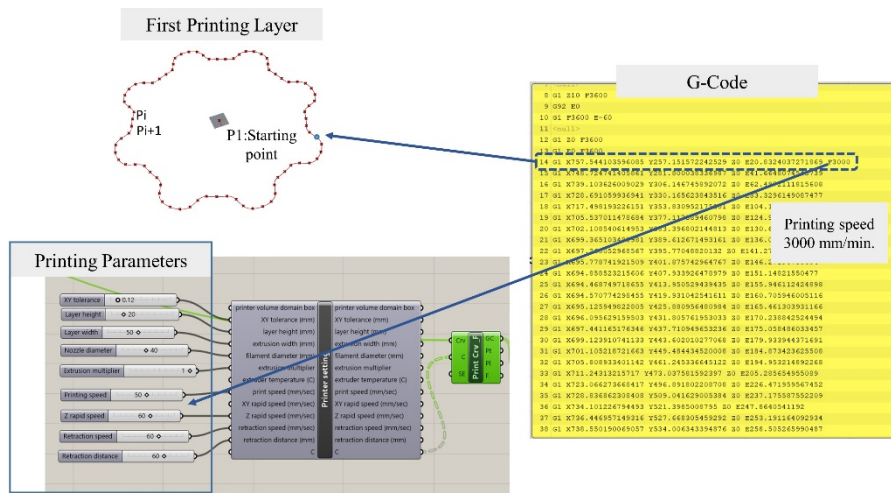


Fig. 11 Definition of a fabricated data model

design thinking from conventional concrete techniques to realize the full architectural potential of 3DCP structures (Gaudillière *et al.* 2018, Anton *et al.* 2021). As observed in the 3DCP process for the bespoke columns, the quality of the printed concrete during the target service life is the most challenging problem. The initial cracking and long-term deterioration should be controlled to satisfy design requirements. In this study, a permanent concrete formwork is suggested by the 3DCP process, which is considered as non-structural part. As illustrated in Fig. 9, geometrically complex segments were designed through digital design methods, such as the parametric design. As a pilot implementation, a twisted column form considering technical specifications of concrete printing, such as overhang capacity and level of geometric complexity, was implemented. The overhang angle was designed between  $-10^{\circ}$  to  $10^{\circ}$  to achieve good quality printing. The geometric freeform of printed concrete formwork enables to facilitate the functional integration, such as space for reinforcements, ducts, and tendons.

The designed concrete formwork was fabricated using a 3D concrete printer. Through preliminary printing, appropriate target properties of fresh concrete were determined to obtain a stable layer thickness and width. A systematic preparation for mix design, nozzle size and

shape, flow rate, print speed is necessary for quality control of the printed concrete part. The designed digital model was used to create printing path for the motion of the printer.

The control parameters for the printing are chosen as in Fig. 11. It shows an example of G-code generation by using the Grasshopper interface, namely Xylinus. When the printing parameters such as layer height, width, nozzle size, and printing speed are determined, the printing path is established using the sliced model. The printing path has a significant influence on the shape accuracy of the printed section. By preliminary printing simulation, the parameters can be adjusted to evaluate the printing process with various scenarios. The movement of the printer nozzle is recorded as a G-code file, which is imported to the printer controller. Fig. 11 shows the definition of a fabricated model from the design digital model.

The model authoring algorithm contains prescribed constraints for the concrete printing process and its material properties. Fig. 12 presents the process of test printing with the imported BIM model from the design stage. The layer height, width, and printing speed are the first consideration. Based on the parameter of layer thickness and nozzle size, the printing path was automatically established using the sliced model. The printing path generation is considered in the early design stage to decide the level of structural

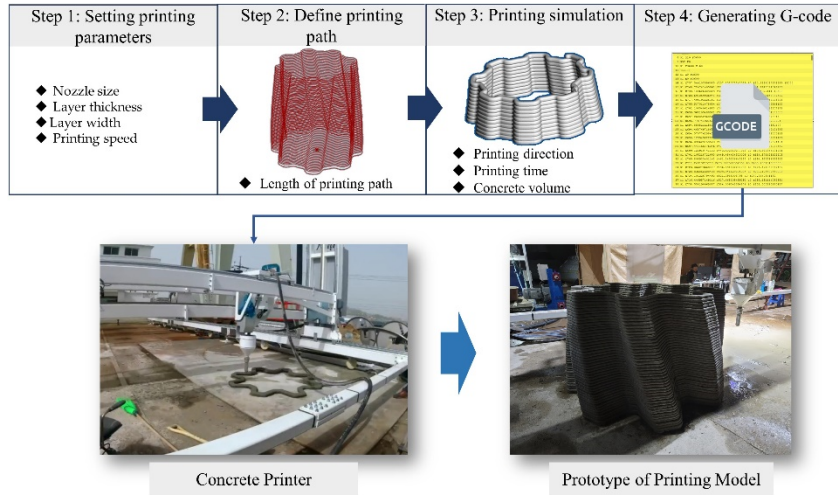


Fig. 12 Test printing using a generated G-code

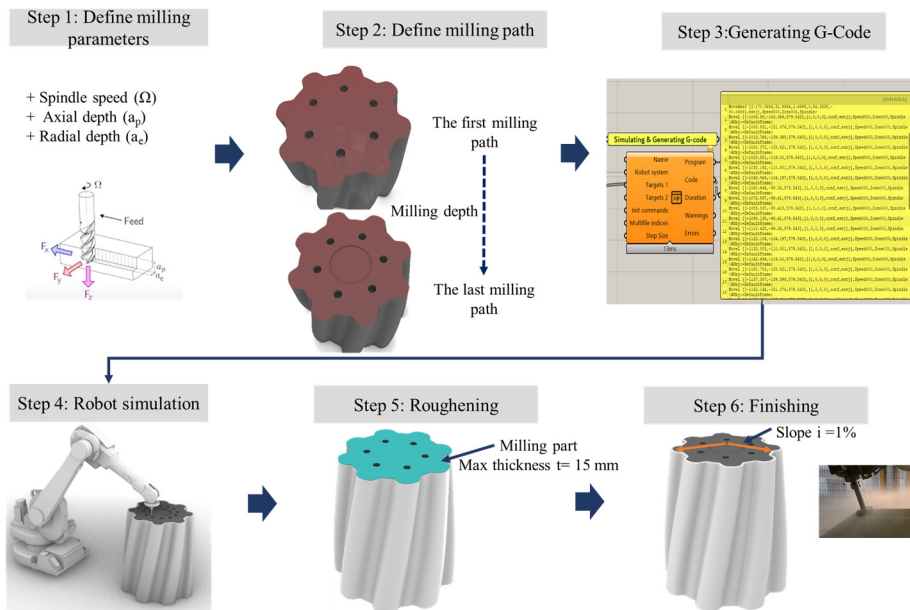


Fig. 13 Robot milling of the top surface of a prefabricated column segment

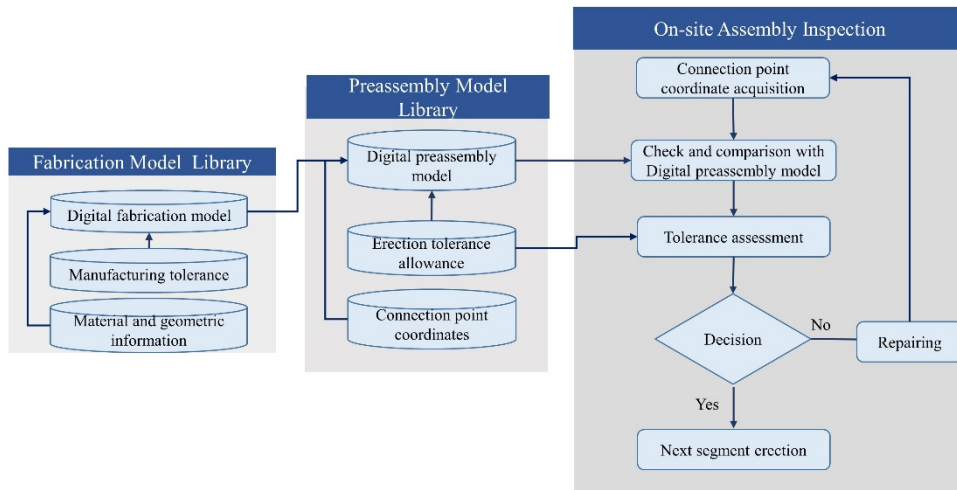


Fig. 14 Digital assembly for prefabricated members

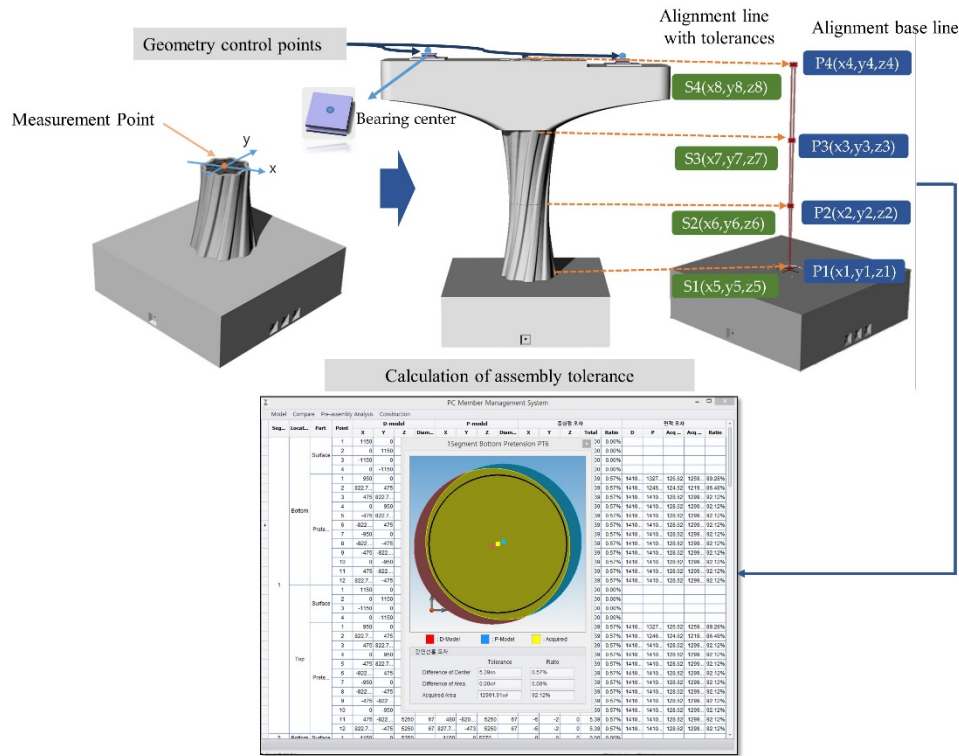


Fig. 15 Management of assembly tolerance

complexity. The basic motion of the nozzle is simulated to validate the input printing parameters. The G-code file includes the coordinate of the spatial points on the defined printing path. The coordinate dataset presents the direction and speed of the printer nozzle. The small size of the designed column has been printed with printing parameters: 40 mm nozzle size, 20 mm layer height, 50 mm layer width, and 3000 mm/min speed. After mixing the concrete, several trial printings were necessary to obtain appropriate setting time for the stability of the printed column. Therefore, managing uniform consistency during the printing process or between multiple mixes is critical.

Prefabricated members with prestressing action require perfect matching of contact surfaces to provide uniform compression by prestressing. In this digital manufacturing procedure, the 3D printed formwork and manually filled concrete require an additional surface finish. As illustrated in Fig. 9, preassembled reinforcements and ducts are inserted in the printed permanent formwork. The control point of each segment, which can be determined by the center points of the ducts, robot milling was performed. The digital geometry model provided final target geometry and generated milling parameters, such as the spindle speed, axial depth, and radial depth, as shown in Fig. 13. In this process, obtaining a stable reference point is critical to generate the G-code for the milling path using the Grasshopper interface. As in the case of common CNC milling, roughening and finishing processes are performed. The maximum thickness for milling is limited by 15 mm, considering the printed layer thickness, fabrication time, and cost. For the durability measure at the joints, 1% slope is designed to prevent any water penetration by rainwater.

## 2.4 Digital assembly models

Quality control is ensured by measuring geometrical properties, such as section dimension and duct locations. The determination of acceptable assembly tolerance is a crucial part of the digital preassembly model. The digital preassembly model is used to simulate the construction sequence based on the alignment baseline. The coordinate of measurement points on the alignment baseline is associated with design points. The duct holes should match perfectly before the insertion of prestressing tendons. In particular, the connection points are defined as the center of the segments at the connection plane. These coordinates are exported to the assembly dataset in the DEM central database. The connection coordinates can be used for on-site tolerance check at every stage of the assembly. Fig. 14 presents the workflow of using the digital preassembly model for controlling assembly tolerance. The as-built fabrication model is an updated model with manufacturing and assembly error. The erection tolerance is calculated from the coordinate of connection points in the preassembly model and on-site assembly. When the erection error is lower than the tolerance allowance, the segment can be assembled and moved to the next segment. Shim *et al.* (2018) developed a preassembly process of the precast bridge columns and used point cloud data for checking the geometry error to fit the final target coordinates of bearings. Bearing pads can be used to adjust a small error of the assembled pier (see Fig. 15). By enhancing the process using DEM, measured coordinates during each assembly step are compared with target coordinates for geometry control. Engineers decide error adjustment when some error

occurs in terms of verticality or level. When the whole assembly process is completed, as-built DEM can be stored for handover.

### 3. Data models and their applications

Yuan *et al.* (2018) stated that the successful DfMA implementation requires multi-party collaborations from designers, engineers, and manufacturing teams based on BIM parametric model. The information exchange in multi-party collaborations is one of the challenges for implemented DfMA project (Gao *et al.* 2018, Jin *et al.* 2018). Furthermore, data-driven engineering is an essential technology for BIM-based DfMA (Gbadamosi *et al.* 2020). The proposed federated data in DEMs improve the process of information exchange through the predefined design parameters in the geometry data model. The geometric data is then transferred directly to digital fabrication and assembly using the algorithms based on the BIM parametric model itself.

DfMA-oriented parametric modeling combines BIM

parametric modeling with the parameters of design for assembly (DfA) and design for manufacturing (DfM) at the early design stage. The design process of the prefabricated pier for DfMA can be effectively managed through the DEM. The main aim of the parametric digital modeling is to assist designers in increasing manufacturability and assemblability (BCA 2016). Model authoring of the initial BIM model for DfMA requires a level of development (LOD) more than 300 and depends on the requirement of fabrication machines in the factory. Algorithms to create the models are developed through the investigation of data for design, analysis, fabrication, and assembly. First, the DfMA requirements are established using digital engineering data for achieving ease of assembly and manufacturing. The optimization of part count, assembly, and manufacturing readiness is the first consideration. Second, the design parameter database, a spreadsheet with the classified geometric data from LOD 200 to 400 is created. Next, a BIM parametric model for DfA is determined. The DfA model contains the connection parts, connection coordinates, and erection tolerance allowance along the alignment line of the footing, column segments and pier

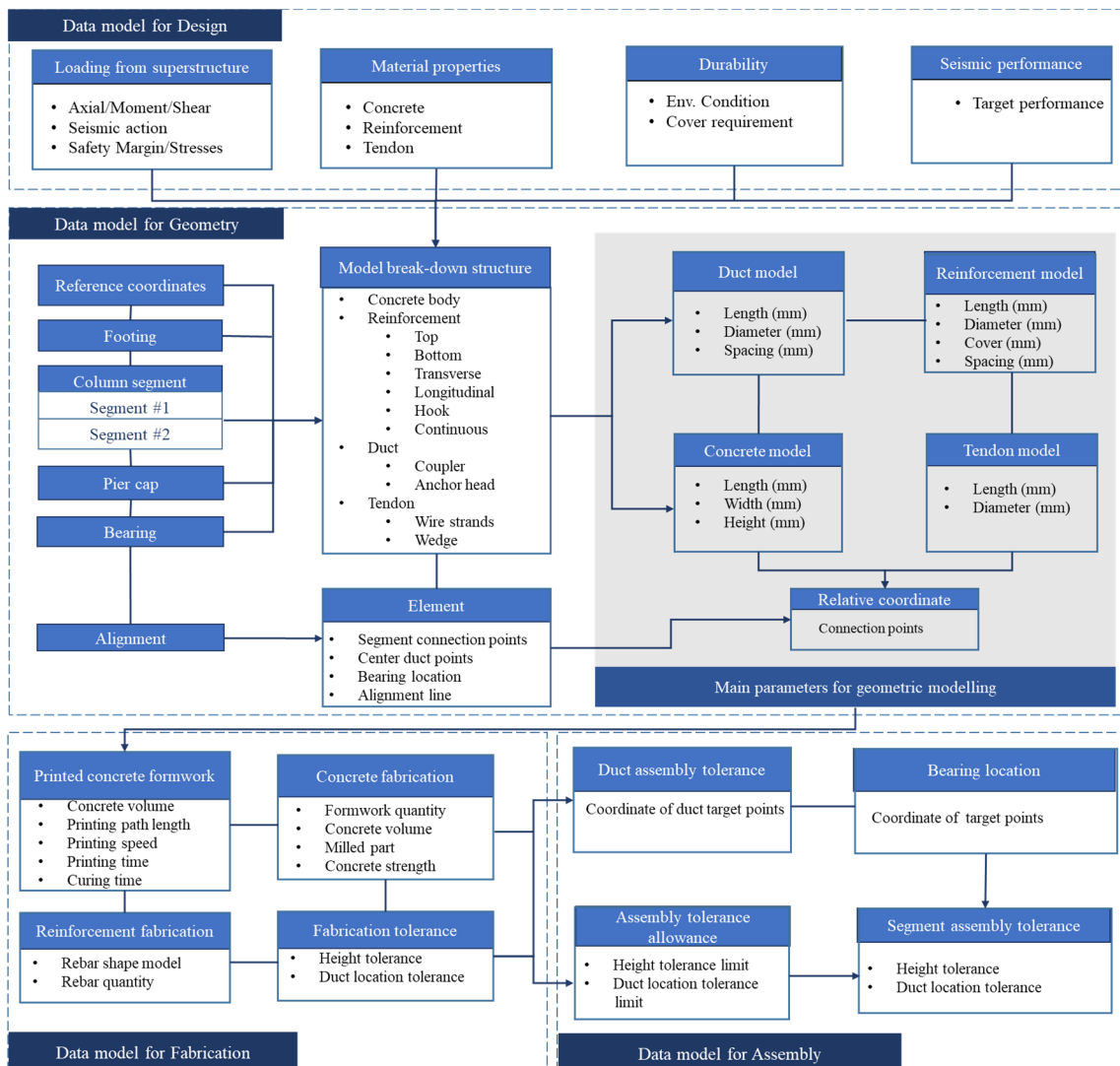


Fig. 16 Federated data model for DEM

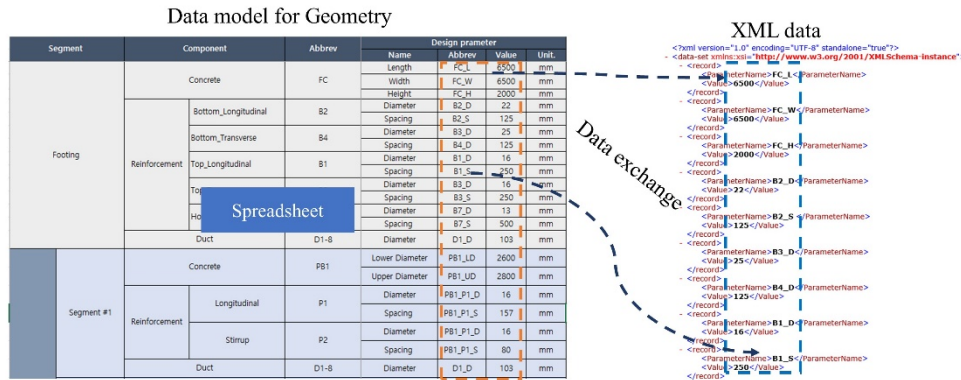


Fig.17 XML data extract from data models

cap. After DfA requirement satisfaction, the model for DfM is created. The requirements of DfM are considered to minimize the complexity of the manufacturing process and manufacturing tolerance. Finally, the result of DfMA-oriented parametric modeling is used in the inventory models of prefabricated model, which consists of digital design, manufacturing, and digital preassembly models. When the models are established, designers can use design digital models without consideration of manufacturing and assembly models. Manufacturers and assemblers will have necessary design data from design stage and prepare their own task using the relevant digital models that are linked with design digital models.

As summarized in Fig. 16, a federated data model for DEMs of prefabricated bridge piers is presented. The data model includes design conditions and choices of material and products as non-graphical information. Among parameters of the data model for design, assumed values, such as material properties and prestressing forces are updated at fabrication and assembly stages. For maintenance of the prefabricated bridge, the information of safety margin needs to be considered, such as  $\phi M_n/M_u$ ,  $\phi V_n/V_u$ , and  $\phi P_n/P_u$ . Every prefabricated member has its own structural performance under given design conditions so that engineers can save time for assessment of existing members. As-built information is crucial for reliable assessment of old deteriorated bridge members. Especially, introduced prestressing forces and stress conditions are essential for serviceability check of prestressed concrete members (Jeon *et al.* 2021). Data model for geometry is generated in the design stage and updated at fabrication and assembly stages. Quality control process produces the geometry error of fabrication and assembly. Measured geometry should have pre-specified locations and values for dynamic change propagation to update the design digital models. Each digital model has its own unique identification code and variables to accommodate these changes. Even though various participants have separated roles in design, fabrication and assembly, DEM can federate and deliver exact information for their tasks. The defined data models for prefabricated members can be used for automation of fabrication or automatic machine guidance by converting the data model into the extended mark-up language (XML) format, as shown in Fig. 17. The 3D geometry model of one bridge pier in a BIM software is 329

MB but data model in XML is only 20 kB. By the shared modeling algorithms and data requirements, digital resources can be significantly reduced.

#### 4. Conclusions

Prefabrication ensures superior fabrication of bridge members in off-site factories with better conditions. Superior, fast, and cheap products are desirable. To accelerate the effort of prefabrication, this study proposed the novel concept of DEM for seamless collaboration of digital design, fabrication, and assembly process. The digital models using the DEM definition were used to accumulate knowledge for design tasks considering fabrication, and assembly requirements. Compared with conventional parametric modeling, the DfMA-oriented parametric model provided enhanced manufacturing productivity and assembly. The proposed DEM can improve value of digital models by improving the lifecycle of the prefabricated bridge piers regarding the following issues:

- (1) Through the predefined data models and federated DEMs, the shared parameters from digital design, fabrication, and assembly can enable comprehensive project collaboration and concurrent engineering. The data-driven information delivery minimizes rework by design changes.
- (2) Totally prefabricated bridges can be realized by the suggested rule-based modeling and control points of each object. Project participants should satisfy the tolerance requirements for assembly of the system. Digital fabrication enables more tight geometry error control during fabrication and assembly.
- (3) The use of 3DCP for permanent concrete formwork and robot milling for finishing the top surface of column segment can replace the typically used match-casting method and reduce time and cost for the fabrication of geometrically complex structures.
- (4) Data models are more effective for information delivery in terms of memory requirement than 3D geometry models and allow open interface to develop relevant software. By the proposed digital

modeling algorithms and data requirements, digital resource for a bridge construction project can be considerably reduced.

The information requirements of DEM should be expanded its for maintenance. The interoperability for analysis and database of bridge maintenance systems can contribute to the development digital twin models for prefabricated members for lifecycle management.

In this study, DEMs have been specifically developed for prefabricated bridge pier as a new methodology for prefabricated bridge structures. However, the implementation of DEMs faces limitations, such as the lack of fabrication and assembly data in the early design development and the converting fabrication and assembly factors to the parameters in the parametric modeling algorithm. Furthermore, the current process of DEMs needs to be continuously improved for the complexity of the whole prefabricated bridge system.

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