Research Article

Development of an Efficient Steel Beam Section for Modular Construction Based on Six-Sigma

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This study presents a systematic approach for the development of an efficient steel beam section for modular construction based on Six-Sigma. Although the Six-Sigma is frequently implemented in manufacturing and other service industries, it is a relatively new concept in the area of building design and construction. As a first step in this approach, market studies and surveys are conducted to obtain the opinions of potential customers. Then the opinions of customers are converted into quality characteristics for the steel beam using the quality function deployment methodology. A steel hollow flanged channel is chosen as the main modular beam shape, and the design concept is derived and developed by applying the Pugh matrix methodology. A pilot test was performed to validate the effectiveness of the developed beam section. The results indicated that the developed channel beam section showed excellent performance and retained high accuracy in fabrication, thus resulting in a significant reduction of steel consumption.

1. Introduction

Modular construction is an industrialized construction system, with a process that mainly consists of the factory production of preengineered building units, the delivery of the fabricated units to the construction site, and their fast assembly [1]. The structural system of steel frame modular buildings can be largely classified into two types. The first is the beam-column frame system and is suitable for use in school buildings or military barracks, which require relatively large open space [2]. The second is the load-bearing wall system, and dormitories or bachelor officer quarters are good applications of this type as they can be built with a series of transportable unit room modules [3, 4].

In general, the modular unit of the beam-column frame system is constructed by connecting structural members such as corner columns, internal columns, floor beams, and ceiling beams by bolting or welding. Figure 1 illustrates an example of standard modules for elementary schools in Korea. The

dimensions are 9.8 m (length), 7.5 m (column to column span), 3 m (width), and 3.2 m (height). Table 1 provides the composition ratio of the main structural members used in this standard module. In the beam-column frame system, the upper beam of the lower level unit is connected with the lower beam of the upper level unit. This connection scheme is called the double beam system. As a result, beam members make up a larger portion of the structural components of the standard module, which is 81% as shown in Table 1. The beam members play an important role as they not only contribute greatly to the overall construction cost of modular buildings, but also may affect various factors such as story height and floor vibration. Therefore, the selection of adequate beam members is essential to improving the cost efficiency and performance of modular buildings.

Six-Sigma was first developed by Motorola in the 1980s [5] and became well known in the 1990s when Jack Welch made it central to his business strategy at General Electric. Since the late 1990s, most manufacturing companies in Korea

(a) Framed modular unit

(b) Structural members of the modular unit

FIGURE 1: Standard modular unit and structural members.

TABLE 1: Composition ratio of main structural members used in the standard module.

Component	Shape	Weight ratio (%)	
Longitudinal floor beams	Built-up rectangular hollow section	41	81
Longitudinal ceiling beams	Rectangular hollow section	32	
Transverse floor and ceiling beams	Roll-formed C shape	7	19
Columns	Square hollow section	19	

have applied the Six-Sigma for productivity enhancement, process improvement, and new product development. While the Six-Sigma has been applied to construction management and housing design on several occasions such as [5, 6], this is one of very few studies where the Six-Sigma concept is employed to develop new steel structural members for modular construction.

In general, Six-Sigma projects follow either the DMAIC or DFSS methodology. The DMAIC focuses on improving an existing business process, while the DFSS aims at creating new products or process designs. Based on this discussion, this study proposes a systematic approach for the development of a steel modular beam section that can be used in the beam-column frame system and validates its effectiveness through a pilot test.

2. QFD Methodology and Derivation of CTQ

2.1. QFD Methodology. The philosophy of the Six-Sigma approach emphasizes the reflection of customers' needs in the development of production processes. In order to achieve this, the identification and categorization of potential customers are required, and the importance of each customer group needs to be evaluated. In the Six-Sigma methodology, these customer requirements are referred to as the voice of customers (VOCs), which are obtained through surveys and interviews and utilized as basic data for product development. According to the results of the interviews, module manufacturers require a decrease in manufacturing cost as well as a

FIGURE 2: HOQ required to conduct QFD.

shortening of order-delivery period, while designers expect various construction-related requirements to be satisfied. The VOC of the building owner is mainly focused on the excellent performance of the manufactured modules.

This study adopts the quality function deployment (QFD) methodology to convert customers' needs into quality characteristics for the products to be developed. The QFD methodology, first proposed by Akao in the 1960s [7], is a tool that can provide a quantitative evaluation on the relation between customer requirements and product characteristics using a correlation matrix [8, 9]. Figure 2 illustrates the house of quality (HOQ), which is required to conduct QFD.

In general, the QFD methodology follows a number of procedures: (1) determination of required quality; (2) importance rating for customers' needs; (3) identification of quality characteristics; (4) correlation analysis between the required quality and quality characteristics; (5) technical evaluation; (6) interrelation analysis of the quality characteristics if required; (7) target specification setup for the quality characteristics. In this study, the required quality is

TABLE 2: Priority rating for the customer requirements.

Customers' required quality	(1) Importance rating	(2) Satisfaction rating	(3) Possible quality levels	(4) Level-up ratio	(5) Sales Point	(6) Absolute priority	Priority Ratios	Ratings
Small steel quantity	4.6	2.8	4	1.4	○	7.7	10%	2
Low manufacturing cost	4.6	2.6	5	1.9	◎	13.1	17%	1
Easy structural design	3.6	3.4	4	1.2		4.3	5%	7
Easy architectural design	3.6	3.4	4	1.2		4.3	5%	7
Easy connection	3.6	3.4	4	1.2		4.3	5%	7
Transportation with low-bed trailer	3.6	3.2	4	1.3		4.7	6%	5
Transportation with cargo truck	3	3	3	1		3	4%	15
Easy installation of plumbing equipment	3.4	3.2	4	1.3		4.4	6%	6
A short time for stocking after order	3.6	2.8	4	1.4	○	6	8%	4
The stock is secured in advance	3	2.6	3	1.2	○	4.3	5%	7
Small manufacturing deformation	3.8	3	4	1.3	◎	7.4	9%	3
Less surface defects	3.6	2.8	3	1.1		4	5%	12
Easy application of high-strength steel	3	2.8	3	1.1		3.3	4%	14
Structural safety	3.6	3.6	4	1.1		4	5%	12
Less floor vibration	4.2	4	4	1		4.2	5%	11

(1) Importance rating: values obtained from customer survey (1~5).

(2) Satisfaction rating: values obtained from customer survey (1~5).

(3) Quality levels that may be obtained from the viewpoint of developers (1~5).

(4) Level up ratio: (3)/(2).

(5) Sales point from the viewpoint of developers (◎: 1.5, ○: 1.2).

(6) Absolute priority: (1)*(4)*(5).

determined from the VOCs obtained from the first round of interviews, and then the quality characteristics are prioritized based on the evaluations of customers and experts. Finally, the target values and importance ratings for the quality characteristics are assigned.

In this study, QFD methodology is used for the development of a new steel modular beam section. The results of priority ratings for the VOCs, where the requirements of both customers and product developers are considered, are provided in Table 2. The item labeled “customers’ required quality” in Table 2 is a reorganization of the VOCs of each customer group for QFD analysis, and its priority ratings are determined based on the results of the customer surveys. From the results of the table, items with high priority are found to have “low manufacturing cost,” “small steel quantity,” “small manufacturing deformation,” and “short time for stocking after order.” In the determination of the priority rating in Table 2, the importance of customers’ requirements and satisfaction with existing products are determined from the surveys. The “planning quality” and “sales point” in Table 2 are the indicators for the attainable quality and sales quantity from the perspective of developers, respectively.

2.2. Derivation of CTQ. From a correlation analysis between the required qualities and quality characteristics, parameters that are critical to quality (CTQ) from the customers’ perspective can be derived. The quality characteristics are given different weight values (◎: 5 points, ○: 3 points, and △: 1 point) depending on the relationship with the corresponding customer requirements. The overall importance can be calculated by summing up the multiplications of the weighted value and absolute importance in Table 3. The quality characteristics with high importance score can be selected as the potential CTQs.

This process of deriving CTQs is important in the Six-Sigma methodology, which reflects the customers’ needs as much as possible. The VOC does not contain any direct statements on the quality characteristic, but it can be converted into designable quality characteristics through QFD analysis. Table 3 lists the importance ratings derived from the correlation analysis on the required quality and quality characteristics.

From the QFD analysis, the quality characteristics with high importance are found to be “weld length per unit length,” “moment of inertia per sectional area of beam,” and “weight of floor beams per unit area of plan.” These items

TABLE 3: Correlation analysis between the required qualities and quality characteristics.

Customers' required quality	Quality characteristic																
	Price of beams		Contribution to competitiveness of modules					Structural performance of bema			Quality of manufacturing		Absolute priority	Priority ratios	Ratings		
Surface area per unit length	Welding length per unit length	Span length	Thickness of webs	Diameter of web opening	Number of webs	Thickness of flanges	Number of openings	Height of ceiling and floor beams	Weight of floor beams per unit area of plan	Moment of inertia per sectional area of beam	Section modulus per sectional area of beam	Lever arm of bolts at the end plate				Number of axes of symmetry	Radius of curved section
Low cost of beams																	
Small steel quantity		●				△			●	●	○				7.7	10%	2
Low manufacturing cost	○			○											13.1	17%	1
Easy design of modular building																	
Easy structural design	●		●		○			○		●	○	●			4.3	5%	7
Easy architectural design			●											○	4.3	5%	7
Easy fabrication and transportation																	
Easy connection				●			●					●		○	4.3	5%	7
Transportation with low-bed trailer								●				○			4.7	6%	5
Transportation with cargo truck								●				○			3	4%	15
Easy installation of plumbing equipment					●										4.4	6%	6
Short time for stocking																	
A short time for stocking after order	○	●						○							6	8%	4
The stock is secured in advance			●												4.3	5%	7
High quality of manufacturing																	
Small manufacturing deformation		○				●							●		7.4	9%	3
Less surface defects														○	4	5%	12
Easy application of high-strength steel	●								●					○	3.3	4%	14
Structural performance																	
Structural safety										●	●				4	5%	12
Small floor vibration					○					●	●				4.2	5%	11
Absolute priority	126	194	116	62	92	90	46	110	95	138	182	72	101	80	48		100%
Priority ratios	8.1%	12.5%	7.5%	4.0%	5.9%	5.8%	3.0%	7.1%	6.1%	8.9%	11.7%	4.6%	6.5%	5.1%	3.1%		
Ratings	4	1	5	13	9	10	15	6	8	3	2	12	7	11	14		

TABLE 4: CTQ definitions and target levels.

CTQ	Definition	Measuring method	Current level		Target level
			Built-up RHS	Channel	
Welding length per unit length	Welding length per 1 m beam length	Measuring welding length	4	0	Less than 2
Moment of inertia per sectional area of beam	Moment of inertia divided by sectional area of beam	Calculation of moment of inertia and sectional area of beams	127 cm ² (7.5 m span)	132 cm ² (7.5 m span)	Larger than 150 cm ² (7.5 m span)
Weight of floor beams per unit area of plan	Total weight of beams used for modules divided by plan area of module	Calculation of weight of beams after redesign of modules	0.30 kN/m ² (7.5 m span)	0.25 kN/m ² (7.5 m span)	Less than 0.28 kN/m ² (7.5 m span)

TABLE 5: Classification of key functions for the steel modular beam section.

Main process	Manufacturing beams	Assembly of modules	Transportation and installing	Ensuring structural performance
Must be functions	—	Welding end-plate	Transportation of modules	Flexural strength of beam
		Connecting beam and column		Shear strength of beam
		Connecting beam and slab		Minimize deflection of beam
		Connecting beam and ceiling track		Minimize floor vibration
Delighter functions	—	Connecting beam and wall track	Plumbing equipment penetration	Earthquake and wind resistance
		—		Fire resistance
Primary satisfier functions	Minimize a space for stock	—	—	—

are selected as CTQs in the following step and expressed quantitatively. Among the 15 quality characteristics, the top 3 items are selected as CTQs and defined as shown in Table 4, which shows their definitions, measurement methods, current, and target levels. The target levels are determined using the existing built-up RHS (rectangular hollow sections) and channels as references.

3. Product Design Using Pugh Matrix Methodology

3.1. Function Analysis and Pugh Matrix. The core functions of the steel modular beam section are determined and its optimal design is developed utilizing the CTQs derived in the previous phase. Table 5 describes the main processes required for the manufacturing of the steel modular beam section and classifies the functions required in each process into one of three functions, namely, the basic function (necessary), attractive function (delighter), and discriminative function (primary satisfier). The basic functions must be satisfied, while the attractive and differentiated functions can be optionally considered in the design process.

Key functions can be determined from a correlation analysis between the quality characteristics and associated functions by applying the same method used to create CTQs in Table 3. Table 6 shows the relationship between the quality

characteristics and the key functions. From this relationship, “minimize deflection and vibration of beam,” “flexural strength of beam,” “earthquake and wind resistance,” and “piping equipment penetration” are selected as key functions.

After derivation of the key functions, an optimal design concept satisfying the derived key functions needs to be developed. In order to achieve this, various methods can be used such as the benchmarking of advanced technologies, brainstorming by experts, TRIZ, and mind mapping. In this study, various solutions that can satisfy the key functions are created, and several possible design options are obtained by combining these solutions. Finally, the Pugh matrix is employed to select the optimal design among the designs obtained.

Table 7 lists the available solutions for each of the key functions of the steel modular beam section. The table indicates that there are two solutions for “piping equipment penetration” and “connecting beam and slab,” four solutions for structural functions, specifically “flexural strength of beam,” “minimize deflection and vibration of beam,” and “earthquake and wind resistance,” and one solution for all of the remaining functions. These solutions can be combined to produce an optimal design concept. By combining the solutions listed in Table 7, seven design concepts are derived. They satisfy various functions required for the floor and ceiling

TABLE 7: Available solutions for each of the key functions.

Key functions	Solutions			
Piping equipment penetration	Install reinforcing device at penetration Solution A		Penetrate without reinforcing Solution B	
Transportation of modules	Limiting module height less than 3.3 m			
Welding end-plate	Limiting flange width less than 120 mm			
Connecting beam and column	Ensuring bolting space at end-plate			
Connecting beam and slab	Integrate beam and slab support Solution a		Separate beam and slab support Solution b	
Connecting beam and ceiling track	Connect track to web of beam with screw			
Connecting beam and wall track	Ensuring flange width of 60 mm			
Flexural strength of beam	Use hollow flange (flange thickness = web thickness) Solution I	Use hollow flange (flange thickness > web thickness) Solution II	Use open flange (flange thickness = web thickness) Solution III	Use open flange (flange thickness > web thickness) Solution IV
Minimize deflection and vibration of beam				
Earthquake and wind resistance				

TABLE 8: Design concepts obtained by combinations of the available solutions.

Combination of solutions	Solutions A + a + I	Solutions A + b + I	Solutions A + a + II	Solutions A + b + II	Solutions B + a + III	Solutions B + b + III	Solutions B + b + IV
Design concepts
Manufacturing cost	Very high	High	Very high	Very high	Middle	Middle	Very high
Steel quantity	Very low	Low	Very low	Very low	Low	High	Low
Compatibility between floor and ceiling beam	Not compatible	Compatible	Not compatible	Compatible	Not compatible	Compatible	Compatible

beams of the modular beam-column frame system and show different characteristics with regard to manufacturing cost, steel consumption, and availability for both of ceiling and floor beams. Their characteristics are summarized in Table 8.

In order to select the optimal design among the candidates listed in Table 8, a Pugh matrix is created in Table 9. In this methodology, a relative evaluation is performed on each candidate by comparing it with the reference design for each of the key criteria. The built-up RHS is chosen as the reference design for this comparison. Thus, if a candidate shows better performance than the reference design, it is denoted as +. If the candidate is worse than or is equal to the reference design, it is denoted as – or S, respectively. The candidate with the greatest difference between the sum of pluses and that of minuses is chosen as the optimal design. The results in Table 9 indicate that design concept 2 is the optimal design. Thus, it is selected as the prototype for the steel modular beam section.

The prototype has hollow flanges in both the upper and lower parts of the section as shown in Table 9. It can be manufactured by a roll forming method, in which thin steel sheets are passed through several rolls and are consecutively bent at room temperature. The cross-sectional shape is illustrated in Figure 3. The steel beam member with the cross-sectional shape shown in Figure 3 is hereafter referred to as the modular construction optimized (MCO) beam for convenience.

3.2. Detailed Design of MCO Beams. In this section, a detailed design of the MCO beam is discussed considering the manufacturing process. With the detailed design components, the cross-section has a variable portion as well as an invariable portion as shown in Figure 4. Although MCO beams manufactured through the roll forming process require smaller manufacturing costs than general built-up beams, a variety in depth is also necessary for their applications to modular

TABLE 9: Selection of the optimal design using the Pugh matrix methodology.

		Better + Same S Worse –	Reference	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6	Concept 7
Key criteria	Weight
Manufacturing cost	5	S	S	+	+	S	S	+	+	–
Fire proofing cost	4	S	S	–	–	–	–	–	–	–
Steel quantity	4	S	S	+	+	+	+	–	–	+
Easy fabrication	3	S	S	+	+	+	+	+	+	+
New investment	5	S	S	–	–	–	–	+	+	–
Compatibility	4	S	S	–	+	–	+	–	+	–
Creativity	3	S	S	+	+	+	+	S	S	S
Sum of +		0	0	4	5	3	4	3	4	2
Sum of –		0	0	3	2	3	2	3	2	4
Sum of S		7	7	0	0	1	1	1	1	1
Weighted sum of +		0	0	15	19	10	14	13	17	7
Weighted sum of –		0	0	13	9	13	9	12	8	18

FIGURE 3: Cross-sectional shape of the MCO beam and its roll forming simulation.

FIGURE 4: Cross-sectional design of the MCO beam.

buildings with diverse spans. Therefore, the upper and lower hollow flange parts are designed as the invariable portion and produced using a single roll. In contrast, the thickness and width of the web section are variable. The design requirements for each design factor of the MCO beam are listed in Table 10. SPA-H steel is used for manufacturing the MCO beams since it has high durability as well as a high tensile strength of 490 MPa.

The design procedures for the MCO beam with invariable cross-section (hollow flange) can be summarized as follows.

Step 1 (setting up the range of the flange width as shown in Figure 5). (i) If the minimum width of the column is 125 mm, the flange width is in the range of 100~120 mm.

(ii) The minimum width of the horizontal flat flange portion must be at least 50 mm.

Step 2 (determination of r_1 and r_2 shown in Figure 6). These parameters are constant regardless of the steel plate thickness if the same roll forming process is used.

(i) Bending capacity of SPA-H steel: if the bending angle is 180 degrees, the inner radius must be at least 1.5 times the flange thickness.

TABLE 10: Design requirements for each design factor of the MCO beam.

Design factor	Design requirement
Invariable section	
Flange width	(i) Limit the flange width to less than the column width (column width: 125 mm or 150 mm) (ii) Require the minimum flat flange width (50 mm) to be connected to the wall stud
Radius of curved section	(i) Minimum radius of curved section less likely to cause a crack
Flange height	(i) Flange to thickness ratio is larger than 61 ($h_f > (h - 61t)/2$)
Welding length	(i) Prevent local buckling
Variable section	
Thickness of steel plate	(i) Variable sections for variable floor loads and spans
Web height	(i) Variable sections for variable floor loads and spans (ii) Able to penetrate pipes

FIGURE 5: Range of the flange width.

- (ii) The maximum steel plate thickness is limited to 10 mm.
- (iii) If the bending angle of r_1 is in the range of 90 to 180 degrees, $r_1 = 15$ mm.
- (iv) If the bending angle of r_2 is 90 degrees, $r_2 = 12$ mm.

Step 3 (determination of the flange width). (i) If the steel plate thickness is 10 mm and r_1 and r_2 are 15 and 12 mm, respectively, the flat flange width is in the range of 53 to 73 mm, thus satisfying the condition in Step 1.

(ii) The flange width is determined as 120 mm, which is the maximum value allowed by the condition in Step 1, considering its easy attachment onto ceilings and floor tracks.

Step 4 (determination of r_3). This value is constant if the same roll forming process is used regardless of the flange thickness.

- (i) If bending angle of r_3 is less than 90 degrees, $r_3 = 12$ mm, which is the same as r_2 .

FIGURE 6: Determination of r_1 and r_2 .

FIGURE 7: Determination of the flange height.

Step 5 (setting up the range of the flange height shown in Figure 7). (i) If it is assumed that the upper and lower flanges are parallel to each other and the flange thickness is 10 mm, $h_{f,min1} = 10 + 15 + 15 + 10 = 50$ mm.

(ii) The flange height can be calculated by considering the maximum beam height of 400 mm and minimum steel plate thickness of 4.5 mm and applying the maximum width-thickness ratio of 61 to prevent elastic local buckling as $h_{f,min2} = (400 - 61 \times 4.5)/2 = 63$ mm.

Step 6 (final selection of invariable dimensions of the upper hollow flange). (i) Front welding is performed on the steel plate connection as shown in Figure 8.

The following design conditions for the variable portion of the MCS beam cross-section are assumed for three module spans of 6, 7.5, and 8.1 m: floor beam load in the range of 2~5 kN/m², floor beam live load in the range of 2~5 kN/m², ceiling beam load in the range of 0.3~0.5 kN/m², and ceiling beam live load in the range of 0.5~1 kN/m². Various cross-sectional shapes for the MCO beam are designed by changing the steel plate thickness and web height as design variables, while satisfying the requirements on the dimensions of the cross-section discussed above. As shown in Table 11, 6 steel plate thickness values and 7 web heights are used as design values. The effective moment of inertia for the cross-sections

FIGURE 8: Invariable dimensions of the upper hollow flange of the MCO beam.

TABLE 11: Design requirements and values on the variable sectional portion of the MCO beam.

Design factors	Design requirements	Design values
Thickness of steel plate	Use standard steel products	(i) 4.5 mm, 6 mm, 7 mm, 8 mm, 9 mm, 10 mm
Depth of beam	Apply modular coordinate	(i) Floor beam: 270 mm, 300 mm, 330 mm, 360 mm, 390 mm (ii) Ceiling beam: 200 mm, 240 mm

in the table ranges from 1,530 to 18,218 cm⁴. A total of 42 of the designed MCO beam cross-sectional shapes are given in Figure 9.

4. Design Verification and Pilot Test

As the final stage of the DFSS methodology, MCO beam rolls are produced using the roll forming facilities of a local company in Korea, and their formability and welding workability are assessed. Figure 10 shows the procedure for a pilot production of the MCO beam sections developed. A long strip in coiled steel is passed through sets of rolls until a shape with upper and lower hollow flanges is obtained. Then the production of the MCO beam section is completed by performing welding on the roll formed shape. Figure 11 shows an example of the assembled modular unit with the produced MCO beams.

The results of CTQ and productivity assessments on the final products are summarized in Table 12. The deformation level of the MCO beam that occurs during its production is less than 5 mm per 10 m. While some deformation may take place during secondary machining such as welding of brackets and end plates, additional correction can be performed in the process of module assembly, resulting in an error less than 3 mm per unit module. To confirm that

the produced beams have a sufficient moment of inertia per unit cross-sectional area, a total of 150 cases are tested for various floor spans and loading conditions. The results of the test show that the average floor span is 183.38 cm² and the standard deviation is 16 cm². Thus, the average is well above the design target, which is 160 cm². For three spans of 6, 7.5, and 8.1 m, floor beams with optimal cross-sections are selected, and then the weight of the floor beams per unit area is evaluated for each case. It can be seen from the results of the table that target values are met for all of the three cases.

5. Concluding Remarks

In this study, a systematic approach was presented for the development of an efficient steel beam section for modular construction based on Six-Sigma. As the first step of this approach, market studies and surveys are conducted to obtain the opinions of potential customers. Then the opinions of the customers were converted into the quality characteristics for the channel-shaped steel beam using the quality function deployment methodology. A steel hollow flanged channel was chosen as the main modular beam shape, and the design concept was derived and developed by applying the Pugh matrix methodology. A pilot test was performed to validate the effectiveness of the developed beam section. The main conclusions of this study are as follows:

- (1) To reflect customers' needs in the development of production processes, the QFD methodology was applied, and "welding length per unit length," "moment of inertia per sectional area of beam," and "weight of floor beams per unit area of plan" were selected as CTQs. Quantitative target values for these items were also set up.
- (2) Seven design concepts were developed from an analysis on the key functions of the steel modular beam to satisfy the derived CTQs. The Pugh matrix methodology was applied to derive the optimal design of the steel modular beam, which has hollow flanges at the top and bottom.
- (3) In the final product design, the cross-section of the MCO beam has the upper and lower hollow flange parts as the invariable portion and the web section as the variable portion. The results of the pilot production of the MCO beam indicate that the weight of the floor beams per unit area can be reduced to an average of 0.25 kN/m² for the standard 7.5 m span, which is 18% less than the corresponding value for the built-up RHS beam. All the modules assembled with the MCO beam products show an error less than 3 mm per unit module, thus satisfying the target value.
- (4) Based on the DFSS methodology of Six-Sigma, this study proposed a methodology which can effectively reflect customers' needs, such as the reduction of manufacturing cost, less material usage, and reduced structural deformation of modular units, in the product design. It is expected that the proposed method

FIGURE 9: Developed cross-sectional shapes for the MCO beam.

FIGURE 10: Pilot production process for the developed MCO beam.

FIGURE 11: Assembled modular unit with the produced MCO beams.

TABLE 12: Design targets and test results for the produced MCO beams.

Design factors	Design targets	Test results
Verification of CTQ		
Welding length per unit length (m/m)	Less than 2	2
Moment of inertia per unit sectional area of beam (cm^2)	Larger than 150	Average 183.86
Weight of floor beams per unit area (kN/m^2)		
6 m span	Less than 0.25	0.18
7.5 m span	Less than 0.28	0.25
8.1 m span	Less than 0.35	0.32
Pilot test		
Pilot production of beam	Flexural deformation is less than 0.05%	Less than 0.05%
Pilot assembly of module	Tolerance of 3 mm	Less than 3 mm

can be utilized to develop other types of structural modular beams and can satisfy the diverse requirements of different customer groups.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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