Study on Comprehensive Evaluation Method for Construction Suitability of Precast Concrete Beam-column Connections

Wanliang Jiang1*, Bin Du2
1Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, Liaoning, 116024, China
2Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, Liaoning, 116024, China
*Corresponding author’s e-mail: wanliangjiang@mail.dlut.edu.cn

Abstract: The key difference between prefabricated structure and cast-in-place structure is the connection of components. The comprehensive reliability of the connection directly determines the overall performance of the structure, and also affects its application scope in the building structure. It is particularly important to select the appropriate beam-column connections in the construction. In recent years, with the continuous development of precast concrete structure, a large number of precast beam-column connections have been invented. However, in view of different construction environment, construction cost and building function requirements, the selection of precast beam column connections is often difficult to choose. Therefore, this paper is based on the Analytical Hierarchy Process (AHP) evaluation model, combined with the evaluation index of the precast concrete beam-column connections, to provide a scientific method for selecting suitable precast beam-column connections for engineering construction.

1. Introduction
In recent years, China has continuously promoted high-quality economic development and sustainable environmental development. Although governments are promoting prefabricated buildings, precast beam-column connections often limit its scope of application. For example, the traditional bolted and corbel connection is convenient for construction, can greatly reduce the construction period. Due to the poor shear bearing capacity of the bolts, its seismic performance is poor[1]. The hybrid beam-column connection has good ductility and seismic performance. The introduction of section steel increases the difficulty of construction and will increase the construction cost[2][3][4]. The prestressed beam-column connections are reasonably designed and have good seismic performance and self-reset ability[5]. However, it is precisely because of the introduction of prestress that the construction accuracy of beam-column connections is required to be high.

There are many factors that need to be considered in choosing suitable connection. At present, there are few studies on construction suitability of precast connection. Choosing connections often depends on the judgment of decision-makers or previous experience, which leads to a single and unscientific form. Therefore, based on the Analytic Hierarchy Process (AHP), this paper takes the multi-objective decision-making problem of choosing suitable precast beam-column connections as a system. The decision-making objective is decomposed into several levels, and the appropriate overall sequence for the construction suitability of precast connection project is calculated through the fuzzy quantitative method of qualitative indicators. It provides a set of scientific and systematic methods for the selection
of precast concrete connections.

2. Selection of evaluation indexes for construction suitability of precast concrete beam-column connections
The function of the precast beam-column connection is to transmit internal forces, so that the structure has a good integrity under the action of external loads. In order to make the precast beam-column connections have better suitability in construction, considering its mechanical connection performance, it is necessary to combine specific engineering construction indicators.

2.1. Construction cost
The construction process of precast beam-column connection is divided into production, transportation and on-site installation. The costs incurred by these three parts of the process directly affect the economics of project construction. Since the prefabricated forms and installation methods of different beam-column connections are quite different, it is necessary to combine the specific forms of beam-column connections for engineering economic analysis.

2.2. Seismic performance
The seismic performance of precast beam-column connections should be considered comprehensively through the selection, so that they can meet the seismic code requirements under the designed ground motion. In order to ensure that the precast beam-column connections have good seismic performance, the connections must have excellent integrity, shear and bending resistance, stiffness, ductility and energy dissipation capacity.

2.3. Simplicity
The suitability of engineering construction requires precast beam-column connections to be as simple as possible. For example, reduce the use of anchors as much as possible, or enable anchors to perform more functions. The simplicity of connection allows workers to quickly familiarize themselves with the installation process and improve the construction quality. Simplicity mainly refers to the simplicity of prefabrication and installation.

2.4. Architectural function
The function of the building is one of the three elements of the building. This refers to the precast beam-column connections selected for engineering construction to ensure aesthetics.

2.5. Adaptability
The project construction selects suitable precast beam-column connections according to the local geographical environment. For example, the thermal insulation performance of the structure and the deformation caused by temperature changes should be considered for cold climate buildings. Therefore, the adaptability of precast beam-column connections in different environments is particularly important for the suitability of project construction.

2.6. Durability
The durability requirements of the connections should not be lower than the durability of the overall structure. The poor durability of beam-column connections is usually manifested in the corrosion of steel components or concrete cracking. The crack resistance of precast concrete is generally good. Due to the different details of the precast beam-column connections, the concrete may crack or peel off.

2.7. Other index
Compared with the cast-in-place structure, the fabricated building structure can reduce material and energy consumption and is more environmentally friendly. In order to give full play to the advantages of fabricated building structures, many precast beam-column connections can be recycled. For
engineering construction, the more recyclable times and components of precast beam-column connections, the more suitable the requirements of contemporary construction and development.

3. Establishment of suitability evaluation model for construction of precast beam-column connections

3.1. Introduction of Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a hierarchical weighted decision analysis method proposed first by Saaty [6]. AHP is simple, widely applicable, clear in thinking, and strong in system [7]. It has become a method that attracts attention in decision-making science. At present, AHP has been successfully applied to the field of the sustainable design proposal for an area, prefabricated building construction bidding, factory optimization site selection, policy evaluation [8][9][10][11], etc.

The basic principle of the AHP is to decompose the decision-making problem, and obtain the weight order of the elements of each level to the elements of the previous level. Finally, weight and recursively merge the final weight of the plan layer to the total goal, and the plan corresponding to the maximum weight is the optimal plan [12].

3.2. Analysis steps

(1) Establishment of hierarchical structure model

AHP hierarchizes and organizes decision-making issues, and establishes a structure model with clear levels. The decision-making problem is decomposed into several sub-problems, and then these sub-problems are decomposed into the following three levels according to their attributes and relationships.

a) Target layer: This layer generally has only one element, which is the goal or ideal effect to be achieved by the decision-making problem.

b) Criterion layer: This layer is an intermediate link in order to achieve the goals of the upper level, and it can be composed of several levels.

c) Scheme layer: This layer is all the specific plans that can be selected to achieve the overall goal.

(2) Establish judgment matrices at all level

Compare the factors in pairs to build a comparison matrix. Take two factors $m_i$ and $m_j$, use $m_{ij}$ to represent the ratio of the influence of $m_i$ to $m_j$. Set the comparison results into the judgment matrix $M=(m_{ij})_{n \times n}$. The factor contrast is divided into 9 to avoid too many classifications that are difficult to judge. As shown in Table 1.

| Scale | Meaning |
|-------|---------|
| 1     | Two elements have the same importance |
| 3     | The former element is slightly more important than the latter |
| 5     | The former element is obviously more important than the latter |
| 7     | The former element is far more important than the latter |
| 9     | The former element is extremely important than the latter |
| 2,4,6,8 | Represents the middle value of the above two values |
| Reciprocal | The latter element is more important than the former |

(3) Single-level element sorting and all-level element sorting

The eigenvector $W$ corresponding to the maximum eigenvalue $\lambda_{max}$ of the judgment matrix $M$ is normalized and transformed into the ranking weight of the importance of the elements of the same level to the elements of the upper level. Next, it is necessary to obtain the sorting weight of the scheme in the lowest layer for the target. The total ranking of levels refers to the calculation of the relative importance of all elements of the same level to the highest level. This process is carried out from high level to low level. The calculation process of all-level element sorting is shown in Table 2.
Table 2. Calculation process of all-level element sorting

| Level $B$ | Level $A$ | Total sort of level $B$ |
|-----------|-----------|-------------------------|
| $A_1, A_2, \cdots, A_n$ | $(a_1, a_2, \cdots, a_n)$ | Weight $W$ |
| $B_1$ | $b_{11}, b_{12}, \cdots, b_{1n}$ | $\sum_{j=1}^{a} a_j b_{1j}$ |
| $B_2$ | $b_{21}, b_{22}, \cdots, b_{2n}$ | $\sum_{j=1}^{a} a_j b_{2j}$ |
| $\vdots$ | $\vdots$ | $\vdots$ |
| $B_m$ | $b_{m1}, b_{m2}, \cdots, b_{mn}$ | $\sum_{j=1}^{a} a_j b_{mj}$ |

(4) Consistency check
The complexity of objective things makes our judgments one-sided and subjective. Therefore, it is impossible for the judgment criteria of thinking to be consistent every time. The judgment matrix deviation should have a degree, so the consistency test is introduced in the AHP, which is mainly used to judge whether the judgment matrix can be accepted. First calculate the consistency index $CI$:

$$CI = \frac{\lambda_{\text{max}} - n}{n-1}$$

$n$ is the order of the judgment matrix. When the judgment is consistent, CI=0.

3.3. The evaluation index system for the suitability construction suitability
According to the aforementioned construction suitability evaluation index, the evaluation index system is divided into four layers. They are the target layer, the criterion layer, the sub-criteria layer and the scheme layer. The evaluation index system of construction suitability is shown in Figure 1.

![Figure 1. Comprehensive evaluation index](image-url)
4. Calculation example of construction suitability of precast concrete beam-column connection

The main purpose of this article is to provide a systematic and scientific method for selecting suitable precast beam-column connections. Through corresponding simplification of complex indicators, some indicators with less impact are ignored. The entire comprehensive evaluation process is simpler and easier for relevant personnel to study.

4.1. Index weight of the target layer

A is the construction suitability of the target layer. The corresponding criterion layer include construction cost B₁, architectural function B₂, and durability B₃, etc. According to the actual acceptance, different construction companies compare the two elements of the criterion level to determine the weight. This article compares the two elements and obtains the factor weights shown in Table 3.

| A   | B₁  | B₂  | B₃  | B₄  | B₅  | B₆  | B₇  |
|-----|-----|-----|-----|-----|-----|-----|-----|
| B₁  | 1   | 2   | 2   | 1/3 | 2   | 1   | 3   |
| B₂  | 1/2 | 1   | 1   | 1/6 | 1   | 1/2 | 3/2 |
| B₃  | 1/2 | 1   | 1   | 1/6 | 1   | 1/2 | 3/2 |
| B₄  | 3   | 6   | 6   | 1   | 6   | 3   | 9   |
| B₅  | 1/2 | 1   | 1   | 1/6 | 1   | 1/2 | 3/2 |
| B₆  | 1   | 2   | 2   | 1/3 | 2   | 1   | 3   |
| B₇  | 1/3 | 2/3 | 2/3 | 1/9 | 2/3 | 1/3 | 1   |

4.2. The weight of each factor at the criterion level

The criterion layer can be further decomposed into sub-criteria level. The two elements are compared, and the corresponding weights of the sub-criteria layer factors are obtained. The focus of this article is to provide a reliable evaluation method, so the weights of a large number of sub-criteria layer factors are not listed individually. Interested readers can contact the author to view the detailed weight list.

The scheme layer is precast concrete beam-column connections, which are mainly divided into hybrid, bolt, corbel and pre-stressed beam-column connections. Due to the large number of precast concrete beam-column connections, the weights of the comparison of the two elements will not be listed individually. Two of the precast concrete beam-column connections is shown in Figure 2.

(a) hybrid precast concrete connections [2]

(b) Post-tensioned precast connection [5]

Figure 2. Precast concrete beam-column connections

Figure 3. Evaluation process
4.3. Evaluation results of construction suitability

The eigenvector corresponding to the largest eigenvalue of each judgment matrix is solved, and the normalization is the relative weight of the same level element to the upper level. In order to get the final program choice. Therefore, it is necessary to sort the weight of the target layer by each scheme. It needs to be transmitted continuously, and the total ranking weight is combined from the top to the bottom of the weights of all the criteria. All judgment matrices have passed the consistency check. The detailed evaluation process is shown in Figure 4.

| Criterion layer | B1 | B2 | B3 | B5 | B7 | B11 | B13 | B22 | B31 | B41 | B42 | B43 | B44 | B45 | B51 | B61 | B62 | B71 | B72 | B73 | B74 | B75 | B76 | B77 | B78 | B79 | B80 | B81 | B82 | B83 | B84 | B85 | B86 | B87 | B88 | B89 | B90 | B91 | B92 | B93 | B94 | B95 | B96 | B97 | B98 | B99 | B100 |
|-----------------|----|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Weight of criterion layer | 0.15 | 0.07 | 0.07 | 0.44 | 0.04 | 0.07 | 0.15 | 0.05 | Total sort | Rank |
| Sub-criterion layer | B11 | B12 | B13 | B14 | B15 | B16 | B17 | B18 | B19 | B20 | B21 | B22 | B23 | B24 | B25 | B26 | B27 | B28 | B29 | B30 | B31 | B32 | B33 | B34 | B35 | B36 | B37 | B38 | B39 | B40 | B41 | B42 | B43 | B44 | B45 | B46 | B47 | B48 | B49 | B50 | B51 | B52 | B53 | B54 | B55 | B56 | B57 | B58 | B59 | B60 | B61 | B62 | B63 | B64 | B65 | B66 | B67 | B68 | B69 | B70 | B71 | B72 | B73 | B74 | B75 | B76 | B77 | B78 | B79 | B80 | B81 | B82 | B83 | B84 | B85 | B86 | B87 | B88 | B89 | B90 | B91 | B92 | B93 | B94 | B95 | B96 | B97 | B98 | B99 | B100 |
| Weight of sub-criterion layer | 0.67 | 0.33 | 1.00 | 1.00 | 0.09 | 0.36 | 0.27 | 0.18 | 0.09 | 1.00 | 0.33 | 0.67 | 1.00 |
| Weight of scheme layer | 0.15 | 0.07 | 0.07 | 0.44 | 0.04 | 0.07 | 0.15 | 0.05 | Total sort | Rank |

Figure 4. Evaluation result of the construction suitability

4.4. Standard steps of determining parameters

The main steps are as follows: (1) Establishment of evaluation index system: The problem is organized and hierarchized, and divided into different levels according to the internal connection. (2) Expert evaluation: In order to accurately obtain representative results, it is necessary to invite experts of construction to participate in the evaluation process. These experts must have rich construction experience and a deep understanding of the actual project’s requirements for precast connection. According to the evaluation index system, determine the degree of importance between the two factors. (3) Arrangement of results: Sorting out expert evaluation results, keeping the data whose median difference is within 30%, and average the values to get the index weight. (4) Establishment of judgment matrix: The judgment matrix of each level is constructed by the above evaluation results. (5) Single-level and all-level element sorting: Using MATLAB calculates the eigenvector of the maximum eigenvalue of each judgment matrix, and normalize the elements of the same level. Combine the weights under the single criterion from top to bottom. (6) Consistency check: Comparing the consistency index CI with the random consistency index RI, the result is acceptable when the consistency ratio CR is less than 0.1.
than 0.1. The detailed process is shown in Figure 3.

\[ CR = \frac{CI}{RI} \] (2)

5. Conclusion
This paper successfully establishes the evaluation indexes of precast concrete beam-column connections, and provides a scientific method for better selecting suitable beam-column connections for construction based on the AHP. According to the passages above, the following conclusions can be drawn:

1. The evaluation indexes established in this paper can comprehensively evaluate the comprehensive performance of precast connections. The comprehensive evaluation based on the AHP can objectively analyze the complex factors that need to be considered in construction, and improve the reliability of decision-making.

2. Selecting the AHP to comprehensively evaluate the construction suitability can simplify the work process and combine quantitative evaluation with qualitative evaluation. It not only meets the actual needs of construction, but also greatly reduces the influence of subjective factors.

3. The AHP has certain qualitative elements when comprehensively evaluating the construction suitability. Different groups have differences in the degree of recognition of the same index, which leads to certain differences in the evaluation results.

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