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# Comprehensive benefits analysis of steel structure modular residence based on the entropy evaluation

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**Abstract:** Steel structure modular residence is the outstanding residential industrialization. It has many advantages, such as the low whole cost, high resource recovery, a high degree of industrialization. This paper compares the comprehensive benefits of steel structural in modular buildings with prefabricated reinforced concrete residential from economic benefits, environmental benefits, social benefits and technical benefits by the method of entropy evaluation. Finally, it is concluded that the comprehensive benefits of steel structural in modular buildings is better than that of prefabricated reinforced concrete residential. The conclusion of this study will provide certain reference significance to the development of steel structural in modular buildings in China.

## 1. Introductions

At present, the domestic development of the assembly building is mainly a relatively low degree of direct assembly of prefabricated structural system, but modular building structure system is still in its infancy. According to the different structure of the main body, the assembled building can be divided into steel structure and concrete structure. In this paper, steel structural in modular buildings, a collection of steel structure and modular building structure, belongs to the prefabricated building with high degree of prefabrication.

With the entropy method, from the point of economic benefit, environmental benefit, social benefit and benefit perspective, this paper analyzes comprehensive benefit of the above residential structures. Finally, the conclusion is drawn that the comprehensive benefit of steel structure modular residential project is better than that of the assembled reinforced concrete residential project. The research results can provide reference for the further promotion of steel structure modular residential projects.

## 2. Establishment of Comprehensive Benefit Evaluation Index System

Based on studies above some references, the following will be from the economic benefits, environmental benefits, social benefits and technical benefits to compare and analyze the comprehensive benefits of steel structure modular residential projects and prefabricated reinforced concrete residential projects.

### *2.1. Economic Benefits*

About two data of economic benefit analysis based on some cases. Cases are shown in Table1.

**Table 1.** The basic situation of the projects

| | Steel Structure Modular Residential Projects | Prefabricated Reinforced Concrete Residential Projects | The cast-in-place Reinforced Concrete Residential Projects | Remarks |
|---|---|---|---|---|
| **Basic Feature Indexes** | 16 floors above ground; 7064 square meters | 18 floors above ground; 8125 square meters | 20 floors above ground; 9631 square meters; | |
| **Construction Schedule** | 45 days | 120 days | 200 days | |
| **Building Cost** | 2050 yuan / sq. M | 1650 yuan / sq. M | 1200 yuan / sq. M | |

Based on the case study, this paper analyzes the economic benefits of the modular residential projects and the assembled reinforced concrete residential buildings. Among them, the two economic benefits will be compared from the overall cost, operating costs and resource recovery.

*2.1.1 Overall Cost.* The overall cost of the project refers to the sum of project construction cost and the equivalent cost which is transformed from the economic income coming from differences between the effective use area, structure materials and construction schedule. [1] In order to facilitate comparative analysis, here to a place of reinforced concrete residential projects as a benchmark for comparison.

Total cost = project cost - interest savings - rental income - the use of the area to enhance the rate of return the direct economic benefits brought by shortening construction period.

Interest savings per unit area = (the number of days to shorten the duration of each layer × layer) ÷365× per unit area of the project cost ×annual rate; Rental income per unit area = (the number of days per week to shorten the length of the floor × layer)÷30÷rental income per unit area the direct economic benefits brought by the increase of residential area.

Rate of increase in unit area utilization = increase in the use of the area rate × unit area residential price.

According to the above cases and formulas, we can get the overall cost per unit area of modular residential buildings.

**Table2.** Comparison of the overall cost of different residential projects

| | Steel Structure Modular Residential Projects | Prefabricated Reinforced Concrete Residential Projects | The cast-in-place Reinforced Concrete Residential Projects |
|---|---|---|---|
| **Construction Cost per unit area (RMB / square)** | 2050 | 1650 | 1200 |
| **Interest Savings per unit area (RMB / square)** | -51.67 | -16.27 | - |
| **Rental Income per unit area (RMB / square)** | -191.67 | -75 | - |
| **Income raised by unit area Utilization Rate(RMB / square)** | -430.5 | 0 | - |
| **Overall Cost per unit area (RMB / square)** | 1376.16 | 1558.73 | 1200 |

We can find that the overall cost per unit area of the modular residential project of steel structure is slightly lower than or similar to that of the reinforced concrete residential building.

*2.1.2 Operating costs.* Because of the lack of data on the maintenance cost of the steel structure modular residential and the prefabricated reinforced concrete residential, the experts in the field are invited to estimate the daily maintenance cost and the overhaul cost of the different residential projects according to the parameter estimation method and analogy method. The estimation results are as follows: the modular steel structure housing is 107 RMB / square meters (converted to present value after the maintenance cost per unit area, the same below), prefabricated reinforced concrete residential 81 RMB / square meters.
*2.1.3 Resource recovery* The steel structure and the new type of enclosure materials are the green building materials with high recovery rate. At the end of the life, its resource recovery rate is up to 80%. But reinforced concrete is difficult to achieve resource recovery. At the end of the life, its resource recovery rate is only 10%.

### *2.2. Environmental Benefits*

*2.2.1 Carbon emissions.* The carbon emissions of building life cycle are mainly from the physical and chemical phase, the operation stage and the disposal and recovery stage [3]. In the operation process, the influence of different building materials on the environment is different. In this paper, 6 kinds of main building materials are selected.

**Table3.** $CO_2$ emissions per unit area of major materials [2]

| | Cement(kg/m$^2$) | Wood(kg/m$^2$) | Steel products(kg/m$^2$) | The total(kg/m$^2$) |
|---|---|---|---|---|
| **Case1** | 87.6 | 0.3 | 163.5 | 251.4 |
| **Case2** | 182 | 1.6 | 143 | 326.6 |

We find that carbon emissions of steel are much greater than that of cement, but the carbon emissions of the steel structure housing unit area are lower than that of reinforced concrete housing. Because the overall amount of materials to the steel structure housing is lower than concrete, the advantage of carbon emissions per unit is more obvious.

Carbon emissions in operation stage is mainly brought by the requirement for heating and air conditioning and consumption of electricity and gas to the realization of the building itself.

The disposal of carbon emissions in the recovery phase is mainly brought by the removal and disposal of waste. Measured from the whole life cycle, the $CO_2$ emission of reinforced concrete buildings is 1.4 times that of steel structures [2].

### *2.3. Social Benefits*

*2.3.1 The degree of industrialization.* Prefabricated rate refers to the completion of the single building, the proportion of the factory production volume of the total construction volume. According to the case analysis of the steel projects, the current steel structure modular residential prefabricated rate is up to 90% [3]. The prefabricated concrete project of prefabricated rate is only 60% [4].

*2.3.2 The satisfaction of users.* The demand of the customer is mainly reflected in the thermal insulation and sound insulation performance, residential comfort, order purchase, etc. User satisfaction is determined by expert scoring method. This paper invites 6 experts in the field of steel structure modular residential projects to score the user satisfaction of above residential projects.

**Table 4**. Scoring table of user satisfaction

| | Expert 1 | Expert 2 | Expert 3 | Expert 4 | Expert 5 | Expert 6 | Total | Composite Score |
|---|---|---|---|---|---|---|---|---|
| Case1 | 6 | 7 | 5 | 6 | 7 | 6 | 37 | 62 |
| Case2 | 7 | 8 | 6 | 7 | 6 | 7 | 41 | 68 |

### *2.4. Technical Benefits*
The technical benefit analysis of the main body is carried out from the safety of the structure.

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*2.4.1 Structural safety.* Many results of the survey showed good seismic behavior of steel structures. In September 21, 1999, a magnitude 7.6 earthquake occurred in Taiwan, China, which is in the vicinity of Riyuetan Pool, with a magnitude of about 6, and the damage rate of the steel structure is only about 0.6%, and the failure rate of reinforced concrete and brick structure is more than 75% [4].

**Table 5.** Comparison of failure rates of building structures with different structural systems

| Structure Types | RC | Steel Structure | Brick Structure | Wood Structure | SRC | Adobe | Iron | Others |
|---|---|---|---|---|---|---|---|---|
| Failure Rate | 52.5 | 0.6 | 24.1 | 1.5 | 0.2 | 13.1 | 7.9 | 7.2 |

As can be seen from the above table, the damage rate of steel structure and SRC is low, the structural safety is higher. In contrast, the failure rate of reinforced concrete structure and brick structure is high, and the structural safety is low.

*2.5. Establishment of Index System*

Based on the above analysis, the relevant indicators are selected in the following table.

**Table 6.** Comprehensive benefit evaluation index system

| Target Layer | Criterion Layer | Index Layer | Meaning of Indicators |
|---|---|---|---|
| Comprehensive Benefits(A) | Economic Benefits(B1) | Overall cost | Considering the overall cost of the unit area of the construction period and the room rate |
| | | operating costs | Maintenance cost during operation |
| | | Resource recovery | Resource recovery at the end of life |
| | Environmental Benefits(B2) | $CO_2$ emissions | Physical phase carbon emissions |
| | Social Benefits(B3) | Industrialization degree | Prefabrication rate |
| | | User satisfaction | User needs satisfaction |
| | Technical Benefits(B4) | Main structure safety | Failure rate of building structure |

According to the above established index system and research results, this article sorted out the corresponding index system of the comprehensive benefit of steel structure modular residential and prefabricated reinforced concrete residential with the data shown in the table below.

**Table 7**. Evaluation index data of different residential projects

| | Case1 | Case2 |
|---|---|---|
| **Overall Cost** | 1376.16 | 1558.73 |
| **Operating Costs** | 107 | 81 |
| **Resource Recovery** | 80% | 10% |
| **$CO_2$ Emissions** | 251.4 | 326.6 |
| **Prefabrication Rate** | 90% | 60% |
| **User Satisfaction** | 62 | 68 |
| **Failure Rate of Building Structure** | 0.6% | 52.5% |

## 3. Evaluation Method

There are M evaluation objects and N evaluation indexes, $a_{ij}$ is the $J_{th}$ index of the $I_{th}$ evaluation object, all the original data constitute the original matrix $A = (a_{ij})_{m\times n}$. The inverse method is used to forward the reverse index, and the mean value method is used to get the original data $X = (x_{ij})_{m\times n}$.

According to the original data of the research above, we get the matrix X:

$$X = \begin{bmatrix} 1.062 & 0.862 & 1.778 & 1.130 & 1.200 & 0.954 & 1.977 \\ 0.938 & 1.138 & 0.222 & 0.870 & 0.800 & 1.046 & 0.023 \end{bmatrix}$$

The proportion of the target value $P_{ij}$:

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, (i = 1,2, \ldots\ldots m;\ j = 1,2, \ldots\ldots n) \quad (1)$$

According to the formula (1), the P matrix of modular residential buildings and fabricated reinforced concrete residences.

$$p = \begin{bmatrix} 0.53 & 0.43 & 0.89 & 0.57 & 0.60 & 0.48 & 0.99 \\ 0.47 & 0.57 & 0.11 & 0.43 & 0.40 & 0.52 & 0.01 \end{bmatrix}$$

$$e_j = -k\sum_{i=1}^{m} p_{ij}\ln p_{ij} \qquad k = \frac{1}{\ln m}, 0 \le e_j \le 1. \quad (2)$$

According to the formula (2), $e_j$ can be obtained by the 7 indicators of entropy:

$$e_j = \begin{pmatrix} 0.997 & 0.986 & 0.503 & 0.988 & 0.971 & 0.999 & 0.089 \end{pmatrix}$$

According to $e_j$, $d_j$ can be obtained:

$$d_j = 1 - e_j \quad (3)$$

Coefficient of variation of 8 indexes:

$$d_j = \begin{pmatrix} 0.003 & 0.041 & 0.497 & 0.012 & 0.029 & 0.001 & 0.911 \end{pmatrix}$$

Weight of item $J_{th}$:

$$\omega_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (4)$$

According to the formula (4), entropy weight of 8 indexes are as follows:

**Table 8.** Entropy weight of evaluation indexes

| | **B1** | **B2** | **B3** | **B4** | **A** |
|---|---|---|---|---|---|
| $\omega_1$ | 0.005 | | | | 0.002 |
| $\omega_2$ | 0.027 | | | | 0.009 |
| $\omega_3$ | 0.968 | | | | 0.337 |
| $\omega_4$ | | 1 | | | 0.008 |
| $\omega_5$ | | | 0.956 | | 0.020 |
| $\omega_6$ | | | 0.044 | | 0.001 |
| $\omega_7$ | | | | 1 | 0.623 |

Comprehensive benefit coefficient of the $i_{th}$:

$$v_j = \sum_{j=1}^{n} \omega_j p_{ij} \quad (5)$$

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According to the formula (5), comprehensive benefit index of different structural system is as follows.

**Table 9.** Comprehensive benefit index of the housing with two different structural systems

| | B1 | B2 | B3 | B4 | A |
|---|---|---|---|---|---|
| **Case1** | 0.591 | 0.565 | 0.763 | 0.985 | 0.935 |
| **Case2** | 0.409 | 0.435 | 0.237 | 0.015 | 0.065 |

## 4. Conclusions

As can be seen from the table 11, the comprehensive benefits of the modular residential project of steel structure are better than that of the reinforced concrete residential project. Its economic benefits, environmental benefits, social benefits and technical benefits are better than the assembly of reinforced concrete residential projects.

According to the above analysis, the economic benefits of the steel structure modular residential projects are better than that of the assembled steel mixed residential projects. At present, it is important to develop research module technology, and promote the design and construction level of the modular.

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