Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Rethinking truss beams and rigid structural frames of The Crystal Palace

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Abstract

The Crystal Palace was a temporary structure built in Hyde Park, London, as the site of the Great Exhibition of the Works of Industry of All Nations in 1851. Seven schematic drawings and 21 detailed drawings can be found in Ref. [1]. Enormous studies for The Crystal Palace (for example, see Ref. [2]) have been conducted from the viewpoint of architectural history. However, to the author's knowledge, very few studies have investigated from an engineering view [3]. The authors think that extracting the engineering idea for the Crystal Palace would be beneficial for designing structures that need easy construction or rebuilding.

This paper focuses on the Crystal Palace from the structural engineering perspective. The entire structural frame is reproduced on the Rhinoceros, referring to the drawings. The structural system is estimated through a 3D model. The authors first focus on the truss beams. FE analysis simulates various kinds of truss girders. Then, the structural frame in the short side direction is extracted and numerically simulated to confirm the structural behavior under vertical loading.

Keywords: The Crystal Palace, truss structure, reverse engineering, 3D-CAD, FE analysis

1. Introduction

The Crystal Palace was a temporary structure built in Hyde Park, London, as the site of the Great Exhibition of the Works of Industry of All Nations in 1851. This building comprised large-span truss beams and modularized structural elements detached and reconstructed after the exposition.

From the view of architectural history, the Crystal Palace is a large space with glass. Additionally, the design by an engineer named Joseph Paxton and the pre-fabricated construction process also can be mentioned remarkably. However, several different opinions can be found regarding the material comprising it. For example, S. Giedion evaluated the Crystal Palace as a building made of "wood," iron, and glass in Ref. [2], while N. Pevsner described it as a building made of iron and glass "entirely" [3]. Notably, it is remarkable that a few of the subsequent literature mention the use of wood.

It is hard to observe the actual structure of The Crystal Palace because it had already been demolished. However, seven schematic drawings and 21 detailed drawings can be found in Ref. [1]. Many documents have been discovered since the beginning of the 2000s. Enormous studies (for example, see Ref. [4]) have been conducted from the viewpoint of architectural history. The author thinks extracting the engineering idea for the Crystal Palace would be beneficial for designing structures that need easy construction or rebuilding. However, to the author's knowledge, very few studies have investigated from an engineering view [5].

This paper focuses on the Crystal Palace from the perspective of structural engineering. In the previous study [6], the third author investigated the drawings and reproduced the architectural image, as seen in Fig. 1. Firstly, the entire structural frame is constructed on Rhinoceros, referring to the drawings in Refs. [1, 6]. The authors first focus on the truss beams. FE analysis simulates various kinds of truss girders. Then, the structural frame in the short side direction is extracted and numerically simulated to confirm the structural behavior under vertical loading.

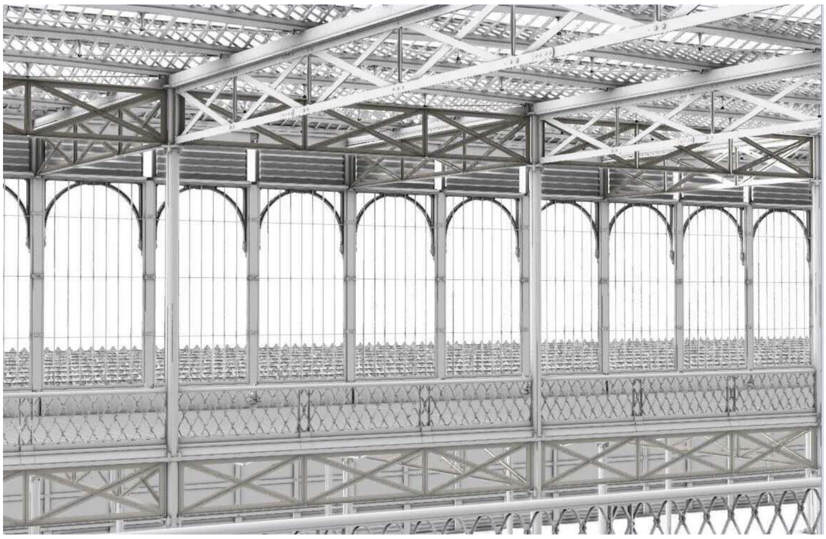
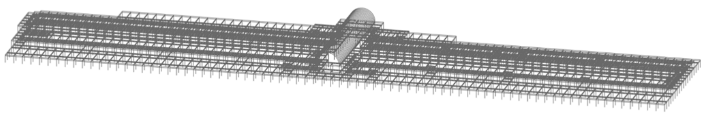


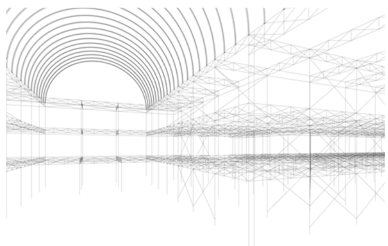
Figure 1: Representative view of the Crystal Palace modeled on Rhinoceros [6].

2. Main structure

A 3D FE model (Fig. 2) is constructed based on Refs. [1, 6]. The structural material of these elements can be classified as shown in Fig. 2(c). The Crystal Palace has seven types of girders, depending on their strength, construction method, and structural materials. The characteristics of each girder can be summarized in Table 1. This paper validates girders and rigid frames extracted from the whole FE model.



(a)



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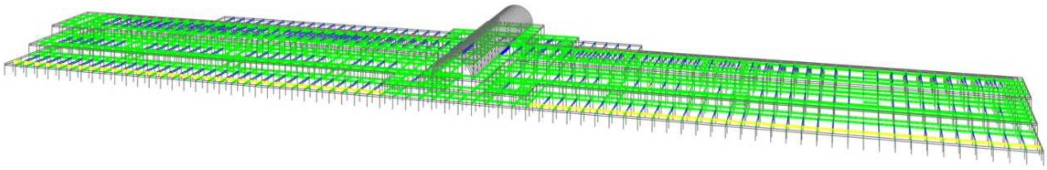

■ : Cast iron, ■ : Wrought iron, ■ : Wood

(c)

Figure 2: FE model for the Crystal Palace; (a) Exterior perspective view, (b) Interior perspective view, (c) Layout of structural material.

Table 1: Structural characteristics of each girder

<table>
<tr><th>ID</th><th>Structural Material</th><th>Span
(ft)</th><th>Girder depth
(ft)</th><th>Location</th><th>Notion</th></tr>
<tr><td>1</td><td rowspan="3">Cast iron</td><td rowspan="4">24</td><td rowspan="6">3</td><td rowspan="3">Both short/long directions</td><td>For general roof structure</td></tr>
<tr><td>2</td><td>For corridor roof</td></tr>
<tr><td>3</td><td>For transept roof</td></tr>
<tr><td>4</td><td>Wood</td><td>Long direction</td><td>For lower roof</td></tr>
<tr><td>5</td><td rowspan="3">Wrought iron</td><td>48</td><td rowspan="3">Short direction</td><td>48 ft span</td></tr>
<tr><td>6</td><td rowspan="2">72</td><td rowspan="2">72 ft span</td></tr>
<tr><td>7</td><td>6</td></tr>
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2.1. Floor system and truss beams

Fig. 3 shows the drawing for the slab and the joist beam. Structural elements made of wrought iron and wood are colored with blue and orange, respectively. As seen in Fig. 3, it can be found that floor load is transmitted from the wooden slab to the cast-iron girders via joist beams, which are reinforced wrought iron tension members.

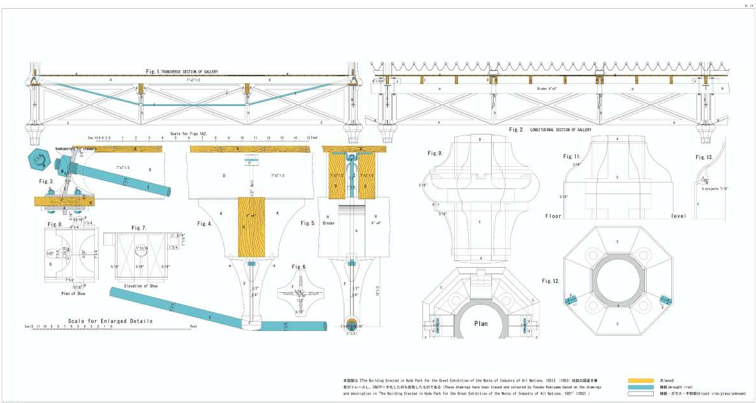
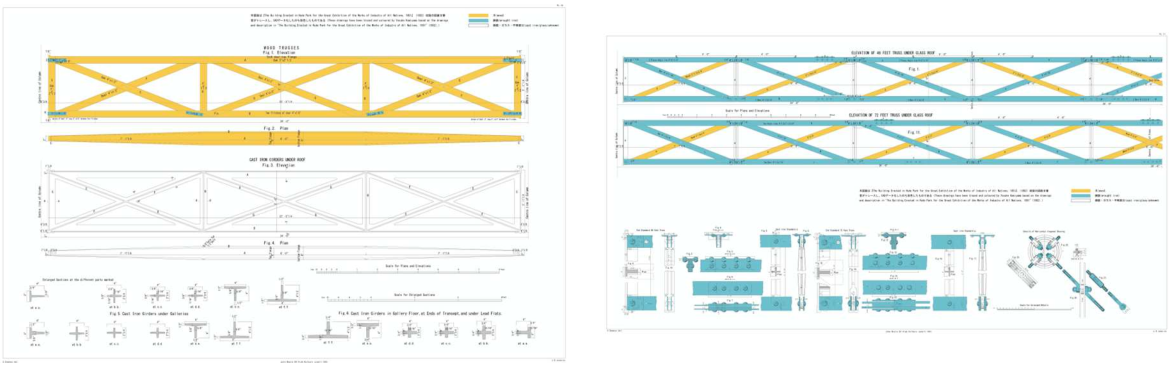


Figure 3: Floor system (slab and joist beam) in PL.14 (traced and colored by third author).

Fig. 4 represents the truss beams. The upper and lower figures in Fig. 4(a) show the wooden truss and cast-iron girder, respectively. By assuming these structures as simple beams, it can be found that the joint design for diagonal members is considered a stress state; tensile diagonal members against the vertical load connect with top and bottom chords via an iron element, which is colored blue, while there is simple joining for compressive diagonal members. Fig. 4(b) shows the trusses of 48 feet and 72 feet span. As seen in Fig. 4(b), iron material (in this truss, wrought iron) is used for the tensile diagonal members. At the same time, wooden material is also used for the diagonal members in other directions. It can be found that the cross sections of tensile diagonal members are different in each grid. There is a possibility that they are designed as varied sections corresponding to the shear stress against the vertical load.

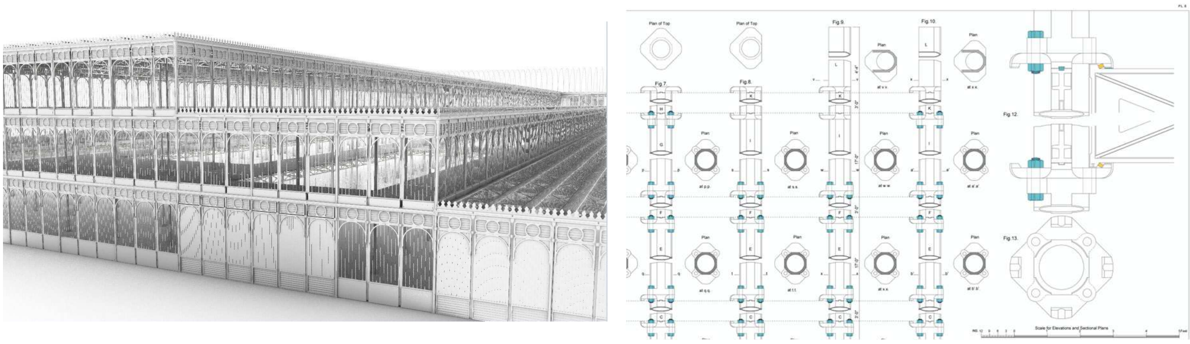


(a) (b)

Figure 4: Drawing of truss beams (traced and colored by third author): (a) Wooden truss and cast-iron girder in PL.10, (b) 48-foot and 72-foot truss in PL.11.

2.2. Rigid structural frame

Fig. 5 (a) shows the exterior view of the representative rigid structural frame in a short direction. Fig. 5 (b) shows the cross sections of cast-iron columns and details of the joint between the cast-iron girder and column.



(a) (b)

Figure 5: Rigid structural frame, (a) Exterior view of the Crystal Palace on Rhinoceros, and (b)Cross sections of cast-iron columns and details of joint between cast-iron girder and column in PL.8 (traced and colored by third author).

3. FE analysis

3.1. Girders

Among the truss girders shown in Table 1, the five types of roof truss girders are validated for comprehensively comparing structural characteristics. The upper and lower chords are modeled by 2D beam elements, the strut and diagonal members by truss elements, and Young's modulus of wrought iron, cast iron, and wood are assumed to be 0.85×105 N/mm2, 1.8×105 N/mm2, and 0.1×105 N/ N/mm2, respectively. Poisson's ratios are 0.27, 0.293, and 6.5 [7]. For ease of comparison, a unit load (1 kN) is assigned at each node for the external forces; 3 kN is assigned for the ID 3 and ID 7 models to account for differences in the roof load. The support conditions are assumed to be the same for all the models, with the lower end supported by pins at one end, rollers at the other, and the upper end supported by pins at both ends. Midas iGen is used for the linear static FE analysis.

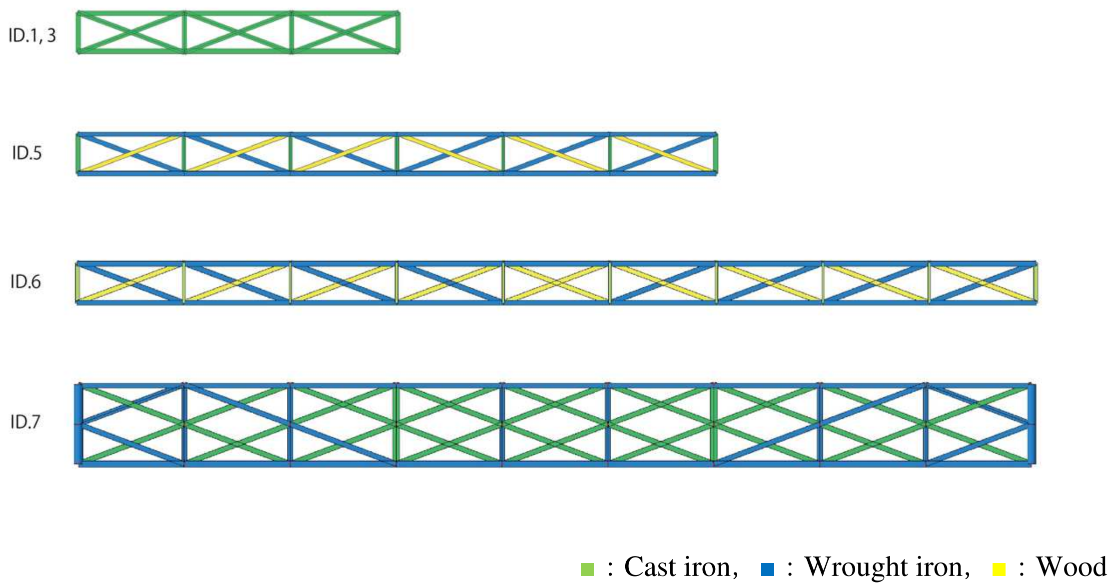


Figure 6: Truss girder with material layout for FE analysis.

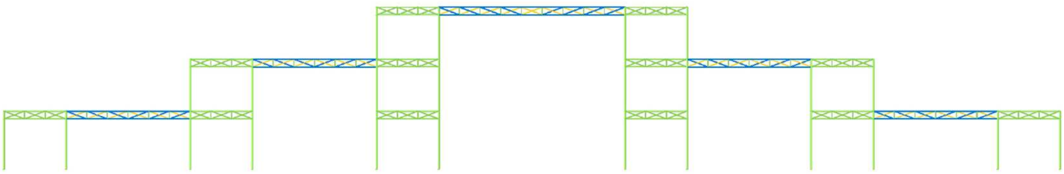
Table 2: Numerical results

ID		1	3	5	6	7
Max. Vertical displacement (mm)		0.20	0.28	1.61	4.06	2.92
Max. axial force (kN)	Upper chord	-2.38	-7.28	-10.6	-26.5	-38.3
	Lower chord	2.9	8.62	11.9	26.5	38.5
	Comp. diagonal member	-1.55	-4.60	-4.61	-10.7	-12.6
	Tensile diagonal member	1.27	3.89	2.47 (7.08)	0.60 (11.3)	12.4
Max. axial stress (N/mm^2)	Upper chord	-1.13	-1.65	-5.73	-4.91	-7.36
	Lower chord	0.75	1.19	5.49	6.09	7.95
	Comp. diagonal member	-1.11	-1.45	-2.73	-4.96	-2.8
	Tensile diagonal member	0.91	1.23	1.39 (3.98)	0.28 (5.28)	4.2
Cross-sectional area ($\times 10\ cm^2$)	Upper chord	2.11	4.41	1.86	5.40	5.20
	Lower chord	3.87	7.24	2.17	4.35	4.84
	Comp. diagonal member	1.40	3.17	1.69	2.16	4.51
	Tensile diagonal member	1.40	3.16	1.78	2.14	2.96

Table 2 shows the numerical results for each girder. The numbers in parentheses in Table 2 represent the maximum values of tensile forces or stresses when the stiffness of the compressive diagonal members is ignored in FE analysis. As seen in Table 2, the maximum stresses of diagonal members are smaller than those of upper and lower chords. Remarkably, these results indicate that the wooden diagonal members for ID 5 and ID 6 can be negligible. Furthermore, the girders of ID 1 and ID 3, which use cast iron, have maximum tensile stresses smaller than their compressive stresses. Conversely, the girders of ID 6 and ID 7, which use wrought iron, have maximum tensile stresses larger than compressive ones. Considering material properties, the cross-sectional area corresponds to the axial stress state.

3.2. Rigid structural frame in short direction

The structural frame in the short side direction, seen in Fig. 7, is numerically simulated to confirm the structural behavior under vertical loading. Young's modulus and Poisson's ratio are assigned, as in Section 3.1. The roof and floor loads are assigned as 15.4 and 61.6 kN/m, respectively. Column cross-sections are considered tubes. According to the drawings, the cross-sectional area of each column is assigned as Fig.9. The bottom of each column is pinned supported. Linear static analysis by using MIDAS iGen is conducted.

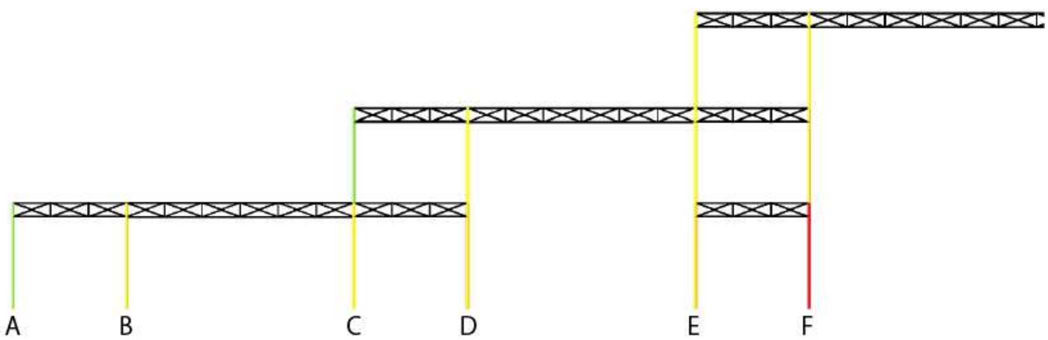


■ : Cast iron, ■ : Wrought iron, ■ : Wood

Figure 7: FE model for rigid structural frame in short direction.

■ : 61.6kN/m, ■ : 15.4kN/m

Figure 8: Load condition.



■ : 73.5 cm^2, ■ : 87.1 cm^2, ■ : 106 cm^2, ■ : 137 cm^2

Figure 9: Distribution of cross-sectional area for each column.

Fig.10 shows the distribution of the axial force against vertical load. It depicts half of the whole structure. The red color represents the maximum compressive force of 685 kN. Table 3 summarizes the compressive axial stress in each column. Note that the total number of ID d is two, and these elements have the same stress value. The results show that the axial forces on the columns increase as the number of stories decreases and that the cross-sectional design corresponds to this stress state.

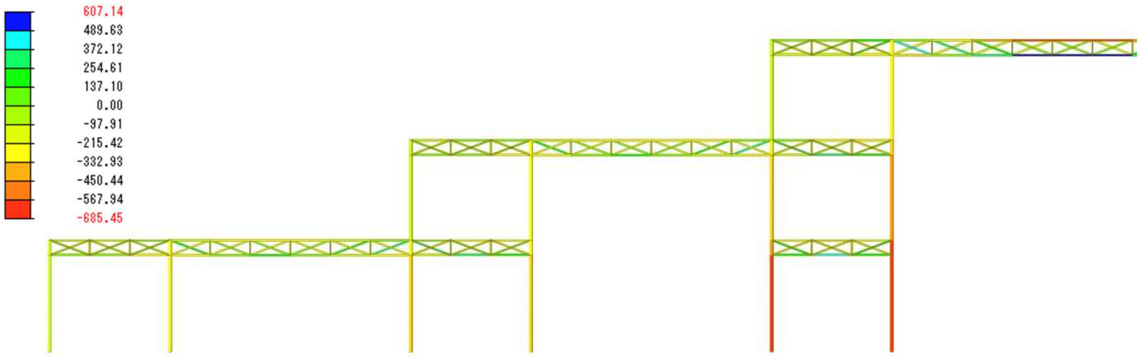


Figure 10: Distribution of axial force against vertical load (Unit: kN).

Table 3: Compressive axial stress in columns.

ID	Cross-sectional area (cm^2)	Compressive axial stress(N/mm2)		
		Max.	Min.	Ave.
a	73.5	4.1	4.0	4.05
b	87.1	46.5	0.8	27.1
c	106	56.1	33.7	43.8
d	137	48.3		

3.3. Future work (How can this structure resist lateral load?)

As an additional investigation, eigenvalue analysis is conducted using the FE model used in the previous section. The structure's natural period shows 3.43 sec. This result indicates that the rigid structural frame in the short direction has low stiffness against lateral load and needs braces. It can be considered that the structure relies on the brace element for resisting lateral loads, such as wind or thermal loads.

The red color in Fig. 11 represents the location of the brace, according to Ref. [1]. As seen in Fig. 11, many braces are embedded in the structure. In future work, the transmission of lateral load is needed to investigate the behavior of the whole structure.

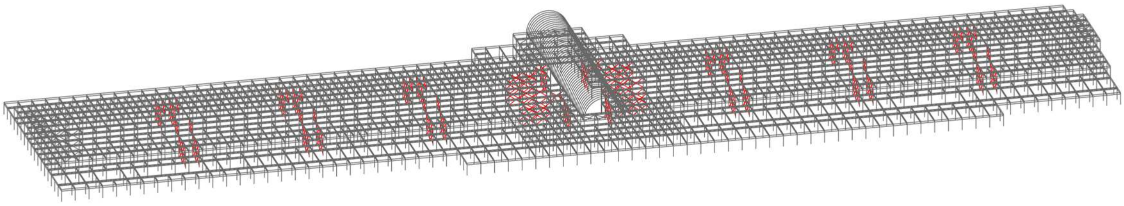


Figure 11: Location of braces

4. Conclusion

This paper focuses on the Crystal Palace from the perspective of structural engineering. Firstly, the idealized structural model is constructed on 3D CAD. The truss beams are focused, and structural characteristics are expressed. The structural behavior of truss girders is examined through numerical analysis. Furthermore, the rigid frame in the short direction, which is extracted from the entire structural frame, is investigated by FE analysis. The conclusion in this paper can be summarized as follows,

[1] A 3D FE model is constructed based on previous studies. The layout of the structural element is investigated. Seven types of girders, depending on their strength, construction method, and structural materials, are identified.

[2] The maximum stresses of diagonal members are smaller than those of upper and lower chords. Remarkably, the wooden diagonal members for ID 5 and ID 6 can be negligible. Furthermore, the girders of ID 1 and ID 3, which use cast iron, have maximum tensile stresses smaller than their compressive stresses. Conversely, the girders of ID 6 and ID 7, which use wrought iron, have maximum tensile stresses larger than compressive ones. Considering material properties, the cross-sectional area corresponds to the axial stress state.

[3] The results show that the axial forces on the columns increase as the number of stories decreases and that the cross-sectional design corresponds to this stress state. However, the structure's natural period of 3.43 sec. indicates that the rigid structural frame in the short direction has low stiffness against lateral load and needs braces. It can be considered that the structure relies on the brace element for resisting lateral loads, such as wind or thermal loads.

Acknowledgments

This study was supported by JSPS KAKENHI (Grants-in-Aid for Scientific Research) No. 23K04209.

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