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Structural design of folded strip forms with planar trusses

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Abstract

This is a structural design proposal for a strip-formed object with folding features, termed a "ribbon." It serves as both street-facing signage and a barrier that subtly separates the plaza space from the adjacent busy street. The architects designed a form that folds into a strip, creating an area that is both open and enclosed. Considering the C-shaped planform, the author proposed a multi-directionally folded planar truss for stability against loads from any direction.

Given that the vibration characteristics of such a structure can vary depending on the positioning of the folds, an evaluation was conducted to understand the relationship between the folds and the overall structural behavior. Additionally, the area has experienced severe typhoons in recent years, necessitating adequate wind resistance. To assess the structure's behavior under typhoon conditions, wind tunnel tests were performed using a model equipped with built-in sensors. The ribbon's realization is also discussed.

Keywords: Structural design, folded strip form, planar truss, wind tunnel test

1. Introduction

With the advancement of technology, realizing any structural form has become feasible. In this context, it is crucial for structural engineers to emphasize design ingenuity over brute force methods. To this end, structural rationales that facilitate efficient, sustainable, and innovative architectural designs previously deemed challenging must be explored. This paper introduces the design process of intricate structures the authors were involved in, showcasing a unique signage project. Named the “ribbon,” this signage extends a total length of 40 m and appears to float above the park. Unlike typical flat signage, it distinctively encircles the park, as shown in Figures 1 to 4. Such an overhung configuration can lead to torsion, necessitating structural design ingenuity. While there are several examples of structures with similar challenges, particularly spiral buildings (e.g., [1] and [2]), these structures' components are subjected to torsional stresses, making stability with a plate section difficult. To the authors' knowledge, there are no existing examples of overhung strip structures, highlighting the novelty of this strip form.

Figure 1: View from the road side

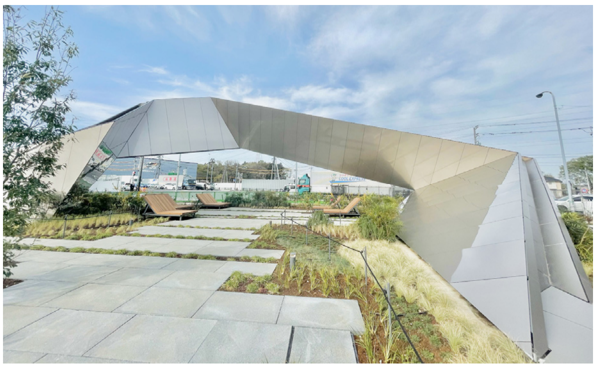


Figure 2: View from the park side

Figure 3: View from the west

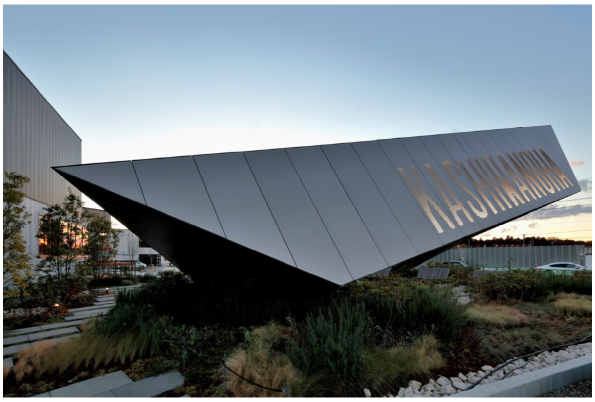


Figure 4: View from the east

On the other hand, as seen in wind turbine blades, twisting a plate changes its stiffness in multiple directions (e.g., [3]). In this paper, the authors propose a method for stabilizing overhung strip objects by multi-directionally folding a planar truss. The structural properties of folded planar trusses are detailed, and wind tunnel tests are examined. The strip object's realization is also discussed.

2. Overview

Completed in 2021 in Kashiwa City, Chiba Prefecture, Japan, the “Ribbon” is located among roadside stores along National Route 16, known as "KOIL 16 Gate by Mitsuifudosan." This area is part of the Kashiwa-no-ha Smart City, currently under development. The signage serves both as a symbolic object and street-facing signage at the city's entrance. Designed by ZGF Architects, who have been significantly involved in the city's development, the strip-like form provides sound insulation against the busy national route and enhances the park's openness with a floating design. The project is a testament to innovative urban planning and architectural design. Table 1 provides an overview of the project. The authors were responsible for the structural design.

Table 1: Overview

Location	Kashiwa city, Chiba Pref.
Client	Mitsui Fudosan
Architect	ZGF Architects + UAo
Structural engineer	Kanebako Structural Engineers
Contractor	Mitsui Home
Complete	March, 2021

As depicted in Figure 5, the ribbon faces the road on the north and west sides. It consists of 5 segments, designated as Panels A-E, starting from the west side. Panels A-D, adjacent to the road from west to north, are constructed to reduce noise in the park area and also serve as advertising panels. Panel E, facing the park or commercial facilities, is designed to maintain an open atmosphere. The total length of the ribbon, excluding Panel A, is about 40 m; the span between the support points is about 13 m; and its maximum height is 9 m. The cantilever extends about 11 m from the ground. In the following discussion, the normal direction of Panel D will be considered the Y-direction of the overall coordinate system.

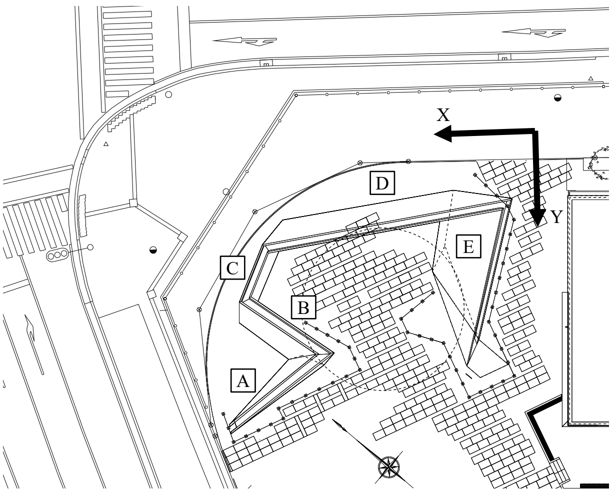


Figure 5: Plan

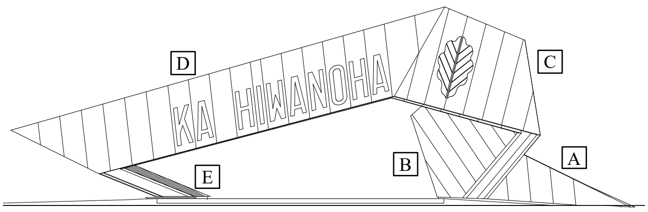


Figure 6: North elevation

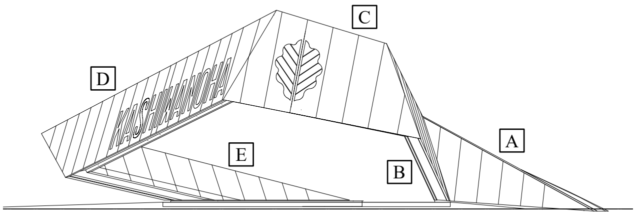


Figure 7: West elevation

3. Analysis

3.1. Feasibility studies

3.1.1. Concept design

The overall shape is influenced by the site's geometry and surroundings, forming a C-shaped planform when adapted to the site. This configuration can lead to twisting and instability, making it desirable for the member cross-section to be closed. However, this structure is inefficient as a closed type due to its plate-like section and long span, increasing steel usage. To address this, a structural form is proposed where the vertical truss on Panel B folds multi-directionally towards a near-horizontal plane on the opposite side, as illustrated in Figures 5 to 7. This form supports the truss at three points—one on Panel B and two on Panel E—providing stability against torsion. The combination of vertical and horizontal trusses also ensures sufficient stiffness against both vertical and horizontal external forces. Initially, the torsion plane truss was assumed to be a simple beam with a 40 m span and an eccentric (cantilevered) length of 11 m. The approximate dimensions of the truss were determined through hand calculations: a depth of about 2.5 m and a chord and lattice member depth (truss thickness) of 400 mm.

3.1.2. Preliminary analysis

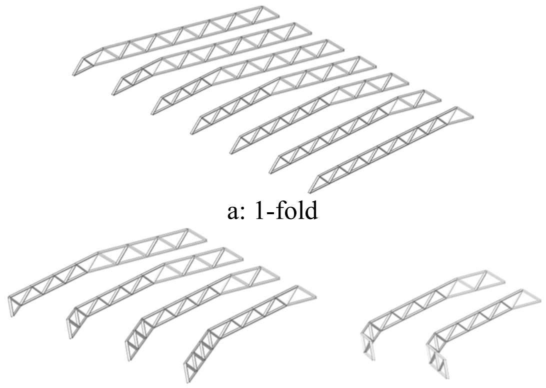
When a truss is folded, the distribution of mass and stiffness changes, affecting its natural frequencies. This is particularly important for long-span structures where dynamic effects are more pronounced. To prevent resonance, which occurs if the natural frequency matches the frequency of external forces, the fold positions must be carefully designed. While rough trends can be obtained through hand calculations, detailed tracking of fold position effects is difficult. To better understand the structural behavior, case studies were conducted for a simple planar truss as the standard truss to adjust the fold positions. A parallel chord truss with a 40 m span, truss depths of 2.5 m, and lattices spaced every 5 m at a 45° angle was used, with pin supports set at both sides of the lower chord and at the right end of the upper chord.

Folds create segments with varying lengths and stiffness, leading to different modes of vibration. While many folding patterns are possible, this paper describes the cases of folding at the lattice positions of the standard truss. Firstly, assume a polyline-like truss that folds and tilts at one location, as shown in Figure 8.a, with each fold varying by 5 m. Folding angles of 45° and 90° were assumed for the respective cases. The relationship between fold positions and frequencies is shown in Figure 9. In the eigenvalue analysis, a lumped mass model was used instead of a consistent mass model. Frequencies above 10 Hz are disregarded, and only frequencies where the effective mass ratio exceeds 10% are plotted.

For the 0-fold truss, the mode of out-of-plane translation (Y-direction) is predominant at low frequencies. The folds add stiffness in certain directions, stabilizing the truss against torsional forces. In these examples, the natural frequencies for Y-directional translation are high. They are most improved with a 45° fold at a 20 m segment length. It is desirable to keep the length of each segment generally between 15 and 20 m, as out-of-plane behavior dominates in longer segments. Conversely, the vertical (Z-direction) modes have low frequencies due to torsional behavior induced by folding. The frequency drops sharply when the fold is located approximately 15 m from the right edge. The mode in the axial direction of the truss (X-direction) exhibits a high frequency of over 10 Hz when the folding position is close to the right end, but it drops significantly when the distance to the folding position exceeds 20 m. Slight differences can be observed in the Y- and Z-directions due to varying eccentricities caused by different folding angles, but the overall trend is similar.

Figures 8.b and 8.c show 2-fold and 3-fold trusses, respectively. In both, the second segment from the right has an upper chord length of 20 m. The natural frequencies of the out-of-plane (Y-direction) mode are higher in the 2-fold trusses because the longer segment is eliminated. The closer the second segment is to the right side with two pin supports, the higher the frequency tends to be. Conversely, the frequency decreases considerably in the Z-direction. In the X-direction, the out-of-plane stiffness of the end segments is affected, resulting in a noticeable decrease in frequency beyond 10 m from the right edge.

In the 3-fold cases, the Y-directional frequencies are slightly lower than those in the 2-fold cases, generally around 4 Hz, closely resembling the trend observed for the segment with a length of 20 m in the 1-fold cases. In the X- and Z-directions, a similar trend to the 2-fold cases is observed, around 3 Hz and 1 Hz, respectively. The Z-direction mode exhibits a shape that rotates around the X-axis.



a: 1-fold

b: 2-fold c: 3-fold

Figure 8: Examples of folded planar trusses

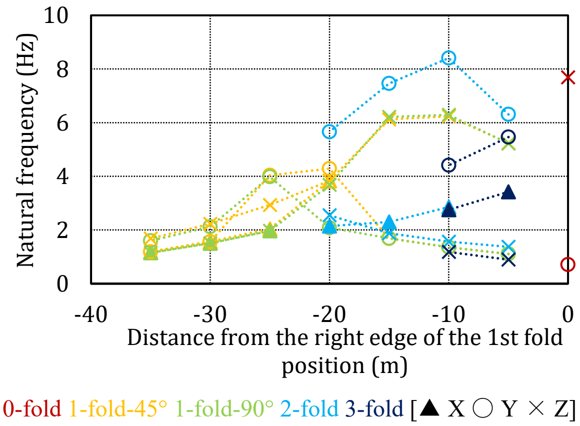
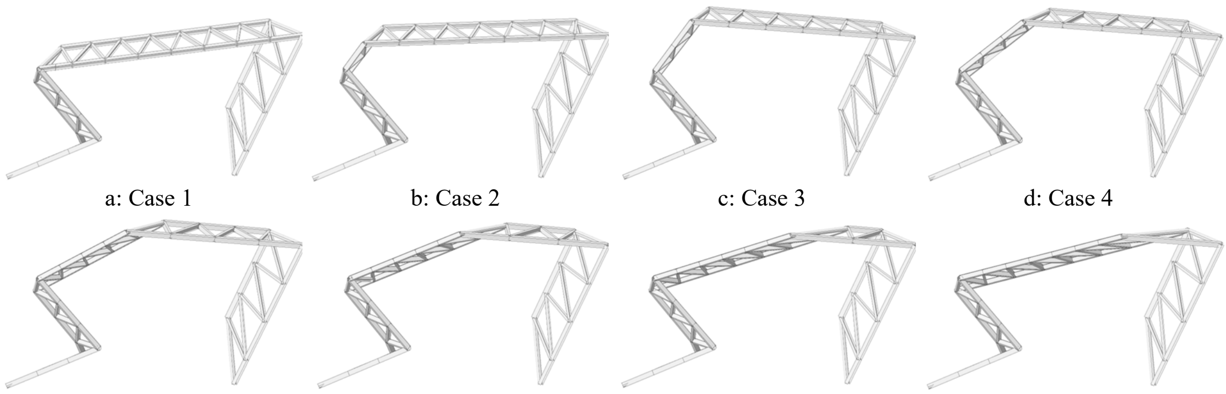


Figure 9: Relationship between fold and frequency

3.1.3. Case study

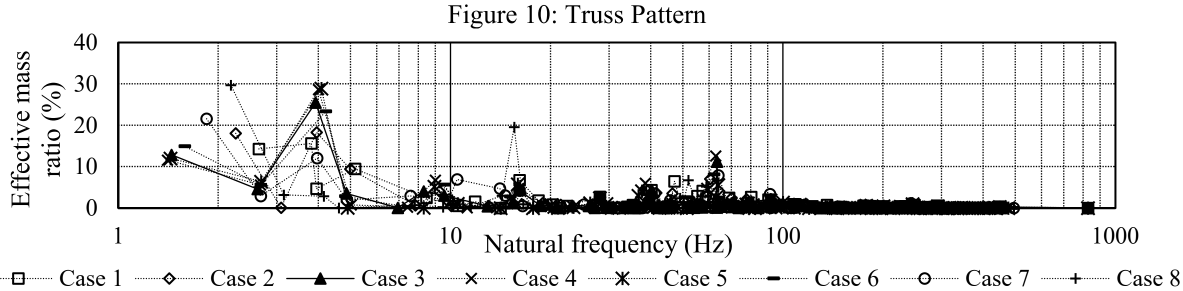
Based on the site outline, Panels A, B, and E were located. The folded seam between Panels A and B serves as the base of the truss, with Panel A acting as an out-of-plane restraint on the edge of Panel B rather than contributing to the main truss. As mentioned earlier, it was decided to tilt the web of the truss at Panel E almost horizontally and support it at two points. Subsequently, the structural behavior across eight cases was examined, with the folds positioned differently between Panels C and D, as shown in Figure 10. In Case 1, Panel C is the smallest, and the sizes of Panels C and D vary incrementally.



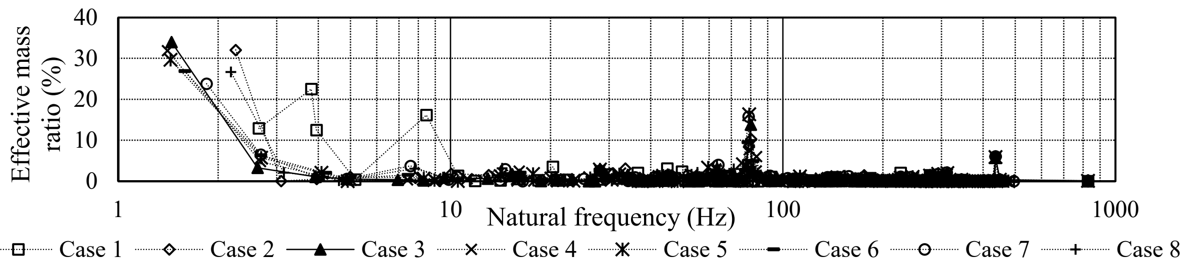
a: Case 1 b: Case 2 c: Case 3 d: Case 4

e: Case 5 f: Case 6 g: Case 7 h: Case 8

Figure 10: Truss Pattern



a: Translational Y direction



b: Rotational direction around the X axis

Figure 11: Natural frequency

Figure 11.a shows the effective mass ratio contributing to Y-direction translation (out-of-plane direction of the trusses) relative to the natural frequency. Figure 11.b illustrates the rotation around the X-axis, due to the Z-directional mode of the overhung areas. Trusses with significantly longer Panels C or D on one side, as in Case 1 and Case 8, exhibit slightly different vibration characteristics compared to other configurations, whereas Cases 3-6 demonstrate similar trends. The overall trend is that the Y-directional translation mode is predominant at around 4 Hz, while the X-directional rotation mode is predominant around 1.5 Hz. Although the folding angles here are more complex, the trend is similar to that observed in the 3-fold case in the previous sub-subsection.

3.2. Structural behavior

Based on the findings from the previous section, the structural form was designed in consultation with the clients and architects. For the project, Case 3 in Sub-subsection 3.1.3 was preferred due to its functionality as signage. An eigenvalue analysis was performed on an analytical model representing the actual truss structure, detailed in Section 5.

Figure 12 illustrates the mode shapes for the 1st through 6th modes: the 1st mode induces vertical movement at the center of the truss; the 2nd mode causes axial deformation of Panel D due to the out-of-plane deformation of Panel E; the 3rd mode is characterized by the out-of-plane deformation of the truss beams, particularly affecting Panels C and D. The 4th through 6th modes show the truss beams twisted. Figure 13 suggests that X-directional translation around 2.6 Hz and rotation around the X-axis (or Z-directional translation) around 1.4 Hz are dominant. A Y-directional translation mode is also observed around 3.9 Hz. The translational mode is dominant up to the 3rd mode and the rotational mode up to the 7th mode.

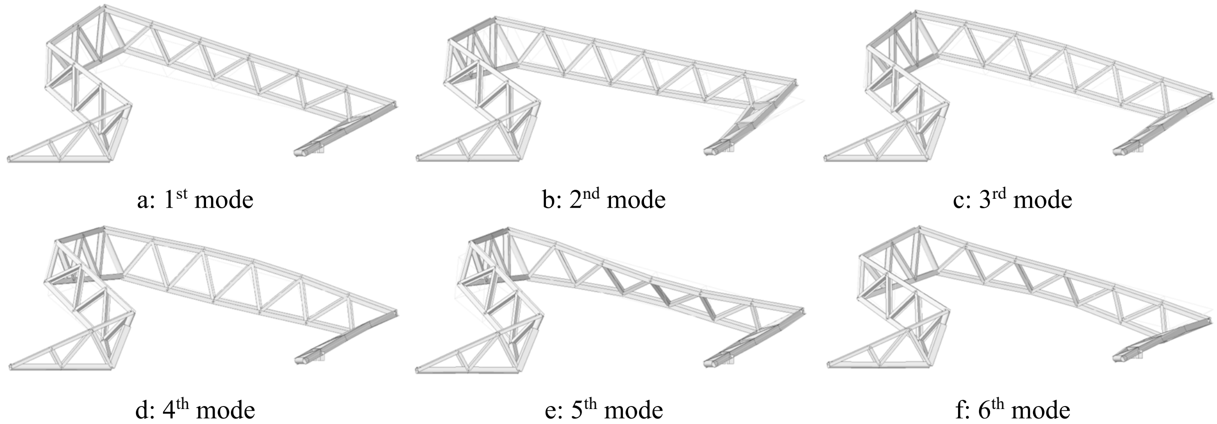
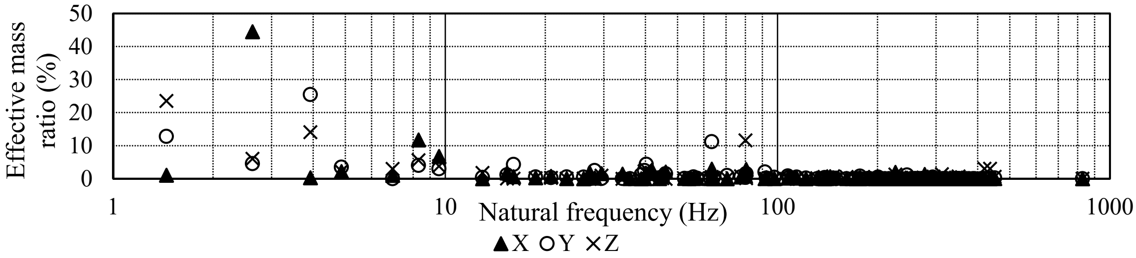
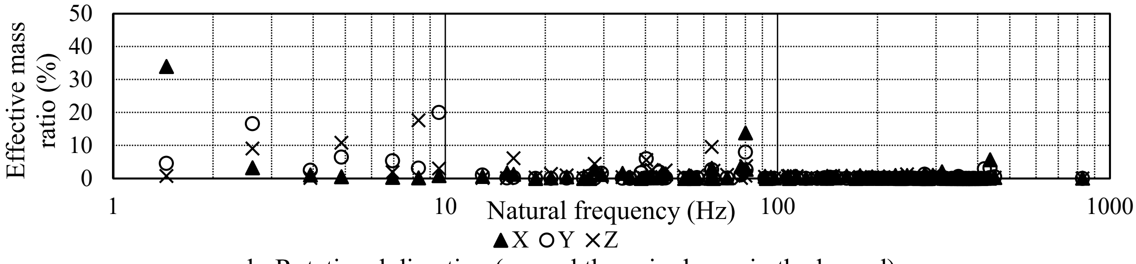


Figure 12: Mode shape



a: Translational direction



b: Rotational direction (around the axis shown in the legend)

Figure 13: Natural frequency

4. Wind tunnel test

4.1. Overview

The complex-formed structure, serving as signage, has its finish (façade) attached to folded trusses, exposing them to wind pressure. Moreover, recent severe typhoons in the region highlight the necessity for robust wind resistance. Evaluating the structure's performance under typhoon conditions is crucial, although calculating wind pressure for complex forms poses challenges. Previous studies have verified wind pressure distributions of buildings with complex forms through wind tunnel tests or Computational Fluid Dynamics (CFD) analysis (e.g., [4] and [5]). However, as far as the authors are aware, the wind pressure distributions of low-rise structures with complex forms have not been confirmed.

This paper presents wind tunnel tests conducted using a 1/30 scale model to evaluate wind loads for design purposes. In this setup, the wind direction perpendicular (normal) to the largest panel was designated as the 0° wind direction. The tests covered a total of 72 wind directions, with 5° intervals counterclockwise from 0° to 355°. The design wind speed, defined as the 10-minute average wind speed at 9 m height (the maximum height), was set at 26.4 m/s, in accordance with Japanese laws and guidelines [6].

The wind tunnel tests were conducted by the Technology Research Institute of Obayashi Corporation (TRI) under the supervision of the Wind Engineering Institute. The experimental setup utilized a closed-circuit type wind tunnel owned by TRI, with an experimental wind speed of 9 m/s. As depicted in Figure 14, blocks were placed on the wind tunnel floor and spires on the windward side to create an airflow that mimics the assumed conditions. Sensors for measuring wind pressure were positioned at 72 locations on both sides of the model, as shown in Figure 15. Since this test focuses on wind fluctuation characteristics and their associated dynamic effects, the dimensionless frequencies were matched as a similarity condition. The dimensionless frequency is expressed by the following equation:

$$n^* = n \cdot \frac{D}{U} \tag{1}$$

where n^* is a dimensionless frequency, n is a frequency (Hz), D is a typical dimension (m) and U is a wind speed (m/s). The relationship between full-scale and model-scale results in the following time scale:

$$\frac{T_{model}}{T_{full}} = \frac{(D/U)_{model}}{(D/U)_{full}} \tag{2}$$

Therefore, for these tests, 10 minutes of real time were translated into 59 seconds of model time.

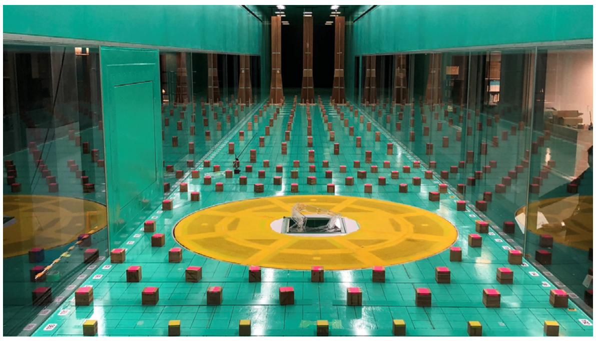


Figure 14: Wind tunnel

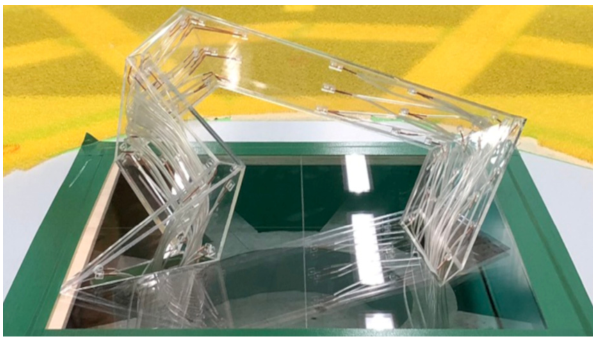


Figure 15: Test model with sensors

4.2. Result

Figure 16 illustrates the wind forces acting on the entire structure for the 50-year interval. The structural design considers 50-year and 200-year storm recurrence intervals, with forces for the 200-year interval being approximately 1.3 times stronger. The positive directions in the X- and Y-axes correspond to those shown in Figure 5, while the Z-direction's positive orientation aligns with gravitational acceleration. Due to the structure's complexity, the transition of wind forces with wind direction deviates from a simple sine curve. The dominant wind direction is in the Y-direction, where the receiving surface is large, featuring a crest at 0° and a trough at 160°, directly normal to Panel D. Wind forces in the X-direction typically present a crest at 90° and a trough at 270°. In the Z-direction, wind forces generally display crests around 225° and 335°, and a trough around 135°.

Figure 17 details the wind forces acting in the normal direction for each panel, with wind orientation from the street side to the park side considered positive. The figure shows the added wind forces on both sides of each panel. Figure 18, which presents wind pressure per segment area, shows that Panels C and D, positioned at higher installation heights, experience larger wind pressure amplitudes, while Panels A and E, closer to the ground, exhibit smaller amplitudes.

Figure 19 illustrates the wind forces acting on each panel for each wind direction within the overall coordinate system. Specifically, the normal vectors depicted in Figure 17 are decomposed relative to the overall coordinate system. Panel A, with a small wind-receiving surface, shows minimal overall impact compared to Figure 17. Conversely, Panel D, with a larger wind-receiving area, significantly influences the overall wind force in the Y-direction. Panel E predominantly affects the Z-direction, while Panels B and C impact the X- and Y-directions, respectively. This generally occurs when the wind direction is perpendicular to the panel. In Panel B, the wind forces in the X- and Y-directions show similar phases, while in Panel C, they tend to be in antiphase, indicating an orthogonal wind effect.

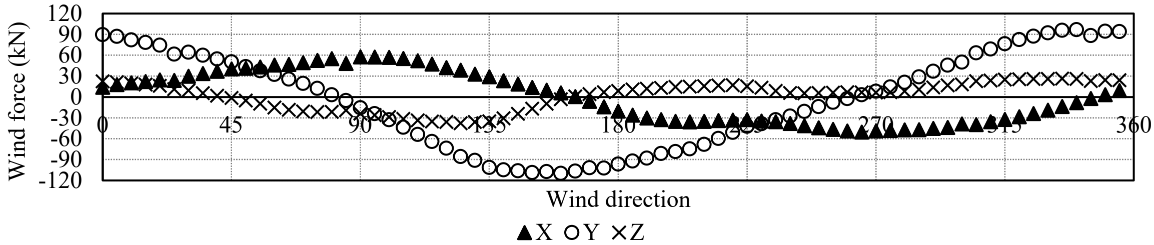


Figure 16: Design wind force

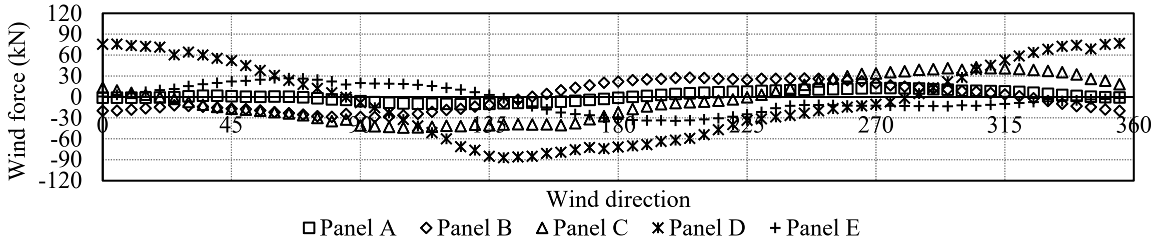


Figure 17: Design wind force for each panel in the normal direction

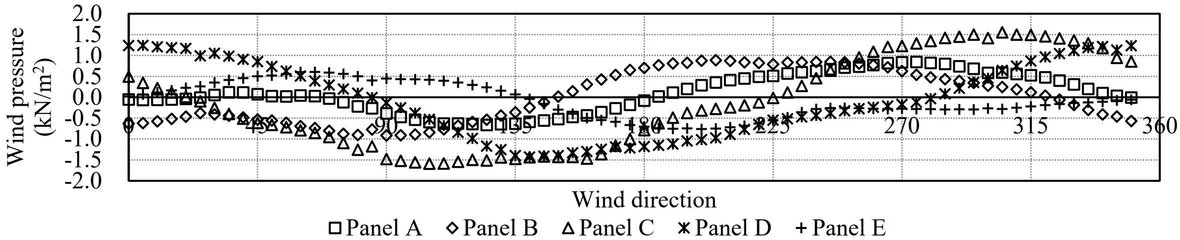


Figure 18: Average wind pressure for each panel in the normal direction

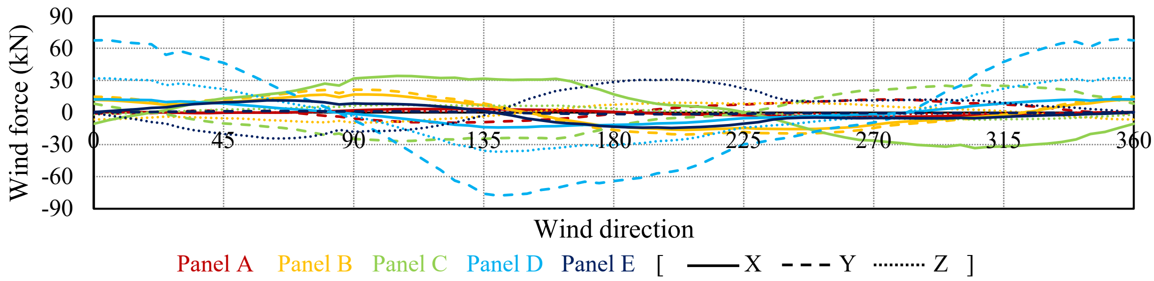


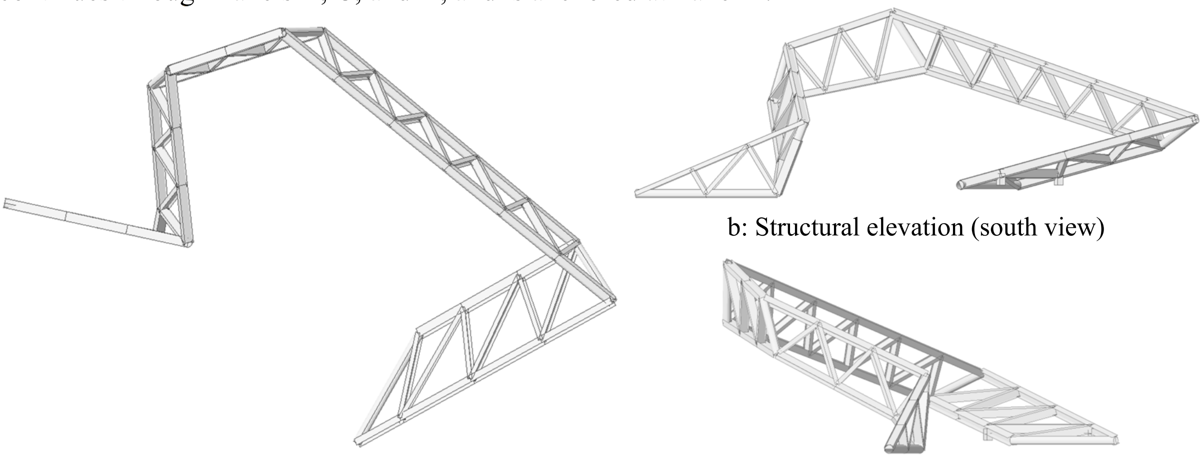
Figure 19: Design wind force of each panel for the global coordinate system

Although not included in this paper, the dimensionless power spectrum for wind direction at 45° peaked at dimensionless frequencies $n^* \approx 20$ in Panels A, B, and C. As detailed in Subsection 3.2, the natural frequency of the structure in the X-direction is about 2.6 Hz. According to equation (1), with $n^* = 20$, $n = 2.6$ Hz, and $D = 9$ m, we have $U \approx 1.2$ m/s. Given that resonance occurs at such low wind speeds, significant vibration amplification is improbable. Additionally, due to the strip's complex form, the likelihood of synchronized vortex shedding is extremely low.

5. Structural Design

5.1. Geometrical features

The structure is a strip-formed entity approximately 40 m in length, anchored only at both ends. In plan view, it adopts a C-shaped folded form. In elevation, it resembles a gate, elevated above ground level at both ends, with a maximum height of approximately 8.7 m near the center of the strip. The central area extends about 11 m beyond the ground contact point in an overhang. Figure 20 illustrates the structural arrangement. Panel A is not part of the truss. The truss begins at the seam between Panels A and B, continues through Panels B, C, and D, and is anchored at Panel E.



a: Structural plan

b: Structural elevation (south view)

c: Structural elevation (west view)

Figure 20: Structural arrangement

5.2. Structural design

The strip-formed structure is engineered as a planar truss with a span of approximately 40 m, folding at four seams into five twist-free segments. The trusses typically range from 2 to 3 m in depth, utilizing H-shaped beam with a depth of 400 mm for both the upper and lower chords, as well as the lattices. These are used so that the web of the H-shaped beam is in the direction of the truss thickness. The development of the truss is illustrated in Figure 21. The joints between segments are constructed from φ-406.4 steel pipes, designed to accommodate any angle of refraction, as shown in Figure 22.

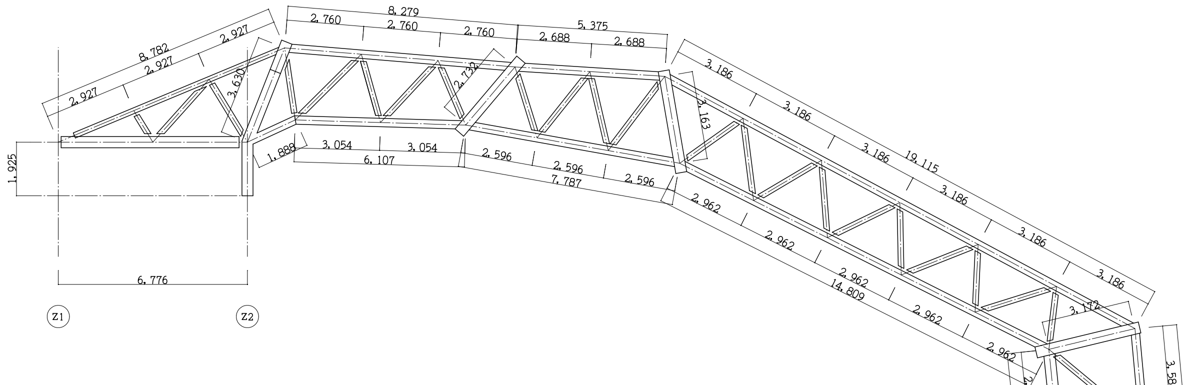


Figure 21: Truss deployment

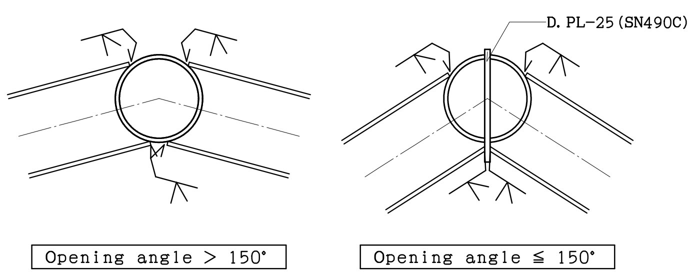


Figure 22: Detail of joints between panels

The structural form was meticulously adjusted by sharing 3D data with the architects. The top and bottom edges of the panels are parallel when the finish is attached, but the structural form is adjusted to fit within the finish, making the upper and lower chords non-parallel, as shown in Figure 21. Aesthetic consideration is given, especially where Panel B is grounded, and the lower chord is veered at the end, as depicted in Figure 23. In Panel E, the ends of the upper and lower chords are fixed and secured at the panel edge and approximately 2.3 m from the edge to enhance bending resistance. To enhance rigidity, all column legs are embedded. Additionally, the column of Panel B transitions from a square to a round cross-sectional shape, as shown in Figure 23. Steel members are hot-dip galvanized to ensure long-term durability in the entire structure.

For the foundation design, piled foundations were used due to the inadequate bearing capacity of the surface ground, disturbed by previous buildings on the site. Piles were placed not only at the grounded positions but also directly beneath the vertically projected positions of the overhung sections, ensuring a well-balanced distribution. This setup ensured the structure could resist overturning due to its own weight and external forces.

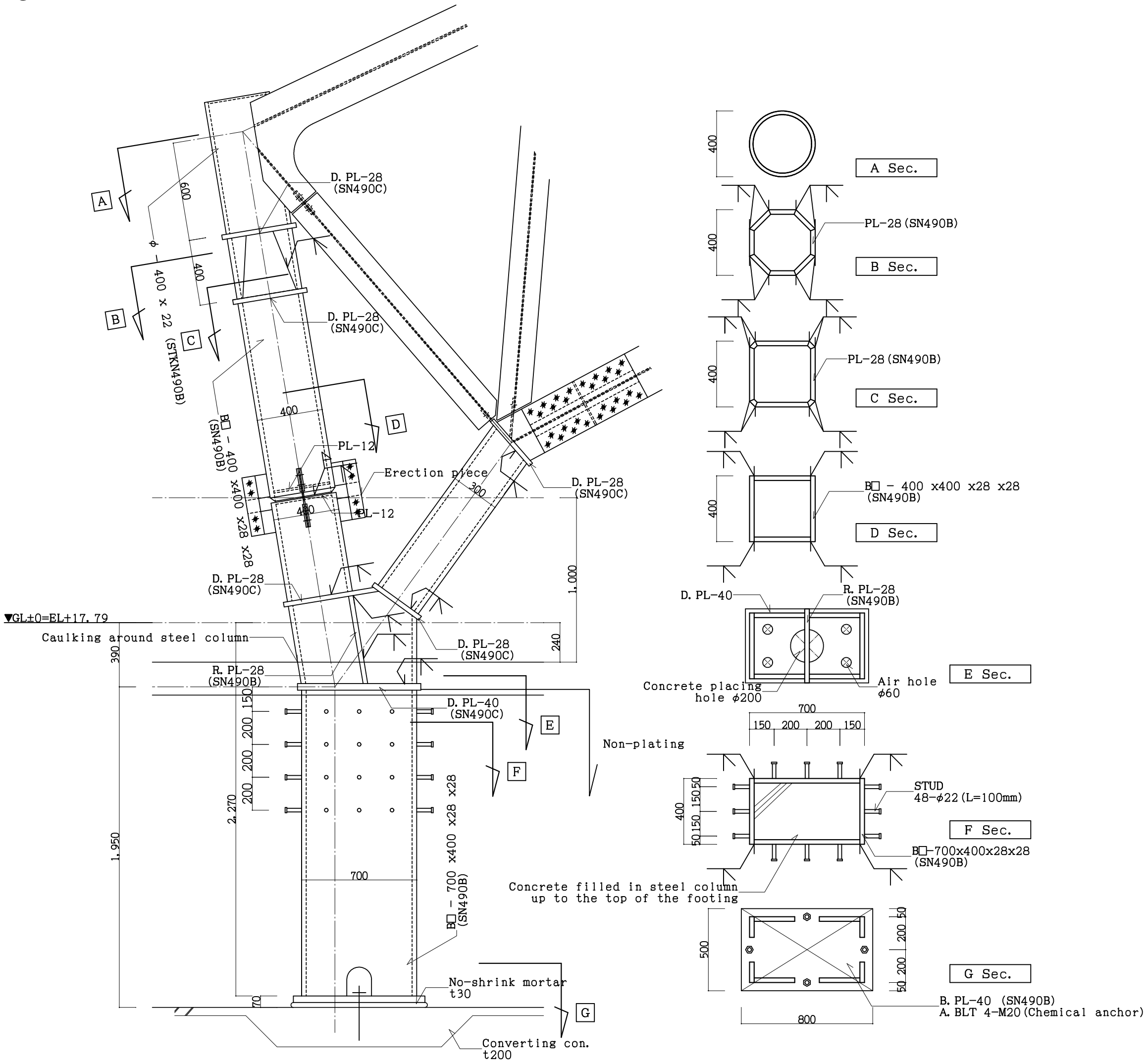


Figure 23: Detail of the column between Panel A and B

5.3. Construction

During the construction phase, designers, engineers, builders, and fabricators collaborated by sharing structural model data to study the connection between the steel truss and the façade. Specifically, 3D data of the sloping terrain was imported to adjust the façade's shape in conjunction with the structure. A mock-up was created to verify the dimensional fitting of each component, including the methods used to attach the façade panels, as depicted in Figure 24. The façade panels were typically spaced at intervals of about 1.0 m in width.


Figure 24: Façade mock-up


Figure 25: Fabrication


Figure 26: Erection

The twisted planar truss was assembled during the fabrication stage in sizes that would not pose transportation challenges, and the façade panels were attached to the base material, as shown in Figure 25. To minimize clearance between façade panels and prevent interference due to elastic deformation, deflection against the dead load was accounted for by adding camber during the erection phase, as detailed in Figure 26. As shown in Figure 27, façade panels were attached to the truss, creating a floating strip-formed object.


Figure 27: Completion

6. Conclusions

This paper describes the structural design of a strip-formed, overhung object, termed a ribbon. The authors proposed a structural form that stabilizes the object through multi-directional folding of a planar truss. This complex form was validated in stages. First, the truss member dimensions were approximated by manual calculations, then a simple model was used to check the vibration properties of the folded trusses and identify trends in the effects of folding angles and segment lengths. Finally, the form was determined with the client and architect through verification on a model close to the real structure. Wind tunnel tests were conducted to determine the forces acting on this complex structure due to wind.

During the construction phase, data was shared among designers, structural engineers, steel fabricators, and contractors to facilitate the rapid realization of complex structures. This collaborative approach ensured alignment among all parties, enabling them to efficiently address the technical challenges of realizing the folded strip structure.

The proposed structural system offers novel possibilities. By varying the folding patterns of the trusses, stiffness can be adjusted in multiple directions, potentially leading to a broader range of applications.

Acknowledgements

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