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GENERATION OF A STRUCTURAL SHAPE AND SYSTEM THROUGH THE INTEGRATION OF TENSEGRIC ELEMENTS INTO A DOUBLE-LAYERED FRAME STRUCTURE

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Abstract

In space frame structures, tensegrity-based designs have the potential to enhance structural stiffness using less material, reduce the weight of structures, and generate well-designed forms. This study proposes a structural design based on Tensegric elements that adds an impressive visual effect to the double-layered frame structure, and the integration of Tensegric elements into a double-layered frame with the aim of developing a rigid and well-designed structure that pursues high transparency with loss of member presence by incorporating the concept of Tensegric structures. To achieve this objective, a model of the frame structure with Tensegric elements was studied to evaluate the stiffness of the structure and the transparency by design indicators. The results show that the introduction of the Tensegric element in the double-layered space frame provides a rigid structure, that brings us closer to achieving the transparency that enhances the impressive visual effect.

Keywords: Tensegrity, Tensegric structure, space frame, double-layered frame structure, transparency, stiffness

1. Introduction

The double-layer space frame has advantages over the single-layer space frame in terms of out-of-plane stiffness and bearing capacity, but at the same time, the number of members and nodes increases, limiting design self-weight. The Puyuan Design and Event Center (PDEC) shown in Fig. 1 is a multi-layered truss structure consisting of a bottom layer, middle layer, and top layer, called a super structure (steel trusses), shown in Fig. 2. By limiting the number of the upper layer's members, both a highly transparent design and structural performance have been achieved [1]. Based on this concept, a highly transparent structural form is studied by introducing a Tensegrity element into the truss structure of the middle layer as a connector to ensure rigidity while eliminating the presence of the members. “Tensegrity” is a structural system that refers to the integrity of a stable structure balanced by continuous structural members (cables) in tension and discontinuous structural members (struts) in compression [2,3,4]. In 1948, K.Snelson invented the Tensegrity structure [5,6]. Later, B. Fuller [7] proposed the concept of a composite term consisting of tension and integrity, and the principle system. The attractiveness of K.Snelson's space art (objet d'art) works is Tensegrity-specific aesthetics, illusiveness, and structural characteristics [8]. On the other hand, Tensegrity is difficult to understand and control because it is likely to cause large deformations and the distribution of prestress (self-balancing force) is complex. For this reason there have only been two examples of its use in building framing [9]. Therefore, since pure Tensegrity lacks stability and rigidity, a Tensegric structure with a relaxed generating principle has been proposed [10,11,12]. Tensegric enables the creation of attractive structural representations with a sense of lightness and transparency as well as Tensegrity. The introduction of Tensegric elements allows for the adjustment of the materials used, and enables both visual attractiveness (creating well-designed forms that provide a sense of floating while increasing transparency) and structural performance. Transparency is considered important in architecture as an element of aesthetic effect [13,14]. Sejima (PDEC architect) talks about how the coarseness and density of the super structure shown in Fig. 2 changes the transparency of the interior space and its relation to the surrounding environment [15]. Therefore, the purpose of this study is to attempt to introduce Tensegric elements into the diagonal members of the double-layer space frame and to attempt verification based on a proposed structural system that seeks to ensure the rigidity of the structure and high transparency. Physical indicators are used to verify the transparency of visual attractiveness. The verification of transparency in this study will build a new design-type structural system in architecture.

The remainder of the paper is organized as follows. Section 2 introduces the N-Strut structure as the Tensegric element to study. In Section 3, the stiffness verification method and the basic properties based on the verification results in the N-Strut structural system are described. Section 4 uses a transparency validation model to validate the transparency of the research objectives with design indicators that assess transparency. The conclusions of this paper are presented in Section 5.

Figure 1: Puyuan Design and Event Center (2020) (copyright: Kazuyo Sejima and Associates)

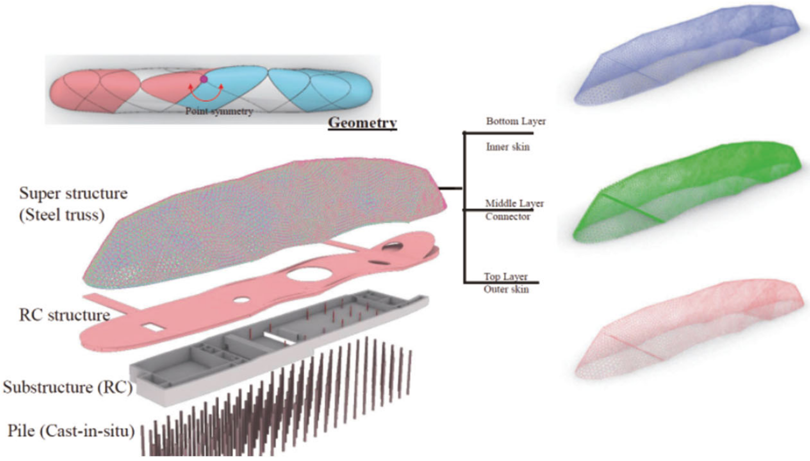


Figure 2: Structural Systems for Puyuan Design and Event Center (copyright: Arup)

2. Overview of N-Strut design as Tensegric elements on UNIT Model configuration

Tensegrity is a structural system in which the compression members are not connected to each other and are in balance with the tension. However, it has the problem of lack of stability and rigidity. The Tensegric structure which allows rigid members to contact each other as proposed to address this problem is a development and application of the Tensegrity concept [10]. The definition of a Tensegric structure includes the joining of unstable members (scattered struts or framework) with tendons and the creation of an attractive structural expression of lightness and transparency.

In this study, the structure shown in Fig.3 is called the Tensegric element and the diagonal material consisting of the central strut and tensile strength material (cable) is called the N-Strut. Figure 4 shows the configuration of the N-Strut for verification. The N-Strut acts as a compressor connecting the upper and lower string members. The placement of the N-Struts was determined after confirming the stresses (compression and tension) in the truss model created in advance (Fig. 5). The compression members not directly connected to each other give the structure a unique sense of floating and transparency. Figure 4 was first validated and then a different N-Strut model was verified for stiffness as well as for transparency (Fig. 6). The problem of bending moment in the initial N-Strut is suppressed by introducing a tensile material (cable) in the intermediate layer. To achieve transparency by integrating the lower elements and reducing the component size, the Tensegric elements were placed in a double-layered space frame. Figure 7 shows the bending moment and the torsion moment. The two types of N-Struts are mesh-divided into triangles for the lower layer consisting of the lower string material and hexagons for the upper layer consisting of the upper string material, and the upper and lower layers are connected to N-Struts and cables. The upper and lower strings are steel pipes and the mesh size is set to 1~2.3m due to the limitation of the glass fabrication size. This is referred to as the UNIT Model. Set the model specifications as shown in Fig. 8, referring to the Tensegric structure shown in the references [10,16]. To further investigate the basic structural performance a part of the model is cut out from the UNIT Model. This is called the BEAM Model. The details of the model consist of the upper and lower strings members as beam elements and the cable member as a tensile truss element. The material of the steel pipe is STKN 400 and the diagonal material is SUS304A. As for the cross section, the upper and lower strut and the arm of the strut (N-Strut) are circular hollow sections of 101.6 × 4.2 mm steel pipes (except for the lower strut member in Fig. 6 which is made of 20 mm diameter round steel), and the diagonal members and N-Strut tensile members are 14.5 mm diameter rod. The Young's modulus (E) is 2.05×10^5 N/mm^2, the cross-sectional area (A) is 12.85 cm^2 for steel pipe, 3.14 cm^2 for round steel, and 1.65 cm^2 for tension rod (cable).

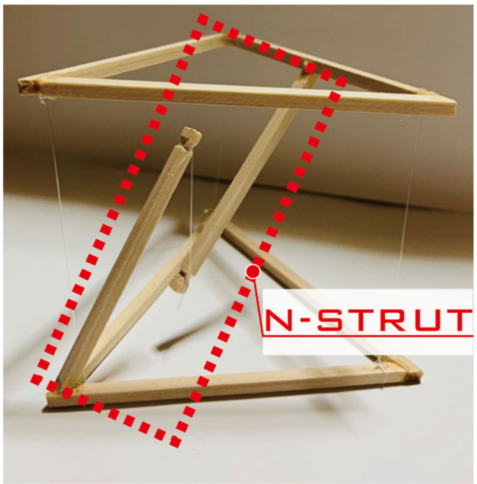


Figure 3: Tensegric Element (N-STRUT)

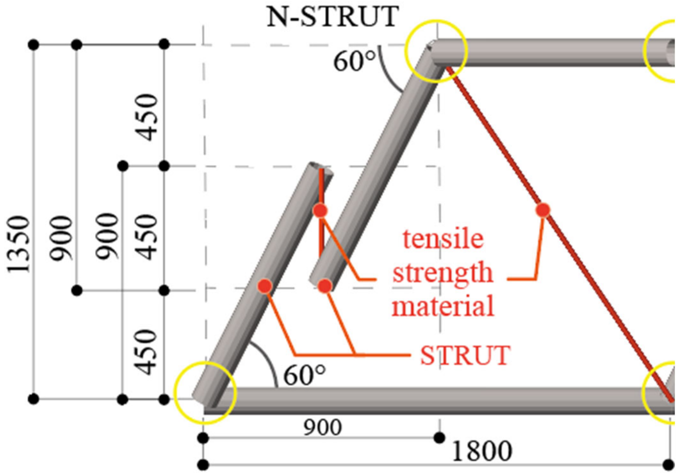
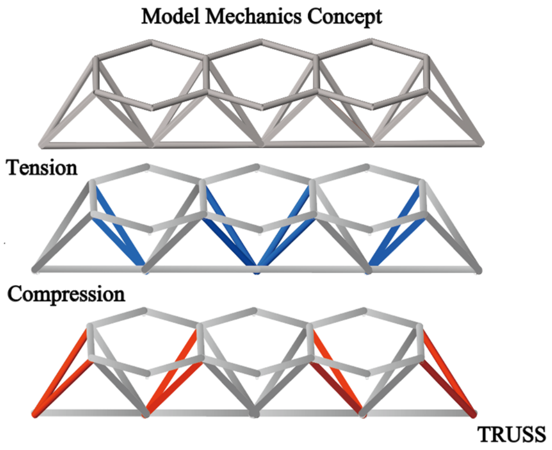


Figure 4: N-Strut Details 1



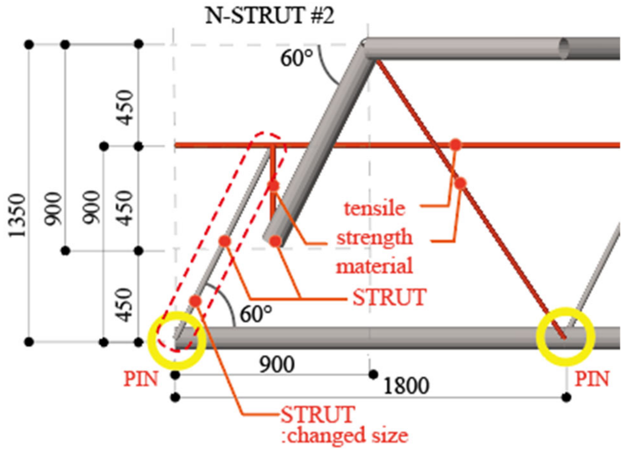
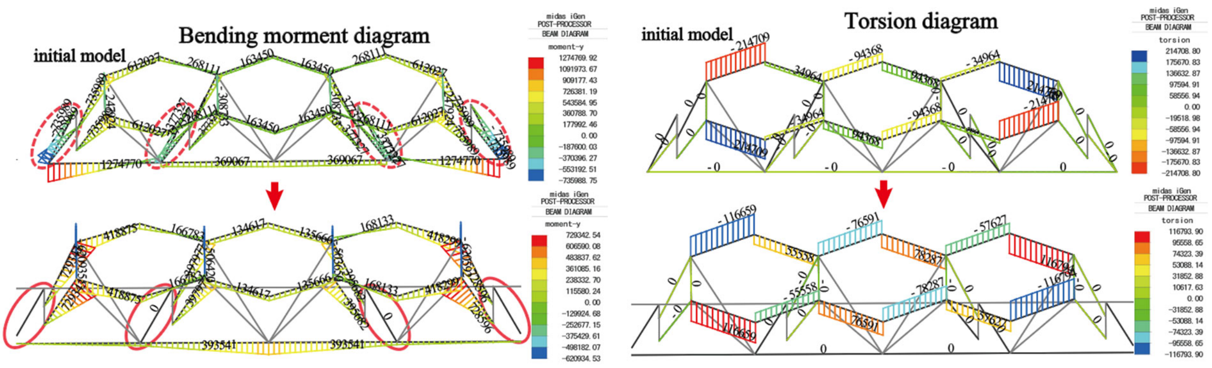


Figure 5: Model Mechanics Concept

(Blue: Tension, Red: Compression)

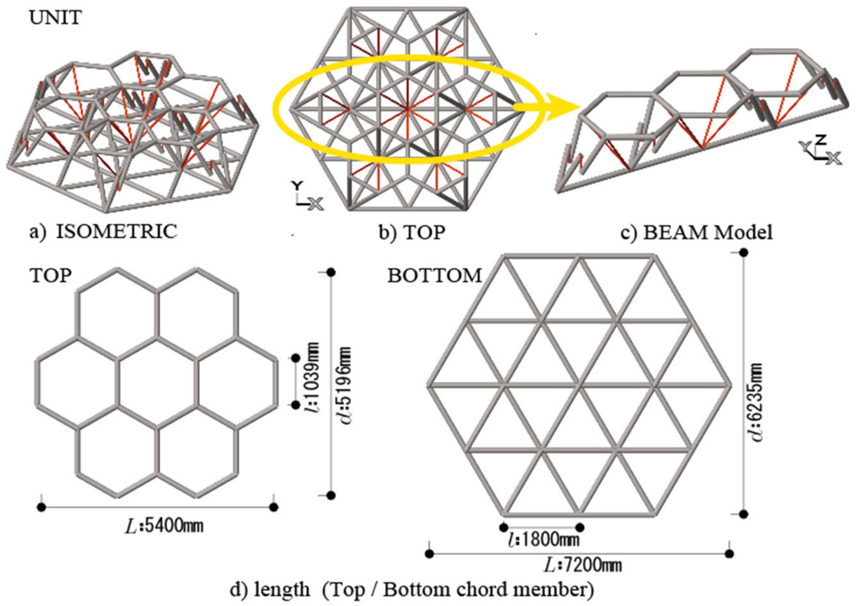
Figure 6: N-Strut Details 2



(a) Bending moment diagram

(b) Torsion diagram

Figure 7: Cross-sectional force diagram of beam elements



a) Isometric, b) TOP, c) BEAM Model, d) length details (TOP & BOTTOM chord member)

Figure 8: Details of UNIT

3. Basic properties based on stiffness analysis results

3.1. BEAM Model

Midas iGen is used to analyze the upper and lower strings as beam elements and the cable members as tensile truss elements. To investigate the properties of N-Strut, a portion is cut away from UNIT (Fig. 8). This is called the BEAM Model, and the following four models are compared. The shapes of these models are shown in Fig. 9. For Model-X, the joints between the lower chord members and the lower N-Strut are pin-jointed to approximate truss elements. Boundary supports were pinned roller supported, and the upper member is constrained in Y to avoid the torsional deformation in the X-axis.

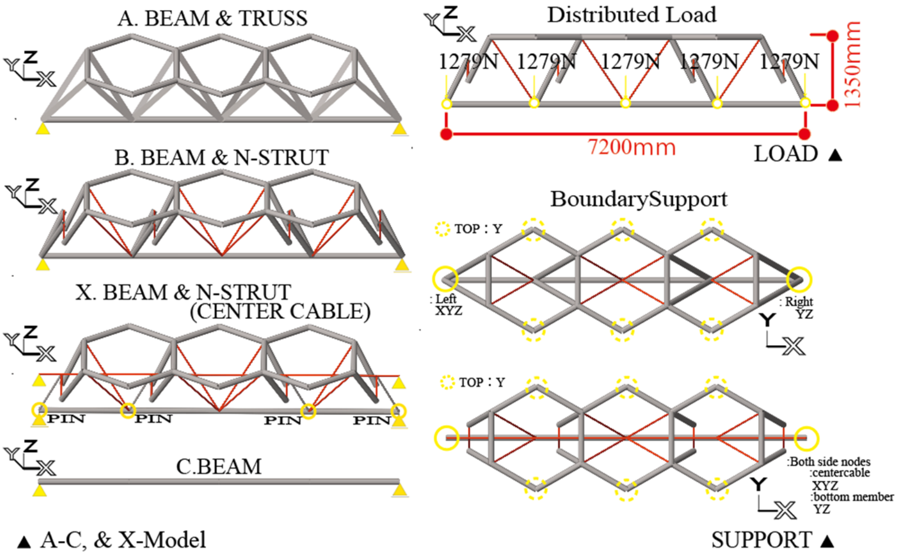
Model-A (double-layered space frame): Model with N-Strut replaced by a truss element that resists tension and compression.

Model-B (Tensegric structure: Bending system): Tensile strength material model in which the compression material of the N-Strut is replaced by beam element and the cable material resists only tension.

Model-X (Tensegric structure: Axial force system): The lower strut moment was reduced and changed to an axial force system, and the lower strut was made thinner for transparency.

Model-C (single space frame): N-Strut and upper beams are deleted and only the lower beam is used.

Model-A is a model to verify the stiffness of N-Strut by comparing it with a truss structure and a single-layer structure to investigate the properties of N-Strut. Model-X is a model adjusted for transparency after the stiffness verification of Model-A. Model-X is the model that pursues transparency which is the primary objective of this study. Therefore, for ease of identification it is designated Model-X. Apply a nodal load of 1,279 N to each node (Fig. 9). Model-A corresponds to a double-layered space frame and Model-C corresponds to a single-layered space frame. Model-B and Model-X are models with Tensegric elements.



(a) The geometry of A-C, X of BEAM Model (b) Distributed load & Boundary condition

Figure 9: Cross-sectional force diagram of beam elements

Figure 10 shows the vertical displacements of the BEAM Model verification for each center point. Model-B can suppress the central deflection deformation angle to about 91% of that of single-layer Model-C. In addition, the bending moment of Model-X was suppressed by 94%, which was 3% less than that of Model-B. The axial force deformation diagram in Fig. 10 shows that Model-X and Model-A (truss structure) have similar deformations in the lower string members. In terms of out-of-plane stiffness, the difference between Model-A and Model-B is about 8%, and the difference between Model-

A and Model-X is 5% (distributed load), indicating that Model-X is similar to the truss structure. This result indicates that N-Strut functions as a compressive material and suggests the effectiveness of the double-layering by introducing Tensegric elements. The deformation value of the proposed Model-B is 6mm/7200mm = 1/1200, Model-X is 4.3mm/7200mm = 1/1700, which is less than 1/250 of the allowable deflection of steel structural design standard beams with no problem. In Model-X, utilized ratio= 0.19 for steel pipes, 0.059 for cables, and 0.289 for the lower strut in the allowable stress method for structural, suggesting that further rationalization is possible.

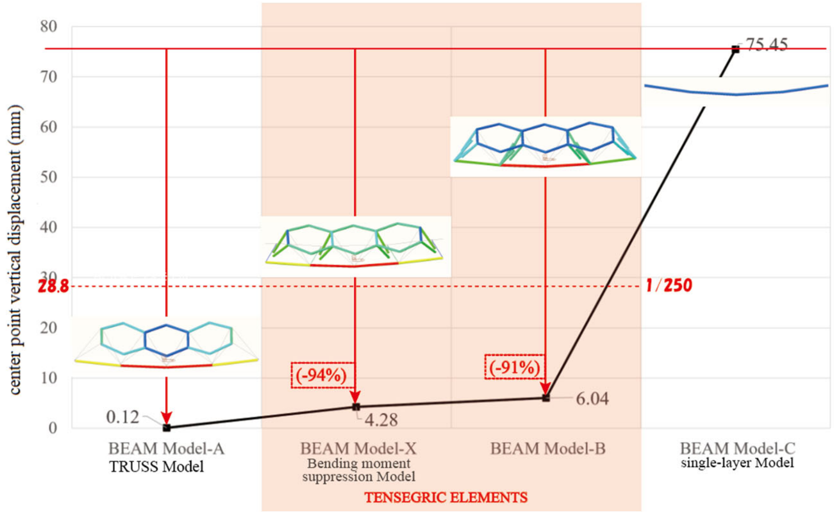
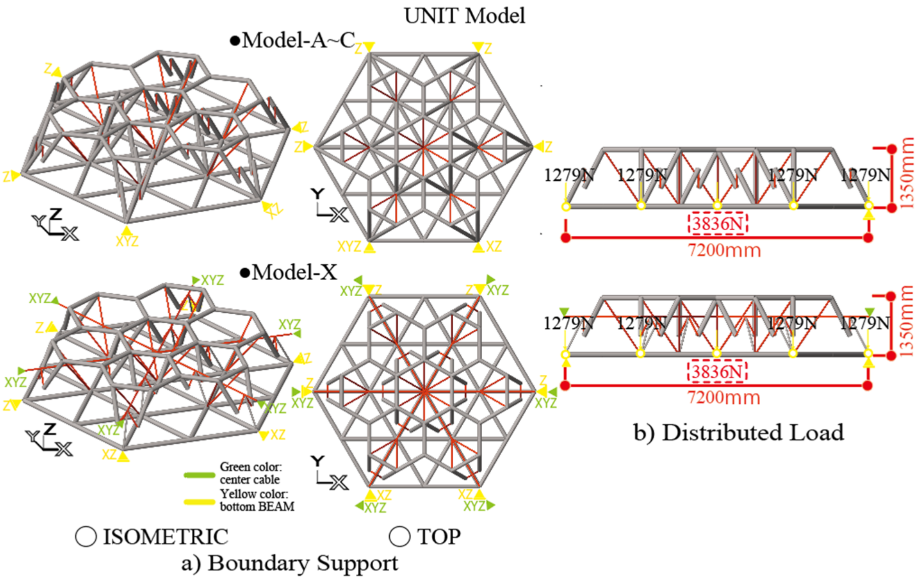


Figure 10: BEAM Model Validation Analysis Results-Distributed Load (Axial force deformation diagram)

3.2. UNIT Model

The BEAM Model verified in section 3.1 was a model in which N-Struts are arranged in a straight line. In contrast, the model shown in Fig.11 is a model in which the N-Struts are arranged in a plane. The UNIT Model is defined as the UNIT Model. As in 3.1, a total of four types of Models are compared: A. BEAM & TRUSS, B. BEAM & N-Strut, X. BEAM & N-Strut (with center cable), and C. BEAM.



a) Boundary Support

b) Distributed Load

(a) Boundary Condition, (b) Distributed Load (Upper: Model-A~C, Under: Model-X)
Figure 11: UNIT Model (Loads and Boundary Support)

Boundary supports were pinned roller supported. If rollers are changed to pins, the behavior remains the same. Therefore, in the present verification, both sides of the lower string members (beams) are analyzed with pin-roller support as in the simple beam structure (static mechanics). The remaining four nodes at each corner of the lower sine material are constrained in the Z direction. The load is an equally distributed load (Fig. 11). The UNIT-Model is arranged planarly from three directions, so that the load at the center node of the UNIT is three times as large as the load at the center node.

Figure 12 shows the vertical displacement at the center point of the UNIT Model. The displacement of Model-C, a single-layer model, is 20.2 mm. In comparison with the two proposed models with Tensegric elements, Model-B and Model-X have a displacement of 4.90 mm and 3.05 mm, respectively, and both models suppress the center deflection angle by more than 80%. Therefore, the BEAM model and the UNIT model were compared with the validation results. (Fig. 13). The red arrows used in the figure show the comparison between the BEAM Model and the UNIT Model. The blue arrows indicate comparisons between the Tensegric elements Model-B and Model-X. The red arrows indicate comparisons between the BEAM Model and the UNIT Model. Comparisons between the BEAM Model and the UNIT Model showed that both Model-B and Model-X suppressed median point vertical displacements by 19% to 28%. The difference between the two is 9 %, with the Model-X being stiffer. On the other hand, a comparison between the same models, indicated by the blue arrows, showed that it was possible to reduce the displacement by 29% to 37%.

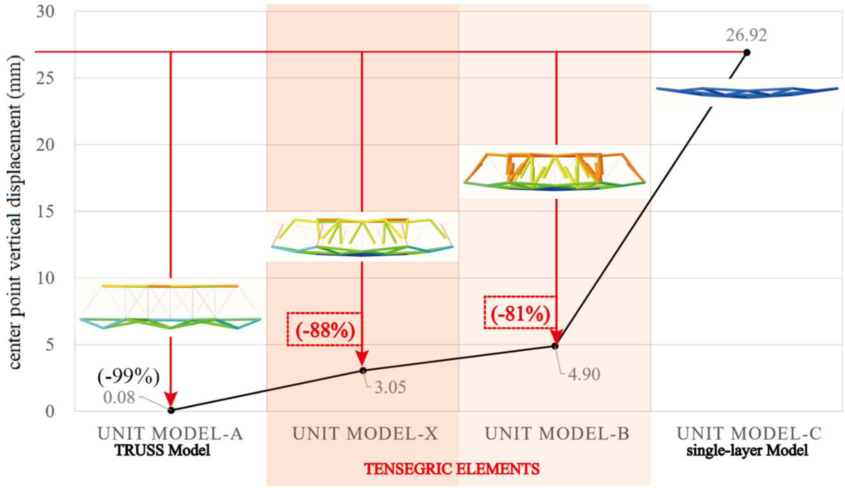


Figure 12: UNIT Model Validation Analysis Results (deformation diagram)

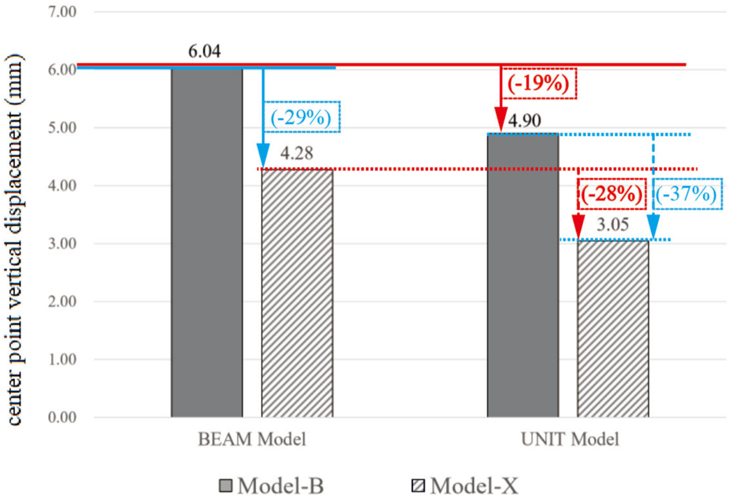


Figure 13: BEAM & UNIT Model Comparison of Results

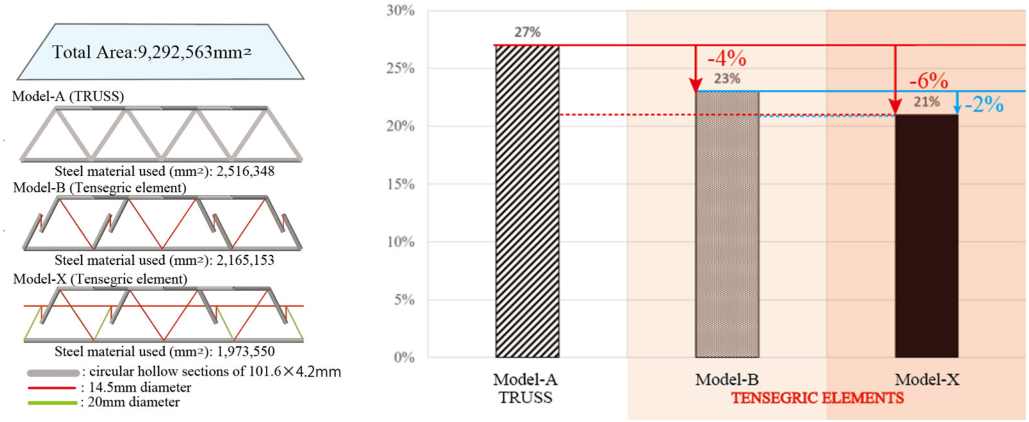
4. Evaluation of Transparency method: Based on Transparency design indicators

The primary objective in this study is to improve visual appeal through lightweight and well-designed forms that provide a highly transparent, floating appearance that reduces the presence of components through the introduction of Tensegric elements. In Section 3, the effectiveness of the introduction of Tensegric elements was confirmed by verifying the rigidity of the structure with Tensegric elements. In this section, transparency is defined as visual attractiveness and is examined. The validation evaluates the transparency by visibility by comparing Models (Model-B and Model-X) with the introduction of the Tensegric element N-Strut and Model-A with the TRUSS structure. The following two types of transparency indicators are used to evaluate transparency.

1) Visibility evaluation: The model is made into an elevated plane. The surface part of each component that is visible when facing the front (lengthwise direction) is the object. The evaluation is based on the vertical projected area which is the sum of the area calculated for each component and divided by the total area.

2) Evaluation by steel volume: Regarding the amount of members used in the model, the volume of each member is calculated by the cross-sectional area x length of each member, and the total volume used in the entire structure is evaluated using the BEAM Model.

Figure 14 shows the results of the visibility evaluation using the area found as the design index as a bar graph. The red arrows indicate a comparison between the two models using N-Strut and Model-A (TRUSS) based on the ratio calculated by dividing the visible area of each component by the total area. The percentage comparison with Model-B is 4% and Model-X is 6%. Therefore, Model-X succeeded in losing the amount of members in view compared to Model-A (TRUSS) and can be considered a model with high spatial transparency. On the other hand, the blue arrows compare two Models using N-Strut. The Model-X is 2% less than the Model-B. Model-B is the initial model considering its function as a compressive material and Model-X is a modified model to increase the transparency of N-Strut. The results of this verification indicate that the transparency of the model can be improved by further study and improvement of the model. Figure 15 shows the results of the volumetric evaluation of steel use as a bar graph. The red arrows indicate comparison of two models with N-Strut compared to Model-A (TRUSS). The blue arrows show a comparison of the two Models with the Tensegric element introduced. Comparing Model-A to Model-B, Model-B (Tensegric element) is reduced by 19%. This is only a slight decrease. On the other hand, Model-X was 35% more effective than Model-B. The comparison between Tensegric elements showed that Model-X was able to increase the reduction by 16%. Overall, it was not possible to reduce the amount of many components to enhance the visual effect of transparency. However, as with the visibility evaluation, the result of the 35% reduction in the amount of members indicates the possibility of realizing a structure with high transparency through further consideration of improvements to the model.



(a) Area of each model structure (b) Comparison of each model structure área

Figure 14: Evaluation of transparency

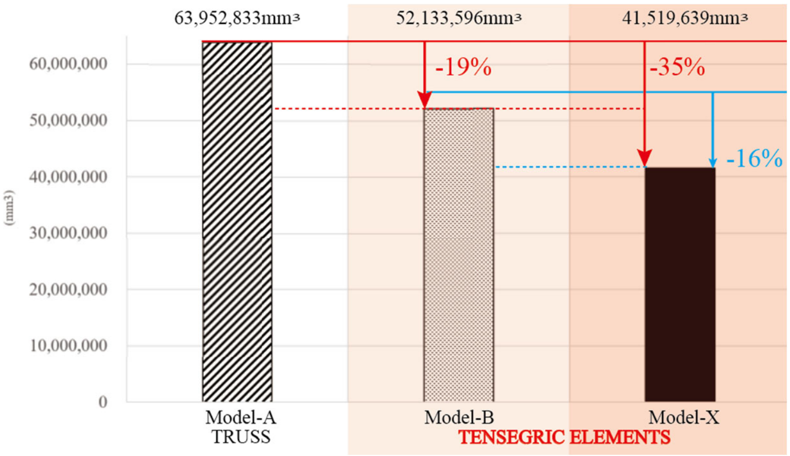


Figure 15: Comparison of volume of materials used in each model structure

5. Conclusion

This study attempted to introduce Tensegric elements into a double-layered space frame structure. Transparency is important, and validation for a stable structure is shown below.

(1) Tensegric elements allow for the adjustment of the members, and the visual space in terms of visibility allows for a design structure with a high transparency.

(2) Tensegric elements can be suppressed by 94% compared to a single layer. This is effective as a diagonal material in space frame, and a highly transparent structural form can be realized by eliminating the presence of elements.

(3) Regarding the model, there is a need to continue verification toward rationalization while adjusting the members in parallel with the mechanical approach by securing rigidity, and a more transparent structural form with enhanced design effects can be expected.

(4) The introduction of Tensegric elements into the double-layered space frame structure is the creation of a new structural form that can ensure a highly transparent space.

Acknowledgment

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