Nonlinear analysis of two-way beam string structures

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Abstract

In this study, structures subjected to bi-directional loading on roof systems can be called as two-way beam string structures. The two-way beam string structure is composed of two types of cables which have diff erent pressure and directions of cable. The cables are used to force the beam through struts supporting both positive and negative loads. This can be solved by introducing proper pre-tension forces to the structure because it prevents slacking of the cables. In addition, it examined how the behavior of the structure varies with respect to changing the angle of the cable. As a result, the evaluation is performed with this system that controls structural behavior by applying the tensile stress of the cables. The parametric studies are performed through nonlinear analysis of displacement control by changing the length and angle of the members. Moreover, the structure is implemented in the ABAQUS finite element package to verify the accuracy and validity of the results.

Keywords: Beam string system, Finite element model, High strength cable, Abaqus

Introduction

In large span spatial structures, one of the major issues is how to handle the horizontal thrust made by vertical loading economically [1]. Tension structures can be solved the issue due to their larger load carrying capacities than typical rigid beam or truss structures. There are two types of the tension structures along the usage of the tension elements, namely, membrane structures and string structures. The string structures can be further classified into two groups: thoroughbred and hybrid tension structures [2]. A beam string structure, which was first suggested in 1984 [3], is a typical type of the hybrid tension structures. In the last three decades, a series of research for the beam string structure has been reviewed mostly in Japan and China. It performed an analytical method in beam string structures [4]. The non-linear finite element method appeared to obtain the buckling load. It introduced an experimental study in Shanghai Yuanshen Areana [5]. The optimum design, namely, the rise-span ratio, beam and string sections, and the pre-stressing force were optimized by the ANSYS program and experimental work. More recently, it developed a new type foldable long-span retractable roof based on the beam string structure [6]. Most of those studies are mainly focused on one-cable beam string structures or string-beam coupled systems without struts. The beam string structure is composed of upper beams and lower strings which are used to stiffen the beam through struts. Because of the advantages in which the pre-tensioned strings elicit pre-camber of the upper beam, the maximum moment and deflection can be greatly decreased. In conclusion, the beam string structure has been widely used in large span roofs of arenas [2,5,7], airport terminals [8], public halls [9], etc. The major purpose of the beam string structure is to carry gravity-load. In contrast, because of their characteristics of light mass and high flexibility, the structures have completed progressively more sensitive to wind loading than most large span spatial structure.

Parametric study

A two-way beam string structure consists of the beam, three struts, and cables. The beams were of the same size with H−150X150X7X10 and a length of 4000 mm. The steel grade was SM490B. The beams had a yield strength of 325 MPa with elastic modulus of 200 GPa. Next, the cables were used as the sagging cable and the arch-shaped cable. The sagging cable has a tensile strength of 1,860 MPa and diameter is the 17.8 mm, while the diameter of arch-shaped cable is 12.59 mm. At last, strut was made by a pair of steel channels whose material was SS400. The cross-sectional information was 2C−125X65X6X8. At that time, a two-way beam string structure with 1860 MPa of cable was named BSS1.

The first variable is the number of struts. When struts were added to existing structures, it was able to check how values of results are changed. Therefore, it is to make a total of five struts by adding one strut each next to the post on both ends, which is the structure BSS1-S_1. Another is a structure that has a total of five struts by adding one strut each side of the center strut, which is BSS1-S_2. The last BSS1-S_3 has a total of seven struts between the two end posts by adding struts to all areas.

In this section, the second variable is cable angle control. When the cable is formed with the center of the circle at both ends of the upper beam and the center of the circle, the angle of theta is formed. The L (length of as the upper beam) and the H (length from the upper beam to the arch-shaped cable) are fixed, and the h of strut length and the c of cable length are indicated by the below formula. If the angle of the cable is different, t hen the length of each cable and the length of the strut are also different. Consequently, the angles of the sagging cable and arch-shaped cable were controlled to make the various structures.

On this occasion, the angle of the sagging cable is top of angle and the name is θ_T. On the other hand, the angle of the arch-shaped cable is bottom of angle and the name is θ_B. Moreover, the angle of the cable is marked N according to the angle which is θ_N . In additions, it was changed the length of cables and struts as the angle of cable increased and decreased. On this occasion, the length of the sagging cable is C_T. Contrarily, the length of the arch-shaped cable is C_B. Similarly, the length of the strut to the sagging cable is H_T and the length of the strut to the arch-shaped cable is H_B. Therefore, the length of each cable and strut presented. Depending on the types of cable angle control, the structure appeared to change.

In the positive pressure, the shape of the structure varies according to the ratio of L/H_T , it was called the shallow type when the ratio of $L/H_T \geq 7.5$, it was called the moderate type when it was the ratio of $7.5 > L/HT \geq 3.5$, it was called deep type when the ratio of $L/HT < 3.5$. On the other hand, in the negative pressure, it was called the shallow type when the ratio of L/HT □ 6.3, it was called the moderate type when it was the ratio of $6.3 > L/HT \geq 3.2$, it was called deep type when the ratio of $L/HT < 3.2$.

According to the formula, the radius of top circle RT and the radius of bottom circle R_B are computed as

$$RT = RB = L/2sin\theta T = L/2sin\theta B \tag{1}$$

2 sin θ_T 2 sin θ_B The length of the strut at the center of the beam H_T is computed as The length of the strut at the ends of the beam H_B is computed as The length of the sagging cable C_T and the length of the arch-shaped cable C_B are computed as

Analytical result and discussion

In this study, it decided to add struts between posts on both ends of the original structure to see how the results change. To increase the number of struts in the original structure, it consisted of three types of cable. It appeared that BSS1-S1, BSS1-S2, and BSS1-S3. The results showed that BSS1-S3, which added struts to all areas, had slightly larger deflection values against load in the positive pressure. Accordingly, three struts were the ideal for this structure. Initially, the number of struts was added to both ends, the center, and all areas. However, the load-deflection curve showed little change. Therefore, it appeared that the three were the most ideal layout.

In this section, it is a curve of the ultimate load values for all structures by dividing into positive and negative pressures. Consequently, the load increased as the angle multiplied. This is the most optimized structure with an angle of 60 degrees when considering ultimate loads.

Second, it is a curve of the initial stiffness values for all structures by dividing into positive and negative pressures. Similarly, the initial stiffness value of all structures was accurately compared by dividing the initial stiffness values by the length of each cable as shown Fig. 16. The result was the largest value at 70 degrees.

The stress values on the top and bottom of the beam and the cable are plotted. First, the stress of all members is reduced as the angle increases in the positive pressure. Among these, it is illustrated two types of stress diagrams by selecting a structure with a cable angle of 30 and 80 degrees. Subsequently, a stress diagram of 80 degrees showed that the stress value at the bottom of the beam was almost zero. The curve of the next negative pressure shows that the stress value is reduced as the angle increases.

Therefore, it calculated the stress sharing ratio of the top and bottom of the beam and the cable with these two curves. In conclusion, the stress divided 60% of the cable and 40% of the beam when the angle was 10 degrees in the positive pressure. Contrarily, the stress sharing ratio of the beam was close to zero as the angle went over 50 degrees. This is proof that beam is not doing the role. In the negative pressure, the stress sharing ratio of the top and bottom of the beam was approximately the same depending on the angle. The beam’s ratio was about 40% when the angle was 10 degrees, but it is found that the ratio dropped to about 20% when the angle was 90 degrees.

Table 1. Specification of structures.

Notation	BSS1
Number of beams	1
Number of struts	3
Number of posts	2
Number of sagging cable	1
Number of arch-shaped cable	1
Length of beam (mm)	4000
Beam	
Material	SM490B

Size	H−150X150X7X10
Sagging cable	
Yield stress (MPa)	1860
Size	ϕ17.8
Arch-shaped cable	
Yield stress (MPa)	1860
Size	ϕ12.59
Strut	
Material	SS400
Size	2C−125X65X6X8

Table 2. Stress sharing ratio of the top and bottom of beam and the sagging cable

θ_T	L/H_T	Top(%)	Bottom(%)	S.Cable(%)
10	22.9	21	17.4	61.6
15	15.2	21	16.6	62.4
20	11.3	20.5	14.5	65
25	9	19.3	11.7	69
30	7.5	17.9	9.2	72.9
35	6.3	15.8	6.6	77.6
40	5.5	14.1	4.7	81.3
45	4.8	12.4	2.7	85
50	4.3	11.5	1.3	87.2
55	3.8	10.7	0	89.3
60	3.5	9.5	0	90.5
65	3.1	9.4	0	90.6
70	2.9	9.6	0	90.4
75	2.6	9.9	0	90.1
80	2.4	10.7	0	89.3
85	2.2	12	0	88
90	2	14	0	86

Table 3. Stress sharing ratio of the top and bottom of beam and the arch-shaped cable

θ_B	L/H_B	Top(%)	Bottom(%)	A.Cable(%)
10	14.5	21.6	21.6	56.8
15	11	21.9	22.2	56
20	8.8	21.4	22.5	56.1
25	7.4	20.5	22	57.6
30	6.3	19.2	20.8	60

35	5.5	17.4	19.3	63.3
40	4.8	16	18	66
45	4.3	14.8	16.4	68.9
50	3.9	13.6	15.4	71
55	3.5	12.3	13.6	74
60	3.2	11.6	13	75.5
65	2.9	11	12.2	76.9
70	2.7	10.3	11.5	78.2
75	2.4	10.6	10.9	78.5
80	2.2	10.8	11.4	77.8
85	2.1	11.3	11.5	77.3
90	1.9	12.5	12.7	74.8

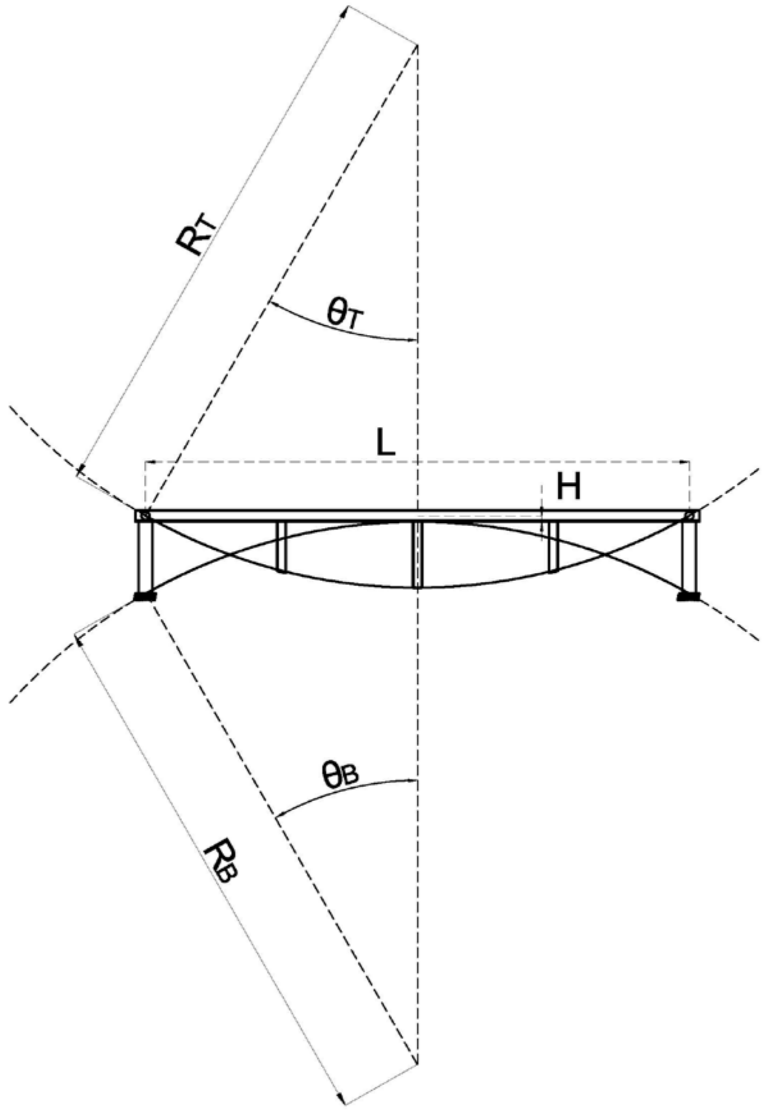

Figure 1. Proposed two-way beam string structures with cable angle control at the top and bottom of the beam.

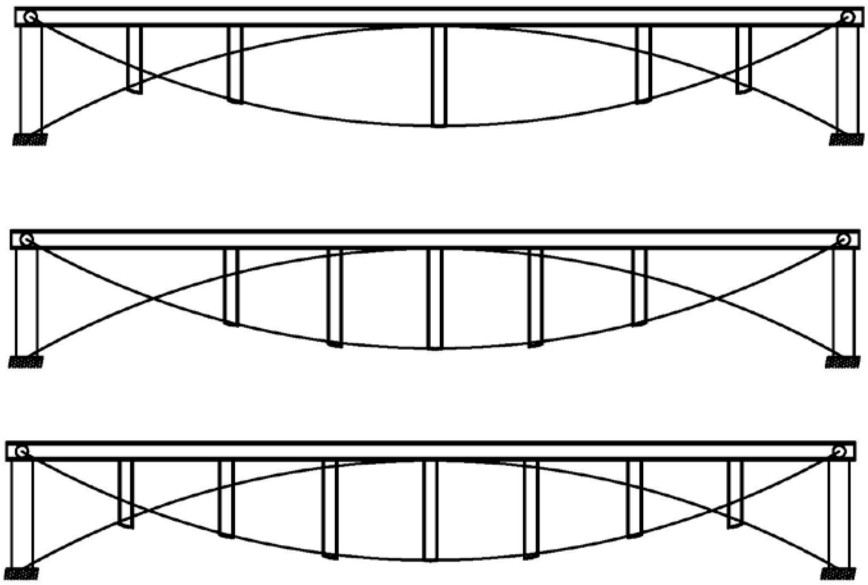

Figure 2. Proposed two-way beam string structures with respect to the three types of struts.

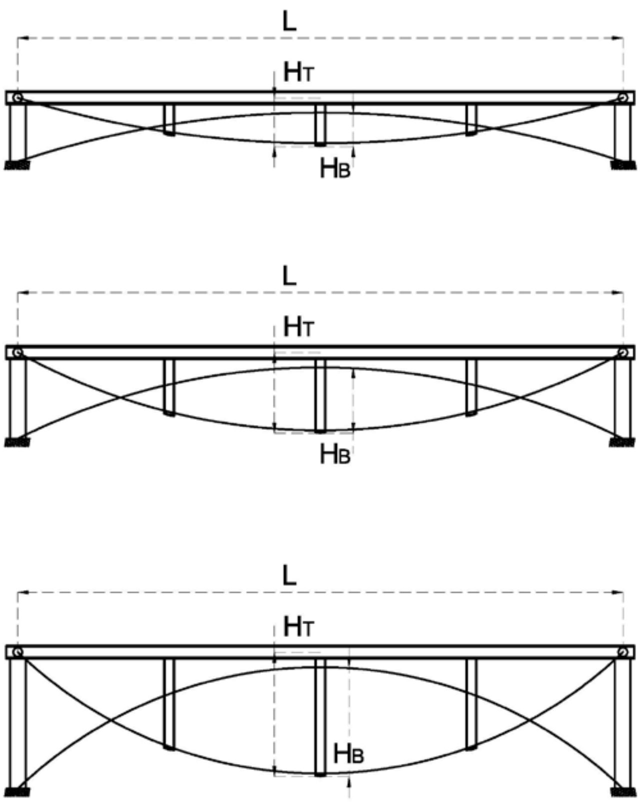

Figure 3. Proposed two-way beam string structures with respect to shallow, moderate, and deep types depending on the cable angle control.

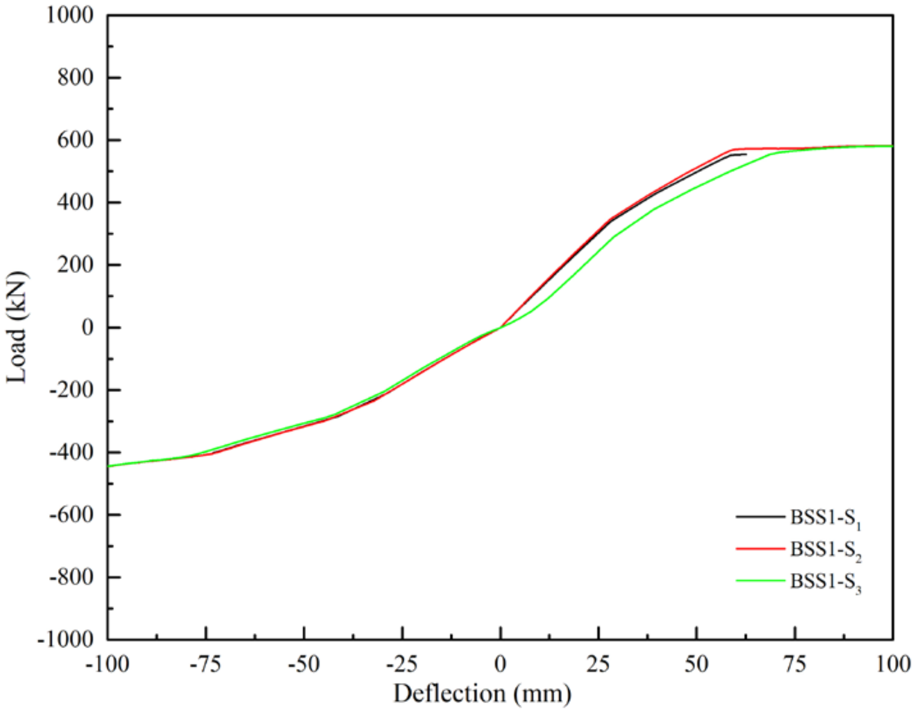

Figure 4. Load-deflection curve of two-way beam string structures with respect to the three types of struts.

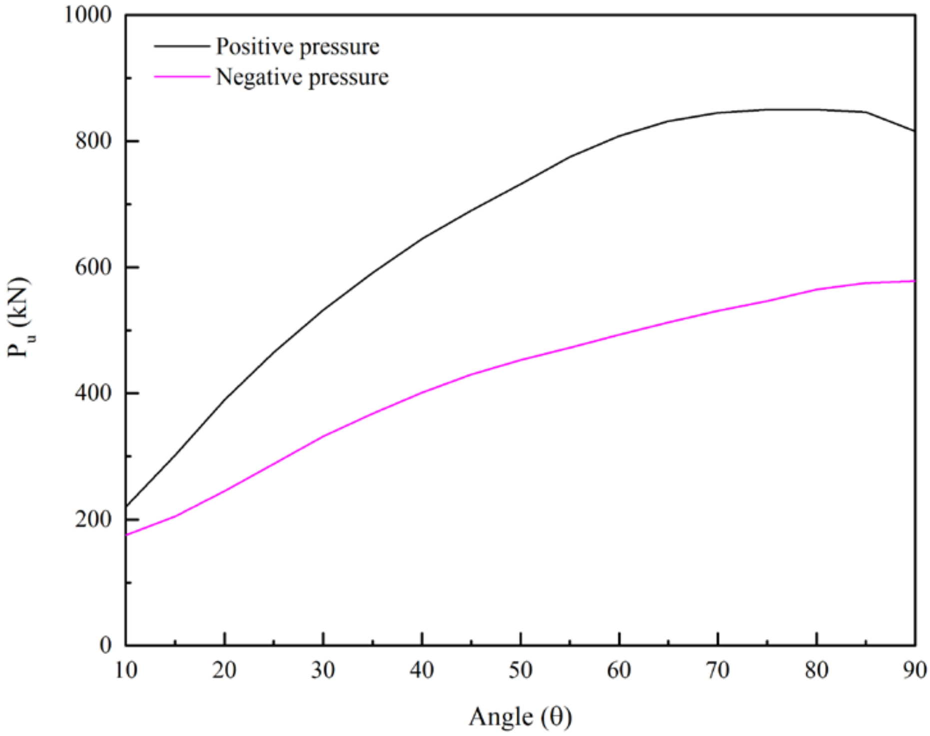

Figure 5. Pu with respect to the angle

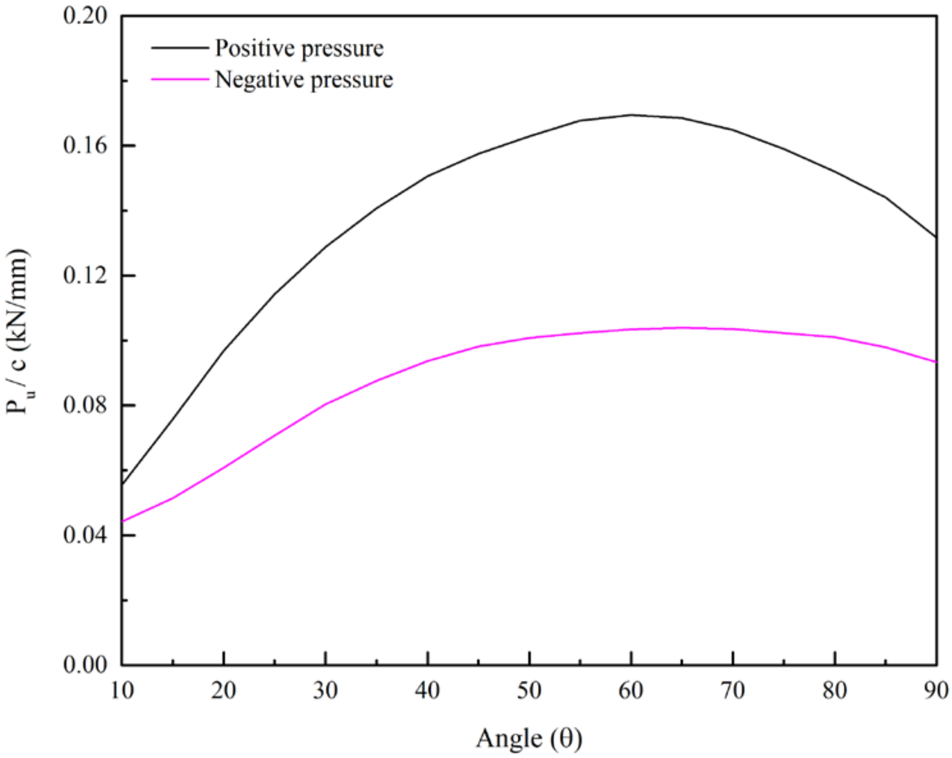

Figure 6. Normalized Pu with respect to the angle

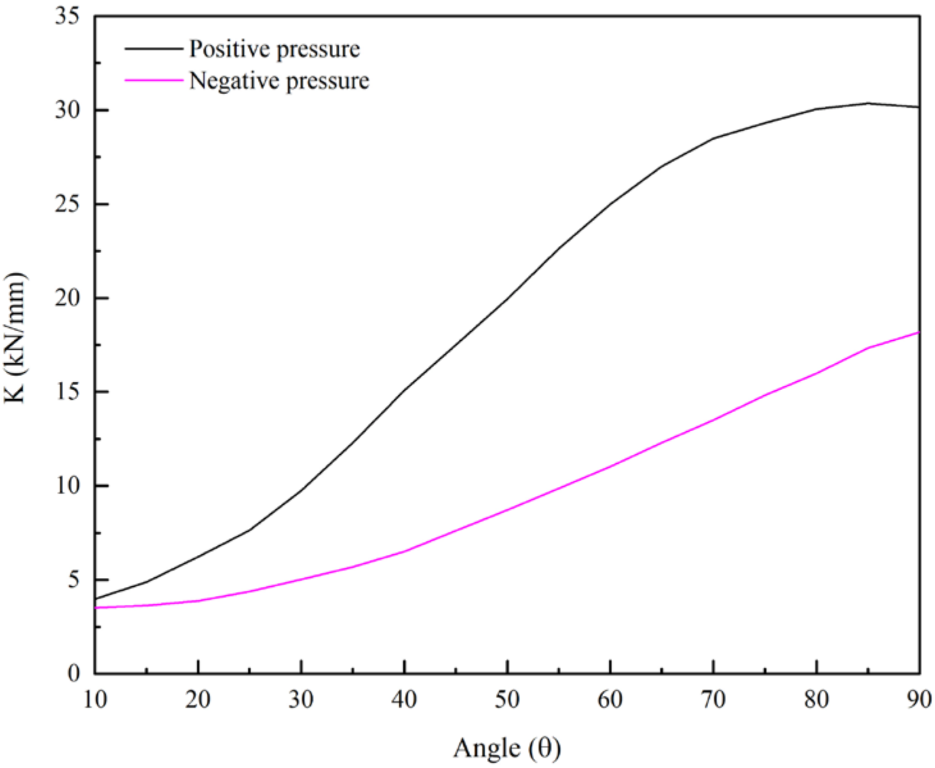

Figure 7. K with respect to the angle

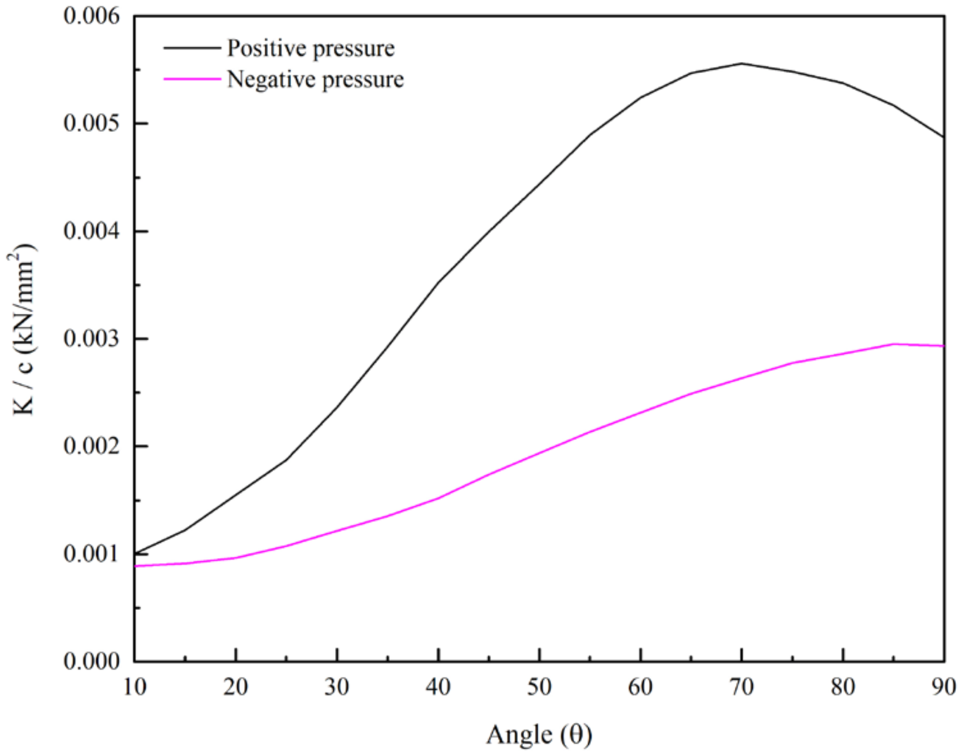

Figure 8. Normalized K with respect to the angle

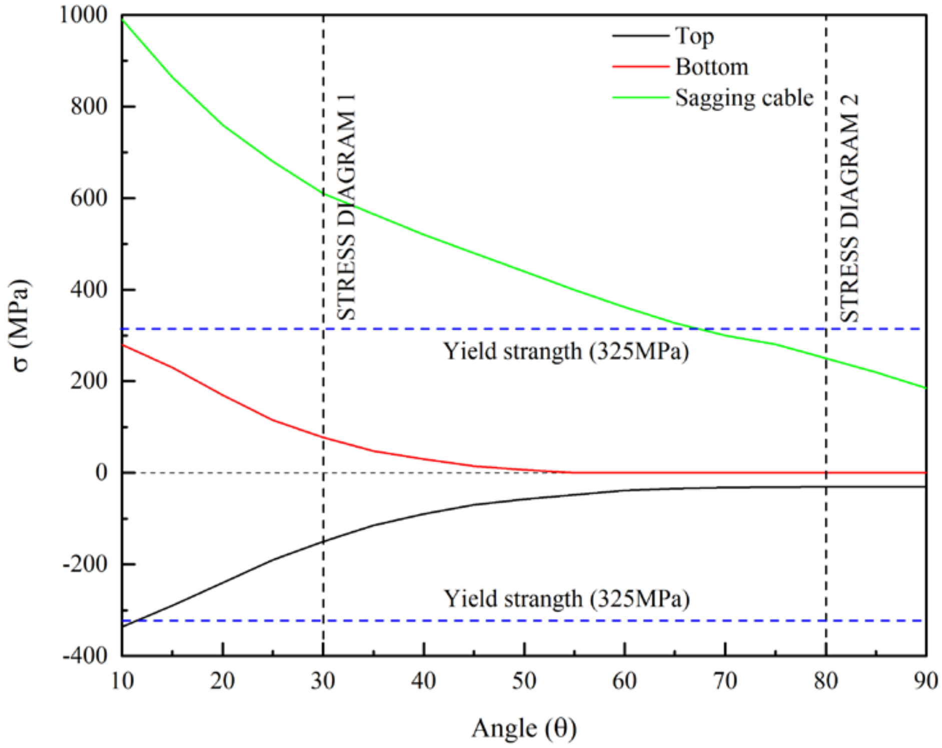

Figure 9. Stress values with respect to the angle in the positive pressure

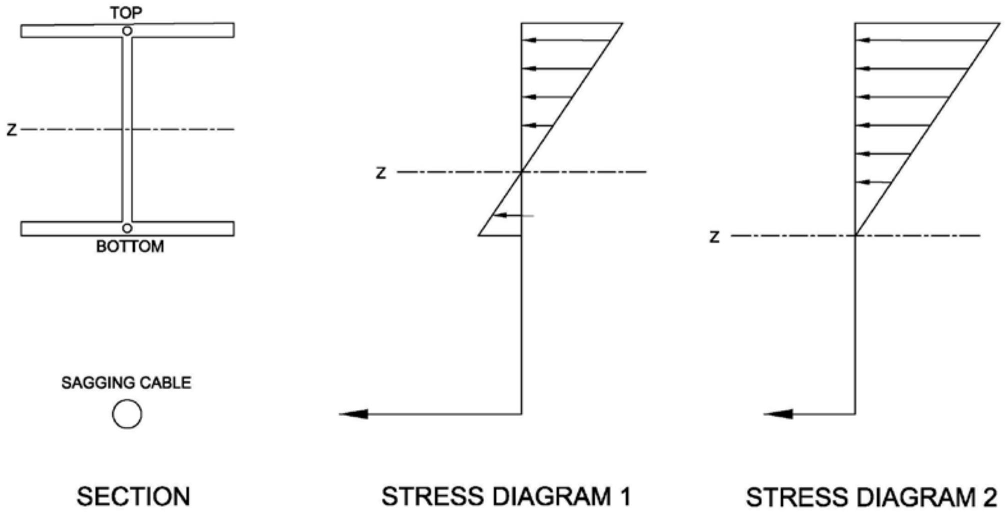

Figure 10. Stress distribution of cross-section in the positive pressure

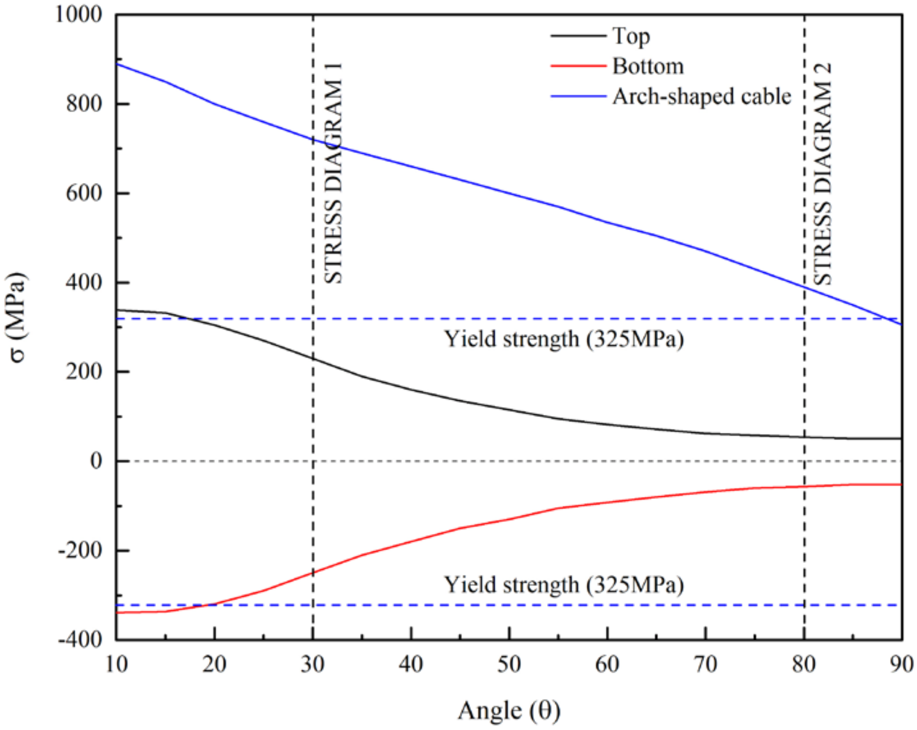

Figure 11. Stres values with respect to the angle in the negative pressure

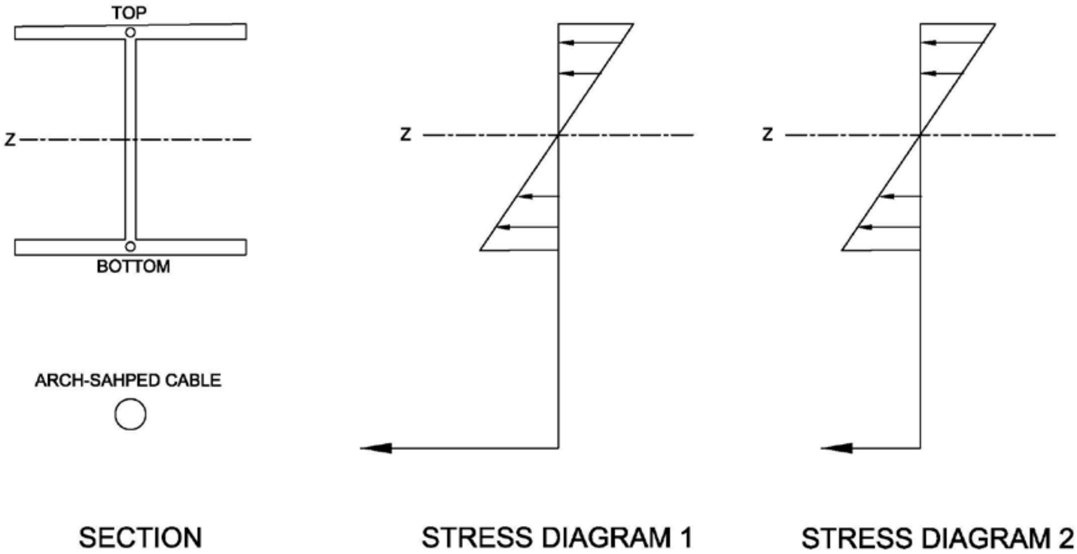

Figure 12. Stress distribution of cross-section in the negative pressure.

Conclusions

From this previous study, a two-way beam string structure was produced that targeted at a two-way roof system. In this study, it performed how the behavior of the structure changes with respect to various variables. The propriety of the proposals was verified by means of reliability analysis. Consequently, the most optimal structure was made through various parametric studies in this study.

-The three struts were the most ideal except for the posts on both ends. Because the performance of the structure was not enhanced when the load-deflection curve was checked despite the addition of struts to the original structure.

-As considering ultimate loads, the load increased as the angle multiplied. However, the structure with cable angle of 60 degrees were most advantageous as a result of the normalized curve.

-As considering initial stiffness values, the structure with cable angle of 70 degrees were also most advantageous.

-When considering the stress of top and bottom of the beam and the cables, the larger the angle, the closer to 0 the stress of the beam is.

-According to the angle of cable increases, struts and cables became longer, which was disadvantageous for economic and aesthetic values.

-Thus, the structure with an angle of 30 to 35 degrees was founded to be the most optimal structure.

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References

[1] Hosozawa, O., Shimamura, K., and Mizutani, T. (1999). The role of cables in large span spatial structures: introduction of recent space structures with cables in Japan. Engineering structures, 21(8), 795-804.
[2] Saitoh, M., and Okada, A. (1999). The role of string in hybrid string structure. Engineering structures, 21(8), 756-769.
[3] Saitoh, M., and Tosiya, K. (1985). A study on structural behaviors of beam string structure. In Summaries of technical papers of annual meeting architectural institute of Japan (Vol. 1, pp. 280-284). Tokyo, Japan, B.
[4] Wu, M. (2008). Analytical method for the lateral buckling of the struts in beam string structures. Engineering Structures, 30(9), 2301-2310.
[5] Xue, W., and Liu, S. (2009). Design optimization and experimental study on beam string structures. Journal of Constructional Steel Research, 65(1), 70-80.
[6] Cai, J., Feng, J., and Jiang, C. (2014). Development and analysis of a long- span retractable roof structure. Journal of Constructional Steel Research, 92, 175-182.
[7] Zhengxing, L. W. S. J. G. (2003). Research on prestress stretching control of a large-span truss string structure [J]. Journal of Southeast University (Natural Science Edition), 5, 013.
[8] Yiyi, C., Zuyan, S., Xianzhong, Z., Yangii, C., Dasui, W., Chengyong, G., and Hongyu, C. (1999). Experimental study on a full-scale roof truss of Shanghai Pudong International Airport Terminal. Journal of Building Structures, 20(2), 9-17.
[9] Sun, W., Yang, S., and Chen, R. (2003). Stiffness performance of trussstring structure of Guangzhou International Convention and Exhibition Center. J South China Univ Technol (Nat Sci Ed), 31(11), 33-36.