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A new configuration of Levy-type cable domes with load-relieving system

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Abstract

Cable domes have garnered significant attention in structural engineering due to their efficient space utilization, aesthetic appeal, and structural stability. However, managing the internal forces generated by applied loads remains a challenge for these structures. This paper proposes a new configuration of Levy-type cable domes with a load-relieving system. This system utilizes magnified deformation to alleviate internal forces, presenting an innovative approach to enhancing the structural behavior of cable domes. To examine the mechanical properties and feasibility of the new configuration, a comprehensive calculation framework based on the finite particle method is developed. A numerical example demonstrates the effectiveness of the load-relieving system in improving the structural performance of the cable dome. The new Levy-type cable dome configuration with a load-relieving system shows promising structural characteristics and feasible mechanical properties, offering potential for practical engineering applications and serving as a valuable reference for further innovation in load-relieving systems for cable dome structures.

Keywords: Cable domes, Levy-dome, Load relieving system, Finite Particle Method (FPM), Structural performance

1. Introduction

Cable-strut tension structure is a three-dimensional spatial structure system which is integrated by cable element and strut element and established stiffness by pretension. It has the advantages of reasonable force, efficient utilization of material strength, large span and light dead weight, etc., and is widely used in long-span industrial and civil buildings [1-4]. Based on the concept of tensegrity, cable dome was first proposed by geiger et al., and was called Geiger dome [5]. Then levy et al. invented a new type of dome called Levy dome [5]. After thirty years of development, a series of new dome configurations have been proposed. Uzun et al. imitated the tensegrity form and made innovations on the Geiger dome [6]. Mojdis et al. invented an adaptive form of cable dome, which can adjust the structural behavior according to the load conditions [7]. Chen et al. mixed two classical dome forms [5]. Asghari et al. replaced the rigid supports of Levy Dome with tensegrity rings [8]. The research of cable dome still attracts wide attention. One of the challenges associated with cable domes is managing the internal forces generated by applied loads. Excessive internal forces will lead to bad structural deformation and potential damage [9, 10].

The concept of a load-relieving system involves integrating a mitigation mechanism into the structure to enable it to adapt to load variations, thereby enhancing its self-protection capability. Under rare load conditions, the structure can store or transfer the energy through shape alteration, minimizing significant changes in internal force. This concept was first introduced by Melbourne for roof structure design [11].

Currently, load-relieving systems are implemented through a combination of elements, including pulley systems, hanging weights, and buffer springs. These mechanically movable devices often require substantial building space and exhibit significant geometric nonlinearity, complicating theoretical analysis.

This paper proposes a new configuration of Levy-type cable domes incorporating a load-relieving system to manage internal forces. The load-relieving system reduces internal force changes by releasing deformation, offering an innovative approach to enhancing the structural performance of cable domes.

The remainder of this paper is organized as follows: Section 2 provides a detailed description of the proposed structural form. Section 3 outlines the force-finding process framework for the structure. Section 4 examines the mechanical properties of the proposed structural form. Finally, Section 5 presents the conclusions.

2. Structural configuration

The proposed cable dome design is a modification of the conventional Levy dome (see Figure 1). The primary structural system of the Levy cable dome includes tensioned ridge and diagonal cables, inner cable hoops, and compressed struts. This paper employs a simplified cross-sectional view of cable domes (see Figure 2). In this representation, a single line denotes a single strut or cable intersecting the upper and lower nodes in a ring section. When two elements connect at the same node, a double line is used.

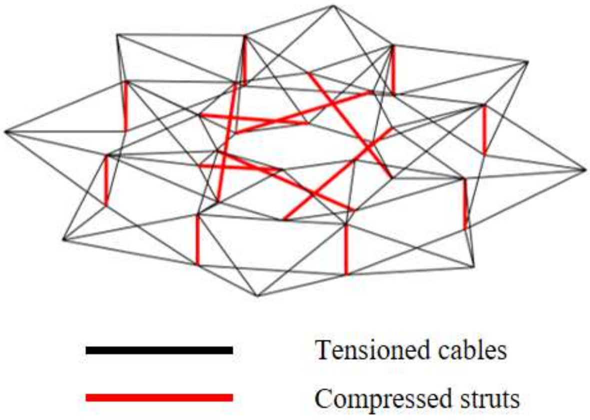
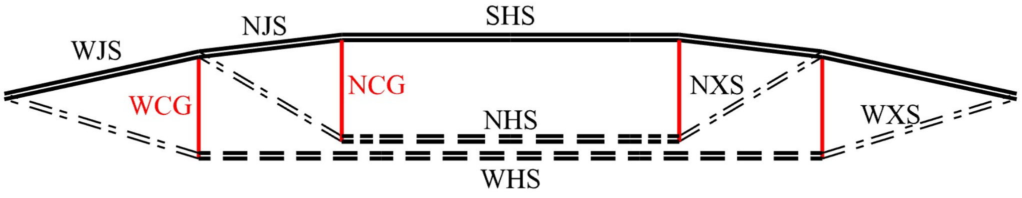


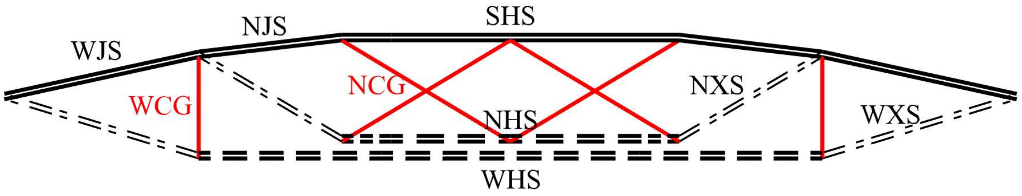
Figure 1: The proposed levy dome configuration

Figure 2 clearly illustrates the differences between the new and original configurations. In the new configuration, the compression strut of the inner ring is inclined rather than vertical. Notably, only one compression strut connects to each node.

In the new dome configuration, the number of lines connected at each node remains consistent with the Levy configuration. This indicates that the number of elements connected to each node does not change. As shown in Figure 2, only the topological relationship of the cable-strut in the first ring has been altered.



Original configuration



New configuration

WJS-outer ridge cables; WCG-outer compressed struts; NJS-inner ridge cables; NCG-inner compressed struts; SHS-upper hoop cables; NHS-inner hoop cables; NXS-inner diagonal cables ; WXS-outer diagonal cables

Figure 2: Configurations of two cable domes

In the subsequent analysis, the effects of node and element weight are neglected. Other parameters, such as cable lengths and strut forces, can be adjusted to meet practical design requirements.

The following assumptions are made for the structural analysis:

1) The nodal volumes are sufficiently small, and their influence on structural performance is negligible.
2) The elements experience only axial forces and are linearly elastic.
3) All loads are applied to the nodes.

3. Force-Finding Process: Determination of Initial Prestressing Forces in Dome

To achieve the necessary stiffness and overall stability of the cable dome, the system's cables were initially subjected to prestressing forces. This section presents a method for designing the initial prestress of the cable dome, which involves determining the appropriate magnitudes of the prestressing forces for a given dome geometry. The objective of the initial prestress design, or force-finding, is to determine the prestressing forces that will achieve the required dome geometry, as illustrated in Figure 1. The lower hoop cable is given the specified initial prestress. The force-finding process consists of two steps, as follows:

1) The objective of the shape-finding process for the cable dome is to determine the stresses in the cables and struts after the initial geometric deformation caused by the constant hoop cable stress.
2) The determined prestressing group is applied to the initial geometry. These analyses are conducted using the finite particle method with virtual damping [12].

The process of form-finding begins with the initial dome geometry. The stress N_0 of the second hoop cable is reset after each calculation ($N_0 = 10000$ N, e.g.). The spatial coordinates of nodes and elements will change, driven by unbalanced forces. The process of form-finding is terminated until the unbalanced force of the particle is within the allowable range (less than 1 N). Finite particle method (FPM) is used to calculate displacements and internal forces. The computational principles of the FPM have been discussed in many papers [13, 14].

The deformed dome geometry is obtained through the form-finding process, which is iterated to achieve the prestressed state of the initial dome geometry. Each iteration begins with the initial dome geometry and applies the prestressed state from the previous form-finding process. The deformed dome geometry, obtained after each iteration, progressively approaches the initial dome geometry. The Finite Particle Method (FPM) is continuously used in this iterative process, which terminates when the displacement deformation is sufficiently small (less than 0.2 mm). The prestressed state of the numerical examples in Section 4 is determined using the process outlined in Section 3.

The form-finding process is illustrated using the Levy dome in Figure 3. The nodal coordinates of the cable-strut system in the section view are presented in Figure 3, and the remaining nodal positions can be determined based on the structural symmetry.

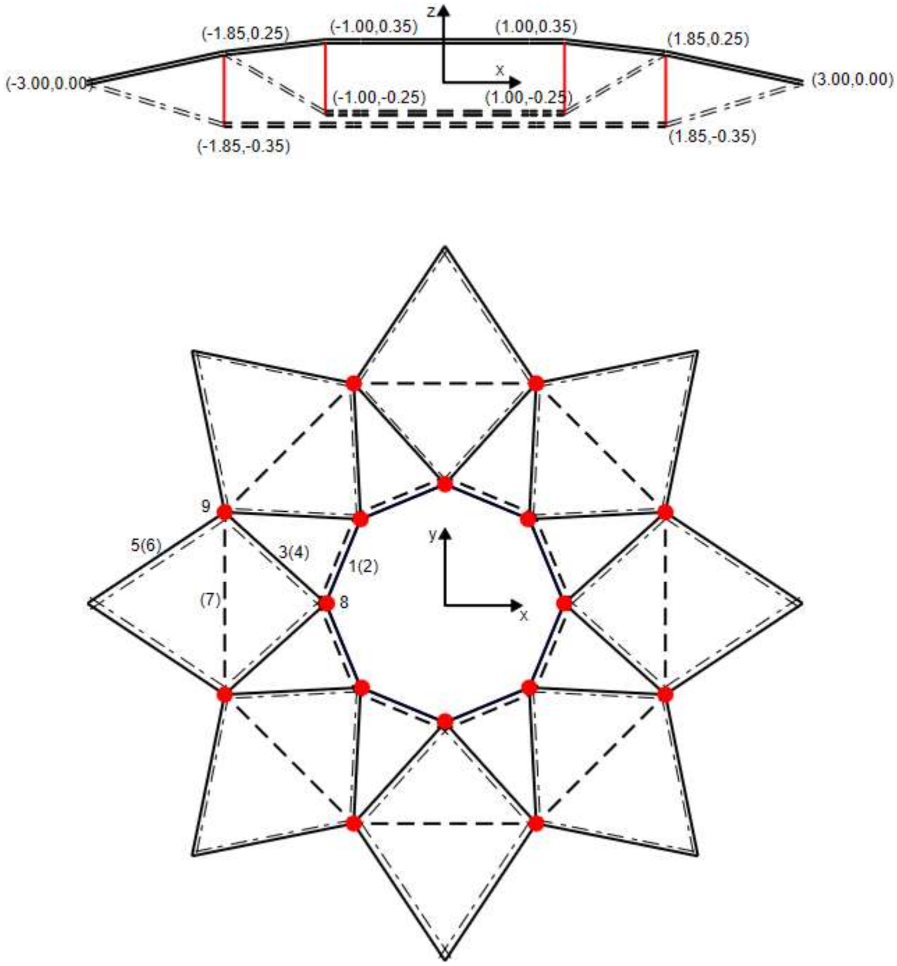


Figure 3: Geometry of levy configuration

The structural properties of the Levy dome configuration are summarized in Table 1. Element numbers are labeled in Figure 3, with the number in parentheses denoting the lower element; properties for the remaining elements can be deduced from the structure's geometric symmetry. Cable and strut elements have cross-sectional areas of 29.71 and 60.82 mm², respectively, with independent modulus of elasticity values of 120 and 179 GPa. Additionally, the prestressing state post form-finding process is provided.

Table 1: Properties of levy configuration

No	ET	IL	IS	FS
1	C	765.4	0	9181.19
2	C	765.4	0	1835.02
3	C	1146.5	0	4752.02
4	C	1246.8	0	1032.51

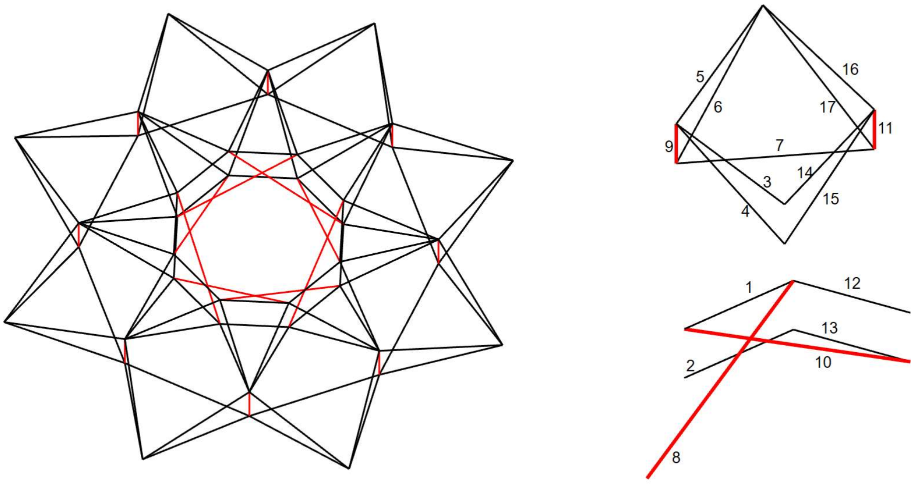
5	C	1405.7	0	9748.67
6	C	1426.9	0	7075.71
7	C	1530.7	10000	10000
8	S	600.0	0	-829.03
9	S	600.0	0	-3469.20

S: strut; C: cable; ET: element type; IL: initial length (mm); IS: initial states (N); FS: final states (N).

4. Numerical example

4.1. Structural parameter settings

Figure 4 shows the system that is used to investigate the flexibility of the proposed cable dome. The structure is composed of 88 cables and 16 struts with two rings of hoop cables and has a span of 6 m. The spatial coordinates of the nodes are the same as the example in Section 3. The structural members are divided into 17 groups (Figure 4 (b)).



(a) (b)

Figure 4: Geometry of new configuration: (a) axonometric view; (b) local view with basic structural members

Table 2 provides the structural properties of the new configuration, while Figure 4 (b) indicates the corresponding element numbers. The properties of the remaining elements can be determined using the geometric symmetry of the structure. The elastic modulus and cross-sectional area of the elements are consistent with those established in Section 3. The prestressing state after the form-finding process is also given.

Table 2: Properties of the new configuration

No	ET	IL	IS	FS	No	ET	IL	IS	FS
1	C	765.4	0	11673.80	10	S	1536.2	0	-2121.67
2	C	765.4	0	2907.80	11	S	600.6	0	-3469.36
3	C	1146.5	0	4828.61	12	C	765.4	0	10292.13
4	C	1246.8	0	1007.49	13	C	765.4	0	4369.42
5	C	1405.7	0	9840.40	14	C	1146.5	0	4671.73
6	C	1426.9	0	7076.36	15	C	1246.8	0	1057.76
7	C	1530.7	10000	10000	16	C	1405.7	0	9651.14
8	S	1536.2	0	-2121.67	17	C	1426.9	0	7076.54

9	S	600.0	0	-3469.13

S: strut; C: cable; ET: element type; IL: initial length (mm); IS: initial states (N); FS: final states (N).

4.2. Load cases

To investigate the mechanical properties of the structure, both full-span and half-span load cases are considered. Loads are applied to the top nodes, with 11 point load values ranging from -500 N to 500 N, in 100 N intervals, specified to be positive in the direction of gravity. The failure criteria include cable slacking, cable or strut yielding, and strut buckling, with a reduction factor of 0.5 applied to the design strength to account for buckling. Thus, allowable stresses range from 0 to 1600 MPa for cables and from -125 MPa to 250 MPa for struts. The relative force variation is defined as the ratio of the force variation to the initial force.

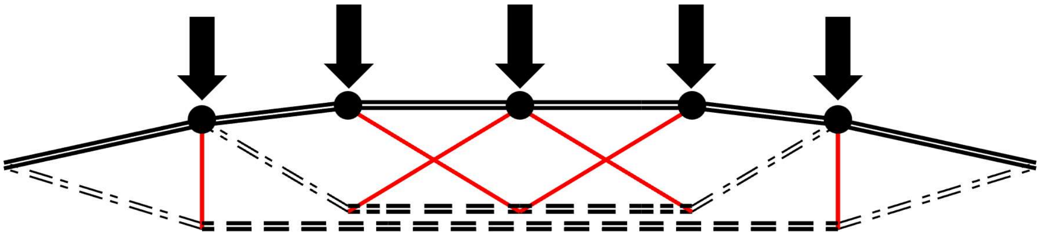


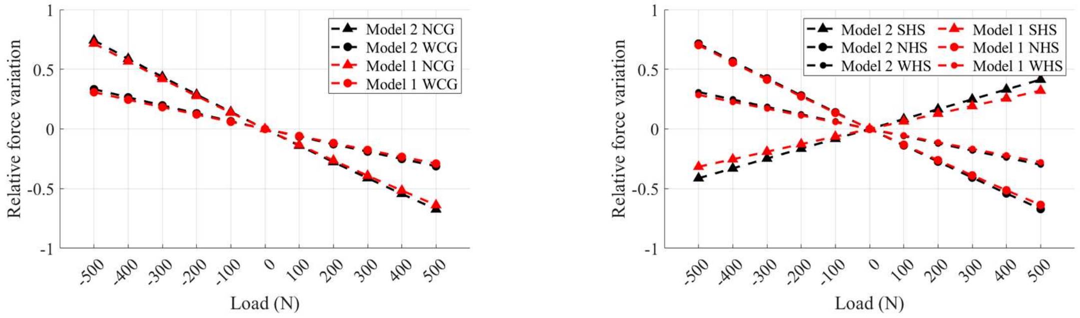
Figure 5: Loads of cable dome

The responses of the structure under different load cases are solved by FPM. The results of these calculations can be seen later in this paper. These findings suggest that the structure performs effectively (i.e., without any element yielding or cable slack) under these specific load cases.

4.3. Comparison between two configuration classes

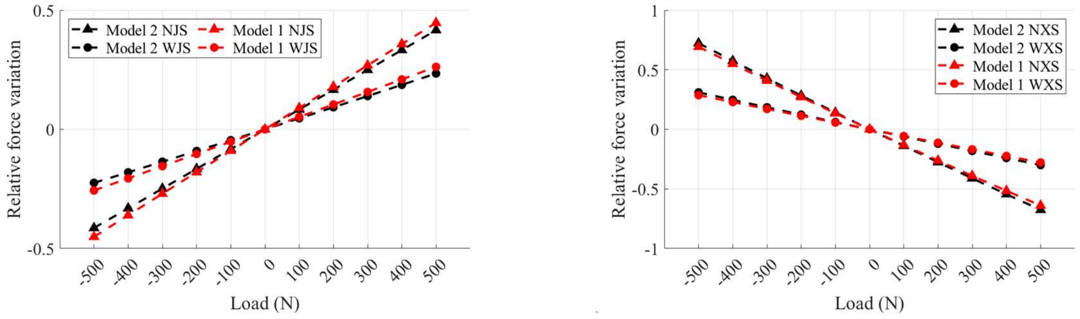
In this section, an analysis is conducted on the traditional Levy dome, as introduced in Section 3, for the purpose of comparison. To differentiate between the two structures, the newly proposed cable dome and the conventional Levy dome are respectively labeled as Model-1 and Model-2. Node coordinates of Model 2 are shown in Figure 3, and element properties are shown in Table 1. Both models share identical geometry, element material, and hoop force.

The calculation results under full-span load cases are shown in Figure 6. All elements are divided into 4 groups for ease of differentiation. Figure 6 shows that the configuration behaves close to the original configuration under full-span load cases. The new configuration can reduce the relative force variation of the strut (Figure 6 (a)), loop cable (Figure 6 (b)) and diagonal cable (Figure 6 (d)), especially the upper loop cable which is directly subjected to the load. This configuration amplifies the relative force variation of the ridge cables.



(a) Compression struts

(b) Hoop cables



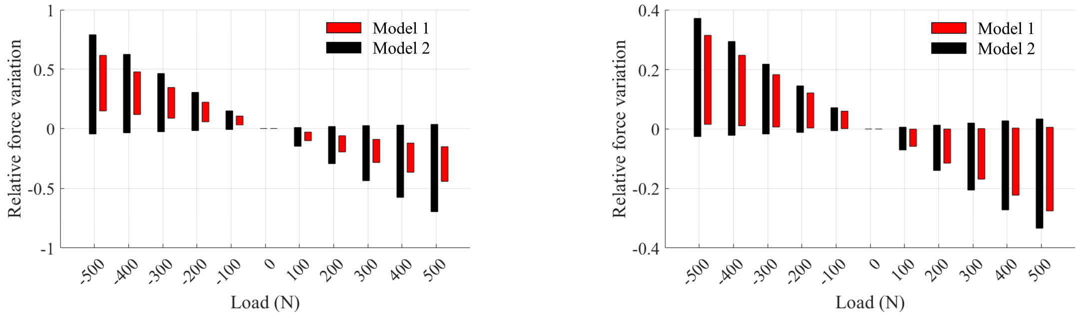
(c) Ridge cables

(d) Diagonal cables

Figure 6: Relative force variation under different loads

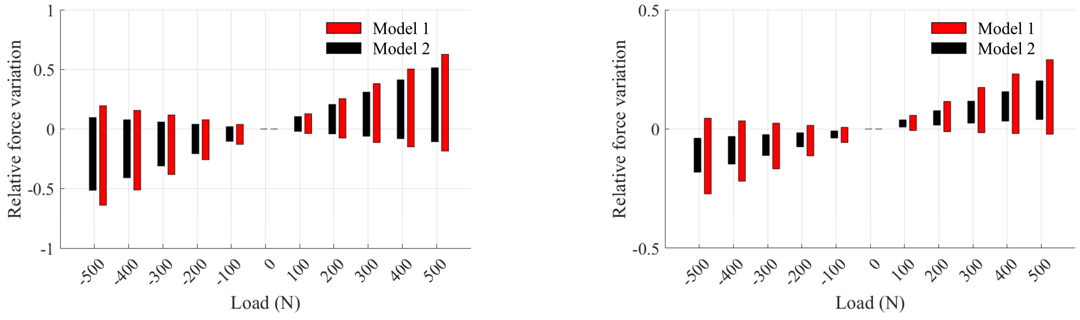
Figure 7 shows the calculated results under the half-span load. Where (a) ~ (h) is the performance of each group, (i) ~ (j) is the overall performance of the cable and strut. The relative force variation of the inner strut is 56% of the original configuration, and that of the outer strut is 75% of the original configuration. As a horizontal force transfer component, the relative force variation of the ridge cable will be amplified. The relative force variation of the diagonal cable and the lower loop cable is reduced. The relative force variation of the inner diagonal cable is 44% of the original configuration, that of the outer diagonal cable is 79% of the original configuration, and that of the lower loop cable is 43% of the original configuration.

This configuration enables the redistribution of internal forces. The relative force variation in the two elements is smaller compared to the original configuration, embodying the load-relieving concept. Under half-span loads, the load mitigation device reduces peak force variation, thereby distributing the effects of the applied load across the structure and mitigating local impacts.



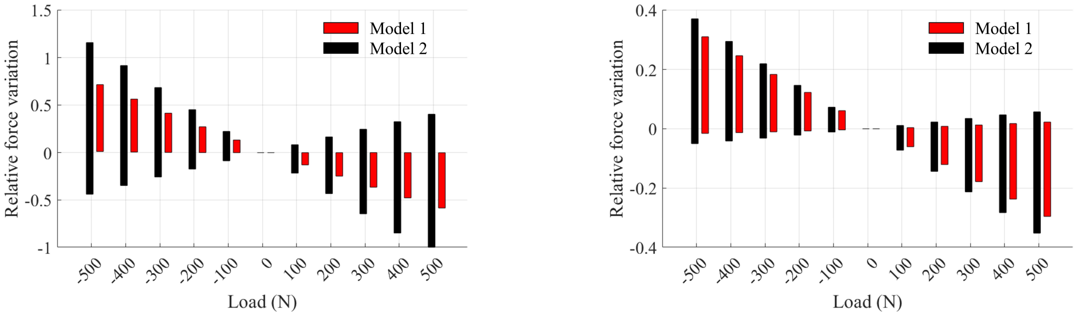
(a) NCG

(b) WCG



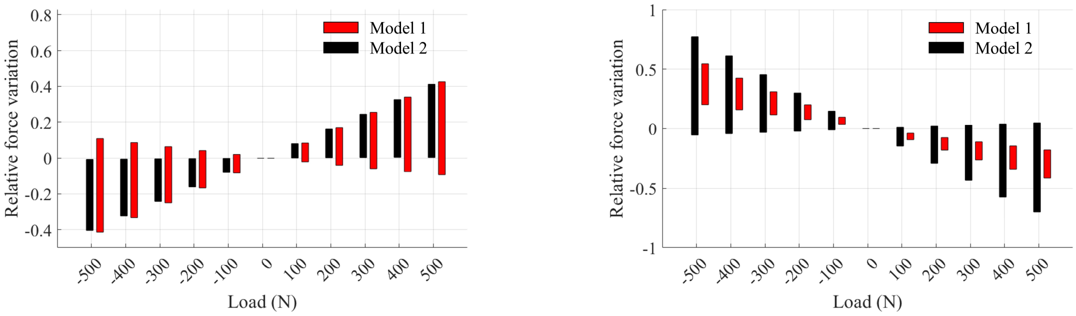
(c) NJS

(d) WJS



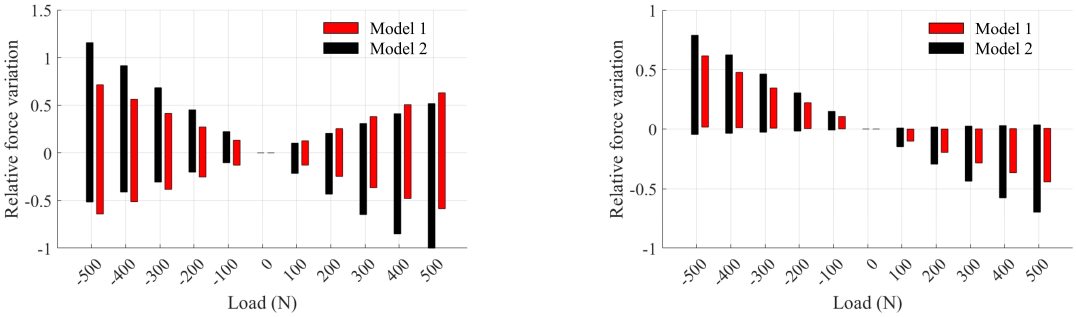
(e) NXS

(f) WXS



(g) SHS

(h) NHS



(i) cables

(j) struts

Figure 7: Relative force variation under asymmetric loads

The results show significant differences in cable and strut force variations between the two models. Under symmetric load, Model 1 experiences a downward cable force, whereas Model 2 sees an upward force. For asymmetric loads, Model 1 exhibits a 24% smaller range of cable force variation than Model 2 (e.g., half-span load, P = 500 N). In all load cases, the strut force variation in Model 1 is 43% smaller than in Model 2 (e.g., half-span load, P = 500 N).

The relative force variation in the hoop cables of Model 1 is significantly smaller than in Model 2, demonstrating the effectiveness of the load-relieving system. Under asymmetric loads, when the load is upward, the variation in cable force also moves upward, and when the load is downward, the variation moves downward. This redistribution of forces reduces peak variations, indicating that the proposed structure can distribute applied loads more evenly across the remaining elements, minimizing local effects.

Overall, the proposed structure demonstrates a certain degree of deformation while alleviating the structural forces when compared to the traditional Levy dome. Moreover, when faced with accidental loads (such as asymmetric or multi-directional loads), the structure exhibits superior material performance.

5. Conclusion

This paper introduces a new Levy dome structure equipped with a load-relieving system. The structure releases a certain degree of displacement to mitigate force changes. Compared to traditional load-relieving systems, the new structure has several advantages: (1) it does not require mechanical movable devices; (2) the number of elements and nodes remains unchanged; (3) the spatial position of the nodes is unaltered. These features facilitate the fabrication of members while preserving the original state of cable tension. To investigate the mechanical properties of the new cable dome, a computational framework based on the finite particle method is established for form-finding and force-finding. A numerical example is presented to demonstrate the structural strength, stiffness, and stability of the new cable dome. By enhancing its own deformation, the new structure effectively maintains its internal energy without significant changes, distinguishing it from traditional cable domes. In conclusion, the new cable dome structure with a load-relieving system exhibits favorable structural characteristics and feasible mechanical properties. It holds potential for practical engineering applications, providing valuable insights for load-relieving system innovation.

Acknowledgements

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References:

[1] N. Zhang, B. Luo, Y. Shen, P. Jiang, H. Li, and Q. Li, "Structural response of the FAST cable-net at large zenith angles," *Journal of Tsinghua University. Science and Technology,* vol. 62, pp. 1809-1815,1822, 2022/1/1 2022.

[2] A. Zhang, X. Liu, J. Li, J. Ge, and G. Zhang, "Static experimental study on large-span cable dome structure," *Journal of Building Structures,* vol. 33, pp. 54-59, 2012/1/1 2012.

[3] X. Yuan, L. Chen and S. Dong, "Prestress design of cable domes with new forms," *INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES,* vol. 44, pp. 2773-2782, 2007/1/1 2007.

[4] Y. Su, J. Zhang, M. Ohsaki, and Y. Wu, "Topology optimization and shape design method for large-span tensegrity structures with reciprocal struts," *INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES,* vol. 206, pp. 9-22, 2020/1/1 2020.

[5] Z. Chen, Q. Ma, X. Yan, and A. S. Lou, "Prestress Design of Ellipsoid Hybrid Form and Parameter Analysis of Design Factors,".

[6] F. Uzun, "Form-finding and analysis of an alternative tensegrity dome configuration," *ADVANCES IN STRUCTURAL ENGINEERING,* vol. 20, pp. 1644-1657, 2017/1/1 2017.

[7] S. K. M. Mojdis, "Adaptive Cable Dome,".

[8] R. Asghari, K. Abedi and M. R. Chenaghlou, "Investigation into pre-stress modes and optimal layout of a new hybrid cable-strut system," *Advances in Structural Engineering,* vol. 23, pp. 1259-1275, 2020.

[9] M. Zhu, S. Dong and X. Yuan, "Failure Analysis of a Cable Dome Due to Cable Slack or Rupture," *ADVANCES IN STRUCTURAL ENGINEERING,* vol. 16, pp. 259-271, 2013/1/1 2013.

[10] X. Li, S. Xue, X. Li, G. Liu, and R. Liu, "A numerical method to solve structural dynamic response caused by cable failure," *ENGINEERING COMPUTATIONS,* vol. 40, pp. 2049-2067, 2023/1/1 2023.

[11] C. Melbourne, "LOAD RELIEVING ROOF SYSTEMS," in *Space Structures for Sports Buildings-International Colloquium on Space Structures for Sports Buildings*, 1987.

[12] Y. Yu and Y. Z. Luo, "Motion analysis of deployable structures based on the rod hinge element by the finite particle method," *PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART G-JOURNAL OF AEROSPACE ENGINEERING,* vol. 223, pp. 955-964, 2009.

[13] E. C. Ting, C. Shih and Y. K. Wang, "Fundamentals of a vector form intrinsic finite element: Part 1. Basic procedure and a plane frame element," *JOURNAL OF MECHANICS,* vol. 20, pp. 113-122, 2004.

[14] E. C. Ting, C. Shih and Y. K. Wang, "Fundamentals of a vector form intrinsic finite element: Part II. Plane solid elements," *JOURNAL OF MECHANICS,* vol. 20, pp. 123-132, 2004.

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