University of Tabriz

Journal of Civil and Environmental Engineering
Volume 53 (2023), Issue 2 (Summer), 1-16

EXTENDED ABSTRACT

Investigation into the Collapse Behavior of a Cable Dome with Hybrid Form and Improvement of the behavior with Force Limiting Devices

Rasoul Asghari [a], Karim Abedi [a,*], Mohammadreza Chenaghlou [a], Behzad Shekastehband [b]

[a] *Faculty of Civil Engineering, Sahand University of Technology, Tabriz, 51335-1996, Iran*
[b] *Faculty of Civil Engineering, Urmia University of Technology, Urmia, Iran*

Received: 17 November 2021; **Review:** 17 January 2022; **Accepted:** 23 January 2022

Keywords:
Cable dome, Tensegrity ring, Hybrid cable-strut system, Force density method, Retrofitting, Force limiting device.

1. Introduction

Tensegrity systems have been used as a class of light space structures in the various forms including flat modular systems, barrel vaults and cable domes. Conventional cable domes achieve their stability through a concrete compression ring, which is inconsistent with the self-support characteristic of tensegrity systems. The previous evidences also showed that the presence of a rigid support system such as a concrete ring around the space structure especially subjected to seismic loads may cause more structural damages in boundary region of structure. In this research, the combination of a Levy-type cable dome with a tensegrity ring created by the semi-regular modules is considered, which leads to a new hybrid cable-strut system. Form-finding of the studied structures is carried out using the force density method. After designing the hybrid structure, its initial collapse behavior is evaluated by the numerical finite elements method. In this regard, static and dynamic analyses are performed on both the hybrid structure and the cable dome attached to rigid supports to evaluate the effect of the tensegrity ring on the cable dome behavior and also the adequacy of static analyses to estimate capacity of the structures. After estimating the initial behavior and the collapse mechanism type of the studied structures, their behavior, are improved by equipping a number of critical struts with Force-limiting devices.

2. Methodology

2.1. Studied hybrid configuration

Semi-regular tensegrity modules were used to create a tensegrity ring. The module is achieved through the trapezoidal transformation of a regular octagonal module. In Fig. 1, the semi-regular module and the final hybrid structure along with geometrical characteristics and grouping of the elements have been shown.

* Corresponding Author
E-mail addresses: ra_asghari@sut.ac.ir (Rasoul Asghari), k_abedi@sut.ac.ir (Karim Abedi), mrchenaghlou@sut.ac.ir (Mohammadreza Chenaghlou), b_shekastehband@uut.ac.ir (Behzad Shekastehband).

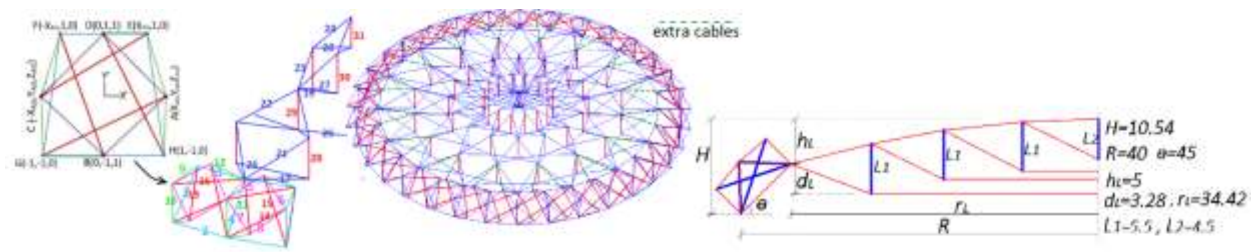

Fig. 1. The semi-regular tensegrity module and the hybrid structure with geometric characteristics and elements grouping

2.1. Form-finding and Design

In this study, duo to high application and simplicity of programming, the force density method together with the double singular value decomposition technique and the linear optimization method are used to determine a feasible pre-stress mode. Applying SVD decomposition on the equilibrium matrix, results in independent self-stress modes satisfying only the self-equilibrating condition. The integral pre-stress modes are obtained considering the geometrical symmetry of the dome and applying DSVD method. In general, these modes do not satisfy the feasibility conditions. Finally, the integral feasible prestress mode is achieved through a linear programming problem on the integral prestress modes. The design of these structures is accomplished considering the dead load and the symmetric/asymmetric snow load on the structure based on ASCE/SEI 19-10 and ASD method.

2.2. FE modeling

The ABAQUS finite element software is used for the numerical modeling and analysis. Truss elements are used for cable and strut members. Static riks and dynamic analyses on the hybrid structure and cable dome without tensegrity ring are performed considering the geometric and material nonlinearities. Compressive behavior of the struts also are extracted by the riks analysis to consider their brittle post-buckling behavior. One of the methods to control ductility and improve behavior in the space structures is to use force limiting devices (FLDs). All FLDs change brittle post-buckling behavior of the struts to desirable ductile behavior. In this paper three FLDs have been selected including PARK model (Park, 1988), BCM model (Chenaghlou et al, 2020) and AFLD model. Only the effect of replacing behavioral model of these devices instead of the strut members on the behavior and bearing capacity of the studied structures has been considered and details of these FLDs are not the concern of the current research.

3. Results and discussion

3.1. Initial static analyses results

In the hybrid structure subjected to the symmetric load, the local collapse with a significant snap-through occurs. The slackening and the 1st buckling load proportionality factors (relative to design loads level) are respectively 1.352 and 2.821. In the asymmetric load case, overall collapse occurs with the capacity of 3.154. In the cable dome structure without tensegrity ring subjected to symmetric load, overall collapse occurs with the capacity of 2.71. In the asymmetric load case, local collapse with successive snap-throughs occurs with the capacity of 2.34. Results indicate that, capacity of the cable dome attached to a tensegrity ring has been increased by 3.9% and 34.8% respectively for the symmetric and asymmetric load cases in comparison with the cable dome without tensegrity ring. Also the effect of prestress levels was evaluated on the hybrid structure behavior. These effects are remarkable on the slackening load level but are very little on the 1st buckling load level.

3.2. Dynamic analyses results

In order to consider the dynamic effect of snap-through phenomenon, dynamic analyses were conducted at the 1st limit point level for two structures. In hybrid structures, response of the structure at the end of snap-through was stabilized and overall collapse did not occur. But in the cable dome without tensegrity ring, collapse progressed and displacement at the end of snap-through increased from 10 m to 18 m. Therefore, the tensegrity ring attached to a cable dome participate in load carrying capacity and prevent the collapse propagation.

3.3. Retrofitting and behavior improvement results

In this section, the buckled struts were equipped with three FLD models at three steps. The process is such that the first set of buckled struts was replaced with FLD and structure was analyzed and new set of the buckled struts (2nd set) were determined. At the 2nd step, the new buckled struts were replaced with FLD and structure was analyzed again to specify the 3rd set of the buckled struts. At the 3rd step, this struts were replaced. These three steps were repeated for two other FLD models. The replacement process was conducted on the hybrid structure and also on the cable dome without tensegrity ring. As shown in Table 1 and Table 2, using of FLDs in two structures results in an increase of the load-carrying capacity of the structures independent of the type of FLD. However, the displacement of the structure at the 1st buckling level is dependent on the type of FLD, being the minimum in the case of AFLD. Also at the 1st step of replacement, the improvement of the load-carrying capacity of the hybrid structure is much more than that of the cable dome structure without tensegrity ring.

Table 1. Three steps retrofitting results in hybrid structure

Retrofitting method	1st step (Using of FLD in strL3)				2nd step (Using of FLD in strR2)				3rd step (Using of FLD in strR3)			
	Replacing %	Cap[1]	ΔCap[2]	Disp (m)[3]	replacing %	Cap	ΔCap	Disp (m)	replacing %	Cap	ΔCap	Disp (m)
PARK FLD	9%	3.424	21.4%	3.496	18%	3.546	25.7%	3.672	27%	3.775	33.9%	4.358
BCM FLD	9%	3.423	21.4%	3.493	18%	3.547	25.8%	3.67	27%	3.772	33.8%	4.301
AFLD	9%	3.409	20.9%	3.237	18%	3.541	25.6%	3.442	27%	3.772	33.8%	3.940

(1) Cap: Load factor corresponding to the first buckling.
(2) The percentage is calculated compared to the original structure (load factor of 2.821).
(3) Displacement at apex of structure in 1st buckling level

Table 2: Three steps retrofitting results in cable dome structure without tensegrity ring

Retrofitting method	1st step (Using of FLD in strL4)				2nd step (Using of FLD in strL3)				3rd step (Using of FLD in strL2)			
	replacing %	Cap[1]	ΔCap[2]	Disp (m)[3]	replacing %	Cap	ΔCap	Disp (m)	replacing %	Cap	ΔCap	Disp (m)
PARK FLD	33%	2.791	3.0%	1.918	65%	3.747	38.3%	3.635	98%	4.507	66.3%	4.782
BCM FLD	33%	2.788	2.9%	1.842	65%	3.748	38.3%	3.630	98%	4.505	66.2%	4.774
AFLD	33%	2.789	2.9%	1.796	65%	3.752	38.5%	3.214	98%	4.409	62.7%	4.220

(1) Cap: Load factor corresponding to the first buckling.
(2) The percentage is calculated compared to the original structure (load factor of 2.71).
(3) Displacement at apex of structure in 1st buckling level

4. Conclusions

In this study, the collapse behavior of a new hybrid form of cable-strut structures including a Levy-type cable dome and a tensegrity ring was investigated through static and dynamic analyses in two load cases. Also, the effect of using three types of the force limiting devices during three replacement steps instead of the buckled struts was studied on the hybrid structure and the cable dome structure without tensegrity ring. The concluding remarks are as:

- The presence of tensegrity ring around the cable dome reduces the load level of slackening but increases the load-bearing capacity of the structure in both loading cases.
- The presence of tensegrity ring, prevents the collapse propagation after the first buckling.
- Use of force limiting devices on the cable dome without tensegrity ring increases the bearing capacity by 3%, 38% and 66% during three steps of the replacement. The corresponding values are 21%, 26% and 34% for the hybrid structures.
- In one-step replacement of FLDs, the increase in bearing capacity for hybrid structure, is much more than a cable dome structure without tensegrity ring (21% compared to 3%). This can be an advantage for hybrid structure due to FLDs costs.
- The rate of increase in bearing capacity of both structures during the three replacement steps is almost independent of the type of FLD, which can be effective in the controlling costs of retrofitting.

5. References

Chenaghlou MR, Kheirollahi M, Abedi K, Akbari A, Fathpour A, “Inherent Adaptive Structures Using Nature-Inspired Compound Elements”, Frontiers in Built Environment, 2020, 186.

Parke G, “The behavior of space trusses incorporating novel compression members”, PhD Thesis, University of Surrey, Surrey, UK, 1988.