Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Modifying the Configuration and Members of Hybrid Cable Dome to mitigate the Progressive Collapse

Karim. ABEDI[*], Rasoul. ASGHARI[a], Mohammadreza. CHENAGHLOU[b], Behzad. SHEKASTEHBAND[c]

[*] Professor of Structural Engineering, Sahand University of Technology, Tabriz-Iran
k_abedi@sut.ac.ir
[a] Ph.D. of Structural Engineering, Sahand University of Technology, Tabriz-Iran
[b] Professor of Structural Engineering, Sahand University of Technology, Tabriz-Iran
[c] Associate Professor of Structural Engineering, Urmia University of Technology, Urmia-Iran

Abstract

Cable domes were introduced as super lightweight space structures and efficient forms of tensegrity systems. The defect of traditional cable domes is that their stability is achieved by creating compressive forces in a rigid concrete ring around the dome. This results in conceptual contradictions and behavioral problems for these domes. Incorporating different structural systems can improve their structural behaviors. Therefore, in this paper, a combination of a tensegrity ring with 32 modules and the central cable-strut part of a Levy-type cable dome with 3 hoops, was considered as a hybrid cable dome. Form-finding, loading, designing, and collapse behavior of this dome have been previously carried out by authors. To evaluate the progressive collapse of this dome, in the first phase, frequency analyses were done on the damaged structures due to the removal of one member of all groups. Based on the frequency reduction factor of all members, possible critical members were identified. Then, dynamic alternate path analyses were carried out on the damaged structures due to the sudden loss of these identified members in a time duration of 0.01 s in ABAQUS software. Results showed that removal of the lower hoop cables results in progressive collapse and there is no alternate path to redistribution of force. In the second phase, three methods were employed to present a progressive collapse-resistant design: 1) Using buckling-controlled members (BCMs) which changes strut behavior from a brittle one to a ductile one, 2) modifying of configuration by adding bracing cables between struts each hoops, and 3) adding bottom cables net. These methods decreased the severity of damages by up to 92%, and adding bottom cables net, provided more suitable alternate paths.

Keywords Hybrid cable dome, Progressive collapse, Alternate path method, frequency analysis, frequency reduction factor Dynamic analysis, BCM, bracing cables, bottom cables net.

1. Introduction

Cable domes were introduced by David Geiger in the 1960s and then were developed in various geometrical forms. Application of boundary concrete rigid ring is in contrast with the tensegrity concept [1] and also it leads to seismic damage concentration adjacent to the rigid supports [2]. Replacing this compression ring with a modular tensegrity ring develops a new hybrid cable dome. Like any cable-strut structure, the stiffness and structural integrity of cable domes are achieved through pre-stressing forces. In recent years, the force density method has been employed with various modifications and techniques [3–5]. The geometry of hybrid cable domes was developed by Asghari et al. [6] based on the pre-stress distribution.

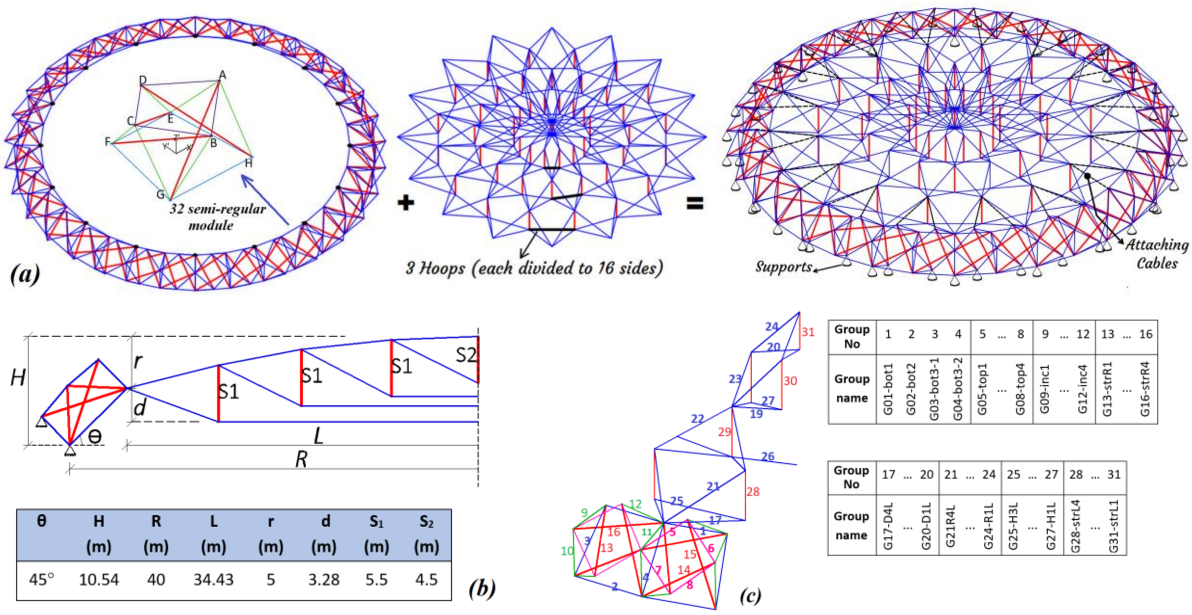
Sudden member loss in the cable domes can be caused by the failure of a faulty connection, buckling of struts, or rupture of cables in which, forces of failed members are dynamically shed into the structure.

These failures can lead to severe damage in the adjacent members and finally progressive collapse in the structure. In this field of research, Abedi and Shekastehband studied numerically and experimentally the effects of strut buckling, cable rupture, pre-stress level, and member loss on the progressive collapse of tensegrity grids [7–9]. Improving the collapse behavior of space structures and especially the tensegrity systems has attracted the attention of researchers in recent years. This improvement is achieved by converting the brittle post-buckling behavior of struts to a ductile one using Force Limiting Devices (FLD) or delaying the buckling of struts using DP modules. Shekastehband [10] employed the FLDs to increase the load-bearing capacity of tensegrity grids. Asghari et al. [11] investigated three-step retrofitting of hybrid cable domes considering three different types of FLDs and also employing DP modules instead of struts. Their results showed that regardless of the retrofitting method, with FLDs or DP in the first set of critical struts, the load-carrying capacity of the hybrid cable dome can be increased up to 35%.

Considering the aforementioned efforts on the collapse behavior of cable domes, this paper concerns the resistant design of hybrid cable domes against progressive collapse due to sudden member loss. In the first phase, frequency analyses are performed on the damaged structures due to the sudden loss of all members to detect potential critical members. Then, dynamic alternate path analyses are carried out after the sudden loss of these members to assess the occurrence of progressive collapse and the existence of alternate load paths. In the second phase, to improve the progressive collapse resistance of the hybrid cable domes subjected to sudden member loss, three schemes are proposed: 1) Employing BCMs on the critical struts; 2) Adding bracing cable net in any hoops and, 3) Adding bottom cables net.

2. Geometry of hybrid cable dome

As shown in Figure 1-a, the tensegrity ring is developed based on the node-on-node junction of 32 semi-regular modules. Details of this module can be found in reference [5]. In the next step, this ring is connected to a levy-type cable dome without the compression ring to obtain the final hybrid cable dome. Figures 1-b and c show the geometrical parameters and grouping of members of the hybrid cable dome which can effectively assist in determining the pre-stress states.



θ	H (m)	R (m)	L (m)	r (m)	d (m)	S_1 (m)	S_2 (m)
45°	10.54	40	34.43	5	3.28	5.5	4.5

Group No	1	2	3	4	5 … 8	9 … 12	13 … 16
Group name	G01-bot1	G02-bot2	G03-bot3-1	G04-bot3-2	G05-top1 … G08-top4	G09-inc1 … G12-inc4	G13-strR1 … G16-strR4

Group No	17 … 20	21 … 24	25 … 27	28 … 31
Group name	G17-D4L … G20-D1L	G21R4L … G24-R1L	G25-H3L … G27-H1L	G28-strL4 … G31-strL1

Figure 1: Hybrid cable dome: **a)** creating process; **b)** geometrical parameters, and **c)** grouping of members

3. Pre-stressing, loading and design

The pre-stress forces should be extracted through a form-finding process. For this purpose, the force density method is implemented along with the dual singular value decomposition method and linear programming to achieve the pre-stress forces. The procedure of finding the pre-stress forces of the hybrid cable dome has been explained in detail in references [6] and [11]. The normalized pre-stress forces of

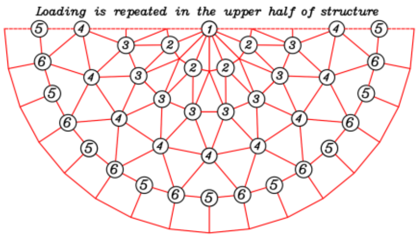
31 groups of members are derived as given in Table 1. The combination of pre-stress (P), dead (DL), symmetric and asymmetric snow (SSL and ASL), wind (WL), and earthquake (E) loads have been considered in the design of the hybrid cable dome, as shown in Table 2. DL and SSL loads, used in dynamic analyses, have been illustrated in Figure 2. The characteristic stress-strain behaviors of cable and strut materials are shown in Figure 3 [8]. The allowable stress design method has been used with allowable stress of cables equal to 0.45 of their rupture limit [12]. The pre-stress forces given in Table 1 were scaled to 75% of the allowable stress of G28-strL4. The final cross-section and also DCR (demand to capacity ratio) of members for various load combinations are depicted in Table 3 and Figure 4, respectively.

Table 1: Normalized pre-stress forces for hybrid cable dome

Group	G01	G02	G03	G04	G05	G06	G07	G08	G09	G10	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20	G21	G22	G23	G24	G25	G26	G27	G28	G29	G30	G31
Pre-stress (kg)	0.161	0.188	0.381	0.381	0.286	0.286	0.183	0.247	0.165	0.310	0.248	0.310	-0.361	-0.464	-0.495	-0.449	0.268	0.095	0.036	0.022	0.388	0.225	0.161	0.276	**1.000**	0.381	0.153	-0.161	-0.072	-0.033	-0.157

Table 2: Load combinations according to ASCE19-16 [12]

C1&2:	**P+DL+(SSL & ASL)**	**C4&5:**	**P+DL+0.75(SSL & ASL)+0.45WL**	**C7:**	**P+DL+0.75SSL±0.75(0.7E)**
C3:	**P+DL+0.6WL**	**C6:**	**P+DL±0.7E**		



Nodes	1	2	3	4	5	6
Nodal Dead	685	291	584	874	349	217
Nodal SSL	7914	3328	6345	8931	3495	2168

Figure 2: Symmetric dead and snow loads and their values (unit: kg)

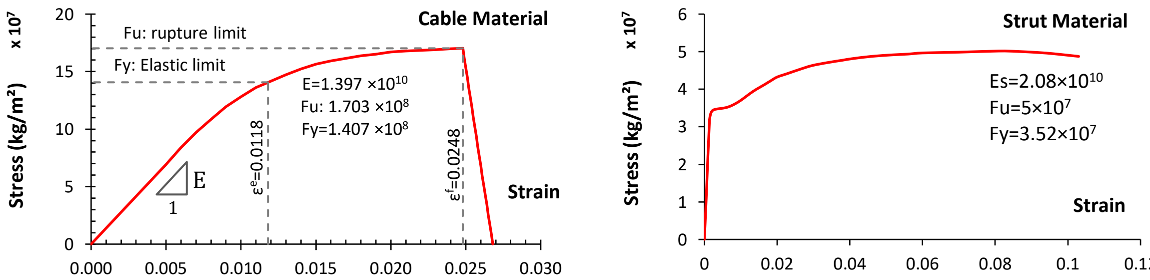


Figure 3: The stress-strain diagram of materials [8]

Table 3: Final cross-sectional areas of elements in the studied structure

Group	G01 To G04	G05 To G07	G08	G09 To G11	G12	G17	G18 To G20	G21	G22 To G24	G25	G26	G27	G13 G15	G14 G16	G28	G29	G30	G31
	Number of 0.6-inch strands												Pipe (Diameter × thickness)					
Section	10	12	20	10	12	8	4	8	6	20	10	4	323.9 × 11	406.4 × 11	193.7 × 5.4	139.7 × 5.6	114.3 × 4.5	139.7 × 6.3
Area (cm²)	14	16.8	28	24	16.8	11.2	5.6	11.2	8.4	28	14	5.6	87.1	136.6	31.9	23.6	15.5	26.4

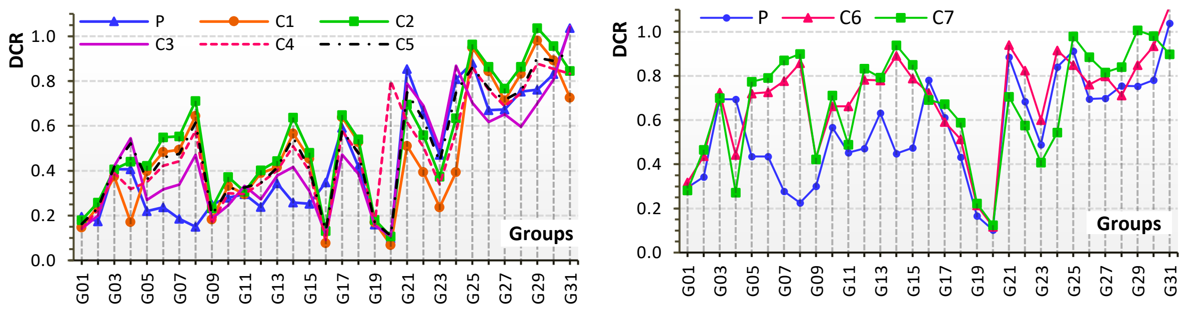


Figure 4: DCR of members in hybrid cable dome for all seven load combinations

4. Finite element modeling

4.1 Frequency and dynamic analyses

The design of hybrid cable domes against progressive collapse requires consideration of the critical damaged states caused by the sudden loss of critical members leading to progressive collapse. To exact identification of critical members, performing the dynamic alternate path analysis is necessary for the removal of all members. This method is not affordable due to computational cost and convergence problems. To estimate the critical members, the "frequency criterion" is very useful [13].

After removing a member at the design load level, the structural stiffness and, consequently the frequency of the first vibration mode is reduced. The frequency reduction factor or F.R.F is defined for the removal of each member as "the reduction percentage in the frequency of the first vibration mode of the damaged structure concerning the intact structure". Based on the "frequency criterion", members with F.R.F higher than 20% are considered potentially critical members. After estimating the critical members based on the above method, nonlinear dynamic alternate load path analysis is conducted on the damaged structure due to the sudden loss of a potentially critical member.

To perform frequency analysis on the damaged structure in ABAQUS software, three steps are employed: in the two first steps, the pre-stress and DL+SSL are applied to the structures. In the third step, member removal is carried out using the "model change" technique in ABAQUS software. Steps 1 to 3 are "Static General" type. In the fourth step, a frequency analysis is carried out to obtain vibration modes and natural frequencies of the damaged structure. These results are also used in the dynamic analyses.

The dynamic alternate path analysis is carried out in 4 steps: steps 1 and 2 are similar to frequency analysis. In the third step, the member loss takes place in 0.01s, complying with the GSA code-specified time limit that must be less than $0.1T_1$, where T_1 is the main period of the structure [14]. In the fourth step, a nonlinear dynamic analysis is performed on the damaged structure. Rayleigh damping coefficients α and β are calculated using the results of frequency analysis as follows:

$$\alpha = \frac{2\omega_i\omega_j(\xi_i\omega_j - \xi_j\omega_i)}{{\omega_j}^2 - {\omega_i}^2} \quad , \quad \beta = \frac{2(\xi_j\omega_j - \xi_i\omega_i)}{{\omega_j}^2 - {\omega_i}^2} \qquad (1)$$

where ω_i and ω_j are the frequencies of the first mode and the mode with a cumulative mass participation factor of 95%, respectively. Also, ξ_i and ξ_j are damping ratios considered as 1% and 1.5%, respectively [15]. By comparing the dynamic displacement of the damaged structure with the static displacement of the intact structure at the design load level, as well as the propagation of collapse in the damaged structure, the availability of "alternate load paths" is evaluated. If, after the dynamic removal of a member, there is no alternate load path, the member will called a "definite critical member".

4.2 Validation of finite element modeling

Validation of the dynamic alternate path analysis and sudden loss of a cable member was carried out considering two 3×3×0.7m tensegrity grids with regular arrangements of modules. This model was loaded up to 5kN in node 25. In this load level, a lower cable was removed deliberately from the model.

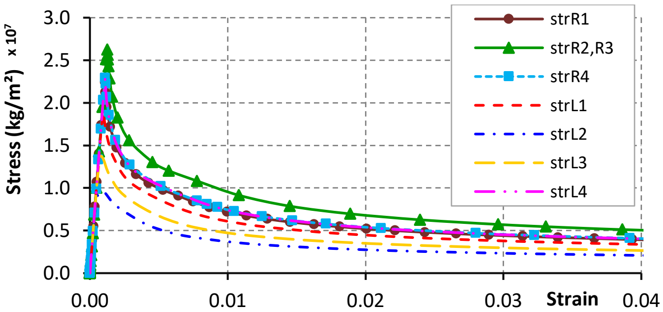
According to Figure 5, the results of the numerical model have an acceptable agreement with the experimental results.

***(a)** Configuration* ***(b)** Sudden loss of cable member no. 51* ***(c)** Verification of dynamic analysis*

Figure 5: Results of finite element modeling verification [9]

4.3 Behavior of members

Figure 6 shows the compressive stress-strain behaviors of the struts, given in Table 3. The parameters **λ**, $\boldsymbol{\sigma_B}$, and **E** are slenderness ratio, buckling stress, and module of elasticity in compression, respectively. It can be seen that after reaching to buckling limit, load load-carrying capacity of a strut is severely decreased and it presents a brittle behavior. To improve this behavior to a ductile one, critical struts were replaced with a BCM ([11] and [16]) (see Figure 7-a). Ductile behaviors of BCMs corresponding to the used struts of the hybrid cable dome have been shown in Figure 7-b.



Strut	λ	σ_B (kg/m²)	E (kg/m²)
StrR1	84	2.241E+07	2.092×10^{10}
StrR2,R3	69	2.624E+07	2.129×10^{10}
StrR4	82	2.295E+07	2.117×10^{10}
StrL4	82	1.895E+07	2.0944×10^{10}
StrL3	116	9.566E+06	2.0557×10^{10}
StrL2	142	1.374E+07	1.951×10^{10}
StrL1	95	2.292E+07	2.082×10^{10}

Figure 6: Compressive stress-strain behavior of struts for hybrid cable dome

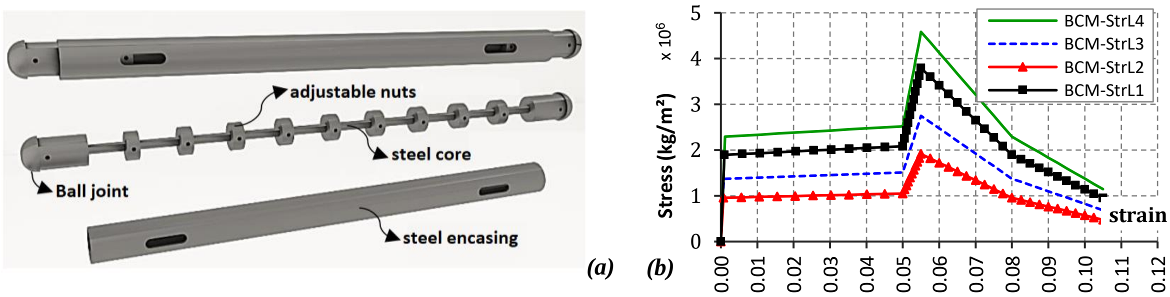


Figure 7: a) Schematic details of BCM [16], and b) behaviors of BCMs correspond to struts

5. Numerical results

5.1 Identification of potentially critical members

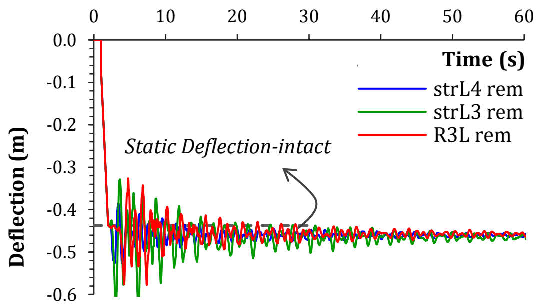
Frequency analyses showed that after the removal of most of the members of the tensegrity ring, the reduction in the frequency of the first vibration mode of the damaged structures (F.R.F) is lower than 1% compared to the intact structure. Results of the frequency analyses for damaged hybrid cable domes due to the sudden loss of members in the central part are shown in Table 4. The removal of seven members leads to F.R.F. higher than 20%. These members are detected as potentially critical members based on the frequency criterion.

Table 4: Results of frequency analyses of damaged hybrid cable dome after removing members

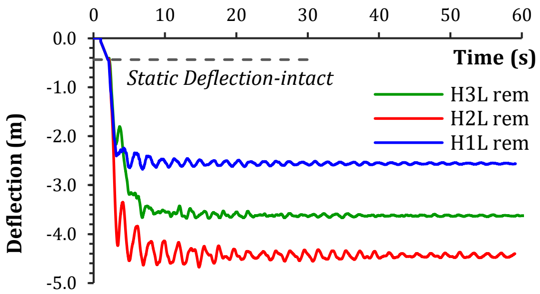
Removed member	Mode i=1 (rad/s)	F.R.F (%)	Mode j No.	Mode j (rad/s)	Rayleigh coefficients α	Rayleigh coefficients β	Removed member	Mode i=1 (rad/s)	F.R.F (%)	Mode j No.	Mode j (rad/s)	Rayleigh coefficients α	Rayleigh coefficients β
Intact	5.189	----					**H3L**	3.457	-33.4%	339	243.2	0.06767	0.000122
D4L	5.071	-2.3%	327	235.5	0.09820	0.000126	**H2L**	3.157	-39.2%	330	235.8	0.06188	0.000126
D3L	4.957	-4.5%	327	235.7	0.09606	0.000126	**H1L**	3.271	-37.0%	338	235.8	0.06407	0.000126
D2L	5.087	-2.0%	327	235.7	0.09849	0.000125	**strL4**	3.543	-31.7%	329	241.6	0.06932	0.000123
D1L	5.188	0.0%	327	235.7	0.10038	0.000125	**strL3**	3.875	-25.3%	327	235.7	0.07560	0.000126
R4L	5.076	-2.2%	327	235.7	0.09829	0.000125	**strL2**	5.182	-0.1%	328	235.7	0.10027	0.000125
R3L	3.629	-30.1%	326	235.7	0.07092	0.000126	**strL1**	3.963	-23.6%	327	235.7	0.07728	0.000126
R2L	5.177	-0.2%	327	235.7	0.10018	0.000125	**Top1**	5.014	-3.4%	329	238.8	0.09717	0.000124
R1L	5.179	-0.2%	327	235.7	0.10022	0.000125	**Top2**	5.014	-3.4%	328	235.4	0.09712	0.000126
							strR3	5.014	-3.4%	328	235.4	0.09712	0.000126

5.2 Dynamic alternate path analyses

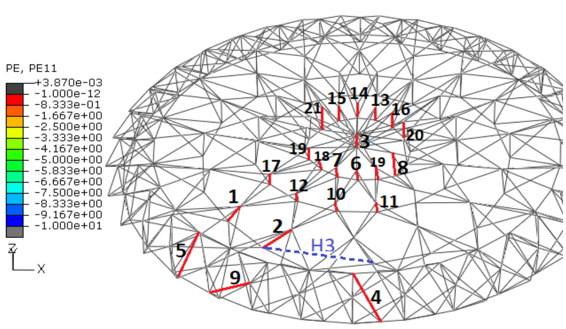
Figure 8, shows the dynamic responses of the hybrid cable dome due to the sudden loss of critical members detected by frequency criterion. Also, the static deflection of intact structures has been shown in the figures. In the hybrid cable dome, after the sudden loss of the member set 1 (strL4, strL3, and R3L), the deflection of the structure increases a little, and the structure shows a damped oscillatory behavior. No buckling has occurred in the struts adjacent to the removed member so that the structure can develop alternate load paths in the event of member set 1 loss. Member set 2 consists of hoop cables whose sudden loss triggers the progressive collapse of the structure (Figure 8-b). The buckled struts in the adjacent hoops during the progressive collapse are illustrated in Figures 8-c and d**.** Therefore, it is proven that there are no alternate load paths for the damaged hybrid cable dome due to the sudden loss of each of the lower hoop cables.



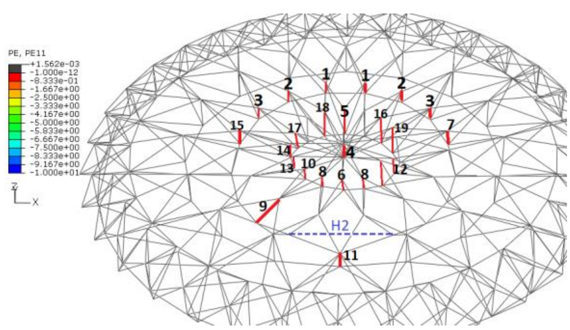
***(a)** Responses after removal of member set 1*



***(b)** Responses after removal of member set 2*



***(c)** Sequence of buckling in struts after removal of H3L*



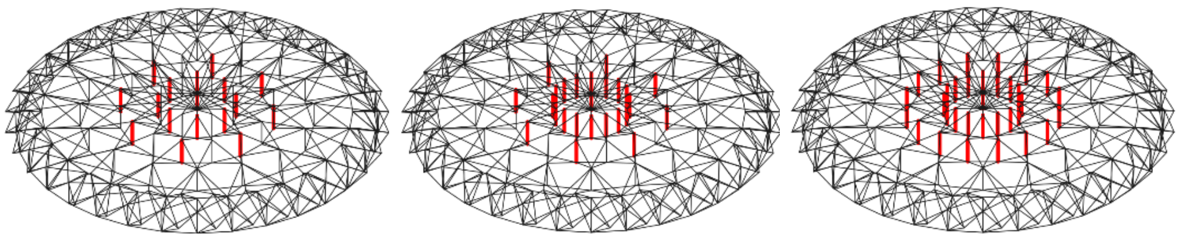
***(d)** Sequence of buckling in struts after removal of H2L*

Figure 8: **a** and **b)** Time-deflection response of hybrid cable dome due to sudden loss of estimated critical members, and **c** and **d**) sequence of buckling in struts due to sudden loss of hoop cables

5.3 Progressive collapse-resistant design

5.3.1 Replacement critical struts with BCM

After the removal of hoop cables, many struts of the cable dome part of the hybrid structure buckle. To reduce the severity of damages, three arrangements of BCMs are employed, as shown in Figure 9, instead of these critical struts to prevent progressive collapse. Idealized characteristic stress-strain behaviors for these BCMs have been previously shown in Figure 7-b. In this Figure, the yield limit of point **A** is considered equal to the buckling load of the strut. After the compressive yielding of BCM, there is a zone with 10% hardening up to point **B** with a controllable strain in the characteristic behavior diagram. The time-history deflection responses of the damaged hybrid cable domes equipped with 3 sets of BCMs after the removal of hoop cables are shown in Figure 10. The highest improvement is related to retrofitted structure by BCMs Set 3 in which dynamic deflection of the damaged structure is decreased by more than 68%. However, it is still far from the static response of the intact structure. Therefore, suitable "alternate load paths" are not provided, but the severity of damages is significantly reduced.



a) *Set 1: strL1+1/2(strL2)+1/2(strL3)* ***b)*** *Set 2: strL1+ strL2+1/2(strL3)* ***c)*** *Set 3: strL1+ strL2+strL3*

Figure 9: Arrangements of BCMs to prevent progressive collapse due to removal of critical members

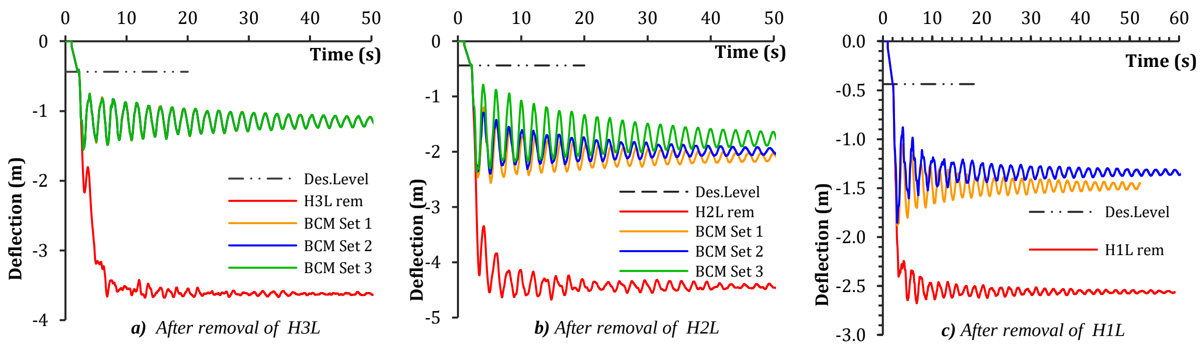
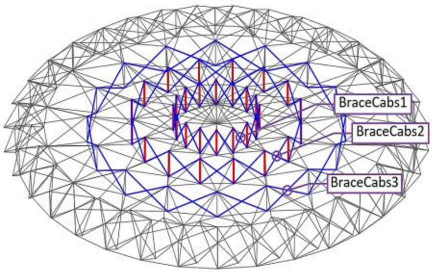


Figure 10: Dynamic responses of hybrid dome equipped by BCMs after the removal of hoop cables

5.3.2 Adding bracing cables net in hoops

In this method, bracing cables are used between the struts of each hoop in the dome section, as shown in Figure 11 to mitigate the progressive collapse in the event of hoop cable loss. Struts of strL3 and strL2 need to be strengthened due to severe stress concentration after the removal of HL cables. The cross sections of bracing cables are selected so that they do not fail after removing the critical hoop cables. The pre-stress of these cables is considered 10% of the cable rupture limit to prevent their slackening at the design load level. Figure 12 shows the time-history deflection of the retrofitted hybrid cable dome in the event of hoop cable loss in which, responses have been decreased in the range of 67% to 84% in comparison with the original hybrid dome. It can be found that the “alternate load paths” have been acceptably provided for the hybrid cable dome.



Member	Previous Section	New Section
BraceCabs3	------	6×C0.6
BraceCabs2	------	4×C0.6
BraceCabs1	------	4×C0.6
strL3	139.7 × 5.6	193.7 × 5.4
strL2	114.3 × 4.5	139.7 × 6.3

Figure 11: Bracing cables and the strengthened struts to prevent the progressive collapse development

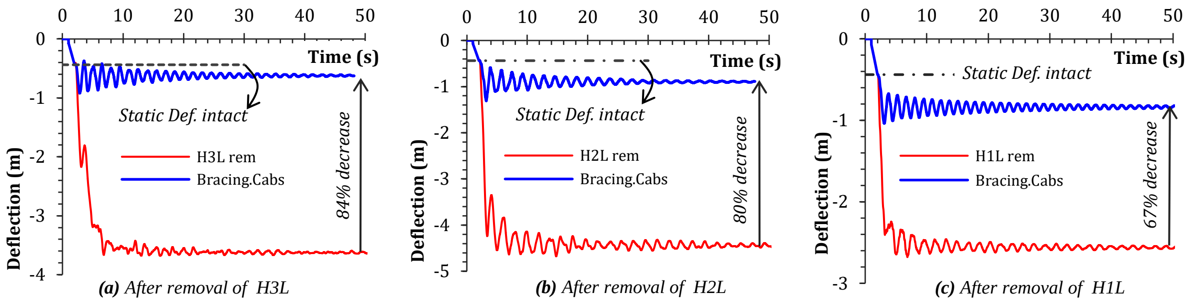


Figure 12: Dynamic response of hybrid cable dome retrofitted with bracing cables after the sudden loss of HL cables

5.3.3 Adding bottom cables net

To prevent displacement of lower nodes of struts in the cable dome part of the damaged structure towards the ring, a new net of cables with an innovative arrangement is added to the lower region of the hybrid cable dome as shown in Figure 13. Three coplanar cables that are the angle bisectors of a triangle in the plan of the structure, connect two ends of each HL cable to the inner hoop. These cables will only act as a fuse after the sudden removal of the main structural members. For this reason, the amount of their pre-stresses is set to be zero. However, some tensile stresses are generated in these cables after applying the design loads, and they are no longer in a slacked state. Figure 14 shows the dynamic responses of the retrofitted hybrid cable dome after the removal of hoop cables. In this method, the dynamic response of the damaged retrofitted dome has been decreased by almost 92% in comparison with the original dome.

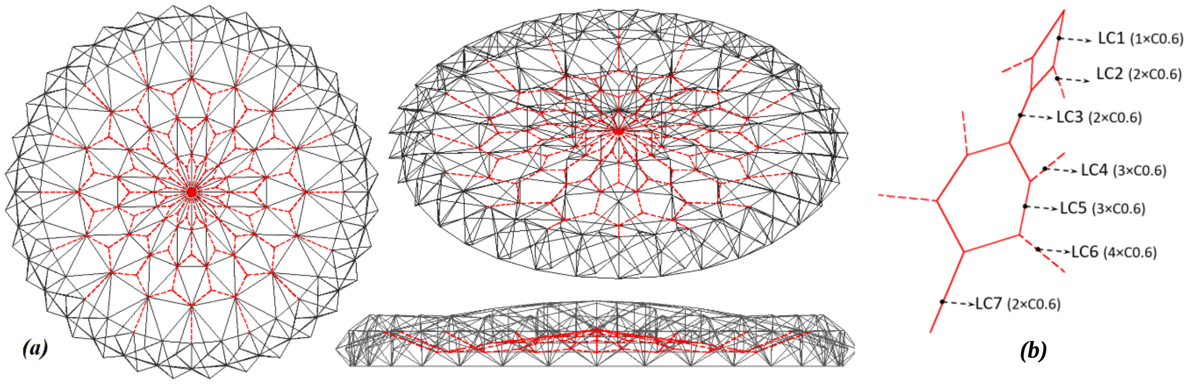


Figure 13: a) Hybrid cable dome with new bottom cables net, and b) Section of bottom cables

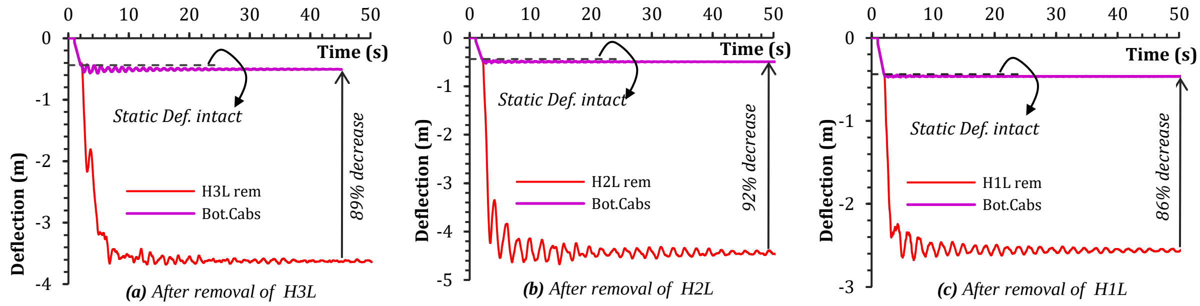


Figure 14: Dynamic responses of hybrid dome retrofitted with bottom cables net after removal of HL cables

The failed members due to the removal of the H3L cable have been shown in Figures 15-a and b. In Figure 15-c, the tensile force of the removed cable can be transferred through three paths (P1 to P3) toward the inner hoop. Two hoop cables, H2-1 and H2-2, in the inner hoop are located in the force redistribution path. Axial stress histories of these two cables are shown in Figure 15-d. At the time of 2.01s and after the sudden loss of the H3L cable, the stress in these two cables has increased at once, which implies the transfer of loads through the bottom cable net towards the inner hoop. Therefore, the existence of “alternate load paths” is well proved in the event of a critical member loss.

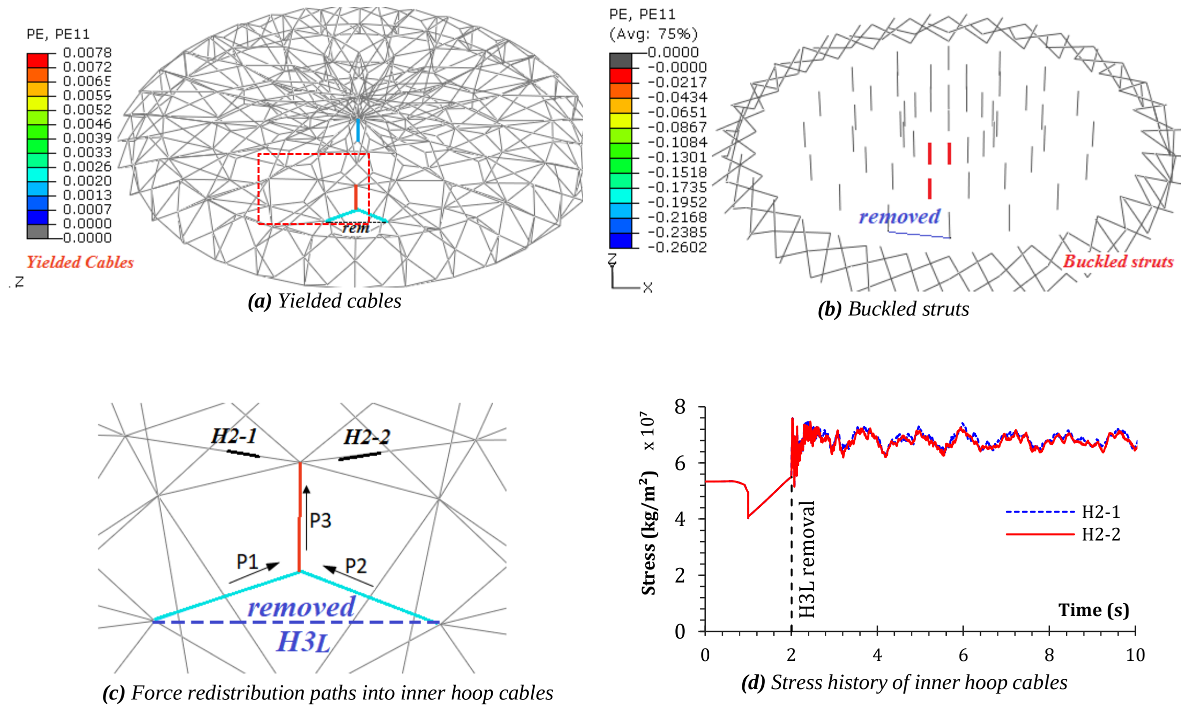


Figure 15: Effects of removing of H3L cable on the hybrid dome with bottom cables net

6. Conclusion

In this paper, the progressive collapse behavior of a hybrid cable dome was evaluated due to the sudden loss of members. The studied dome is a combination of the central part of a traditional cable dome and a modular tensegrity ring around it. Loading and designing of the hybrid cable dome were performed considering pre-stress forces obtained using the modified force density method, dead, snow, wind, and seismic load patterns. In the first phase, using frequency analyses on the damaged hybrid domes due to the removal of all members and based on the reduction of frequency of the first vibration mode, potentially critical members were estimated. Then nonlinear dynamic alternate load path analyses were performed for the sudden loss of estimated members, and definite critical members whose removal led to progressive collapse were detected. After assessing the behavior of the damaged structures due to the sudden loss of these members, three methods were employed to possibly provide alternate load paths to resist the removal of the specific elements and prevent progressive collapse. These methods include using BCMs in critical struts; adding bracing cables between struts of any hoops, and adding a new bottom cable net between the hoop cables. The main conclusions obtained from this study are as follows:

1. In the tensegrity ring section of hybrid cable domes, the removal of members does not lead to other failures in the adjacent members. Due to the high degree of indeterminacy in this section of the hybrid structure, there are always alternate paths to redistribute loads after the sudden loss of any member.
2. The sudden loss of hoop cables in the lower layer of the central cable dome section leads to the occurrence of progressive collapse in the structure and there is no alternate path for the sudden loss of these members.
3. Employing an applicable arrangement of BCMs instead of critical struts decreases the severity of collapse to 68%. However, the deflection of the damaged structure is still far from the static deflection of the intact structure, and the "alternate load paths" are not provided.
4. Using frequency criterion in estimating potentially critical members can decrease the computational cost. For the studied structure, dynamic analyses are carried out for the removal of seven members instead of 31 members.
5. Two methods, including the use of bracing cables and a net of bottom cables, can be categorized as "High Effect" retrofitting methods which reduce the response of damaged hybrid and traditional cable domes up to 84% and 92%, respectively. These methods, and especially the second one in which a novel bottom cable net is added to the cable dome section, prevent the occurrence of progressive collapse due to the sudden loss of critical members and provide a reliable alternate path.

References

[1] S. S. El-lishani, Cable domes and their stability, University of Surrey, 2004.

[2] T. Saka and Y. Taniguchi, "Damage to spatial structures by the 1995 Hyogoken-Nanbu earthquake in Japan," *International Journal of Space Structures*, vol. 12, no. 3–4, pp. 125–133, 1997.

[3] X. Yuan, L. Chen, and S. Dong, "Prestress design of cable domes with new forms," *International Journal of Solids and Structures*, vol. 44, no. 9, pp. 2773–2782, 2007.

[4] H. C. Tran, H. S. Park, and J. Lee, "A unique feasible mode of pre-stress design for cable domes," *Finite Elements in Analysis and Design*, vol. 59, pp. 44–54, Oct. 2012.

[5] J. Lu, X. Dong, X. Zhao, X. Wu, and G. Shu, "Form-finding analysis for a new type of cable–strut tensile structures generated by semi-regular tensegrity," *Advances in Structural Engineering*, vol. 20, no. 5, pp. 772–783, 2017.

[6] 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, no. 7, pp. 1259–1275, 2020.

[7] K. Abedi and B. Shekastehband, "Static Stability Behaviour of Single Curvature Tensegrity Structures," I*n Proceedings of IASS Annual Symposia, Venice, Italy,* 2007.

[8] B. Shekastehband, K. Abedi, and N. Dianat, "Experimental and numerical studies on the progressive collapse behavior of tensegrity systems," *International Journal of Space Structures*, vol. 29, no. 1, pp. 9–24, 2014.

[9] B. Shekastehband, K. Abedi, N. Dianat, and M. R. Chenaghlou, "Experimental and numerical studies on the collapse behavior of tensegrity systems considering cable rupture and strut collapse with snap-through," *International Journal of Non-Linear Mechanics*., vol. 47, no. 7, pp. 751–768, 2012.

[10] B. Shekastehband, "The influences of force-limiting devices and high-stiffness cables on the behavior of tensegrity structures," *Archive of Applied Mechanics*, vol. 88, no. 12, pp. 2293–2316, 2018.

[11] R. Asghari, K. Abedi, M. Chenaghlou, and B. Shekastehband, "Retrofitting of hybrid cable domes against strut buckling using di-pyramid (DP) module and force-limiting devices (FLD)," *Thin-Walled Structures*, vol. 180, p. 109737, 2022.

[12] Structural Applications of Steel Cables for Buildings, ASCE/SEI 19-16. American Society of Civil Engineers, 2016.

[13] R. Asghari, K. Abedi, M. R. Chenaghlou, and B. Shekastehband, "Retrofit strategies for mitigating progressive collapse of hybrid and traditional cable domes," *Journal of Constructional Steel Research*, vol. 204, p. 107807, 2023.

[14] U. Gsa, *Progressive collapse analysis and design guidelines for new federal office buildings and major modernization projects*, Washington, DC, 2003.

[15] I. Tatemichi, T. Hatato, Y. Anma, and S. Fujiwara, "Vibration tests on a full-size suspen-dome structure," *International Journal of Space Structures*, vol. 12, no. 3–4, pp. 217–224, 1997.

[16] M. R. Chenaghlou, M. Kheirollahi, K. Abedi, A. Akbari, and A. Fathpour, "Inherent Adaptive Structures Using Nature-Inspired Compound Elements," *Frontiers in Built Environment*, p. 186, 2020.