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Investigation into the progressive collapse of double-layer space structures with double-layer vertical walls using the alternative path method

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Abstract

Double-layer space structures with double-layer vertical walls are predominantly utilized in large-scale industrial constructions. The major concern among designers has centered around progressive collapse, an exceedingly undesirable form of structural failure. This study aims to investigate the progressive collapse of double-layer space structures with double-layer vertical walls using the alternative path method. The primary goal is to ensure the structure's ability to withstand applied loads even if crucial components are lost. The method employed to counter progressive collapse is the alternate path method. In the present study, the studied structures are designed to absorb localized damage and establish a new load transfer route. The alternate path method was conducted using nonlinear static and dynamic analyses, in the ABAQUS software, considering structures exposed to both symmetrical and unsymmetrical snow loads. Identification of critical elements whose sudden removal led to progressive collapse enabled the proposal of reinforcement strategies, establishing a viable alternative route to mitigate progressive collapse. The results of this study demonstrate the efficacy of the alternate path method in the progressive collapse-resistant design of double-layer space structures with double-layer vertical walls.

Keywords: Progressive collapse, Alternate path method, Double-layered space frame structures, Double-layer walls and ceilings

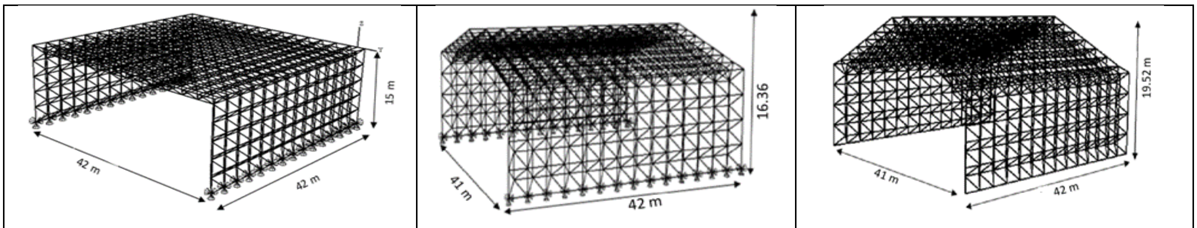
1. Introduction

Today, the use of flat space structures has been expanded due to their optimal shape in creating large openings for the construction of all kinds of industrial warehouses, etc. Progressive collapse means the spread of an initial local failure from one member to another, which eventually leads to the collapse of the entire structure or a large part of it [1]. This is considered an example of catastrophic failures in space structures, but there is not enough research in this field. Examining different methods of progressive collapse shows that the alternate path method is a suitable method to deal with progressive failure [2]. The alternate path method allows local failure of the structure but provides load transfer paths in such a way that local failure in the structure does not cause progressive collapse.

In the present paper, three double-layer space structures with double-layer vertical walls were designed based on the conventional regulations in space structures, and then stability analyses were performed on the intact structure under symmetrical and unsymmetrical snow loads. The collapse behavior of the structures and their critical members were determined. The used approach in selecting critical members is based on member buckling in the limit load level of the structures and members with the highest stress in the design load level. Then, nonlinear static alternative path analyses were performed on the damaged structure, and the safety coefficients of the structure were determined due to the removal of critical members. Since the static analysis of the alternative path cannot take into account the dynamic effect of removing the member, nonlinear dynamic alternative path analyses were also carried out, and the safety coefficients in the damaged structures were determined. In the end, a buckling control member (BCM) as a force-limiting device, has been used to prevent progressive collapse.

2. The specifications of the studied structures

The structures examined in this study are double-layer space structures with double-layer vertical walls, with the specifications as shown in Figure 1. The combination of dead, symmetric, and asymmetric snow, wind, and earthquake loads have been considered in the design of these structures. Due to the complexity of behavior in this type of structure, nonlinear time history analysis for earthquake load has been used.



(a) (b) (c)

Figure 1: (a) The structure with a flat roof, (b) the structure with a sloping roof of 0.1 span length, and (c) the structure with a sloping roof of 0.2 span length

2.1. Compressive behavior of members

The strain-stress behavior of the members of the structures is shown in Figure 2. In most static collapse analysis methods used in the appraisal of double-layer space structures, considering the member buckling, primarily the axial stress-axial strain response of the compression members is determined. The axial stress-axial strain response of a compression member is then used to represent the member's behavior in the nonlinear collapse analysis of the structure. Therefore, the representation of the behavior of the compression members has a central role in the collapse analysis of double-layer space structures. It would be necessary to establish the post-critical characteristics of compression members to represent their axial stress-axial strain relationships to be used for the analysis. Therefore, a nonlinear (elastoplastic, large displacement) static analysis was carried out. In the present study, only the initial curvature associated with the bowing of the member was considered as an initial imperfection. The bowing of a compression member was taken to be symmetric with a maximum amplitude ε=0.001L at the mid-length of the member. Also, the compression members were considered to act as pin-ended members under pure axial force (without any eccentricity), as shown in Figure 3 [3]. The compressive behavior of members is depicted in Figure 4.

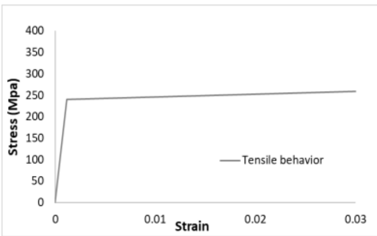


Figure 2: The strain-stress behavior of the members of the structures

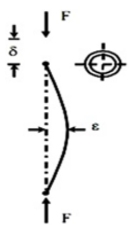


Figure 3: Compression member with small curvature as initial imperfection

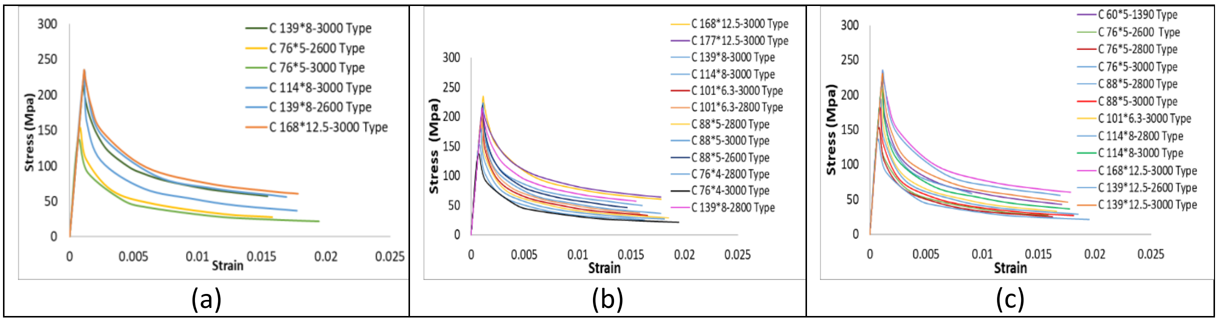


Figure 4: The Compressive behavior of members: (a) with a flat roof, (b) with a sloping roof of 0.1 span length, and (c) with a sloping roof of 0.2 span length

2.2. Results of stability analyses

For the instability analysis of these structures, the material and geometric nonlinear analysis should be carried out. In the present study, to determine the equilibrium paths through limit points into the post-critical range, the ‘Arc-Length-Type Method’ was used which is the most efficient method for this purpose and it was now predominantly used in structural nonlinear analysis programs. Figure 5 shows the LPF-displacement responses of the studied structures under symmetrical and unsymmetrical snow loads. The collapse loads of studied structures are expressed as LPF or load proportionality factor, which is the ratio of the load at every step of static collapse analysis to the symmetrical and unsymmetrical snow design load. For the displacement, the crown node of the structures was selected to extract LPF-displacement responses. For the structure with a flat roof, the LPF is equal to 1.6 because this structure is designed only under the effect of a symmetrical snow load.

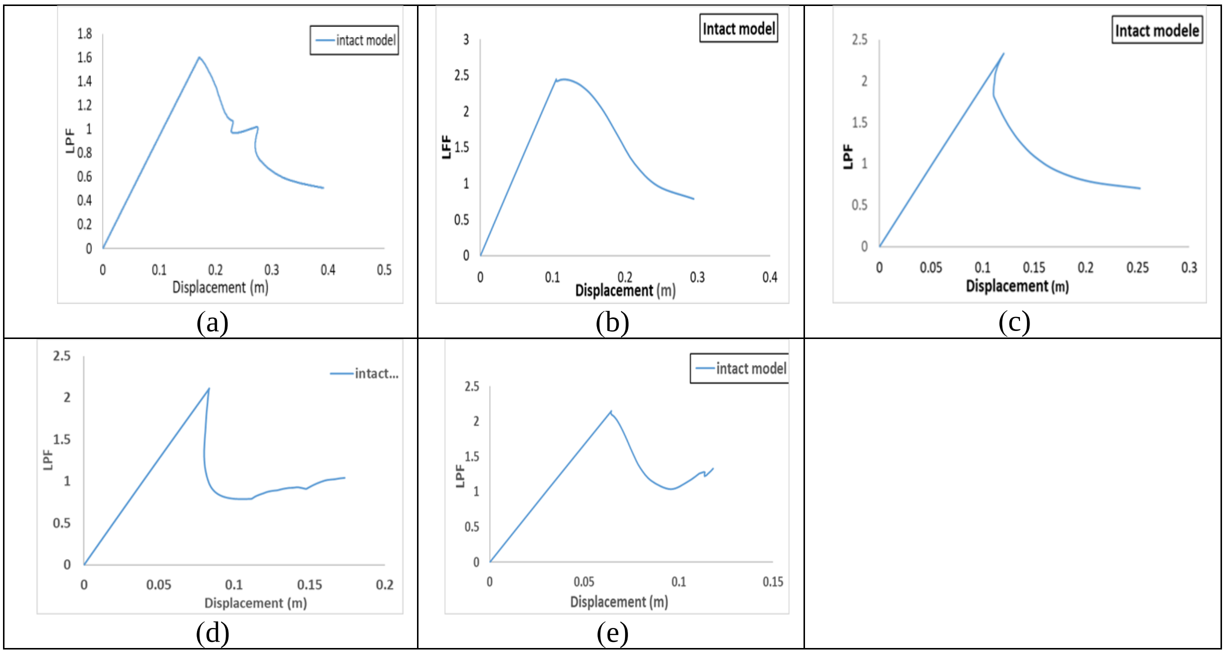


Figure 5: The LPF-displacement responses of the studied structures, (a) flat roof under symmetrical snow load, (b) sloping roof of 0.1 span length under symmetrical snow load, (c) sloping roof of 0.1 span length under unsymmetrical snow load, (d) sloping roof of 0.2 span length under symmetrical snow load, and (e) sloping roof of 0.2 span length under unsymmetrical snow load.

2.3. Determining critical members

To identify the critical members, the results of the stability analyses of the intact structures have been used. The members that buckle at the ultimate load level are selected as the first category of critical members. Also, the members with the highest compressive load in the design load level are selected as critical members of the second category. As an example, the critical members in the structure with a flat roof under a symmetrical snow load are shown in Figure 6.

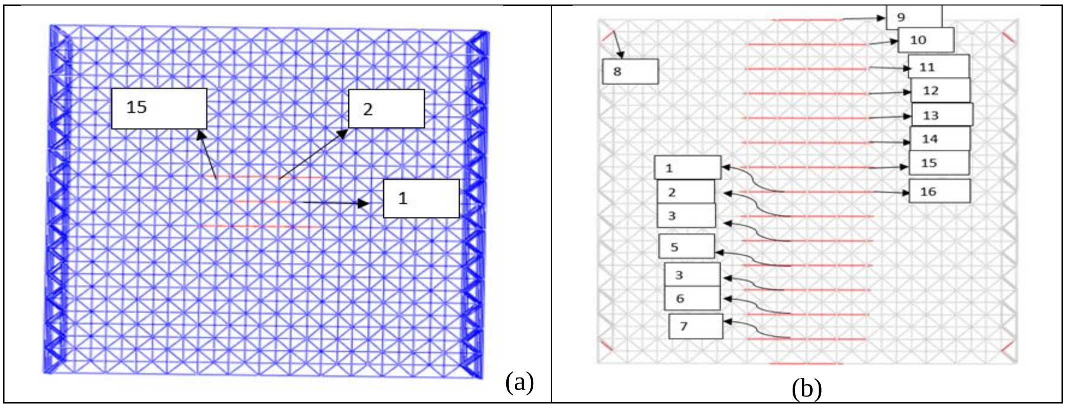


Figure 2: Position of critical members in the structure with a flat roof under symmetrical snow load, (a) first category, and (b) second category.

2.4. The results of nonlinear static and dynamic alternative path analyses

In the alternative path method, the stability of the structure, with the removal of a critical member at the level of the design load, is evaluated for the ability to redistribute the forces caused by the removal of the critical member and also for the occurrence of the progressive failure [5]. Alternative path methods can be carried out using geometric and material nonlinear static and dynamic analyses, considering the gradual or sudden removal of critical members, respectively.

Due to the symmetry in the structure, the critical members have been removed both singly and symmetrically. As given in Table 1, all of the obtained safety factors are greater than 1, which demonstrates the availability of the load transfer path due to the gradual removal of the critical members. Also through nonlinear static analysis of the alternate path method, it can be concluded that the possibility of the occurrence of the progressive collapse for the models with the safety factor value of near 1 is high due to the dynamic effects of member removal.

Table 1: The safety factor values obtained through the nonlinear path method for all models under different loading conditions

	Safety factors of nonlinear static alternate path analyses									
	Structure with a flat roof		Structure with a sloping roof of 0.1 span length				Structure with a sloping roof of 0.2 span length			
	Symmetrical snow load		Symmetrical snow load		Unsymmetrical snow load		Symmetrical snow load		Unsymmetrical snow load	
	R1[1]	R2[2]	R1	R2	R1	R2	R1	R2	R1	R2
Intact structure	1.60	1.60	2.33	2.33	2.45	2.45	2.11	2.11	2.15	2.15
Removal of member 1	1.18	1.22	1.37	1.25	1.37	1.36	1.64	1.39	1.24	1.24
Removal of member 2	1.17	1.02	1.74	1.72	1.99	1.93	1.88	1.68	1.19	1.20
Removal of member 3	1.18	1.16	1.87	1.85	2.06	2.05	1.54	1.25	1.48	1.48
Removal of member 4	1.19	1.23	1.87	1.87	2.02	2.02	1.70	1.52	1.58	1.59
Removal of member 5	1.18	1.21	1.92	1.95	2.10	2.12	1.80	1.70	1.64	1.64
Removal of member 6	1.20	1.26	1.80	1.78	2.03	1.95	1.68	1.35	1.55	1.54
Removal of member 7	1.18	1.24	1.83	1.78	2.00	2.03	2.01	1.87	1.63	1.63

Removal of member 8	1.45	1.43	1.58	1.57	1.72	1.71	2.07	2.07	1.59	1.60
Removal of member 9	1.32	1.22	1.72	1.70	2.09	2.01	1.98	1.88	1.62	1.62
Removal of member 10	1.36	1.39	1.90	1.85	2.10	2.08	1.95	1.89	1.61	1.62
Removal of member 11	1.48	1.43	1.94	1.93	2.25	2.22	2.08	2.04	1.61	1.62
Removal of member 1۲	1.35	1.41	1.90	1.86	2.23	2.19	2.01	1.97	2.01	2.01
Removal of member 13	1.32	1.38	1.89	1.83	2.22	2.17	2.08	2.07	2.14	2.14
Removal of member 14	1.32	1.32	1.88	1.70	2.21	2.09	2.09	2.07	2.05	2.04
Removal of member 15	1.31	1.16	1.87	1.68	2.22	1.93	2.07	2.04	2.05	2.04
Removal of member 16	1.32	1.22					2.10	2.08	2.13	2.13

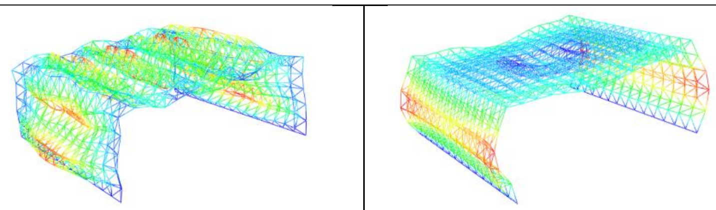
1. single removal of the critical members (R1) 2. Symmetrical removal of the critical members (R2)

Therefore, in the following, nonlinear dynamic analyses are carried out. For this purpose, an eigenvalue frequency analysis is performed to determine the input values of the dynamic analysis. For the determination of the damping matrix, the "Rayleigh damping method" is used. This is achieved by introducing two factors α_m and β_s, which are constants to be determined from two given damping ratios that correspond to two unequal frequencies of vibration. The factor α_m defines the mass proportional damping, and the factor βs expresses the stiffness proportional damping [4]. The damping ratios of the corresponding modes with the mass contribution of 60% and 95% are assumed as $\xi_i = 1.5\%$ and $\xi_j = 2.5\%$. The Rayleigh's damping factors α_m and β_s are determined using the following equations:

$$\alpha_m = 2\omega_i\omega_j(\xi_i\omega_j - \xi_j\omega_i)/({\omega_j}^2 - {\omega_i}^2) \quad (1)$$

$$\beta_s = 2(\xi_j\omega_j - \xi_i\omega_i)/({\omega_j}^2 - {\omega_i}^2) \quad (2)$$

As an example, mode 139 with 97% mass contribution, and mode 22 with 60% mass contribution of the intact structure with a flat roof under symmetrical snow load are shown in Figure 7. These modes have been used to calculate the Rayleigh damping coefficients. The cumulative mass contribution percentage up to mode 300 is given in the diagram of Figure 8.



Mode 139
(a)

Mode 22
(b)

Figure 7: Mode 139 with 97% mass contribution, and mode 22 with 60% mass contribution of the intact structure with a flat roof under symmetrical snow load

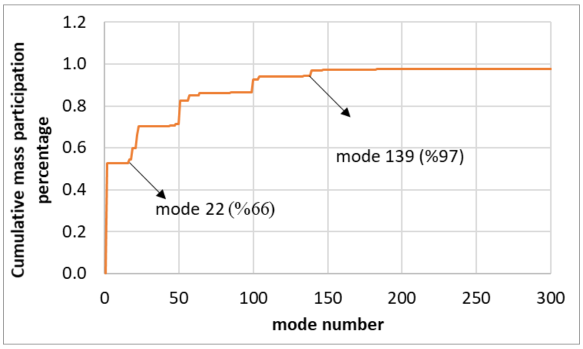


Figure 8: Cumulative mass contribution percentage up to mode 300

The potential of progressive collapse can be assessed after carrying out the nonlinear dynamic analyses. For this purpose, the design load is applied to the structure statically or dynamically at a slow pace. Then, critical members are suddenly removed when the structure is under the design load and implicit dynamic nonlinear analysis is carried out. The removal time should be less than 0.1 of the first natural period of the structure according to the GSA code (GSA, 2003) [6]. In the present study, the removal time has been considered 0.001 sec, as shown in Figure 9.

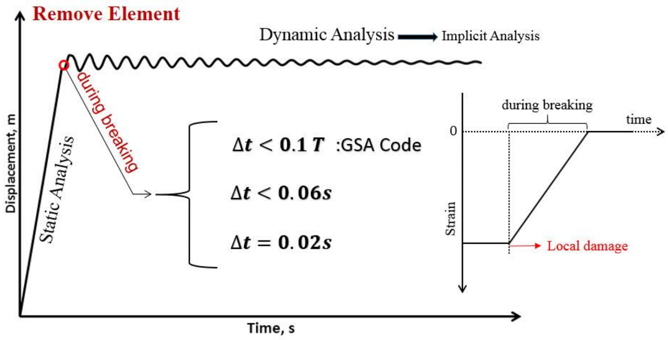


Figure 9: Schematic view of the nonlinear dynamic alternate path method

As an example, Figures 10 & 11 show the displacement-time behavior of the structure with a flat roof under a symmetrical snow load considering the sudden removal of a single critical member and the symmetrical removal of a critical member, respectively. Tables 2 & 3 give the updated safety values obtained from the dynamic nonlinear alternate path analysis for this structure.

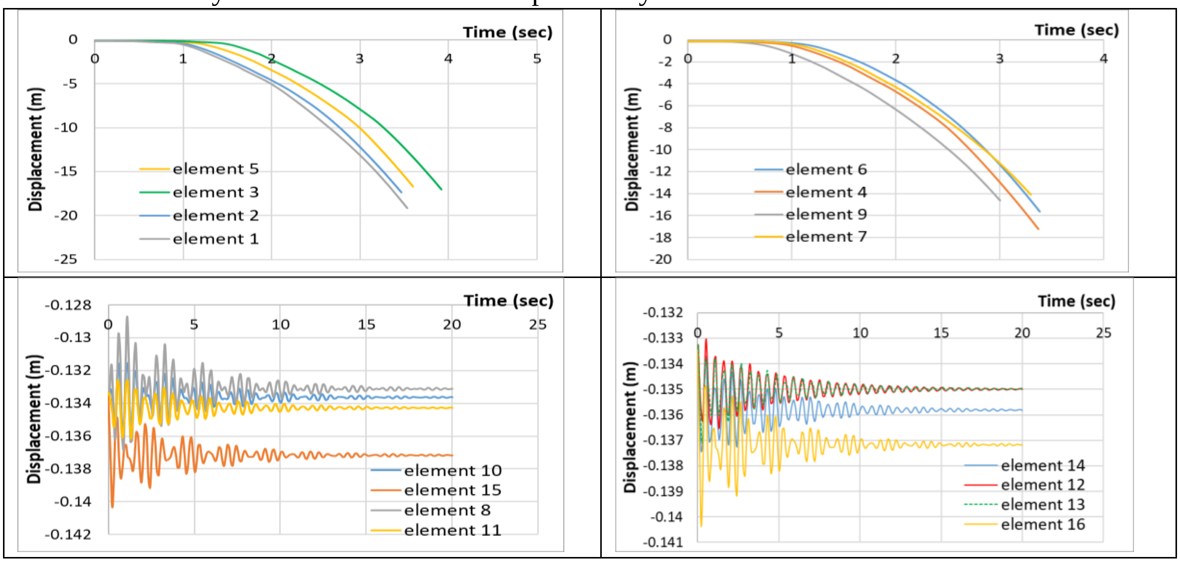


Figure 10: The time-displacement responses of flat roof structure under symmetrical snow load after the sudden removal of a single critical member

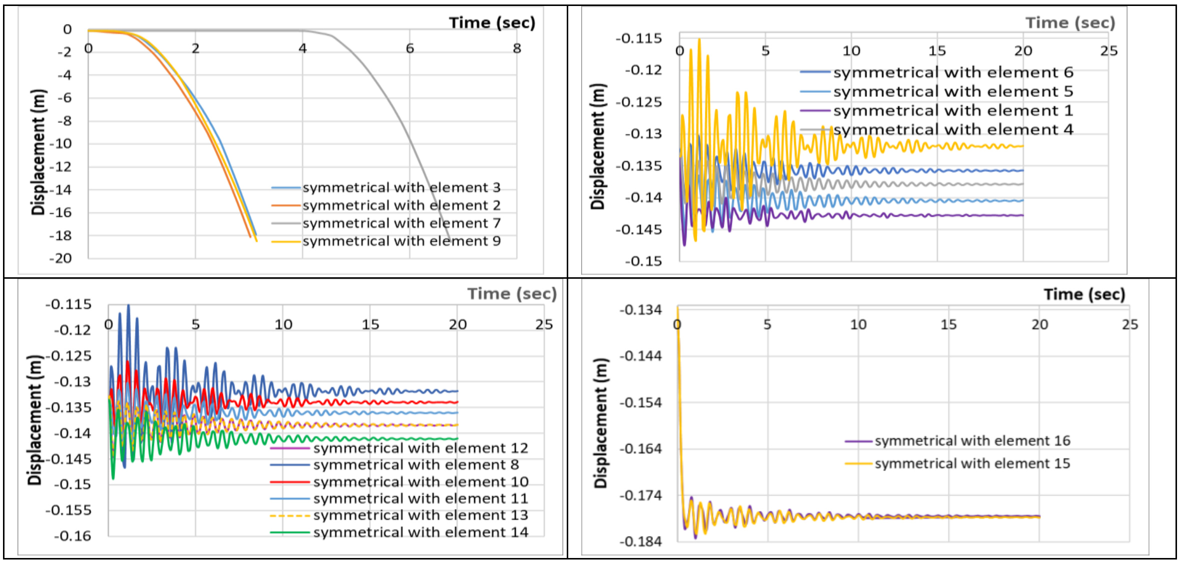


Figure 11: The time-displacement responses of flat roof structure under symmetrical snow load after the sudden symmetrical removal of critical members

Table 2: Updated safety values in a structure with a flat roof under a symmetrical snow load (single removal)

Occurrence of progressive collapse	Safety factor	Critical member number	Occurrence of progressive collapse	Safety factor	Critical member number
Yes	Less than 1	9	No	1.6	intact
No	1.36	10	Yes	Less than 1	1
No	1.48	11	Yes	Less than 1	2
No	1.35	12	Yes	Less than 1	3
No	1.32	13	Yes	Less than 1	4
No	1.32	14	Yes	Less than 1	5
No	1.31	15	Yes	Less than 1	6
No	1.32	16	Yes	Less than 1	7
			No	1.46	8

Table 3: Updated safety values in a structure with a flat roof under a symmetrical snow load (symmetric removal)

Occurrence of progressive collapse	Safety factor	Critical member number	Occurrence of progressive collapse	Safety factor	Critical member number
Yes	Less than 1	9	No	1.6	intact
No	1.36	10	No	1.22	1
No	1.48	11	Yes	Less than 1	2
No	1.35	12	Yes	Less than 1	3
No	1.32	13	No	1.24	4
No	1.32	14	Yes	Less than 1	5
Yes	Less than 1	15	No	1.26	6
Yes	Less than 1	16	No	1.24	7
			No	1.46	8

2.5. Applying Buckling-control member (BCM)

To modify the behavior of double-layer space structures, “Force-Limiting Devices” can be applied to critical compression members. These devices can alter compression members' brittle buckling to elastic-perfect plastic behavior. This action will eventually cause the formation of deformable behavior in the structure, which in turn causes the creation of deformability in the structure and reduces the possibility of progressive collapse in the structure. The force-limiting device used in this study is a type of Buckling-control member (BCM) [7], as shown in Figure 12.

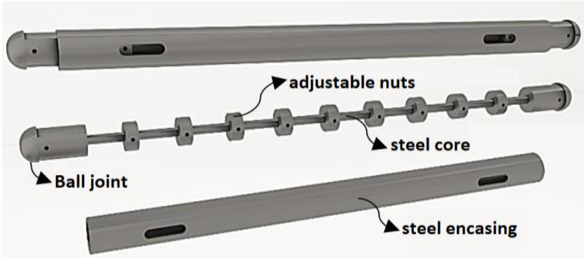


Figure 12: Schematic details of BCM [7]

The strain-stress behavior of the buckling-control member used in this paper is shown in Figure 13. The BCM assignment steps are shown in Figures 14 to 17 for single critical member removal and in Figure 18 for symmetrical critical member removal.

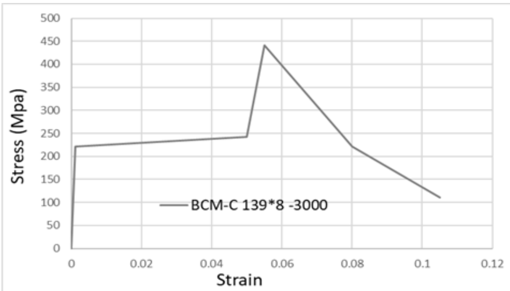


Figure 13: The strain-stress behavior of the buckling-control member used in the models

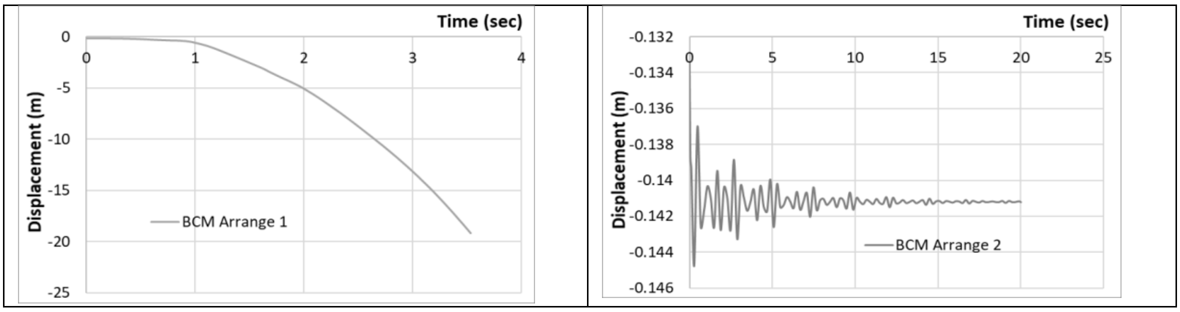


Figure 14: Applying the buckling-control member for removal of critical member 1

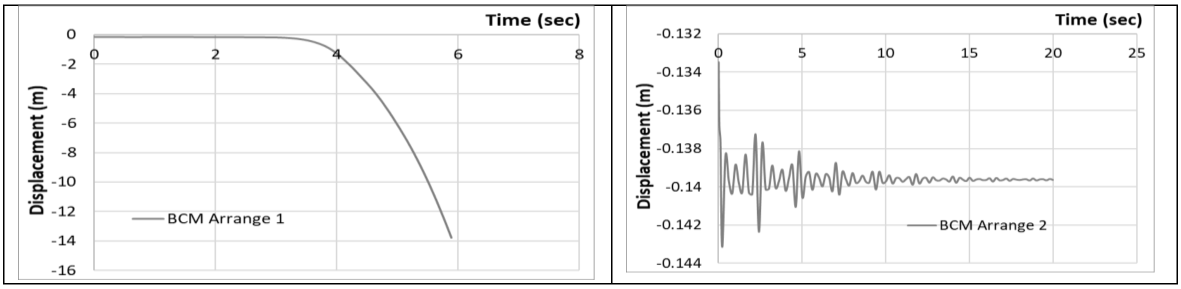


Figure 15: Applying the buckling-control member for removal of critical member 2

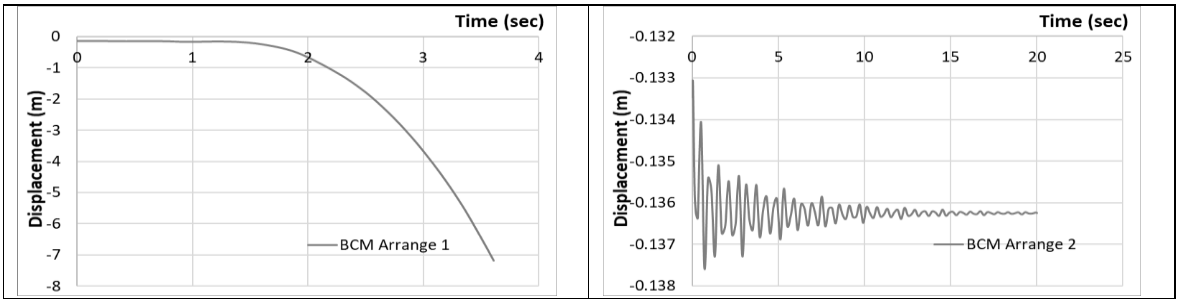


Figure 16: Applying the buckling-control member for removal of critical member 3

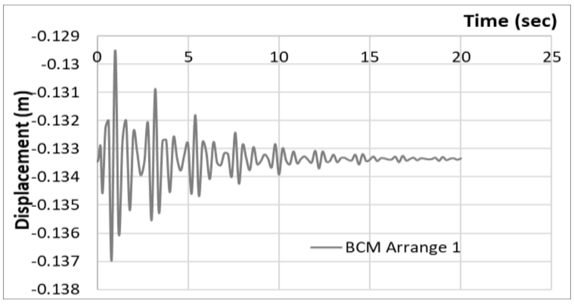


Figure 17: Applying the buckling-control member for removal of critical member 7

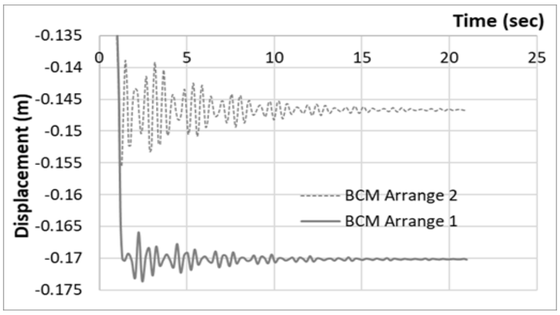


Figure 18: Applying the buckling-control member for removal of critical member 15

As an example, in the structure model with a flat roof under a symmetrical snow load, 1.86% of the members are replaced with buckling-control members, as shown in Figure 19.

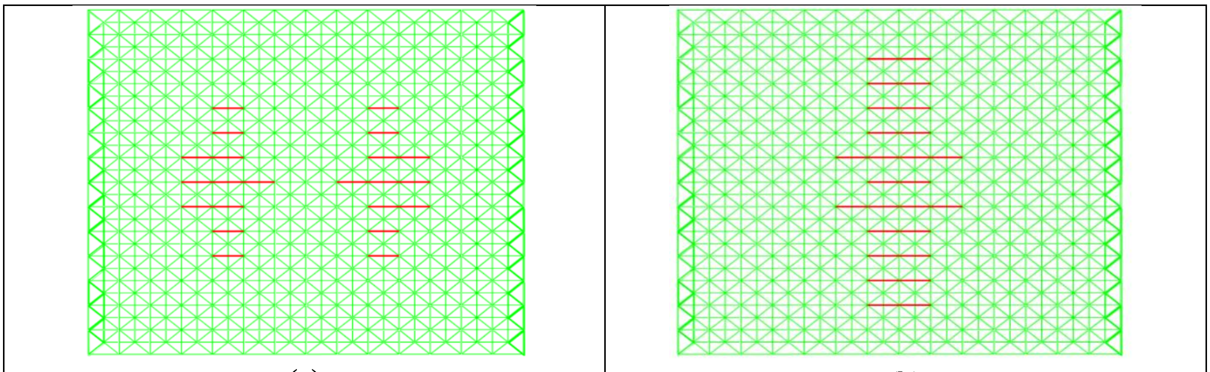

(a) (b)

Figure 19: Buckling-control members used in (a) single critical member removal case, and (b) symmetric critical member removal case

4. Conclusion

In the present study, double-layer space structures with double-layer vertical walls are designed to absorb localized damage and establish a new load transfer route. The alternate path method was conducted using nonlinear static and dynamic analyses, in the ABAQUS software, considering structures exposed to both symmetrical and unsymmetrical snow loads. The results of this study are as follows:

- The alternate path method is a suitable method to deal with progressive collapse in double-layer space structures.
- If the critical members are close to the axis of symmetry, a symmetric critical member removal case can be more critical than a single critical member removal case in the alternate path analyses. The members whose gradual removal in the nonlinear static alternate path method had a lower safety factor are prone to progressive collapse nonlinear dynamic alternate path method.
- The safety factor obtained in the nonlinear static alternate path method, considering the gradual removal of the critical members, was greater than 1 for all models, which demonstrates that the progressive collapse has not occurred. However, in the nonlinear dynamic alternate path method, considering the sudden removal of critical members, for some of the structures, progressive collapse has occurred.
- It was also shown that the progressive collapse in double-layer space structures with double-layer vertical walls can be well controlled using a buckling-control member.

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