buildings

MDPI

Article

Analysis and Evaluation of the Progressive Collapse of Cable Dome Structures Induced by Joint Damage

Lian-Meng Chen [1,*], Kai-Yu Huang [1], Yi-Jie Liu [1], Ze-Bin Li [1], Yi-Hong Zeng [1], Wei Li [1], Yi-Yi Zhou [2] and Shi-Lin Dong [3]

[1] College of Civil Engineering and Architecture, Wenzhou University, Wenzhou 325035, China; kive163202104@163.com (K.-Y.H.); 194611571239@stu.wzu.edu.cn (Y.-J.L.); 21461544038@stu.wzu.edu.cn (Z.-B.L.); 20461542066@stu.wzu.edu.cn (Y.-H.Z.); liweiwoaini521@163.com (W.L.)
[2] College of Civil Engineering and Architecture, Changzhou Institute of Technology, Changzhou 213002, China; zhouyy@czu.cn
[3] Space Structures Research Center, Zhejiang University, Hangzhou 310027, China; wzchenlm@sina.com
* Correspondence: 00151034@wzu.edu.cn; Tel.: +86-13957790090

Abstract: The current literature lacks an effective progressive collapse analysis of a cable dome structure induced by joint damage. In this study, a dynamic analysis was performed using actual construction cases, an ANSYS LS-DYNA analysis platform, and a fully dynamic equivalent load instantaneous removal method. First, the structure's dynamic responses and collapse modes induced by different joints with different types of damage were explored. Subsequently, joint importance coefficients were proposed depending on the structure's displacement before and after joint removal, and the relationships between the joint importance coefficients and the joint properties and collapse modes, respectively, were then identified. Finally, the relationship between the joint damage and the connected component damage was explored. The results revealed that different joints and identical joints with different types induced a variety of dynamic responses. However, the dynamic response induced by the discontinuous joint damage was more apparent than that induced by the continuous joint damage. When a continuous joint model was used, the damage on all joints did not result in the progressive or local progressive collapse of the structure. Thus, all these joints were considered as common joints. However, when a discontinuous joint model was used, the failure of the joints resulted in three distinct collapse modes, namely a progressive collapse, a local progressive collapse, and a nonprogressive collapse, corresponding to the key joints, the important joints, and the common joints, respectively. These three types of joints corresponded to different importance coefficients. When damage occurred in the discontinuous joints separately linked to the key components, the important components, and the common components, the joints resulted in the progressive collapse, local progressive collapse, and nonprogressive collapse, respectively, of the structure.

Keywords: cable dome structure; joint damage; progressive collapse; dynamic response; joint importance coefficient

Citation: Chen, L.-M.; Huang, K.-Y.; Liu, Y.-J.; Li, Z.-B.; Zeng, Y.-H.; Li, W.; Zhou, Y.-Y.; Dong, S.-L. Analysis and Evaluation of the Progressive Collapse of Cable Dome Structures Induced by Joint Damage. *Buildings* **2023**, *13*, 2072. https://doi.org/10.3390/buildings13082072

Academic Editor: Hassan Karampour

Received: 13 July 2023
Revised: 9 August 2023
Accepted: 13 August 2023
Published: 15 August 2023

1. Introduction

Cable dome structures are flexible structure systems consisting of cables and struts as their basic components. They utilise the high strength of cables and adjust their prestress distribution to optimise the stiffness distribution. Cable dome structures offer multiple advantages, such as excellent bearing capacities, high aerial spanning capabilities, and lightweight mechanisms, and have been used in numerous practical applications [1,2]. However, because these structures have low redundancy, emergencies such as blizzard snow overloading, explosive blasts, construction errors, and disturbances from other accidents may easily lead to progressive collapses and failure. These disproportional collapses are caused by local damage, including component damage and joint damage [3,4].

Using the instantaneous removal of elements technique, the element birth and death technique, and other techniques, researchers have analysed the dynamic responses, including the internal force changes and joint displacements, and the structural collapse models introduced by the damaged components of various types of cable dome structures [5–9]. Joints function as interlinking parts of elements. The damage to joints often results in the inability of multiple linked components to function, which may lead to more serious mechanism collapse and failure. Therefore, further analysis of the dynamic responses and collapse modes induced by the joint damage is highly relevant. Liu et al. [10] analysed the collapse mode of the beam-to-column connections after joint damage. They reported that semirigid connection steel frames were more capable of resisting the progressive collapse of structures under unexpected loading than the rigid connection steel frames. Hm et al. [11] used numeral simulations and theoretical analyses to explore the seismic characteristics of single-layer reticulated shell structures with prefabricated joints. After establishing four typical structure failure modes, they discovered that the joint stiffness and joint bearing capacity had a substantial effect on the structural failure models. Zhang et al. [12] undertook a research based on the concept of damage immunity. By examining the spatial reticulated shell structures, they analysed the collapses and failures induced by the local element or joint failures. Their results indicated that these reticulated shell structures had high damage immunity and that the failure of joints in such structures did not result in their progressive collapse. Huang [13] used single-layer three-way spherical reticulated shell structures to conduct a finite element simulation analysis. They reported that the failure of different numbers of highly sensitive joints resulted in a variety of failure modes. They also proposed a joint importance indicator. Zheng [14] used ANSYS LS-DYNA software to investigate the effect of an assembled hollow hub joint on the performance of aluminium alloy single-layer reticulated shells in terms of resisting progressive collapse. They found that when the component and joint failed, respectively, the critical loads of the progressive collapse of the assembled hollow hub joint reticulated shell were 33~61% and 26~55% of a rigid connection reticulated shell respectively. Xie [15] used structural nonlinear bearing capacities to determine the coefficient for the importance of the reticulated shell structure joints. They also investigated the overall processes of collapse induced by local failures. Liu [16] reported that during joint failure, the progressive collapse critical loads of single-layer spherical reticulated shells connected by assembled hollow hub joints were 7–25% lower than those of the reticulated shells connected by welded hollow spherical joints. Gao et al. [17] reported that removing structural nodes from Levy-type stiffened domes resulted in progressive structure collapse. Zhang et al. [18] used a nonlinear dynamic analysis method and proposed a cable element model to equivalently replace all substantial joint models. By using a progressive collapse analysis of joint equivalent modelling of a Geiger cable dome structure model, they reported that the numerical simulation results adequately matched the experimental results. These results confirmed the effectiveness of the joint equivalent modelling method. Sun et al. [19] used an ANSYS instantaneous dynamic analysis method along with the element birth and death technique to simulate the instantaneous failure of the supports with maximum force loading. They reported that the support failures had a substantial effect on the support failure parts and neighbouring frame column internal forces.

In summary, analyses of large-span spatial structure collapses after joint damage have predominantly focused on rigid structures, such as reticulated shells. However, only a few studies have investigated the dynamic responses, collapse analysis, and evaluation of joint importance induced by joint failure for flexible structures, such as cable domes. In this study, an ANSYS LS-DYNA analysis platform and a fully dynamic equivalent load instantaneous removal method were used to identify and analyse the dynamic responses and collapse mechanisms of a cable dome structure induced by different types of joint damage. The joint importance coefficients were also proposed in accordance with the displacement of structures before and after the joint removal to determine the joint importance coefficients and the relationship between the joint importance coefficients and the joint properties and collapse modes were then identified. Finally, the relationship between the joint damage and the connected component damage was determined.

2. Structure Model and Analysis Method

2.1. Case Information

A Geiger cable dome structure in Yi Jin Huo Luo Qi of Inner Mongolia was adopted as a case study. The span and rise of the structure were 71.2 m and 5.5 m, respectively. The structure was composed of 20 units, with a design load of 0.4 kN/m^2. The structure model, plan, and profile are presented in Figure 1, and the cross-sectional area A of each element and the prestress P are illustrated in Table 1. In this structure, the moduli of elasticity of cable and strut were 160 GPa and 206 GPa, respectively.

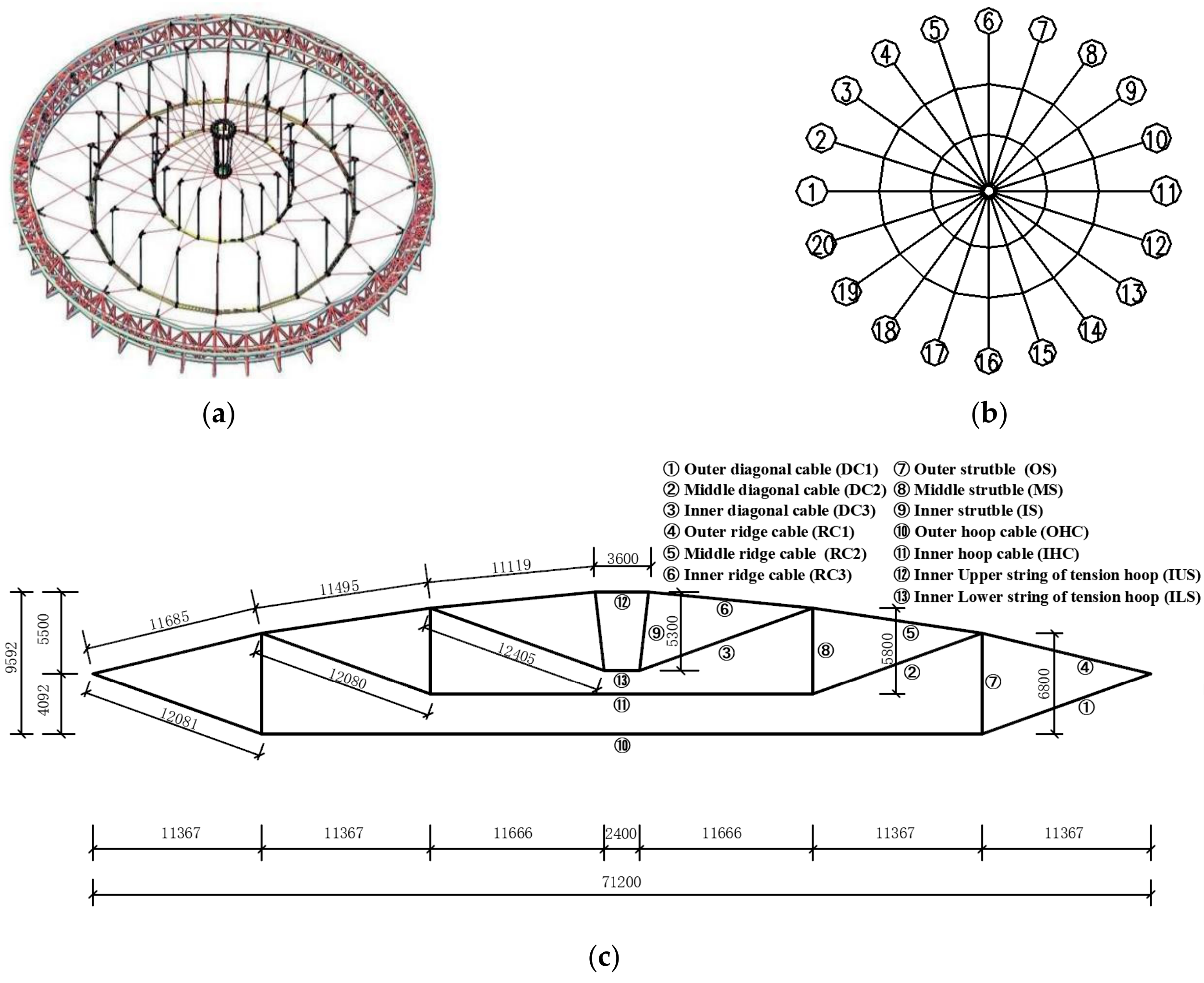


Figure 1. Cable dome structure. (**a**) Structure model, (**b**) structure units, (**c**) elements and sizes (mm).

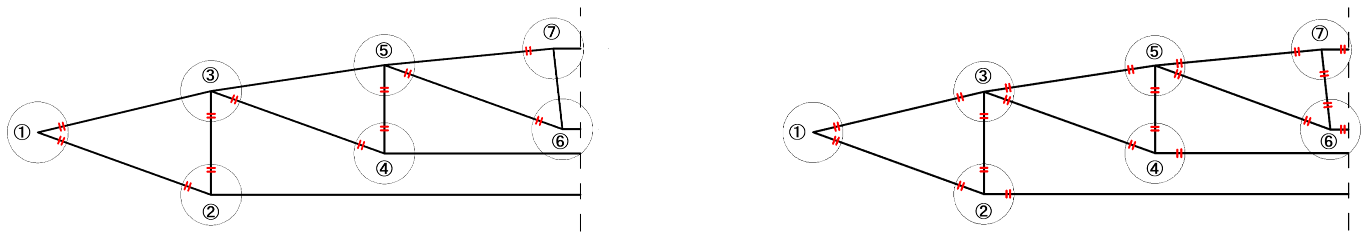
Table 1. Parameters and prestress of the initial model elements.

Member	DC1	DC2	DC3	RC1	RC2	RC3	OS	MS	IS	OHC	IHC	IUS	ILS
Area (mm^2)	2490	853	605	1840	1360	853	7800	4670	4670	7470	3320	3320	3320
Prestress (kN)	466.6	208	105.9	682.2	473.1	370	−158	−70.4	−36.2	1403.2	625.7	1190.1	305.3

2.2. Joint Type

Cable dome structures are characterised by complex topological relationships. Depending on their topological relationships, the joints are divided into continuous joints and discontinuous joints. Continuous joints refer to joints that are connected to discontinuous and continuous components. Among them, the discontinuous components mainly refer to the diagonal cables and struts, and the continuous components mainly refer to the ridge cables and hoop cables. When such joints fail, the connected discontinuous components cease to function because of the loss of the joint constraint at one end. However, the connected continuous components keep functioning. Discontinuous joints refer to joints that are connected to only the discontinuous components. That is, all the components connected to the joints are discontinuous components. When such joints fail, all of the connected components lose their joint support and cease to function.

In this study, a cable truss in a cable dome model (shown in Figure 2) was used as an example. The numbers in Figure 2 represent the joint codes: joint ① is the support joint, joint ② is the lower joint of the outer strut, joint ③ is the upper joint of the outer strut, joint ④ is the lower joint of the middle strut, joint ⑤ is the upper joint of the middle strut, joint ⑥ is the lower joint of the inner strut, and joint ⑦ is the upper joint of the inner strut. Here, the joints were classified according to these categories. As shown in Figure 2, when the joints failed as continuous or discontinuous joints, the corresponding components ceased to function (marked with double red lines).



(**a**) (**b**)

Figure 2. Different types of joints correspond to damaged components. (**a**) Continuous joint corresponding to the damaged components, (**b**) discontinuous joint corresponding to the damaged components.

2.3. Analysis Method

2.3.1. Element Selection and Modelling

In this study, given the cable and strut loading characteristics of cable dome structures, LINK167 and LINK160 units were selected for analysis in the ANSYS LS-DYNA software. The prestress was applied by defining the offset. The specific formula is as follows:

$$F = K \times max\{\Delta L, 0.0\} \quad (1)$$

$$K = EA/(L_0 - offset), \quad (2)$$

where ΔL and L_0 are the component length change and initial length, respectively, E and A are the component modulus of elasticity and cross-sectional area, respectively, and offset is the quantity of the offset. The failure strain of the strut was defined as 0.01 for the LINK160 element. During the analysis, when the strut strain exceeded 0.01, the component was automatically deleted from the structure [6].

2.3.2. Replacement and Removal of Equivalent Forces

To analyse the observed dynamic responses after joint removal, a fully dynamic equivalent load instantaneous removal method was used. After a joint was removed from the structure, multiple equivalent forces were applied to replace the internal forces of the elements connected by the joint. The equivalent forces were then removed to simulate joint damage. During the analyses of such processes, the substitution time, duration, and removal time were determined as twice, 20-fold, and one-tenth, respectively, of the natural vibration period of the residual structure to eliminate the effect of the increased static loads on the structure's dynamic responses, as shown in Figure 3. The natural vibration period of the residual structure was approximately 2 s, and the damping was 0.2 in this work.

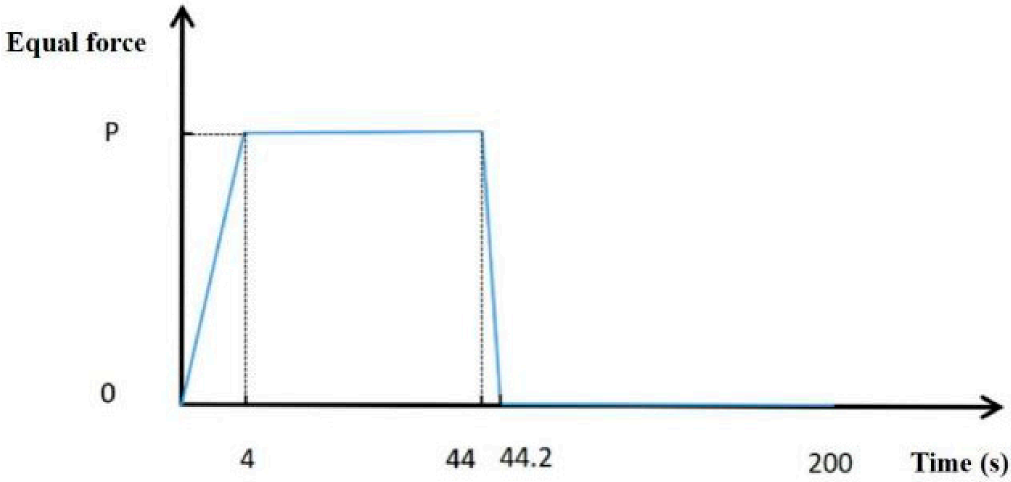


Figure 3. Whole progress of the equivalent force.

3. Analysis of the Structure's Dynamic Responses and Collapse Modes after Joint Damage

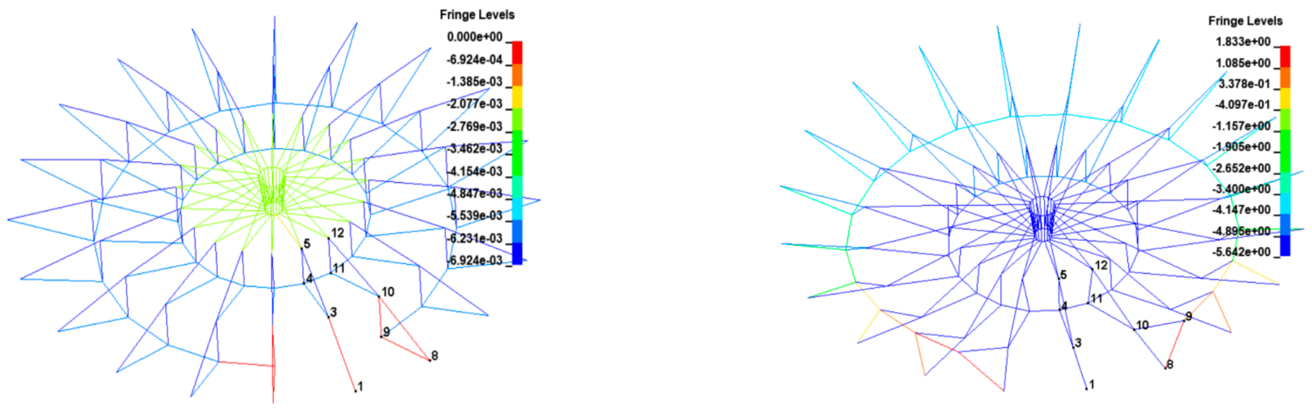
For the sake of brevity, this section describes only the dynamic responses and collapse modes induced by the outer strut's lower joint ② damage in a discontinuous joint design.

3.1. Analysis of the Outer Strut's Lower Joint Damage in a Discontinuous Joint Design

Joint damage led to the loss of constraint at one end of the linking outer strut, outer hoop cable, and outer diagonal cable, resulting in their shrinkage and inability to function.

3.1.1. Displacement Response

Figure 4a,b show the vertical displacements during the removal of the equivalent forces from the structure (t = 44 s) and the final state of the structure under damping (t = 200 s). The research results are shown as follows. First, after the outer strut's lower joint was damaged, the outer strut, outer diagonal cable, and outer hoop cable immediately ceased to function. The failure of the outer strut and outer diagonal cable had a substantial effect on the cable truss. At joint ③, a large vertical displacement of 5.39 m was observed. Second, the failure of the outer hoop cable had a considerable effect on the entire structure. Following the outer hoop cable failure, the linking joints moved towards the two ends, and the entire structure collapsed. On average, all the joints had a vertical displacement of approximately 5 m. Third, during the process of the joint damage, all the joint displacement changes were significant, indicating considerable structural changes.



(**a**) (**b**)

Figure 4. Displacement response. (**a**) t = 44 s (m), (**b**) t = 200 s (m).

3.1.2. Kinetic Energy Response

Figure 5 shows the kinetic energy changes of the structure with an analysis duration of t = 200 s. The research results are shown as follows. First, during the initial 44 s, because the equivalent forces replaced the joint at this stage, and the structure reached a self-equilibrium, the dynamic responses rapidly increased and then stabilised. Second, at t = 44 s, the joint removal process began, the structure equilibrium deteriorated, and the internal forces began to be redistributed, thereby resulting in a higher kinetic energy. Third, the peak energy reached 1100 kJ, representing an approximately sevenfold increase in comparison to the approximate 140 KJ under the condition of the continuous joint, with the duration increased 1.5 times. These results indicated that the joint had a considerable damaging effect as a discontinuous joint on the structure.

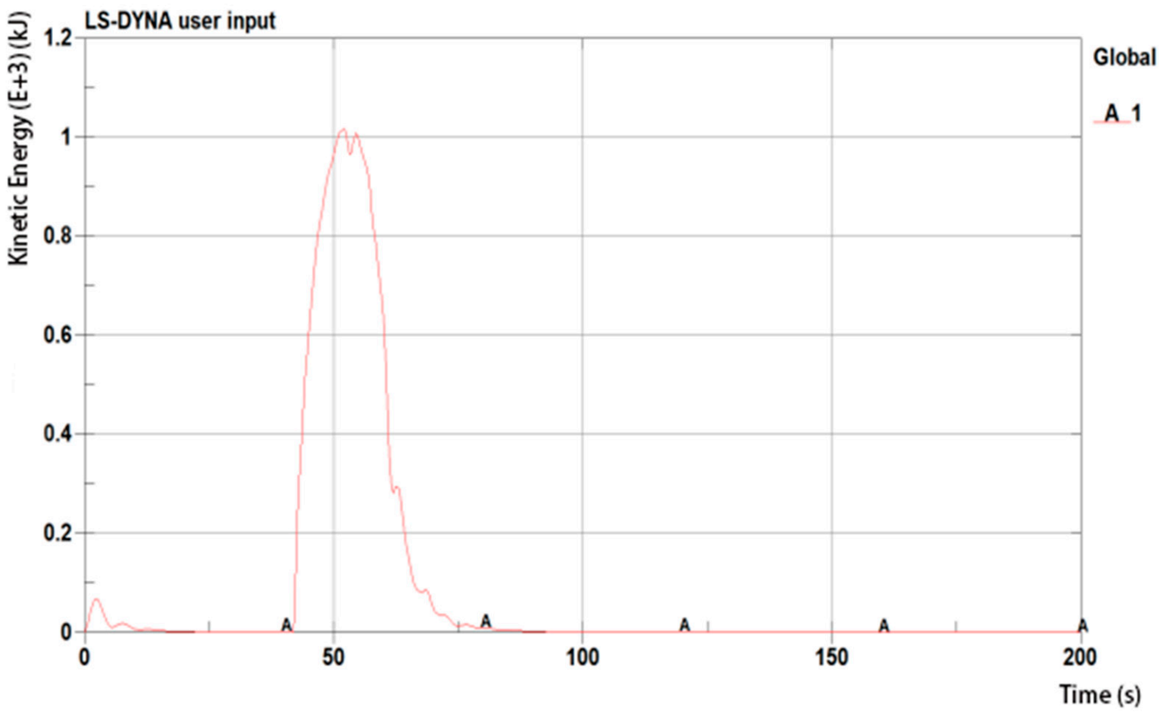


Figure 5. Kinetic energy response.

3.1.3. Internal Force Response

Figure 6 indicates the internal force changes of the components next to the failure joint on the left. The research results are shown as follows. First, following joint damage, the breakage of the outer hoop cable considerably reduced the original prestress by 90%. Second, the internal forces of the other components decreased by varying degrees. Among them, the outer diagonal cables and outer strut lost 80% or more of their internal forces, whereas the outer ridge cable, middle ridge cable, middle diagonal cable, inner hoop cable, and other elements lost approximately 50% of their internal forces.

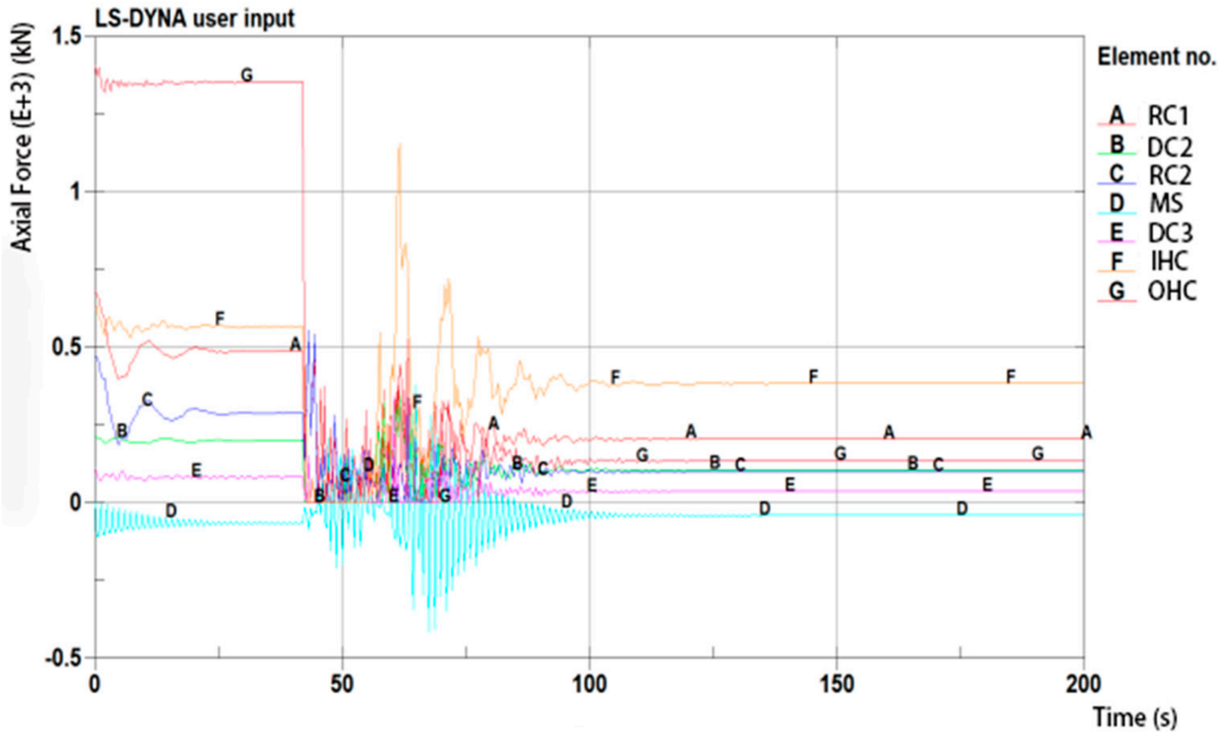


Figure 6. Internal force response.

3.1.4. Collapse Mode

Following the joint damage, excessively large structure dynamic responses were observed, and the structure underwent progressive collapse. This joint failure caused all the joints to have a joint displacement of more than 1/50 of the span. The maximum displacement was observed at joint ③, with a vertical displacement of 5.39 m.

Table 2 lists the research results of the damage induced by the continuous and discontinuous joints. The research results are shown as follows. The damage induced by different joints led to a variety of dynamic responses, and the damage induced by different types of the same joint also contributed to a range of dynamic responses. The dynamic responses and collapse areas of the discontinuous joints were substantially greater than those of the continuous joints. In the discontinuous joint design, the failure of the lower joints in the outer and middle struts resulted in large collapse areas (100% and 47%, respectively). In addition, the support joint and upper joint of the outer strut resulted in large vertical displacements (10.5 and 8.1 m, respectively). By contrast, in the continuous joint design, the majority of the joints (except for the support joint) induced small collapse areas during failure, and their vertical displacements were minimal. Therefore, this study focused on the analysis of the discontinuous joints.

Table 2. Dynamic responses and collapse modes generated by the joint damage.

Joint Damage	Continuous Joints				Discontinuous Joints				
	Description of Collapse				Description of Collapse				
	Collapsed Area (Proportion of the Plan Area)	Maximum Displacement	Collapse Models	Joint Properties	Collapsed Area (Proportion of the Plan Area)	Maximum Displacement	Collapse Models	Joint Properties	Importance Coefficient
Support joint	10%	10.5 m at Node 3	Nonprogressive collapse	Common joint	10%	10.5 m at Node 3	Nonprogressive collapse	Common joint	0.0325
Lower joints of the outer struts	0%	0.92 m at Node 3	Nonprogressive collapse	Common joint	100%	5.39 m at Node 3	Progressive collapse	Key joint	0.5415
Upper joints of the outer struts	0%	1.25 m at Node 3	Nonprogressive collapse	Common joint	10%	8.61 m at Node 5	Nonprogressive collapse	Common joint	0.0131
Lower joints of the middle struts	0%	0.51 m at Node 5	Nonprogressive collapse	Common joint	47%	2.98 m at Node 5	Progressive collapse	Key joint	0.2223
Upper joints of the middle struts	0%	0.41 m at Node 5	Nonprogressive collapse	Common joint	0%	0.24 m at Node 4	Nonprogressive collapse	Common joint	0.0017
Lower joints of the inner struts	0%	0.1 m at Node 7	Nonprogressive collapse	Common joint	0%	0.60 m at Node 7	Nonprogressive collapse	Common joint	0.0339
Upper joints of the inner struts	0%	0.1 m at Node 7	Nonprogressive collapse	Common joint	20%	1.51 m at Node 5	Local progressive collapse	Important joint	0.1549

3.2. Analysis of the Collapse Models Induced by Joint Damage

In this study, to examine the correlation between the importance of each type of joint and the structure collapse modes, the UFC4-023-03 [20] standards for the progressive collapse of cable dome structures were adopted. According to these standards, under the condition that the maximum vertical joint displacement of a cable dome exceeded 1/50 of the span, and the failure area reached 30% of the entire structural plan area, the cable dome was considered to be undergoing a progressive collapse. Under the condition that the maximum vertical joint displacement of a cable dome exceeded 1/50 of the span, but the failure area did not reach 30% of the entire structural plan area, the cable dome was considered to be undergoing a local progressive collapse. Under the condition that the maximum vertical joint displacement of a cable dome was shorter than 1/50 of the span, or when it exceeded 1/50 of the span, but the failure area did not reach 15% of the entire structural plan area, the cable dome was considered to not be undergoing a progressive collapse.

According to the aforementioned standards, the modes of cable dome collapse after joint damage are divided into progressive collapse, local progressive collapse, and nonprogressive collapse. As shown in Table 2, these three modes correspond to the key joints, important joints, and common joints, respectively. Overall, the results indicated the following. First, when a continuous joint model was used, none of the joint damage types resulted in progressive or local progressive collapse of the structure. Thus, all these joints were considered as common joints. Second, when a discontinuous joint model was used, the failure of the different joints resulted in a variety of collapse modes. For instance, damage to the outer strut's lower joint and middle strut's lower joint resulted in large vertical displacements exceeding 1/50 of the span and a failure area exceeding 30% of the entire structural plan area, indicating a progressive collapse. Similarly, damage to the inner strut upper joint resulted in large vertical displacements exceeding 1/50 of the span and a failure area between 15% and 30% of the total plan area of the structure, indicating a local progressive collapse. The remaining types of joint damage did not result in large displacements or failure areas in the structure, thereby representing common joints.

4. Analysis of the Joint Importance Coefficient

4.1. Analysis Methods

This study incorporated the U.S. standards UFC4-023-03 [20], in which the structure's displacement and collapse area were used as evaluation indicators, to compare the displacement values before and after joint removal from a structure and to determine the joint importance coefficients (for the sake of brevity, only discontinuous joints were analysed) and the relationship between the joint importance coefficients and the joint properties and collapse modes. The sum of the squares of the displacement variations of all joints before and after the removal of a given joint was used as an evaluation indicator. The formulae are presented as follows:

$$\Delta^j_{ix} = \left(u^j\right)'_{ix} - \left(u^j\right)_{ix}, i = 1,2,3,\ldots,n \tag{3}$$

$$\Delta^j_{iy} = \left(u^j\right)'_{iy} - \left(u^j\right)_{iy}, i = 1,2,3,\ldots,n \tag{4}$$

$$\Delta^j_{iz} = \left(u^j\right)'_{iz} - \left(u^j\right)_{iz}, i = 1,2,3,\ldots,n, \tag{5}$$

where n is the overall quantity of the structure joints and $\left(u^j\right)_{ix}$, $\left(u^j\right)_{iy}$, $\left(u^j\right)_{iz}$ and $\left(u^j\right)'_{ix}$, and $\left(u^j\right)'_{iy}$, and $\left(u^j\right)'_{iz}$ are the displacements of the ith joint along the x, y, and z directions before and after the removal of joint j, respectively. The definition is as follows:

$$\delta^j = \sum_{i=1}^{n} \sqrt{\left(\Delta^j_{ix}\right)^2 + \left(\Delta^j_{iy}\right)^2 + \left(\Delta^j_{iz}\right)^2}, i = 1,2,3,\ldots,n. \tag{6}$$

The importance coefficient of joint j can be calculated as follows:

$$\gamma^j = \delta^j / d^j, \tag{7}$$

where

$$d^j = \sum_{i=1}^{n} \sqrt{(u^j)_{ix}^2 + (u^j)_{iy}^2 + (u^j)_{iz}^2},\ i = 1,2,3,\ldots,n; \tag{8}$$

when the importance coefficient of joint j increases, the structure's displacement variation after the removal of joint j increases. Stronger displacement responses indicate a greater importance of the joint.

4.2. Result Analysis

According to stepwise analyses, the importance coefficients of the discontinuous joints were normalised as follows:

$$\gamma^{j\prime} = \gamma^j / \sum_{i=1}^{7} \gamma^i. \tag{9}$$

The results (see Table 2 and Figure 7) indicated the following. First, each joint had a different importance coefficient. Among all the coefficients, the importance coefficients of the outer strut's lower joints and middle strut's lower joints were the highest. Removing these joints induced strong structural dynamic responses. These joints were all key joints. Second, the importance coefficients of the inner strut's upper joints were secondary. Removing these joints induced local progressive collapse, resulting in considerable effects on the structure. These joints were all important joints. Third, the remaining joints had low importance coefficients. Removing these joints produced a minor impact on the structure without causing progressive collapse. These joints were all common joints.

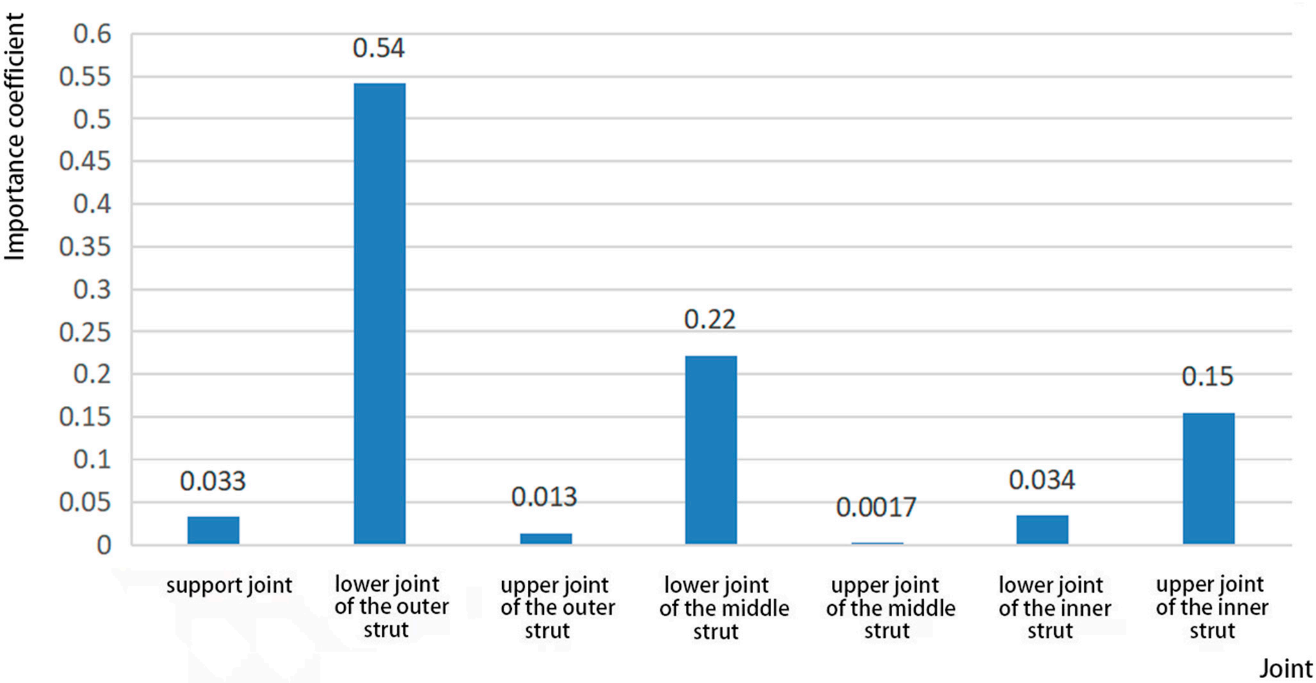


Figure 7. Importance coefficient of the discontinuous joints.

5. Analysis of the Relationship between the Joint Damage and the Connected Components' Damage

To analyse the relationship between the joint damage and the connected components' damage (for the sake of brevity, only discontinuous joints were analysed), all component damage-induced dynamic responses, collapse modes, and corresponding component importance coefficients were compiled. The calculation method for the component importance coefficients is the same as for the joint importance coefficients. The results (see Table 3) indicated the following. First, removing different components contributed to various dynamic responses and collapse modes. For instance, removing the inner and outer hoop cables induced large collapse areas and vertical displacements. Therefore, these components corresponded to high component importance coefficients and were considered key components. Removing the upper string of the tension hoop cable induced secondary collapse and deformation. Therefore, this component is an important component. Removing the outer diagonal cable and other remaining components resulted in minor collapse and deformation. Therefore, these components corresponded to low component importance coefficients and were considered common components. Second, when discontinuous joints were connected to key components, for example, the outer and middle struts' lower joints connected to the outer and inner hoop cables, respectively, joint damage induced the disconnection of the outer and inner hoop cables, thereby resulting in progressive structure collapse. These joints were all key joints. In this case, the importance coefficients of both the joints and the components were comparable. Third, when discontinuous joints were connected to important components, for example, the inner struts' upper joints connected to the tension hoop upper strings, joint failure resulted in local progressive collapse. These joints were all important joints. In this case, the importance coefficient of the joint was comparable to that of the important component. Fourth, when a discontinuous joint was connected to a common component, joint failure could not induce progressive collapse. These joints belonged to common joints.

Table 3. Types of collapse induced by the removal of different types of cable–strut components and the importance categories of these components.

Components	Description of Collapse		Collapse Models	Importance Coefficient	Important Properties
	Collapsed Area (Proportion of the Plan Area)	Maximum Displacement			
Outer diagonal cable	10%	0.64 m at Node 3	Nonprogressive collapse	0.01	Common component
Middle diagonal cable	0%	0.36 m at Node 5	Nonprogressive collapse	0.0049	Common component
Inner diagonal cable	0%	0.10 m at Node 7	Nonprogressive collapse	0.0009	Common component
Outer ridge cable	10%	9.93 m at Node 3	Nonprogressive collapse	0.023	Common component
Middle ridge cable	4.6%	8.30 m at Node 5	Nonprogressive collapse	0.01	Common component
Inner ridge cable	0%	0.10 m at Node 7	Nonprogressive collapse	0.0015	Common component
Outer strut	0%	1.42 m at Node 3	Nonprogressive collapse	0.0061	Common component
Middle strut	0%	1.10 m at Node 5	Nonprogressive collapse	0.002	Common component
Inner strut	0%	0.10 m at Node 7	Nonprogressive collapse	0.000074	Common component
Outer hoop cable	100%	5.58 m at Node 3	Progressive collapse	0.54	Key component
Inner hoop cable	47%	3 m at Node 7	Progressive collapse	0.23	Key component
Inner upper string of tension hoop	16.6%	1.56 m at Node 3	Partial progressive collapse	0.15	Important component
Inner lower string of tension hoop	16.6%	0.756 m at Node 7	Nonprogressive collapse	0.033	Common component

6. Conclusions

To address the current lack of an effective analysis and evaluation of the anticollapse performance of a cable dome structure following joint damage, this study involved the use of actual engineering cases, the ANSYS LS-DYNA platform, and a fully dynamic equivalent load instantaneous removal method to perform a dynamic analysis. The dynamic responses and collapse modes of various joints after different types of damage were then explored. In addition, joint importance coefficients based on the structure's displacement variations before and after joint removal were proposed, and the relationship between the joint importance coefficients and the joint properties and collapse modes were determined. Lastly, the relationship between the joint damage and the connected components' damage was investigated. The results revealed the following:

(1) Different joints' damage induces a variety of dynamic responses. Different joint types also induce various dynamic responses. However, the dynamic responses induced by discontinuous joints are more apparent than those induced by continuous joints.

(2) When a continuous joint model is used, all types of joint damage have a minor effect on the structure without causing progressive or local progressive collapse. All joints in this model are common joints.

(3) When a discontinuous joint model is used, the failure of different joints induces a variety of collapse modes. Damage to the outer and middle struts' lower joints induces progressive collapse. Therefore, these joints are regarded as key joints with high importance coefficients. Damage to the inner struts' upper joints induces local progressive collapse. Therefore, these joints are regarded as important joints with intermediate importance coefficients. Damage to other joints does not result in large displacements or collapse areas in the structure. Therefore, these joints are regarded as common joints with low importance coefficients.

(4) Joint importance and connected component importance coefficients are related. When discontinuous joints are connected to key components, joint damage induces progressive collapse. In this situation, the importance coefficients of the joints are comparable to those of the key components. When discontinuous joints are connected to important components, joint failure induces local progressive collapse. In this situation, the importance coefficients of the joints are comparable to those of the important components. When discontinuous joints are connected to common components, joint failure does not induce progressive collapse.

Author Contributions: Conceptualization, L.-M.C.; Methodology, L.-M.C., Z.-B.L. and Y.-H.Z.; Software, K.-Y.H. and Y.-J.L.; Validation, Y.-J.L., Z.-B.L. and Y.-H.Z.; Resources, L.-M.C., W.L., Y.-Y.Z. and S.-L.D.; Writing—original draft, L.-M.C.; Writing—review & editing, L.-M.C. and K.-Y.H.; Supervision, L.-M.C., W.L., Y.-Y.Z. and S.-L.D.; Project administration, L.-M.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant number 51578422 and 51678082.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Geiger, D.; Stefaniuk, A.; Chen, D. The design and construction of two cable domes for the Korean Olympics Shells. In *Membranes and Space Frame, Proceedings of pf IASS Symposium*; Geiger Associates: Tallahassee, FL, USA, 1986; Volume 2, pp. 265–272.
2. Levy, M.P. The Georgia dome and beyond achieving light weight-long span structures. In *Spatial, Lattice and Tension Structures*; ASCE: Reston, VA, USA, 1994; pp. 560–562, ISBN 0-87262-953-8.
3. Philipp, D. Robustness of large-span timber roof structures–Structural aspects. *Eng. Struct.* **2011**, *33*, 3106–3112.
4. Starossek, U. Progressive collapse of structures: Nomenclature and procedures. *Struct. Eng. Int.* **2006**, *16*, 113–117. [CrossRef]
5. He, J.; Yuan, X.f.; Jin, B. Local Broken Cable Analysis of Cable-Domed Structures. *J. Vib. Shock.* **2010**, *29*, 13–16+249–250.
6. Hui, Z.; Qin, W.H.; Xu, J.W.; Zhang, P. Nonlinear analysis of progressive collapse behavior of Geiger type carbon fiber cable dome structure. *J. Vib. Shock.* **2021**, *40*, 114–122.
7. Yuan, W.J.; Zhang, A.L.; Zhang, Y.X.; Wen, W. Anti-continuous collapse analysis of cable dome with spatial three-struts and double-hoop cables. *Build. Struct.* **2021**, *51* (Suppl. S2), 366–373.

8. Zhang, C.; Fu, X.D.; Du, X.L.; Yan, X.Y.; Xu, L.; Jia, H.-Y. Dynamic Analysis of Multi-loop Cable-string Dome Due to Sudden Cable Failure. *Eng. Mech.* **2021**, *38*, 64–77.
9. Zhang, Z.J. Force Finding Optimization and Cable-Strut Rupture for Kiewitt Cable Domes. Master's Thesis, South China University of Technology, Guangzhou, China, 2018.
10. Liu, Y.; Lei, X.; Grierson, D.E. Influence of Semi-Rigid Connections and Local Joint Damage on Progressive Collapse of Steel Frameworks. *Comput.-Aided Civ. Infrastruct. Eng.* **2010**, *25*, 184–204. [CrossRef]
11. Ma, H.; Ma, Y.; Fan, F.; Zhang, Y. Failure mechanism and design method of reticulated shells considering joint damage accumulation effect under earthquake load. *Structures* **2022**, *39*, 667–678. [CrossRef]
12. Zhang, S.; Li, T.; Du, X.X. Anti-collapse property analysis for long-span spatial latticed structures. *Build. Struct.* **2010**, *40*, 22–26.
13. Huang, B.Q. Stability and Collapse Resistance Analysis of Large Span Single-layer Three-Way Spherical Reticulated Shells. Master's Thesis, Guangzhou University, Guangzhou, China, 2021.
14. Zheng, J.X. Research on the Stability and Progressive Collapse Resistance of Aluminum Alloy Single Layer Latticed Domes with Assembled Hub Joints. Master's Thesis, Tianjin University, Tianjin, China, 2018.
15. Xie, Q.M. Research Upon Progressive Collapse Resistance of Lamella Cylindrical Reticulated Shell Based on Importance Coefficients of Joints. Master's Thesis, Southwest Jiaotong University, Chengdu, China, 2015.
16. Liu, Y.M. Mechanical Behavior of Joints and its Influence on Stability and Progressive Collapse Resistance of Single Layer Latticed Shells. Ph.D. Thesis, Tianjin University, Tianjin, China, 2018.
17. Gao, Z.Y.; Xue, S.D.; Luo, D.J.; Yang, W.Q. Progressive Collapse Analysis of Levy Type Rigid Bracing Dome. *Eng. Sci. Technol.* **2021**, *53*, 178–183.
18. Zhang, W.J.; Su, Y.J.; Lu, K.; He, J. Progressive collapse analysis of cable dome structure model with equivalent joints. *Build. Struct.* **2021**, *51* (Suppl. S1), 599–604.
19. Sun, S.; Hu, H.; Zhu, Z.; Li, J.; Liu, Y.; Wang, W.; Wang, Z.; Chen, Y. Design on wheel-spoke shaped cable-membrane structure roof of stadium of Kuishan Sports Center in Rizhao. *Build. Struct.* **2021**, *51*, 1–8.
20. *UFC 4-023-03*; Design of Buildings to Resist Progressive Collapse. Department of Defence: Washington, DC, USA, 2005.