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Numerical and experimental study on loaded suspendome subjected to sudden cable failure

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ABSTRACT

Cables are key components of suspendome structures and usually bear a high level of tension force. Thus, their sudden failure may cause a dramatic vibratory response and disproportionate internal force redistributions. This study investigated the cable failure effect of a 10.8 m scaled-down suspendome model during in-service state through numerical simulations and failure tests. The deforming behaviors, internal force redistribution pattern, and oscillatory responses were studied and compared. Results showed that cable failure causes evident oscillations to the rest of the members. However, the suspendome exhibited strong structural stiffness, and no obvious collapse or failure behaviors were observed. Cable sliding occurred at rolling joints, which could influence the internal force redistribution patterns and dynamic effects at cables or strut members around the break region. Cable sliding behaviors reduced tension recovering ability and the dynamic effect at cable segments. Dynamic amplification factor and dynamic coefficient methods were both employed to evaluate the dynamic effect from the cable rupture because of different oscillatory patterns between cable segments and the rest of the members. Dynamic amplification factor was more applicable for shell and strut members, and the safety of cable segments can be evaluated and ensured with the dynamic coefficient method. The suggested values for the two indexes were also derived based on the test data, which could easily be used in the structural design process.

1. Introduction

Suspendome was first proposed by M. Kawaguchi [1–3] at Japan Hosei University in 1993. This new type of structure combines single-layer latticed shell with struts and cables to create an innovative and highly efficient structure. The sectional view of the structure, which reflects the structure principle, is shown in Fig. 1(a). The sub pretension cable-strut system can improve the strength, stiffness, and stability of the entire structure, which increases the ability of a superdome to achieve a larger span and possesses high mechanical efficiency. The upper single-layer latticed shell provides rigid support and reduces the flexibility of the lower tensegric system, thereby reducing the required pre-stress force in the cables compared with that in the cable-dome system [4]. The first suspendome, the 30-meter Hikarigaoka Dome (Fig. 1(b)), was built in Japan in 1994. Thereafter, more suspendomes have been built worldwide, especially in East Asia. The Gymnasium of Jinan Olympic Sports Center in China (Fig. 1(c)) is the largest suspendome in the world and spans 122 m. Compared with cable-dome structures, suspendomes are easier to construct because of the stiffness of the upper latticed shell. Usually, the upper shell is erected first and supported with scaffolds. After the upper shell is completed, cable tensioning, which is the most important and difficult step, commences. Three methods exist for tensioning cable-strut systems, namely, lengthening the vertical struts (Fig. 2(a)), tensioning the diagonal struts (Fig. 2(b)), and tensioning the hoop cables (Fig. 2(c)). Owing to the numerous vertical and diagonal struts, many tensioning devices are needed for the first two tensioning types, which is problematic during construction. Therefore, tensioning hoop cables is often used to pre-stress the cable-strut system. With the designed pre-stress in the sub-cable-strut system, the structure can bear the designated loads. Moreover, the supporting scaffolds can be removed and roof panels can be installed on the upper shell.

Nowadays, suspendomes are widely used in various major engineering projects, including stadiums, gymnasiums, conventions, exhibition centers, and transportation hubs [4–5]. In the past decades, many studies were conducted on the structural design and constructional technologies because of the prominent structural performance of superdomes [6–8]. By contrast, because of the short history of suspendomes, the in-service evaluation and studies on structural safety under dynamic impact, such as explosions or sudden member failures,

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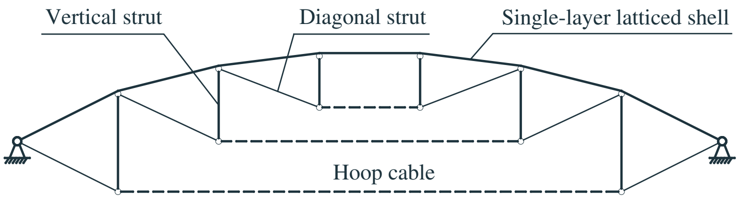
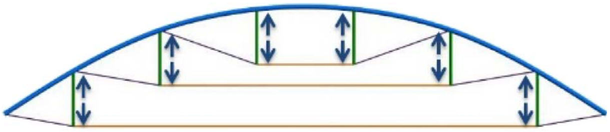


(a) Sectional view of suspendome

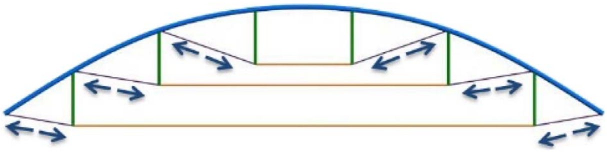
(b) Hikarigaoka Dome

(c) Gym of Jinan OSC

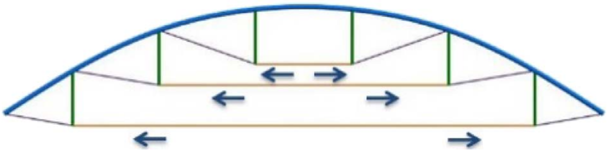
Fig. 1. Suspendome structures.



(a) Lengthening the vertical struts



(b) Tensioning the diagonal struts



(c) Tensioning the hoop cables

Fig. 2. Three ways to prestress sub-cable-strut system.

are still at the starting stage.

During service life, the structure may suffer sudden cable failure as a result of material degradation, terrorist attacks, or construction errors in the cable joints [9]. The pretension force of suspendome structures usually reaches 40%–55% of the ultimate tensile strength of cables. Sudden cable failure would result in substantial energy release and dramatic dynamic effect to nearby members and the entire structure because of the high stress level. Sudden cable failure and the abrupt loss of sub-supports may cause the destruction of the original self-balance system, resulting in the redistribution of internal force and even progressive collapse of the structure [10–11]. The safety and robust behavior of cables in public building structures for extreme loads or member failures are crucial [12].

Past research mainly focused on cable stayed bridges, tensegrity systems, cable domes, and transmission line towers and often employed numerical simulations with few experimental investigations. Mozos [13] discussed the internal force response of a cable stayed bridge with a cable's sudden break and the influence of a single cable failure on the dynamic response of the entire bridge. The mutual influence between the rest bridge cables during the rupturing process was also identified. Zhou [14–16] proposed a time-progressive nonlinear dynamic analysis approach and a framework of nonlinear dynamic simulation to investigate the influence of an abrupt cable-breakage in a cable-stayed bridge and evaluate the safety of a cable-stayed bridge under cable loss scenarios. Shekastehband [17] conducted experimental and numerical studies on the collapse behavior of a tensegrity structure considering the cable failure and strut buckling with snap-through. Nabil Ben Kahla [18] studied the nonlinear dynamic behavior of a guyed tower and found that a sudden rupture of a selected guy may lead to the collapse of the entire structure. Dynamic failure modes and the robustness of cable-supported structures were studied in recent years because of the widespread application of suspendomes and cable-supported structures in China. He [19] studied the local failure response of cable dome structures before and after the cable rupture scenario through static analysis using element death technology in ANSYS. Cai [20] discussed the dynamic magnification factor in string structures based on stress ratio method and examined the influence of strut loss on the progressive collapse performance of string structures. Zhu [21] conducted a numerical failure analysis of suspendome structures by vector form intrinsic finite element method. Liu [22] conducted the dynamic response analysis of an annular crossed cable-truss structure under local cable or rod failure by adopting numerical simulations.

Considering these studies, we believe that cable failure problems should be investigated when designing suspendomes. The question is how these problems can be included in the design process. Model tests may seem accurate but are time-consuming and expensive. Moreover, the accuracy of numerical simulation needs to be verified. A simple approach is needed. Therefore, the numerical simulations of a sudden hoop cable failure in a 10.8-diameter loaded suspendome model were initially performed using an explicit, dynamic, and finite-element analysis program called ANSYS/LS-DYNA. The effectiveness and accuracy of the simulations were verified through comparison with experimental data. A simplified method to evaluate the dynamic effects in sudden cable failures was proposed, and it can be used in the practical design