Thin-Walled Structures 132 (2018) 208–216

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Full length article

Failure modes and failure mechanisms of single-layer reticulated domes subjected to interior blasts

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ARTICLE INFO

Keywords:
Large-span spatial structure
Single-layer reticulated dome
Interior blast
Failure mode
Failure mechanism

ABSTRACT

Single-layer reticulated domes are very common spatial structures. As landmarks, these types of structures can more easily be the targets of terrorist attacks than other buildings. However, blast resistance is not taken into consideration in the design of most civil structures. Therefore, it is important to know the damage level that may be imparted to single-layer reticulated domes after a blast attack. In this study, the dynamic response of reticulated domes subjected to an interior blast was investigated with numerical simulations, and five typical failure modes were identified from the results. In addition, the effects of some important parameters were investigated with a case study. Relationships between failure modes and interior blast impulses were summarised. Finally, the failure mechanisms were analysed, which could provide some design suggestions to decrease the probability of severe damage in spatial structures subjected to extreme dynamic loads.

1. Introduction

Large-span spatial structures are always landmarks in cities. At present, bomb attacks occur almost daily across the globe, and many people have lost their lives to terrorist attacks. It would be extremely dangerous if a large-span spatial structure was attacked with bombs. Therefore, predicting the potential damage to these structures subjected to blast loading is a significant issue for civil engineers. In addition, elucidating the failure modes and failure mechanisms is important to effectively minimize the damage to the structures.

To study the failure modes and mechanisms, it is first important to know the blast loads on the structures. There are many studies on the topic of blast loading, encompassing numerous theories, blast tests, and numerical simulations. However, most of the existing studies concern very particular applications. For example, although the US army guideline UFC 3–340-02 (2008) provides various blast loading parameters for a large range of different situations [1] covering most common building types, it is only suitable for some special cases. The unique configurations of spatial structures are not well considered in the UFC guideline, particularly for interior blasts. The blast loading distribution in lattice shells was investigated in a previous study [2]. For long-span structures, the most important blast parameter is the impulse, which was proposed by comparing a series of numerical simulations. To some extent, it was believed that the blast impulse would directly affect the maximum dynamic responses for these structures with long vibration periods.

Traditionally, pressure-impulse (P-I) diagrams are the most common and simplest method to evaluate the damage level of a component or simple structure subjected to blast actions [3–7]. However, with a P-I diagram, it is difficult to distinguish the failure modes for more complicated structures such as single-layer reticulated domes, which are one of the most common types of large-span spatial structures. Studies of the failure modes of reticulated domes have focused on research areas including seismic, impact, and blast effects. Zhi investigated the failure modes of reticulated domes under severe earthquakes, and two different failure modes were identified and defined [8]. The effect of substructures on failure behaviour was investigated by Yu [9]. In addition, the failure modes of domes caused by impact were analysed by Wang, and the failure modes and failure mechanisms were addressed in detail [10–13]. The effects of the roof system on the failure modes of domes were further investigated by Lin [14,15]. Moreover, an interesting phenomenon of counter-intuitive behaviour of reticulated domes subjected to interior blasts was evaluated with an energy method [16]. These studies have all made fundamental contributions to the study of the failure modes and failure mechanisms of single-layer reticulated domes subjected to blast loading.

This study proposes a reasonable method for investigating the dynamic response of a reticulated dome subjected to an interior blast. In

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https://doi.org/10.1016/j.tws.2018.07.028
Received 2 March 2018; Received in revised form 3 July 2018; Accepted 17 July 2018
0263-8231/

addition, five failure modes for the single-layer dome are identified from a series of numerical simulations. These failure modes include minor vibration, local failure, swelling deformation, global collapse, and tension fracture. In addition, the effects of some common parameters are compared with the results of a case study. Failure mechanisms are also analysed and discussed. Finally, some suggestions for structural design are given which may effectively decrease the occurrence of severe damage from extreme dynamic loads.

2. Methodology and FE model

In consideration of the features of the problem, the methodology for single-layer reticulated domes subjected to interior blast loading is introduced. The finite element (FE) model of a reticulated dome is also established. At the same time, structural behaviours under high strain rates are considered with the Johnson-Cook constitutive model. This subsection introduces the methodology and details of the FE model.

2.1. Methodology

Determination of the blast waves applied to a single-layer reticulated dome is a complicated problem which involves aerodynamics. According to the conclusions of a previous study, the fluid-structure interaction (FSI) effects during blast loading can be ignored for large-span spatial structures [17]. The analysis procedure was divided into two separate steps. In the first step, the aerodynamics of a blast wave field on a rigid structure was simulated using AUTODYN software, and some simplified equations for describing the blast loading field were proposed. In the second step, the dynamic behaviour was simulated under the excitations proposed in the previous step using time-history response analysis with LS-DYNA software.

In addition, structures are naturally stressed and deformed by gravity during and following construction. Therefore, the stress initialization of the dome and the blast procedure were considered successively with analysis methods shown to be effective in a previous study [16,18–20]. In this study, the gravity and blast loading were independently imposed as two successive processes, as shown in Fig. 1.

2.2. Dome model

A comprehensive FE model of the Kiewitt dome was developed with integrated roof elements (purlins, roof panels, and rivets), as shown in Fig. 2.

With a very thin panel, the roof system is relatively weak, and it could offer limited contribution to the stiffness. In addition, the roof systems are the non-structural components, which are not as important as the primary structures during the research of dynamic response and failure modes of the reticulated domes. In this paper, more attentions were paid to the severe damage of the primary structures than the other non-structural components. Therefore, the FE model of the single-layer reticulated dome was simplified by ignoring the stiffness contribution of the roof panel. However, the weight of roof elements was still considered, as many mass elements are attached on the corresponding nodes. The simplified Kiewitt-8 dome model is shown in Fig. 3(a), and has a span of 40 m with six rounds. The model comprises 456 circular-section hollow tubes and 169 spherical hollow weld joints. The four-integration-point beam element in the LS-DYNA package was used to consider the bending deformation, as shown in Fig. 3(b). In the following analysis, the notation '1P' indicates that one integration point of the beam element becomes plastic during the response process. The '2P,' '3P', and '4P' notations have similar meanings for two, three, and four beam elements, respectively. In addition, the spherical hollow weld joints were assumed to be rigid connections. All dome constraints were simulated with 48 hinged supports. The indexes of the joints and tubes are shown in Fig. 3(c).

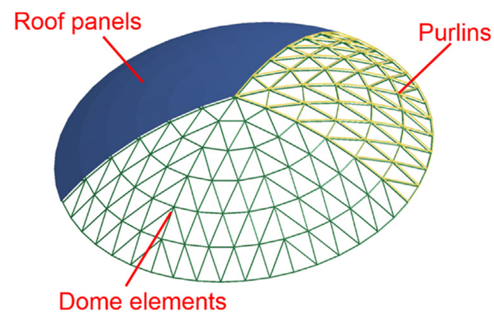

Fig. 2. Comprehensive FE model of the dome with roof system.

It should be noticed that the numerical model of reticulated dome has been already verified in a series tests previously, including the drop hammer impact tests and the shaking table tests, and blast tests. The confident simulation results were achieved in these references [8–15].

Blast loads were studied systematically with multiple tests and numerical simulations [21–23]. In some previous studies, the blast loads were simply described as triangle excitations to obtain the structural dynamic response [4–7,24–26]. The durations of blast shocks are extremely short, and it can be assumed that the total energy of the blast

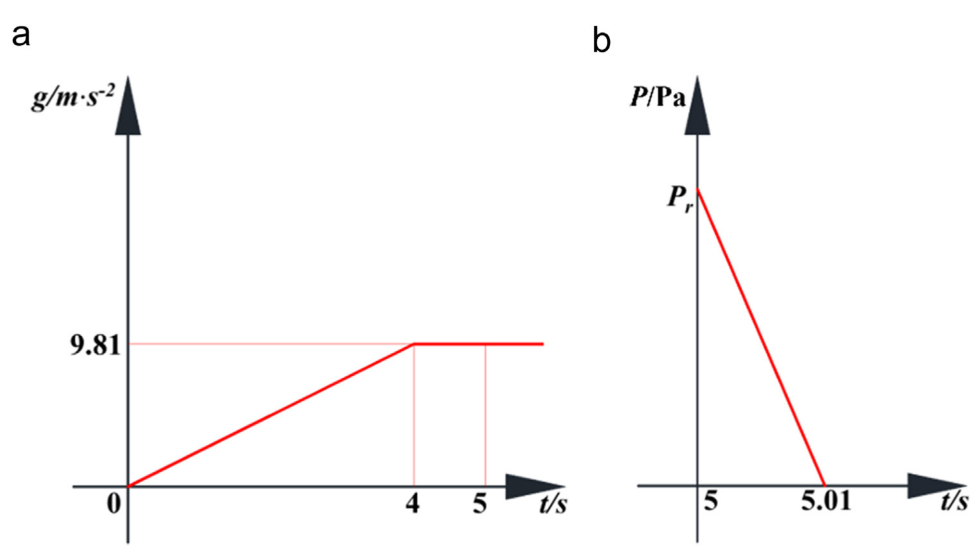

Fig. 1. Two-step loading process.