Research Article

Failure Modes of a Reticulated Dome in a Small Airplane Crash

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Since the 9/11 incident, many engineering research works have been conducted on the impact resistance of large-span space structures. In the present study, a small airplane, Bombardier Challenger 850, was chosen as the test subject. An airplane crash on a single-layered Kiewitt-8 reticulated dome with span 60 m considering roof sheathing effect was simulated using ANSYS/LS-DYNA software. The principles of establishing the numerical model of small airplanes were determined. In addition, the impact styles of small airplane and impact positions on the dome were investigated. The failure modes of reticulated dome with roof sheathing due to small airplane crash were identified. Furthermore, the failure modes between reticulated domes with and without roof sheathing were compared and the effect of roof sheathing on the failure modes of reticulated dome under a small airplane crash was investigated.

1. Introduction

Terrorist attacks have increased in the past few years, not only leading to enormous economic and infrastructure losses, but also causing a huge impact on the spirit of people. Airplane hijacking has been one of the most common forms of terrorist attacks in recent decades. After 9/11 incident, researchers are increasingly investigating the performance of building structures under airplane crashes. In addition, many airplanes and other flying objects have impacted buildings due to air accidents and other reasons. In 1980s, a small airplane crashed Sao Paulo Exhibition Center, which had a roof with grid structure [1]. Therefore, it is necessary to conduct more research on the impact resistance of reticulated domes subjected to airplane crashes.

There has been an increasing interest in research on the impact resistance of large space structures since 9/11 incident. Many previous studies, such as Lynn and Isobe [2], Samuel and Astaneh-Asl [3], Zhou et al. [4], Bonder and Symonds [5], and Zhao et al. [6], have concentrated mainly on the frames of buildings under accidental impacts. Shi [7] and Guo [8] investigated the performance of single-

layer Kiewit-8 reticulated domes subjected to low-speed and low-weight impacts. Fan and Wang conducted more systematic research works on the behavior and failure modes of a single-layer reticulated domes under impact [9–11]. Lin et al. investigated the effects of size and material properties of the impact body on the damage modes of single-layer Kiewit-8 reticulated domes using 3D numerical simulations [12]. Ma et al. investigated dynamic response, failure modes, and failure mechanisms of single-layer reticulated domes subjected to interior blast loading [13] and established a precise and simple model to predict blast loading in these structures [14]. Lin et al. [15] studied the dynamic response of a single-layer Kiewit-8 reticulated dome subjected to small airplane crash.

Based on previous studies, this paper investigated the failure modes of a large space structures under impact. Roof sheathing effect cannot be ignored in evaluating the impact resistance of reticulated domes and has to be verified experimentally. We also studied the effect of roof sheathing on failure modes by comparing the failure modes of a reticulated dome in the presence and absence of roof sheathing.

First, different characteristics of the impact body, such as size and material, which affect the impact resistance of reticulated domes were studied. The aim of this study was to investigate the failure modes of reticulated domes under the impact of a real size airplane model. The complexity of large space structures subjected to airplane crashes is reflected in need for the nonlinear analysis and control of calculation accuracy. Because the material, size, and construction complexity of an airplane significantly increase computational requirements, a simplified airplane model was developed to simulate the behavior of a reticulated dome under a small airplane crash.

Once the model was developed, the style and position of impact were selected. In this paper, different impact styles at different positions, different failure modes under actual airplane crashes, and the effect of roof sheathing on failure modes have been investigated.

2. FE Model and Impact Style

2.1. FE Model. A finite element model (Figure 1) was developed based on actual airplane parameters, and the main factors affecting the impact were simulated. Actual material properties and geometry of an aircraft are very complicated, and specific data are often unavailable to public. Based on existing research methods for airplane crashes, the principles of developing numerical models of airplanes were determined as follows:

- (1) The parameters of the developed airplane model, including size, quality, and mass distribution, were as close as possible to a real airplane. The minute constructional details of airplane had little effects on its crash performance, and therefore, they were not considered in the modelling.
- (2) It was necessary that the FE model of the airplane be simple and the number of units be as few as possible, to save calculation time and resources.
- (3) The accuracy of the developed airplane model was verified by comparing the curve of impact force and failure modes obtained from experimental data of airplane crashes on rigid structures and those obtained from the simulation.

Considering the three abovementioned principles, a Bombardier Challenger 850 airplane model was developed with a length of approximately 27 m and wingspan of 21 m weighing 24.50 tons. The chosen size was apt for application to a single-layer reticulated dome with the span of 40–60 meters.

The deformation of a small airplane when impacting a rigid structure and the variation curve of impact force were simulated, and the accuracy of the developed model in the analysis of a small airplane crash on a reticulated dome was confirmed.

The aircraft chosen for this study was different from those used by previous researchers [16]. The research equipment in this paper is a single-layer reticulated dome with the span of 40–60 meters. The Bombardier Challenger

FIGURE 1: Finite element model of a small airplane.

850 airplane model was chosen to match the size of the test equipment. Since in their planes, wings were connected with the fuel tank and engine, the strength of wings was very high, and they would not break after colliding with rigid structures. Sometimes these wings could cut the columns and enter into structures. On the contrary, the engine of Bombardier Challenger 850 is located in the back of the airplane, and the fuel tank is placed in fuselage. The wings of this plane are thin and could be deformed after crash. Therefore, a single-layer shell element was applied to the FE model of wing tips instead of a box section. Some research results have shown that the load curves of rigid structures under airplane crashes should reflect the quality distribution of airplane. The deformation of a rigid structure under airplane crash is shown in Figure 2. As can be seen in the figure, the head of the airplane was flattened on collision with rigid structure and the final deformation of rigid structure was consistent with the results reported in previous works.

The developed airplane model had uniform quality distribution from the head to front wing, but the remaining parts of it were heavy. The shock of impact force was violent in the first 0.2 s and reached its peak at 0.0075 s before starting to decrease gradually. In general, the shape of impact curve was very similar to the mass distribution of the airplane. The curve of impact force for a rigid structure subjected to a small airplane crash is shown in Figure 3.

2.2. Impact Style. The failure modes of a reticulated dome under a small airplane crash with three different impact styles were studied, as shown in Table 1. In Impact 1, the flight attitude of the airplane was generally horizontal and its flight speed was primarily along the horizontal direction. When vertical speed was also considered in the approach of the airplane to the dome, the impact style was denoted as Impact 2. Finally, an out-of-control airplane approaching with large vertical velocities was denoted as Impact 3.

The reticulated dome was assumed to be below the airplane when it was close to the dome, as shown in Figure 4. So, Joint A was most likely to be impacted by the small airplane, followed by Joints B and C.

The reticulated domes belong to the class of large space structures. These structures cannot be built too high due to height limitations. However, airplanes can crash these structures just like when they land in an airport, unless they

FIGURE 2: Deformation of a rigid structure under small airplane crashing obtained by numerical simulation. (a) 0 s, (b) 0.02 s, and (c) 0.05 s, and (d) 0.1 s.

FIGURE 3: Curve of impact force for rigid structure under a small airplane crash.

land at a certain height. The speed of airplane had to be decreased because during their imminence, there is a decrease in velocity; therefore, airplane speed was set at 100 m/s.

The failure modes of a reticulated dome without roof sheathing under a small airplane crash have been described in reference [10]. In order to compare the obtained results for failure modes, we developed an FE model of a single-layer Kiewit-8 reticulated dome with 60-meter span and investigated the effect of roof sheathing while keeping other parameters same as that reported in Reference [10]. The thickness of roof sheathing could be changed, and in this study, we set the value of this parameter at 2 mm. Rise to the span ratio was 1/7, and roof load was assumed to be 60 kg/m². It was assumed that the main members of the reticulated

TABLE 1: Styles and velocities of small airplane crashes.

Serial no.	Impact styles	Impact velocity (m/s)
Impact 1	Horizontal impact	Horizontal: 100 Vertical: 0
Impact 2	Yaw impact	Horizontal: 98.0 Vertical: 20
Impact 3	Oblique impact	Horizontal: 86.6 Vertical: 50

dome were steel pipes such that latitudinal and radial members were $\Phi 180 \times 7.0$ mm and diagonal members were $\Phi 168 \times 6.0$ mm. In Reference [10], the effect of roof sheathing on the failure modes of reticulated domes under small airplane crashes were not considered and roof load was applied on joints in the form of mass elements Mass 166. However, in this work, the effect of roof sheathing was considered, and the

FIGURE 4: Impact positions of the reticulated dome.

roof load was uniformly applied on the roof sheathing in the form of gravity load `LOAD_BODY_Z`. The structure of the roof sheathing is shown in Figure 5.

3. Failure Modes of a Single-Layer Kiewit-8 Reticulated Dome with Roof Sheathing under a Small Airplane Crash

Because Impact 3, which was mentioned in Reference [10], has almost never been seen in real life, we focused on Impacts 1 and 2 for the crash position of Joint A, and Impact 2 for the crash positions of Joints B and C. Impact velocity was assumed to be 100 m/s. Airplane crash at Joint A with impact style 1 was denoted as 1-A, and impacts 2-A, 2-B, and 2-C were named following the same procedure.

3.1. Failure Mode of Reticulated Dome in 1-A. The airplane crash on the dome in 1-A mode is shown in Figure 6, and deformation development due to this impact style is shown in Figure 7.

Under this condition, the members in the impacted area were ruptured when the head of small airplane contacted the reticulated dome and entered into it. Then, the wings of aircraft crashed the dome and created distortion significantly expanding the damaged area. After that, the airplane overturned around its central axis and its front wings contacted the dome, further intensifying deformation. Finally, the airplane overturned nearly 180 degrees and detained in the dome. Meanwhile, the deformation of dome continued to develop until it was totally collapsed. In the entire event of small airplane crash, the impacted members were under complex stress states.

It was seen that the deformation caused by a small airplane horizontally impacting Joint A was different from that resulting from impact on a rigid structure. The fuselage was not easily flattened when the small airplane crashed a reticulated dome with roof sheathing, yet it overturned and drove the deformation of the dome. The final failure mode was the local dent. Because the small airplane did not fly out of the dome, this condition was unsafe.

FIGURE 5: The structural diagram of roof sheathing.

FIGURE 6: Airplane crashing the dome in 1-A.

3.2. Failure Mode of Reticulated Dome in 2-A. The airplane crash on the dome in 2-A mode is shown in Figure 8, and deformation development is shown in Figure 9.

In contrast with previous mode, in 2-A mode, the small airplane had a considerable vertical velocity component and with the flipping angle of less than that of 1-A. Similarly, the tail of the small airplane did not enter into the dome and its front wings got stuck in the dome. It drove dome deformation development, and finally the structure was collapsed.

3.3. Failure Mode of Reticulated Dome in 2-B. The airplane crash on the dome in 2-B mode is shown in Figure 10, and corresponding deformation development is shown in Figure 11.

Since the impact position of the reticulated dome in 2-B was high, its deformation was different from previous conditions. The small airplane made contact only with the top of the reticulated dome, and its head did not enter the structure. Small airplane first contacted reticulated dome at Joint B and its surrounding area. Then, the bottom of fuselage and tail crashed into the dome. The top of the dome and its neighboring areas showed a certain dent. After that, airplane flew out of the dome along the radial tangent direction of the dent. The deformation of the reticulated dome was continued until the structure was collapsed.

FIGURE 7: Deformation development of the dome in 1-A. (a) 0.2 s of the whole structure, (b) 0.2 s of the main members, (c) 0.9 s of the whole structure, (d) 0.9 s of the main members, (e) 2.2 s of the whole structure, and (f) 2.2 s of the main members.

FIGURE 8: Airplane crashing the dome in 2-A.

FIGURE 9: Deformation development of the dome in 2-A. (a) 0.03 s of the whole structure, (b) 0.03 s of the main members, (c) 0.15 s of the whole structure, (d) 0.15 s of the main members, (e) 0.6 s of the whole structure, (f) 0.6 s of the main members, (g) 1.5 s of the whole structure, and (h) 1.5 s of the main members.

In this condition, although the small airplane did not enter the reticulated dome and the number of damaged members was small, this impact style was extremely dangerous to the dome and global collapse took place very rapidly.

3.4. Failure Mode of Reticulated Dome in 2-C. The airplane crash on the dome in 2-C mode is shown in Figure 12. The characteristics of small airplane crashing the dome in this condition were similar to that in 2-A, and a dent was created.

FIGURE 10: Airplane crashing the dome in 2-B.

FIGURE 11: Deformation development of the dome in 2-B. (a) 0.3 s of the whole structure, (b) 0.3 s of the main members, (c) 0.6 s of the whole structure, (d) 0.6 s of the main members, (e) 1 s of the whole structure, (f) 1 s of the main members, (g) 2.6 s of the whole structure, and (h) 2.6 s of the main members.

FIGURE 12: Airplane crashing the dome in 2-C.

Since the airplane was detained in the dome, the deformation of reticulated dome was continued until the structure was collapsed. Deformation development for the dome in 2-C is shown in Figure 13.

4. Roof Sheathing Effect on the Failure Modes of Reticulated Domes under Small Airplane Crashes

The effect of roof sheathing on the failure modes of a reticulated dome when a small airplane crashed onto it was verified in this paper. Identical single-layer K8 reticulated domes with a span of 60 m, light roofs, and same roof loads and main member sizes with and without roof sheathing were investigated. Then, the effect of roof sheathing on the failure modes of the reticulated domes was investigated. The failure modes of the reticulated domes with and without roof sheathing under different conditions are shown in Table 2.

Under 2-A condition, there was a great difference between the failure modes of the two kinds of reticulated domes. Therefore, 2-A condition was selected to examine the response of reticulated domes under the crash of a small plane. At the moment of collision, the deformation behaviors of the main members in both domes were similar. The head of airplane contacted the reticulated dome, the members in the impacted area were ruptured, and the head

FIGURE 13: Deformation development of the dome in 2-C. (a) 0.2 s of the whole structure, (b) 0.2 s of the main members, (c) 0.6 s of the whole structure, (d) 0.6 s of the main members, (e) 1.6 s of the whole structure, and (f) 1.6 s of the main members.

of small airplane entered into the dome. However, there was a great difference between the two kinds of reticulated domes.

In the reticulated dome with roof sheathing, the airplane overturned due to roof sheathing and got entangled in the dome. The airplane had a considerable vertical velocity component, and its tail did not enter the dome. The deformation of reticulated dome was continued until the structure was totally collapsed.

In the reticulated dome without roof sheathing, the wings of the airplane contacted the dome, and the damaged area expanded significantly. Then its wings entered the dome and exhibited a cutting action leading to a bar-type opening on the top of the reticulated dome. The airplane flew out of the dome, and the failure mode of the reticulated dome was the local dent.

By comparing the failure modes of the two reticulated domes in Table 2, the following was found:

- (a) In domes without roof sheathing, the failure mode under 2-B condition was global collapse, while in the remaining three conditions, it was in the form of local dent. Similarly, in the domes with roof sheathing, the failure mode 1-A was local dent, while in the remaining three conditions, it was in the form of global collapse.
- (b) In all four conditions, domes without roof sheathing crashed on impact, and the airplane subsequently flew away from the dome. In contrast, the aircraft was detained in the domes with roof sheathing.
- (c) In 1-A and 2-B conditions, failure modes were the same, but instantaneous deformations differed greatly. The collapse range of domes without roof sheathing was smaller than those with roof sheathing in the late period of deformation.
- (d) The rupture of the damaged members in domes without roof sheathing was mainly due to shear failure. Small airplane flew out from the dome, and

the failure mode was local dent. In domes with roof sheathing, airplane overturned within roof sheathing, overall deformation became more extensive, and the failure mode was global collapse of continuous contact.

In the above analysis, it was clear that, compared with reticulated domes without roof sheathing, the failure modes of reticulated domes with roof sheathing were more dangerous. So, the effect of roof sheathing cannot be ignored in numerical simulations.

Concrete examples were used for further research on the effect of roof sheathing on the failure modes of reticulated domes. Some examples of reticulated domes with light roofs were studied, as described below.

Example 1 was a dome without roof sheathing, while example 2 was a dome with roof sheathing (with a roof thickness of 2 mm).

The deformation process in example 2 is shown in Figure 9. The global collapse of the reticulated dome with roof sheathing took place after continuous contact.

The deformation process of example 1 is shown in Figure 14.

Comparing Figures 9 and 14 showed that the main members of the two types of reticulated domes were deformed in the crash and the failure modes of the domes at the moment of collision were not much different. When the head of small airplane contacted the reticulated dome, the members in the impact area were ruptured, and the head of airplane entered the dome. Starting from 0.35 s, the small airplane was overturned about its axis.

Due to the presence of roof sheathing in example 2, the airplane turned over and was subsequently detained in the dome. In this case, the airplane had a vertical downward velocity component. Therefore, the tail of the airplane did not contact the reticulated dome and then entered the dome. The two failure modes were greatly different since the airplane in example 1 continued to go forward, and the deformation was developed when the wings contacted the dome, and the dome was seriously damaged. After that, the

TABLE 2: Failure modes of reticulated domes with and without roof sheathing in different conditions.

Serial no.	Reticulated dome with roof sheathing	Reticulated dome without roof sheathing
1-A	<p>Time = 2.2s</p> <p>Local dent</p>	<p>Time = 2.2s</p> <p>Local dent</p>
2-A	<p>Time = 1.5s</p> <p>Global collapse</p>	<p>Time = 1.5s</p> <p>Local dent</p>
2-B	<p>Time = 2.6s</p> <p>Global collapse</p>	<p>Time = 2.6s</p> <p>Global collapse</p>
2-C	<p>Time = 1.6s</p> <p>Global collapse</p>	<p>Time = 1.6s</p> <p>Local dent</p>

FIGURE 14: Development of deformation for the dome under small airplane crash in example 1. (a) 0.08 s, (b) 0.14 s, (c) 0.35 s, (d) 0.6 s, (e) 1 s, and (f) 5 s.

wing of the airplane entered the dome and cut it causing a strip opening on it. The airplane flew out of the dome, and the deformation of reticulated dome continued, although it did not lead to an overall collapse. The obtained results showed that during the entire impact process, the members impacted in example 1 primarily showed shear failure. The airplane in example 2 continued to go forward, overturned, and detained in the dome, and the deformation of the reticulated dome continued to develop until it was totally collapsed.

It was found from the above two examples that the fuselage of the airplane was not easily compressed and it entered the dome after the impact. The wings of the airplane performed a more obvious cutting action on domes without roof sheathing than those with roof sheathing. Therefore, the airplane was able to break away from domes without roof sheathing after impact, while this was limited by roof sheathing in domes with roof sheathing. The airplane was stuck in the dome and overturned, and dome deformation was rapidly developed causing failure by global collapse after continuous contact.

5. Conclusions

In this study, a Bombardier Challenger 850 small passenger airplane was selected as the prototype to develop a model for its impact on a reticulated dome. Then, a numerical model was developed for reticulated domes subjected to small airplane crashes, and the behavior of the dome under four different impact conditions was simulated. Finally, the behaviors of reticulated domes with and without roof sheathing were compared and the following conclusions were drawn:

- (1) The development principle of the airplane numerical model was determined. The size, quality, and mass distribution of the model were as close to a real airplane as possible because these are the main influencing factors. The detailed structure of the airplane was not important in this respect. An FE model should be simple with as few members as possible. Besides, the scale of the airplane model had to be comparable with that of the dome.
- (2) In the simulation, it was found that the wing of the airplane affected the failure modes of domes and it could not be ignored in investigating reticulated domes subjected to airplane crashes. Different failure modes were observed under different conditions. In general, reticulated domes with roof sheathing were easily collapsed when impacted by an aircraft, which is unfavorable.
- (3) Comparing large space structures with and without roof sheathing, the airplane wing found it more difficult to cut the members of the reticulated dome, and so, the influence was unfavorable in most cases. The deformation of the reticulated dome continued after the airplane was entangled in it changing the failure modes and aggravating

the damage of the dome in certain conditions. Thus, the effect of roof sheathing had to be considered in studying reticulated domes subjected to small airplane crashes. The conclusions drawn in this paper are useful in laying foundations for subsequent research on the impact resistance of reticulated domes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Supplementary Materials

Other researchers choose A320 and A380 aircraft as the research medium according to the requirements of test equipment. The research equipment in this paper is a single-layer reticulated dome with the span of 40–60 meters. The Bombardier Challenger 850 airplane model was chosen to match the size of the test equipment. (*Supplementary Materials*)

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