

## Research Article

### Size Effect and Material Property Effect of the Impactor on the Damage Modes of the Single-Layer Kiewitt-8 Reticulated Dome

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**Abstract:** The dynamic response of large space structures under accidental impact has been the subject of intense research since the occurrence of the 9/11 incident. In the present study, using the 3D ANSYS/LS-DYNA, size effect and material property effect of the impactor on the damage modes of the single-layer kiewitt-8 reticulated dome were investigated respectively, where the impactor was the cylinder and the impact direction was vertical. Firstly, Analytical results with the rigid impactor indicated that the impactor size can change the damage mode of the reticulated dome. It was found that the probability happening to the global collapse has an obvious rise with the size increase of the impactor. Furtherly, the deformable impactor was considered to figure out the difference with the rigid impactor, the comparisons indicated that the deformable impactor, who has the same mass and same striking velocity with the rigid impactor, can contribute to the occurrence of the global collapse at a certain initial striking condition.

**Keywords:** Damage mode, deformable impactor, impact, rigid impactor, single-layer kiewitt-8 reticulated dome, size effect

## INTRODUCTION

Shock dynamics mechanics of large space structure has gained researchers attention since the occurrence of the 9/11 incident. Large space structures are usually such symbolic buildings of social and economic importance. It is very necessary and beneficial to investigate the dynamic behavior of large space structures, aiming to look for the strategy to avoid the global collapse. Yet there are little study work approaching to the dynamic behavior of this kind of structures under impact.

Under accidental impact, lots of previous studies and investigations concentrated mainly on the frames and high-rise buildings, typical researches could be found in several typical works (Bonder and Symonds, 1979; Zhou *et al.*, 1989; Samuel, 2003; Lynn and Isobe, 2007). Yet, the work on the large space structures is relatively few. Analysis of single-layer Kiewitt-8 reticulated domes with low speed and small mass impact was conducted (Guo, 2004; Li *et al.*, 2006; Shi, 2005). Recently, Fan and his colleagues performed a series of study investigating behavior of single-layer Kiewitt-8 reticulated domes under the impact theoretically and numerically (Fan *et al.*, 2008, 2010).

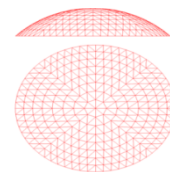


Fig. 1: Simulation model of the single-layer Kiewitt-8 reticulated dome

It is noted that the previous studies on single-layer Kiewitt-8 reticulated domes were paid few attentions to the impact of small size and it is assumed mostly that the impactor was rigid. Thus, in this study, size effect of the impactor to the dynamic response of the reticulated dome was conduct based on 3D numerical simulations. Meanwhile, the differences between the rigid impactor and the deformable impactor were analyzed.

## NUMERICAL MODELS

All the simulations in the study were performed with LSDYNA-3D code. Figure 1 shows a single-layered kiewitt-8 reticulated dome with a 60 m span. The dome consists of eight latitudinal circles and eight

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Table 1: Geometry parameters of single-layered kiewitt-8 reticulated dome

Latitudinal and radial member (mm)	Diagonal member (mm)	Span (mm)	Rise to span ratio	Roof load (kg/m <sup>2</sup> )
Φ180×7.0 mm	Φ168×6.0 mm	60	1/7	60/120

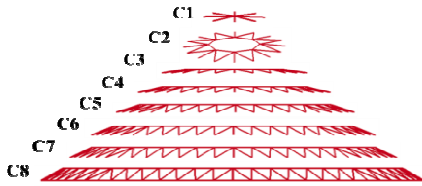


Fig. 2: Labeled number of every segment on the reticulated dome

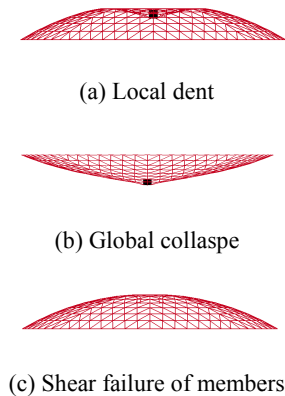


Fig. 3: Damage modes of single-layer kiewitt-8 reticulated dome

main radial ribs that divide the sphere into 8 axi-symmetrical fan-shaped segments, which are labeled to make the numerical results more clearly in Fig. 2. Diagonal members are applied to link the latitudinal and the main radial members and similar triangular grids are thus formed all over the spherical surface. In the present work, two kinds of roof load were involved, as given in Table 1.

For the rigid impactor, in order to assure that the impactor does not deform plastically during the impact process, its strength was artificially set to a relatively high value of 20 GPa in all simulations.

Reversely, for the deformable impactor, the material property is same to the dome structure. Since impact is related to the high strain rate, which is a very important role to the dynamic behavior of structures, thus the constitute model of piecewise JC was adopted for the dome structure and the deformable impactor, which can take into account the strain-rate effect to some degree. The initial yield stress was 207 MPa; the elastic modulus was 206 GPa, the Poisson's ratio was 0.3 and the effective plastic strain at failure was defined as 0.25 (Wang *et al.*, 2008).

In the following section, the impact events with the rigid impactor is named as the rigid impactor, similarly, the impact events with the rigid impactor is took place of the deformable impact.

### ANALYSIS OF DAMAGE MODES

Herein assumptions for damage analysis need to be given:

- Heat energy and gravity are not taken into account.
- The friction between the impactor and the curved beam is neglected.

Based on the model developed above, the damage characteristic of the dome with the initial kinetic energy was investigated. The numerical simulation results from the rigid impact and the deformable impact both indicated that there damage modes could be concluded according to the dynamic responses (Fig. 3).

**Mode 1: Local dent:** Due to the low initial kinetic energy, the impactor does not perforate the reticulated dome; the members on top of the reticulate dome are damaged locally without the break occurrence among the beams. The affect zone on the top of the reticulated dome is small in comparison with the whole structure. The final deformation is shown in Fig. 3a.

**Mode 2: Global collapse:** This damage is global, which can cause the whole structure collapse. Under this impacting load, the top of the reticulated dome moves down until touching the ground, the members around the top members are pull down, as described in Fig. 3b. On this damage mode, there exist two scenarios: global collapse without the plug and global collapse with the plug. The plug is due to that the members around the impactor happen to the break, when the impactor reaches a certain height, as shown in Fig. 6.

**Mode 3: Shear failure of members:** Different from Mode 2, there is only the punching plug without the downwarp phenomenon in this damage mode. The members hit directly by the impactor are broken instantly when the initial kinetic energy are large enough. For the instantaneous damage, the affected zone of the impact load is small in comparison with the other damage modes. The typical damage form is given in Fig 3c.

**Size effect of the impactor to the damage modes:** For the purpose examining the effect of the impactor size, three kinds of different size impactor were chosen. The impactors with the diameter 2, 5 and 10 m were applied to the impact, where the cylinder height with 2 m was kept same. By changing the density of the impactor, a series of different impact events with

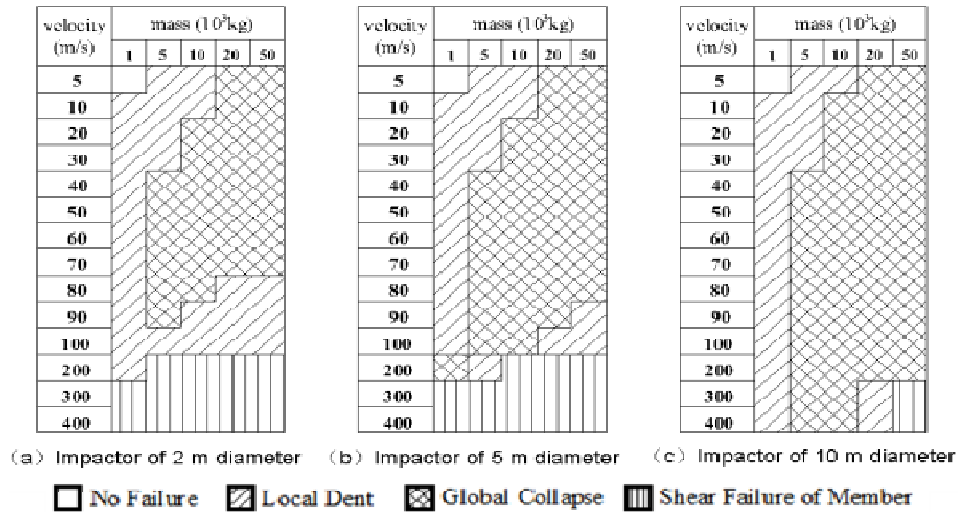


Fig. 4: Damage modes of the impact events with the roof load of 120 kg/m<sup>2</sup>

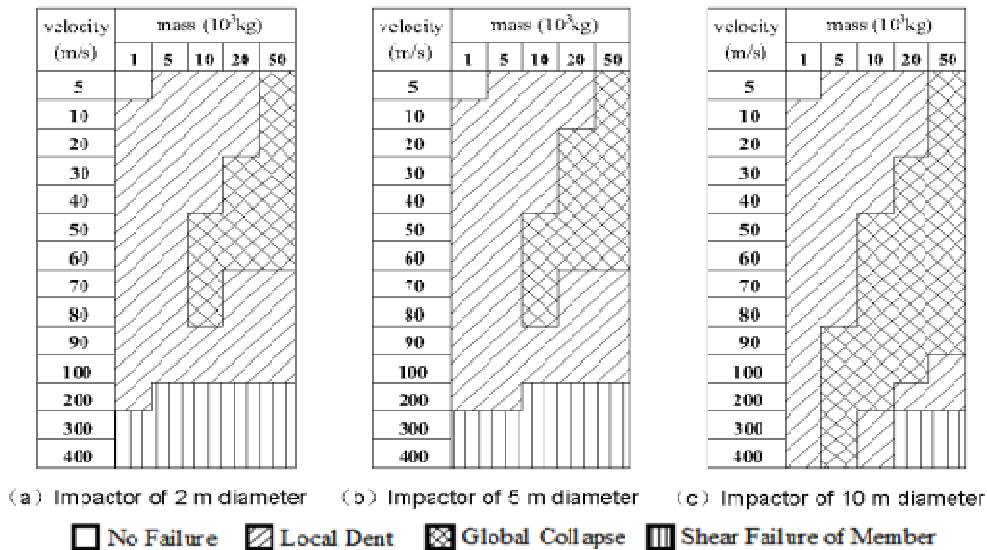


Fig. 5: Damage modes of the impact events with the roof load of 60 kg/m<sup>2</sup>

keeping the same striking kinetic energy were carried out. The range of the impactor mass and the striking velocity were respectively from 1 to 50 T and from 5 to 400 m/s.

Herein, it is necessary to point out that the impactor was assumed to be rigid, aiming to exclude the material property effect of the impactor.

The variations of damage modes with the mass and striking velocity of the impactor are given in Fig. 4 and 5. It was found that the impactor size play a key role in controlling the damage mode of the reticulated dome structure concerned in the present study. As shown in Fig. 4 and 5, the scope of Mode 2 gradually becomes larger with the increase of the impactor size. Conversely, the scope of mode 3 has a descended trend with the increase of the impactor size. On the other

hand, by comparisons between the Fig. 4 and 5, one deduces clearly that the load of roof can enhance the probability happening to the mode 2.

Aiming to make the analysis more clearly, two typical impact events with the same striking velocity and the same mass of the impactor were discussed in detail, where impactors with 2 and 10 m diameter were compared. The mass and the striking velocity of the impactor were respectively 10 T and 100 m/s. The damage processes are shown in Fig. 6 and 7. From the damage features, it could be concluded that the impact event with impactor of 2 m diameter belongs to the Mode 3. Matching with the characteristic of mode 2, the impact event with impactor of 10 m is in the range of mode 3. Thus, it is indicated that the change of the

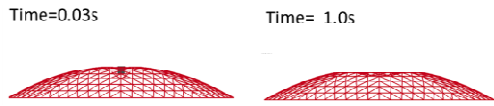


Fig. 6: Damage process of the impact event with impactor of 2 m diameter and 10 T mass and the striking velocity of 100 m/s

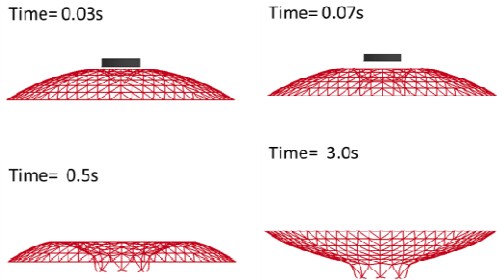


Fig. 7: Damage process of the impact event with impactor of 10 m diameter and 10 T mass and the striking velocity of 100 m/s

impactor size with the same initial striking kinetic energy can lead to the variation of the damage mode.

Furthermore, in terms of the strain energy, it was found that for the impact event with the impactor of 2 m diameter, the strain energy of the C1 has a dramatic increase, the strain energy of the C2 and C3 exhibit a smooth time history and the value of the strain energy is

relatively small. It seems to be zero on the strain energy of the other parts from the Fig. 8. Thus, it is demonstrated that the damage is concentrated on the C1. On the other hand, Fig. 8 shows that for the impact event with the impactor of 10 m diameter, every segment of this structure happens to the deformation in light of the observation of the strain energy and the strain energy of the C2 has a dramatic increase and the peak is relatively large, this leads us to get the conclusion that the members of the C2 are broken during the impact process. This furtherly indicates that the deformation of the impact event with the impactor of 10 m diameter is global. Finally, comparisons of the strain energy on two typical impact events prove again that the impactor size has an important effect to the damage mode of the reticulated dome.

### PROPERTY EFFECT OF THE IMPACTOR

In (Size effect of the impact or to the damage modes), size effect of the impactor was analyzed, where the impactor was assumed to be rigid. The material property of the impactor was ignored. But, in reality the deformable impactor was common, it is necessary to investigate the dynamic response of the dome structure subjected to the deformable impact.

Thus in this section, the work on the deformable impact was approached. The material property is kept

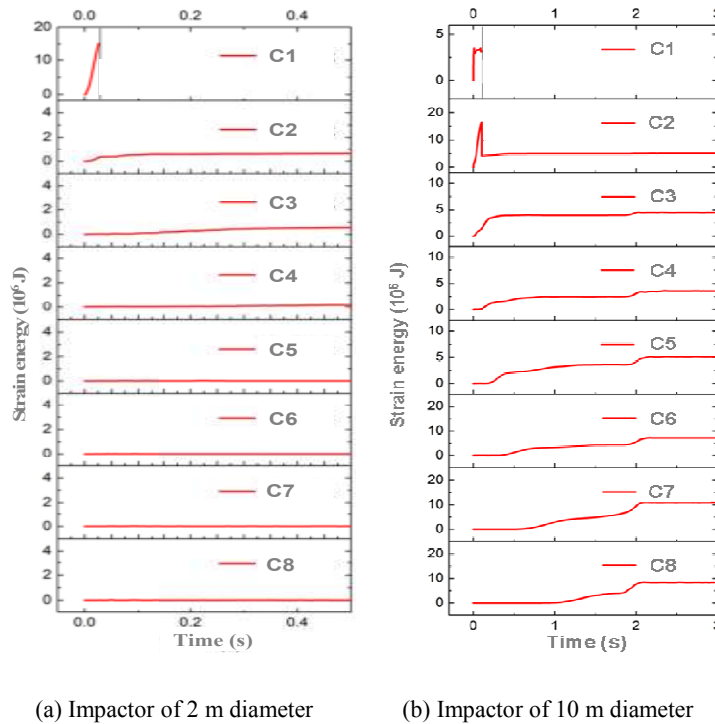


Fig. 8: Time history of strain energy on two typical impact events with two different impactors and the same initial striking kinetic energy

Table 2: Deformable impactors analyzed

Mass (T)	1	5	10	20	50
Diameter (m)	0.543	0.928	1.170	1.474	2.000
Height (m)	0.552	0.943	1.189	1.498	2.033

same with that of the dome structure. The mass of the impactor is changed by adjusting the geometry parameters. The detailed information on the deformable impactor is given in Table 2.

As described in (Analysis of damage modes), the damage modes of the dome structure against to the deformable impact are similar with that of the rigid impact. The final analytical results are given in Fig. 9 and 10. It is found that for the dome structure with the roof load of 60 kg/m<sup>2</sup>, there is no difference between

the rigid impact and the deformable impact. But, when the roof load is 120 kg/m<sup>2</sup>, the distribution of the damage modes happens to the change: the area of the global damage mode becomes larger than that of the rigid impact.

Aiming to check the reason resulting in the difference, two typical cases were discussed, where the roof load was 120 kg/m<sup>2</sup> and the mass and the striking velocity are 10 T and 90 m/s respectively, the corresponding geometry parameters can be gained in Table 2.

Figure 9 shows that at this kind of initial striking condition the case with the rigid impact is corresponding with the local damage mode, reversely,

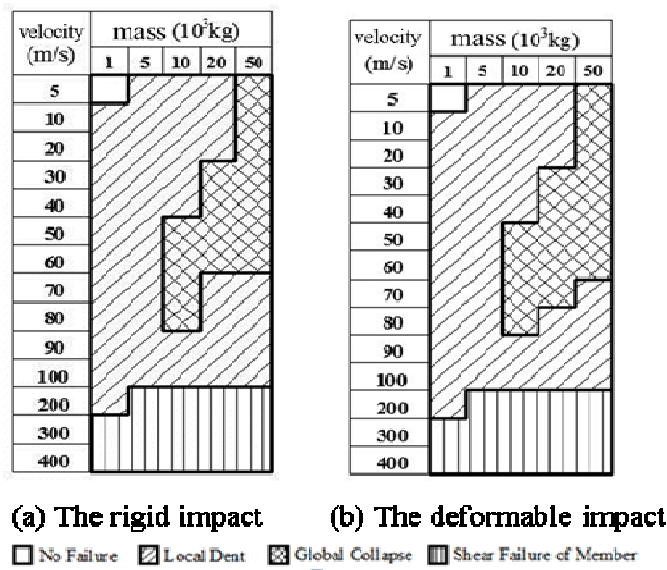


Fig. 9: Comparison of the impact events with the roof load of 60 kg/m<sup>2</sup> between the rigid impact and the deformable impact

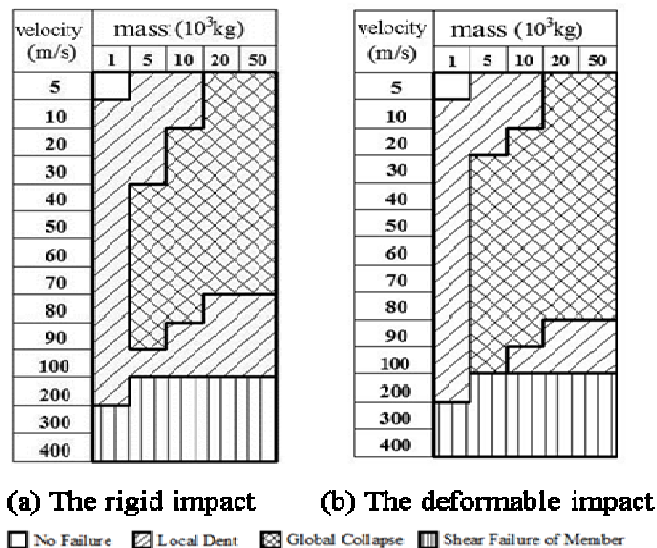


Fig. 10: Comparison of the impact events with the roof load of 120 kg/m<sup>2</sup> between the rigid impact and the deformable impact

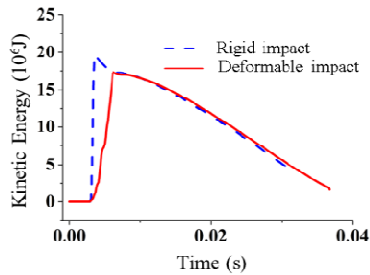


Fig. 11: Kinetic energy of C1 segment

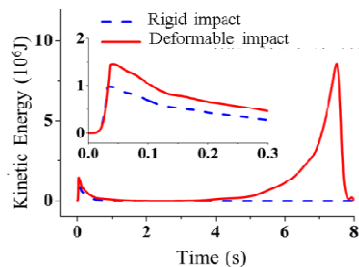


Fig. 12: Kinetic energy of the un-impacting region

the case with the deformable impact is characteristic of the global damage mode. It is found that the variation of C1 strain energy on the case with the deformable impact exhibits a milder trend than that of case with the rigid impact, as described in Fig. 11. And total strain energy of other segments emerges two peaks for the case with the deformable impact in Fig. 12; this indicates the energy gains the deliver from C1 segment to C2 segment. Thus it could be summarized that the difference between the rigid impact and the deformable impact mainly attributes to the succession of the energy from the structure top to the bottom.

### CONCLUSION

In the present study, a series of 3D numerical simulations were conducted to investigate the dynamic response of the single-layer kiewitt-8 reticulated dome against the rigid impact and the deformable impact, where the rigid impact means that the impactor is set to be rigid, reversely, the deformable impact is corresponding to the impact event that the impactor is deformable during the impact process. Firstly, based on the deformation features from the rigid impact and the deformable impact, three damage modes were identified, which are local dent, global collapse and shear failure of members respectively. Furtherly, based on the simulation results from the rigid impact, comparisons of damage modes among impact events indicate that the probability happening to the global collapse has a rise trend with the increase of the impactor size. And this conclusion gets the further validation by the analysis of the strain energy of the typical impact events during the impact process.

On the other hand, the difference between the rigid impact and the deformable impact was conducted, it was found that for the dome structure with the roof load of 120 kg/m<sup>2</sup>, the deformable impact more easily contributes to the occurrence of the global damage mode, the motivation driving to the difference is mainly from the energy delivered from the structure top to the bottom.

### ACKNOWLEDGMENT

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