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Failure modes for reticulated domes under diverse impact

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Abstract

FE models of both the single-layer Kiewitt-8 reticulated domes with a span of 60m and the cylindrical impactor were developed incorporating ANSYS/LS-DYNA. Afterward, fourteen groups impact are simulated by changing the impact position or impacted angle on reticulated dome, and impact velocity and mass of impactor are changed for each group impact. On the basis of large numbers of numerical simulations, characteristics of dynamic response for reticulated dome under impact are shown. And four failure modes (Members slightly damaged, Local collapse of dome, Global collapse of dome, Members shear failed) are presented for single-layer Kiewitt-8 reticulated dome under diverse impact. The distributing of failure modes for the fourteen types impact are different from each other, and the adverse position and angle are summrized.

Keywords: reticulated domes; impact; failure mode; dynamic response

1. Introduction

Large space structures, such as Olympic gymnasiums and hangars, are important structure types and used widely by congested people. If such architecture is attacked, loss is serious. At the same time, though impact load is the accidental load, it can be caused by too many factors, such as war, misplays during construction and wind-borne debris and so on. Yet research of the behavior of this kind of structures under unexpected impact has so far been little.

Published studies of performance of buildings under accidental impact mainly concentrate on frames and high-rise buildings (Bonder S R *et al.* [1]; Symonds P S *et al.* [2]; Lindberg B *et al.* [3]; Zhou *et al.* [4]; Lu *et al.* [5]; Samuel Tan [6]; Zhao *et al.* [7]; Xiong *et al.* [8]; K.M. Lynn *et al.* [9]; Liu *et al.* [10]). Analysis of single-layer Kiewitt-8 reticulated domes under impact with low speed and small mass was conducted (Guo [11];

Shi [12]; Li *et al.* [13]), in which penetration of dome from impact was not involved, and the dynamic responses of domes to the low speed and small mass impact were introduced. Fan and his colleagues conducted a series of study investigating behaviour of single-layer Kiewitt-8 reticulated domes under impact[14-18], by employing the analytical tool ANSYS/LS-DYNA. Wang *et al.* [14] gives solutions of structure under impact by the theoretical analysis and numerical simulations using ANSYS/LS-DYNA, respectively. The results from the two methods were identical to each other, and the FE models developed were thus validated. The characteristics of dynamic response were revealed based on large amount of numerical analysis in Fan *et al.* [15]. The mass and velocity of impactor covered a wider range, and the analysis was conducted with an emphasis on the failure of penetration of domes. While in Wang *et al.* [16], effect of the inertia force to the final deformation of structure was investigated. On the basis of the above work, the whole failure process was divided into three stages, and the failure mechanism was explained from a viewpoint of both energy transfer and ways of member failure (Fan *et al.* [17]; Wang *et al.* [18]). Then impact on diverse position with diverse angle has not been mentioned.

Large amount of numerical simulations are conducted on reticulated dome under impact on diverse position with diverse angle. On the basis of the above work, characteristics of dynamic response (impact force, stress of members, displacement) are introduced. Failure modes for diverse impact are given out. Moreover, adverse position and angle for reticulated dome under diverse impact are both found.

2. Characteristics of dynamic response for reticulated dome under diverse impact

There are mainly two methods to investigate the dynamic response of structures under impact loads, analytical method and the FE method. FE method is based on the Hamilton variation principle. FE method is most efficient method to deal with dynamic response of structures, as FE software is the efficient tool for researchers. ANSYS/LS-DYNA is popularly used to model the behavior of structures under impact load both at home and abroad. Therefore, numerical simulation in this paper adopts ANSYS/LS-DYNA.

2.1. Numerical model of reticulated dome under impact

The single-layer Kiewitt-8 reticulated dome consisted of 8 latitudinal circles and 8 main radial ribs that divided the sphere into 8 axi-symmetrical fan-shaped segments. Diagonal members were applied to link the latitudinal and the main radial members, and similar triangular grids were thus formed all over the spherical surface. Figure 1

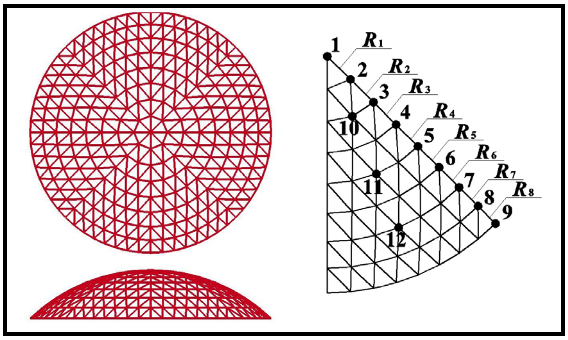


Figure 1: The dome and the designation

shows the single-layer Kiewitt-8 reticulated dome and the designation of main joints and members. The parameters of the dome are shown in Table 1. Based on the commercial FE package ANSYS/LS-DYNA, each member between two joints (a joint was naturally a node in the FE mesh) was modelled with a beam element, Beam161; while solid elements, Solid 164, were used to model the impactor; and mass elements, Mass166, were used to simulate the roofing materials. Published research shows that strain rate plays an important role on behaviour of structures under impact (D. Karagiozova *et al.* [19],[20]). Therefore, the constitutive model of steel was chosen as Piecewise Linear, which takes strain rate into account, and is especially suitable for steel in ANSYS/LS-DYNA. In the meantime, the Rigid Body was chosen as the material model of impactor. To simulate the collision between the impactor and dome, the contact technique NODES TO SURFACE (NTS) was introduced, in which the penalty function algorithm was used. The initial yield stress was 207MPa; the elastic modulus was 206GPa; the Poisson's ratio was 0.3; and the effective plastic strain at failure was defined as 0.25.The dome was simply supported. In the analysis using ANSYS/LS-DYNA, the following assumptions were observed: (1) stress waves spread to the whole beam instantaneously; (2) during the impact, there is the conversion only between the kinetic energy of impactor and the strain energy and the kinetic energy of dome, the heat energy is not taken into account; (3) the effect of friction and damping is neglected; (4) the impactor is rigid (Wang *et al.* [18]).

Table 1 Parameters of the Kiewitt form single-layer reticulated dome

Radial and latitudinal member /(mm•mm)	Diagonal member /(mm•mm)	Span /(m)	Rise to span ratio	Load of roof (N•m^{-2})
φ152x5.5mm	φ146x5mm	60	1/5	900

2.2. Numerical example of reticulated dome under oblique impact

The cylinder impactor, with a mass of 2.0×10^4kg , struck the joint 5 of dome normally with an initial velocity of 60m/s. The impact process is shown in Figure 2.

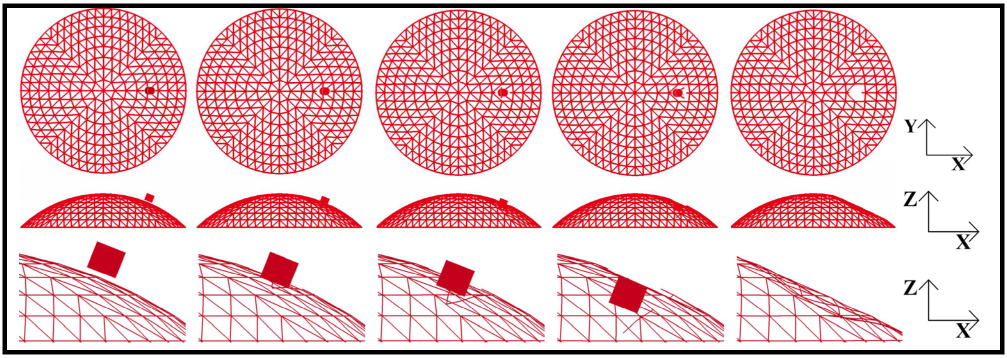
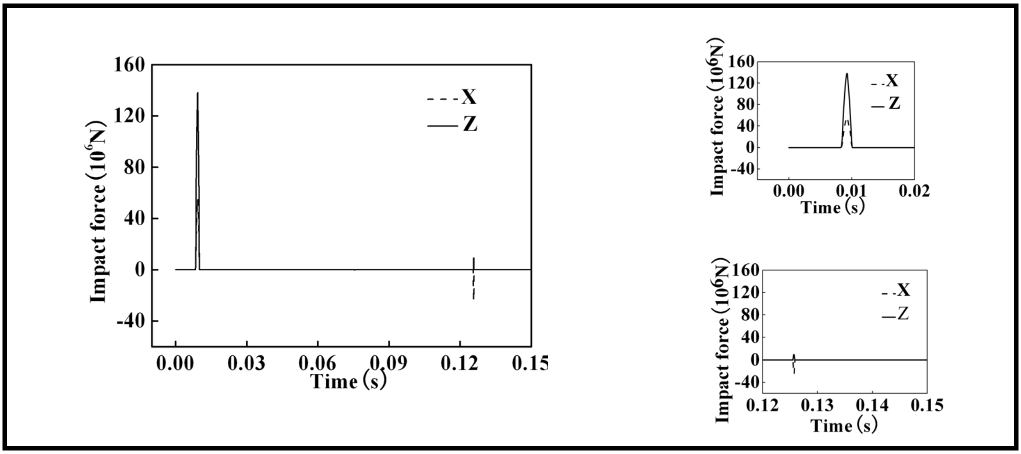


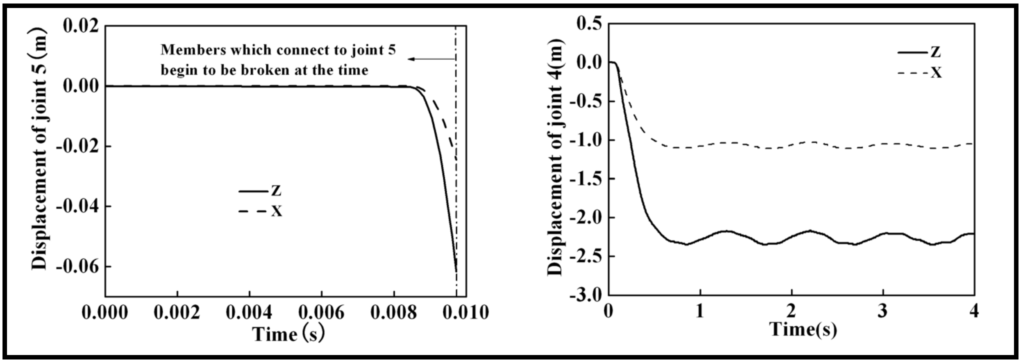
Figure 2: Impact process

The impact force, the vertical displacement of dome and the stress of members R_3 and R_4, all vary with time. The impact force was in the form of half sine shock pulse, with a peak value of over 1.4×10^3kN and a very short impact duration of about 1.8ms, as shown in Figure 3. Figure 4 shows that the dome vabrates after the final deformation occurrence, and time for final deformation occurrence, finish of dent, is measured in second. Members under direct impact were broken with high failure stress. The failure stress exceeds yield stress much for effect of strain rate. Stress in other members reached a peak value, and then the stress vibrated freely as shown in Figure 5. Impact brought six members which connect impacted joint to the strength failure and gave rise to larger displacement around the impacted joint of dome in this case. However, only the local zone is affected by impact and dents.



(a) Impact force (b) Amplification of local of (a)

Figure 3: Impact force



(a) Displacement of joint 5 (b) Displacement of joint 4

Figure 4: Displacement of joints

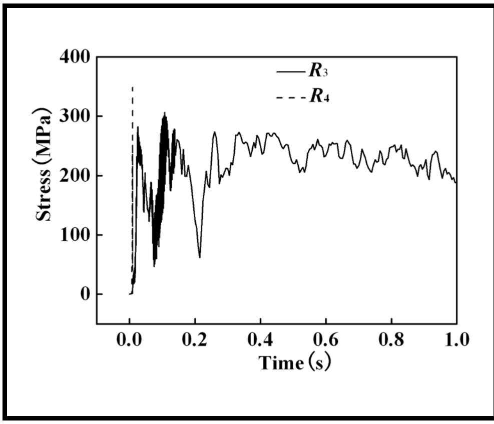


Figure 5: Stress of members

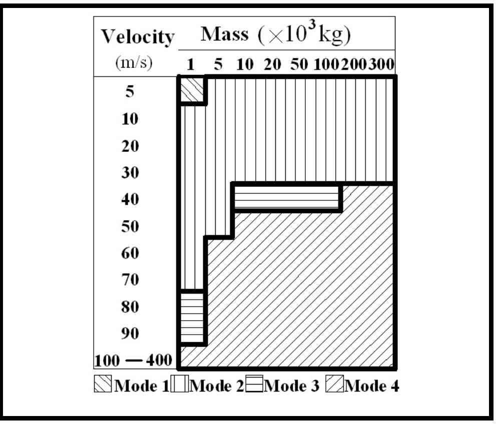


Figure 6: The distribution of failure modes of vertical impact on apex

3. Failure modes of reticulated dome under diverse impact

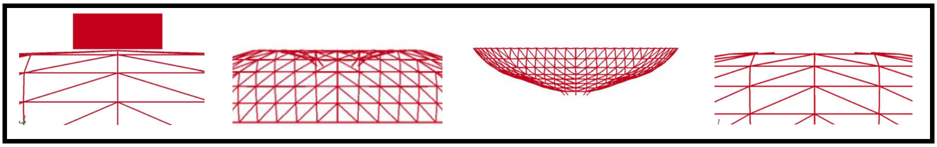
3.1. Failure modes of reticulated dome under vertical impact load

The failure modes of Kiewitt form single-layer reticulated dome under vertical impact on apex were investigated in Fan *et al.* [15]. The FE model was the same as in the previous section. The reticulated dome was struck by an impactor with different mass and velocity. Mass change of the impactor was achieved by adjusting the density, in order to avoid affecting the result due to the volume and shape change of impactor. The impact mass and velocity is shown as below:

Impact mass(10^3kg):1,5,10,20,50,100,200,300;

Impact velocity (m•s-1): 5,10,20,30,40,50,60,70,80,90,100,200,300,400.

Then four failure modes have been summarized according to the dynamic response of impact. Mode 1: Slight damage of member; Mode 2: Local failure of dome; Mode 3: Global collapse of dome; Mode 4: Shear failure of member. The distribution is shown in in Figure 6. The final deformation is shown in Figure 7.



(a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4

Figure 7: The final deformation of four failure modes

3.2. Failure modes of reticulated dome under diverse impact load

It is a special case that vertical impact on apex of reticulated dome. Impactor can come from any direction and impact any position of dome. Therefore, impact on diverse position and angle is conducted in order to make clear the failure modes of reticulated dome under diverse impacts. The impact positions and angles are shown as below:

Impact position: 1,3, 5, 7, 10,11,12;

Impact angle: normal, perpendicularity.

Impact mass(10^3kg):1,5,10,20,50,100,200,300;

Impact velocity (m•s-1):

5,10,20,30,40,50,60,70,80,90,100,200,300,400,500,600,700,800,900,1000

Vertical impact on joint 1 has been done before. Failure modes of the other thirteen groups impact consist with the modes before. Only the distributing of the modes has difference with each other.

Mode 1: Slight damage of member. The members are damaged slightly but not broken. Different from other modes, impactor does not penetrate reticulated dome because of the small mass and low speed. Therefore, the impactor rolls down along the surface of the dome. While if vertical impact on apex of dome, impactor hits the apex of dome and rebounds repeatedly, until the energy is exhausted. The impact process is shown in Figure 8.

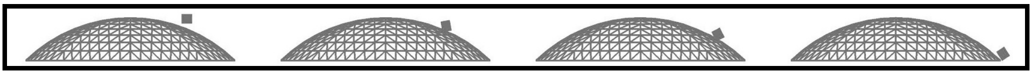


Figure 8: Mode 1

Mode 2: Local failure of dome. Many members around the impact zone are broken by the impactor. The zone around the apex of dome dents. The impact process is shown in Figure 2.

Mode 3: Global collapse of dome. Under large impact, instead of local dent of dome, the dented zone continues from one side of dome to grow to all the loops, resulting in collapse of the whole dome. In this mode, many members around the impact zone are broken, and the dome exhibits a kind of dynamic instability. The impact process is shown in Figure 9.

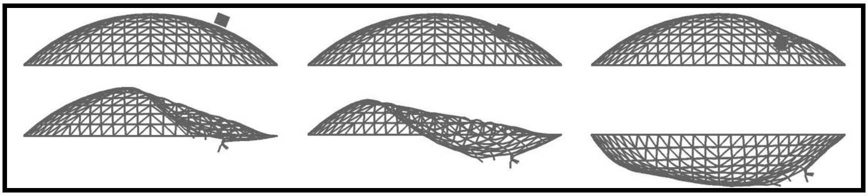


Figure 9: Mode 3

Mode 4: Shear failure of member. The members hit directly by impactor are broken instantly if the impact mass or velocity are large enough. For the instantaneous failure, the affected zone of the impact load is the small area under direct strike of impactor. The energy largely goes with the impactor which penetrates the dome, leaving only very little for the dome to absorb. The impact process is shown in Figure 10, indicating little deformation of dome from the impact. That is the same as the mode in vertical impact on apex of dome.

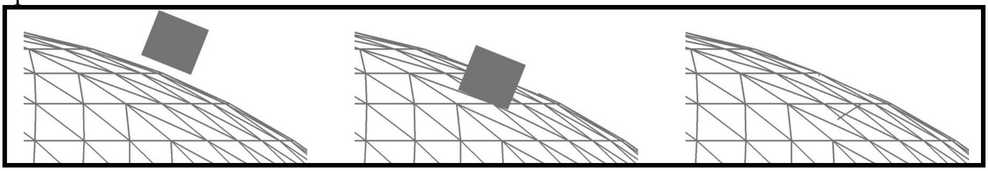


Figure 10: Mode 4

Figure 11shows the distribution of failure modes for some impact.

4. Conclusions

Based on the analytical study on Fourteen groups impacts on reticulated dome, conclusions as bellow have been drawn:

1 Characteristics of dynamic response are that:

(1) Shape of impact force is half sine shock pulse with a high peak value, and impact duration is short that is measured in millisecond;

(2) If the dome is penetrated through, members which impactor contacts are broken immediately, the failure stress exceeds yield stress because of effect of strain rate, and stress of other members vibrates. While stress of members vibrates due to the rolling impactor if no broken members;

(3) The impacted zone will dent, and value of impact load decide the dented range, local dent or global dent. Time for final deformation occurrence, finish of dent, is measured in second.

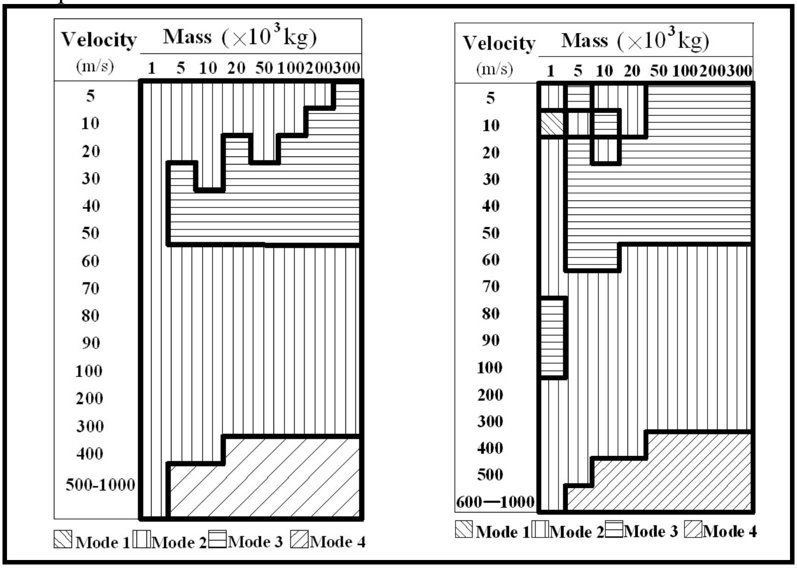
2 Study on failure modes of reticulated dome under diverse impact shows that:

(1) There are four failure modes for single-layer reticulated dome under impact load in all.

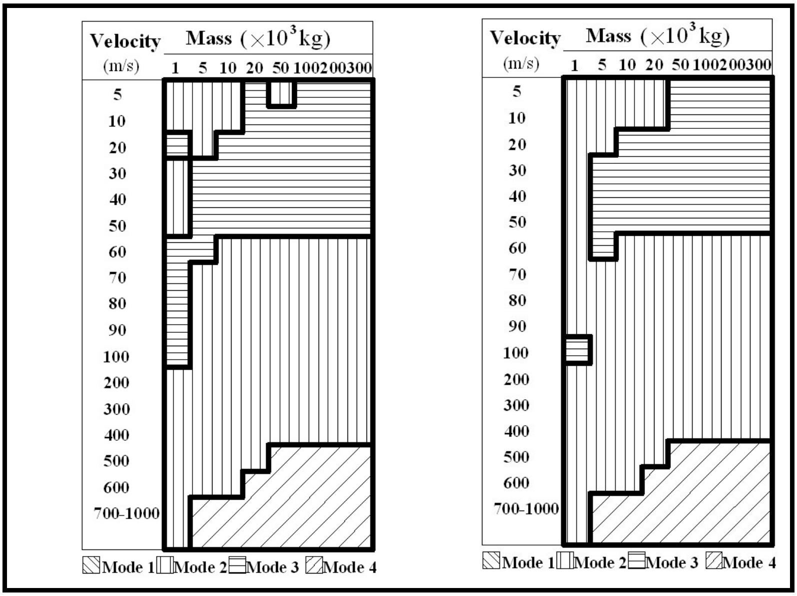
(2) With the incresae of mass and velocity of the impactor, the failure modes change in the order of Mode 1, Mode 2, Mode 3, Mode 2, Mode 4, except distributing of vertical impact on apex is Mode 1, Mode 2, Mode 3, Mode 4;

(3) Impact position closing with the support, results in less failure of Mode 3, Global

collapse of dome; And the normal impact leads to more cases of Mode 3 than the vertial impact.



(a) Vertical impact on joint 11 (b) Normal impact on joint 11



(c) Normal impact on joint 3 (d) Normal impact on joint 7

Figure 11: The distributing of failure modes

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