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Failure mechanism of single-layer saddle-curve reticulated shells subjected to earthquakes

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Abstract
In order to have a good understanding of the failure mechanism of single-layer saddle-curve reticulated shells under earthquake motion, dynamic failure mode of single-layer saddle-curve reticulated shells under earthquake motion is discussed with accumulation of material damage introduced to analyze the failure of these shells under dynamic actions. Based on the comprehension of the mechanical behaviours and structural full-range characteristic responses in an example, dynamic strength failure due to excessive development of plastic deformation is a mainly failure mode for single-layer saddle-curve reticulated shells subjected to earthquakes. Then, a method is proposed for determination of failure state. The relationships between structural responses under ultimate load and different structural parameters are investigated through simulation.

Keywords: single-layer saddle-curve reticulated shells, earthquake, dynamic strength failure, damage accumulation.

1. Introduction
Many researchers often use single-layer reticulated shells as the familiar form of spatial structures to study their structural responses and failures under strong earthquake motion [1-5]. These studies have also involved in dynamic failure mechanism of reticulated shells. Two dynamic failure modes, dynamic instability and dynamic strength failure, are presented in Ref.[6], and the methods for estimating their ultimate loads have been advanced in Ref.[6] and Ref.[7]. Moreover, a method is proposed using the fuzzy synthetic evaluation theory and the structural responses for classification of failure modes [8]. But it should be noted that these studies on dynamic failure mechanism mainly concentrate on single-layer reticulated domes or single-layer cylindrical reticulated shells. Study on single-layer saddle-curve reticulated shells, as another familiar form of spatial structures, is infrequent. Therefore, its failure mechanism under strong earthquake motions should be also concerned.

In this paper, failure mode of single-layer saddle-curve reticulated shells under earthquake is discussed with accumulation of material damage introduced to analyze the failure of these shells under dynamic actions. A method for estimating the ultimate load is proposed based on the comprehension on structural anti-seismic performance. The relationships between structural responses under ultimate load and different structural parameters are then investigated through simulation.

2. Models and analytical method

2.1 Models of single-layer saddle-curve reticulated shells

As shown in Fig.1, the models of single-layer saddle-curve reticulated shells are of orthogonal diagonal grid type. And these shells are of conventional design (the tube cross-sections are shown in Appendix Table1). All the supports located on four sides of the analyzed models are three-way hinged immovable supports.

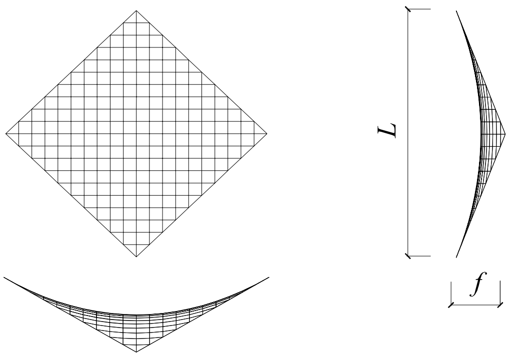


Figure1: Analysis model of a single-layer saddle-shape reticulated shell

Table.1 Analysis parameters of single-layer saddle-curve reticulated shells

Span / *L* （m）	40
Roof Weight (kg/m²)	60 120 180
Rise-Span / *f/L*	1/3 1/5 1/7
Earthquake	Taft (1952) El-Centro (1940)
Geometric Imperfection / *r*	0 *L*/300
Material Damage Accumulation	Considered

The nonlinear time-history response analysis is carried out using the finite-element package ABAQUS with geometrical and material nonlinearity considered. The PIPE element with a cross-section shown in Fig.2 is used to simulate the components of single-layer saddle-curve reticulated shells. Elasto-plastic steel, with a yield stress of 235MPa and Young's modulus E of 2.06×10^5MPa while the material no damage, is used as the material for analysis. Rayleigh damping, which parameters is calculated by the natural periods of the first-order modal and the second-order modal, is adopted during the analysis, and the damping coefficient is 0.02.

2.2 analytical methods and consideration of material damage accumulation

For the study on the dynamic failure mechanism of a spatial structure, the effective method tracing the full-range dynamic responses has been proposed in Ref. [6]. From the full-range of dynamic actions, the researchers observe the relationships between structural responses and its corresponding peak accelerations of dynamic actions, so that the structural performance can be evaluated using these full-range curves and some typical structural responses.

The following are the definition of some typical structural responses:

Ratio of members with different levels of development of plastic deformation on cross-section (1P~8P, as shown in Fig.2): There are eight integration points on the cross-section. Symbol *n*P indicates that at least *n* integration points yield on the cross-section, and 8P indicates the whole section yields. Ratios of 1P~8P members in whole structure represent the range and level of plastic yielding.

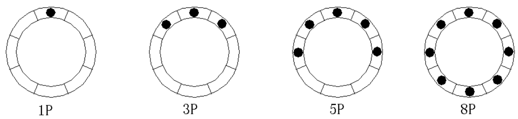


Figure 2: Definition of development different levels of plastic deformation on cross-section

Number of members with different failure levels on cross-section (1F~8F): Symbol *n*F indicates that at least *n* integration points failure on the cross-section, and 8F indicates the member number of whole section failure breaking.

Maximum displacement: The maximum deformation of a single-layer saddle-curve reticulated shell in the whole dynamic action process.

The effect of material damage accumulation should not be neglected because excessive plastic deformation can be found in strength failure examples [9]. A user-defined material subroutine is developed within ABAQUS to take into consideration material damage accumulation. Material damage index D is based on the steel component hysteretic tests in Refs.[10, 11], and it can be given by Eq. (1). The value of D indicates the degree of damage at an integration point in the analysis (i.e. material points in analytical model, the distributing in an element cross-section is shown in Fig. 2). Material damage index D equals to 0.0 means no damage, while D equal to 1.0 means complete failure of material, a fracture status for tension or compression. The corresponding Young's modulus of elasticity E_D and the yield stress σ_D can be expressed by the following equations respectively.

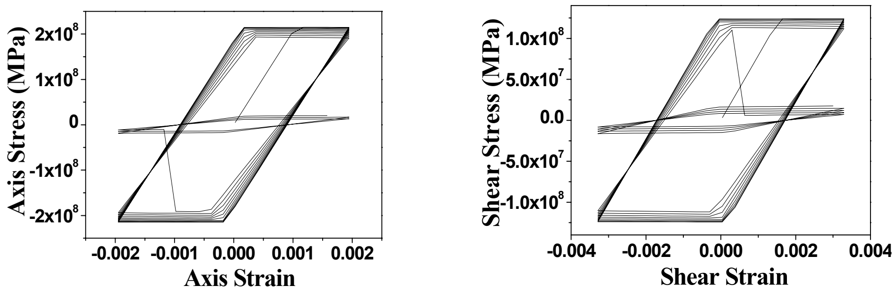
$$D = (1-\beta)\frac{\varepsilon_m^p}{\varepsilon_u^p} + \beta\sum_{i=1}^{N}\frac{\varepsilon_i^p}{\varepsilon_u^p} \tag{1}$$

$$E_D = (1-\xi_1 D)E \tag{2}$$

$$\sigma_D = (1 - \xi_2 D)\sigma_S \tag{3}$$

where, N is the number of half-cycles which causes plastic strain; ε_m^p is the maximum plastic strain during all the half-cycles; ε_i^p is the plastic strain during the ith half-cycle; ε_u^p is the ultimate plastic strain, based on the Q235 steel experimental value of ε_u^p equals to 0.11; β is a weight value equal to 0.0081; ξ_1 and ξ_2 are material parameters equal to 0.227 and 0.119, respectively; and σ_s is the yield stress without material damage accumulation.

The self-developed user subroutine is validated though standard tests. The stress-strain curves simulating the axial tension and the torsional shear of steel are shown in Fig. 3. When D reaches 1.0, elastic modulus E_D becomes $0.02E$ to simulate material fracture as shown in Fig. 3, and here a small nonzero Young's modulus is necessary for convergence in calculation.

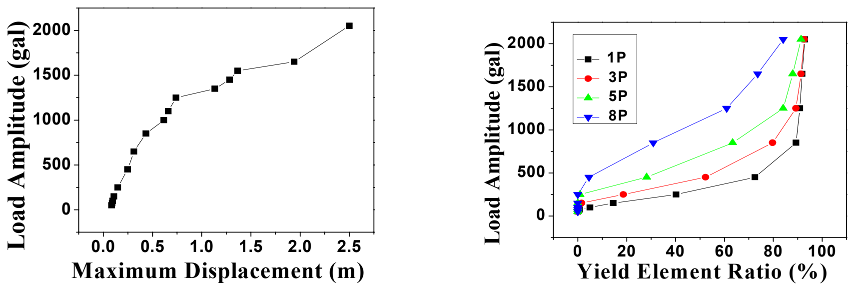


a. Axial tensile-compression test b. Torsional shear test

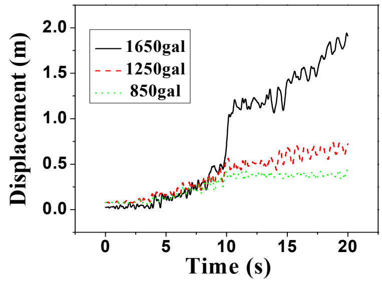
Figure 3: Stress-strain curves of validating user subroutine

3. Failure mode and structural performance

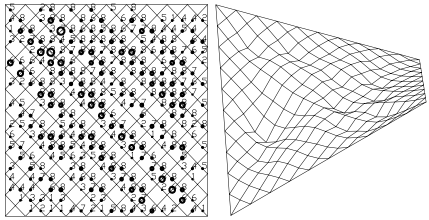
As an example, the dynamic full-range analysis of single-layer saddle-curve reticulated shell SD40185, number means L=40m, roof weight equals to 180 kg/m^2, f/L=1/5, which is the same as that at Taft shown in Fig.4.



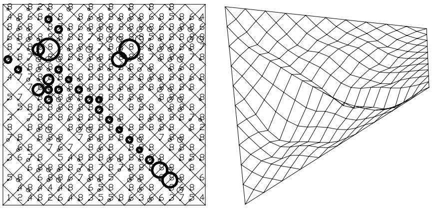
a Full-range curve of maximum displacement b Full-range curves of yielded element ratio



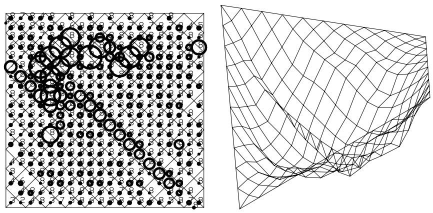
c Time-history curves of node displacement



d Deformation and plastic distribution at 700gal



e Deformation and plastic distribution at 1250gal



f Deformation and plastic distribution at 1650gal

Figure 4: The dynamic full-range responses

It can be seen from Fig.4b, a partial material yield starts at the earthquake wave amplitude of 100gal in the single-layer saddle-curve reticulated shell of this example, and at this state the maximum displacement of shell is only 0.09m. The maximum displacement amplitude and the yield element ratio increase continuously as the loads increase in th range from 100gal to 1250gal. The whole-section yield elements ratio (ratio of 8P) at 1250gal equals to 60%, and the corresponding number of 8F member is up to 109. These characteristics show us that the reticulated shell has attained to failure state for a long time. It should be noted that the post-failure saddle-curve reticulted shell can endure stronger earthquake motion, but these simulating results are insignificance because of structural huge deformation and a large number of cracked members. As shown in Fig.4d, the yielded elements are marked by small circles, the size of which indicates the degree of plastic development. While the integer indicates the number of integration points yielded. The members located in diagonal yield easily, the plastic deformation in diagonal part is also severer.

In the example, excessive development of plastic deformation can be found prior to the structural collapse, and the rigidity of the structure decreases sustainingly along with the growing of load intensity, and the equilibrium positions of vibration of the nodes may seriously drift from their original positions, so that the shell structure can not maintained its original shape, and the structure has reached an ultimate state primarily caused by material strength failure. Consequently, the failure mode is a typical dynamic strength failure. Through investigating results of a number of simulation, the dynamic strength failure is only the failure mode for the single-layer saddle-curve reticulated shell under strong esrthquake motion, and dynamic instability wouldn't happen. This is different with single-layer reticulated domes and cylindrical reticulated shells.

4. The distinguishing of ultimate load

It can be seen from the example in last section that there is not a distinct failure characteristic while the single-layer saddle-curve reticulated shell is subjected to continually increased earthquake motions. So a method for distinguishing the ultimate load is proposed based on general judgement of structural responses and practical factors in engineering. In this example, the maximum dispalcement at 700gal reaches 0.378m. The corresponding ratio of yield elements (ratio of 1P) equals to 86% and the ratio of whole-section yield elements (ratio of 8P) equals to 20%. Moreover, there have been some whole-section fracture members (8F members) in the reticulated shell, and it indicates that the reticulated shell has lost its integrity. The maximum displacement equaling to about 1/100 of shell span is much likely to cause severe damage of accessory roof facility. Based on these factors above, the reticulated shell should reach on ultimate state, and the ultimate load can be determined as 700gal. In like mannar, the ultimate load and the corresponding structural responses of examples in Tab.1 are tabulated in Table 2.

Table.2 Structural responses of single-layer saddle-curve reticulated shells at failure state

Earthquakes	No. of single-layer saddle-curve reticulated shell	Ultimate load (gal)	Maximum displacement (m)	Ratio of 1P / r_1	Ratio of 8P / r_8	Number of 8F member	Ratio of Dis to Span
Taft (1952)	SD40063	800	0.273	0.874	0.201	1	1/146
	SD40123	750	0.283	0.855	0.209	7	1/141
	SD40183	700.	0.289	0.818	0.197	9	1/138
	SD40065	850	0.305	0.891	0.203	1	1/131
	SD40125	800	0.33	0.875	0.201	2	1/121
	SD40185	700	0.368	0.862	0.205	4	1/109
	SD40067	900	0.312	0.907	0.202	2	1/128
	SD40127	850	0.35	0.898	0.201	1	1/114
	SD40187	750	0..388	0.873	0.203	2	1/103
El-Centro (1940)	SD40063	1350	0.305	0.907	0.204	1	1/131
	SD40123	1150	0.33	0.86	0.201	10	1/121
	SD40183	1100	0.378	0.83	0.198	9	1/106
	SD40065	1700	0.307	0.907	0.206	2	1/130
	SD40125	1550	0.343	0.894	0.193	2	1/116
	SD40185	1300	0.391	0.884	0.205	4	1/102
	SD40067	1850	0.354	0.90	0.207	1	1/113
	SD40127	1700	0.366	0.89	0.23	2	1/109
	SD40187	1450	0.398	0.881	0.20	1	1/100

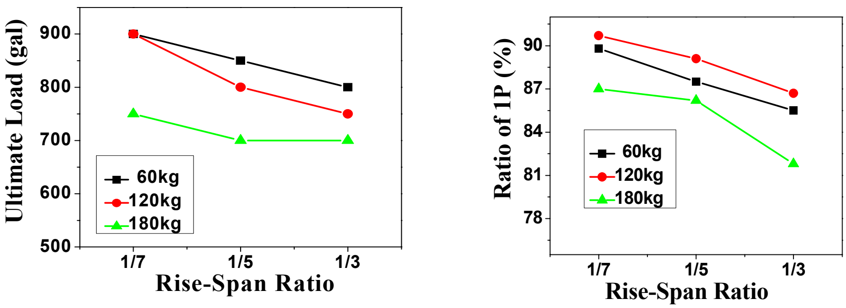
As shown in Table 2, every kind of structural response of a example is approximately located in a fixed position, i.e. the response is approximate to each other in a failure state. It indicates that anyone of these structural responses indexes can be used to distinguish the failure state. Here, 1/150 of shell span (L/150) is suggested to determin the critical state because the limited displacement value of structure has been applied comprehensively in engineering anlysis.

5. Structural dynamic responses characteristic

After a good understanding is achieved of the failure distinguishing of single-layer saddle-curve reticulated shells, the relation of structural responses at critical state and simulating parameters should be concerned, and then the regularity of the failure loads with different structure dimension can be of course comprehended, too.

5.1 Ratio of rise to span

As shown in Fig.5, the ultimate load increases as rise-span ratio decreases; in some cases, with 1/7 rise-span ratio the critical load increases to about 50%. And there is more sufficient plastic deformation at a smaller rise-span ratio while shells are in the critical state. The single-layer saddle-curve reticulated shell with small ratio of riae to span possesses bigger dissipative capacity and better anti-seismic ability, so it should be suggested more application in engineering.

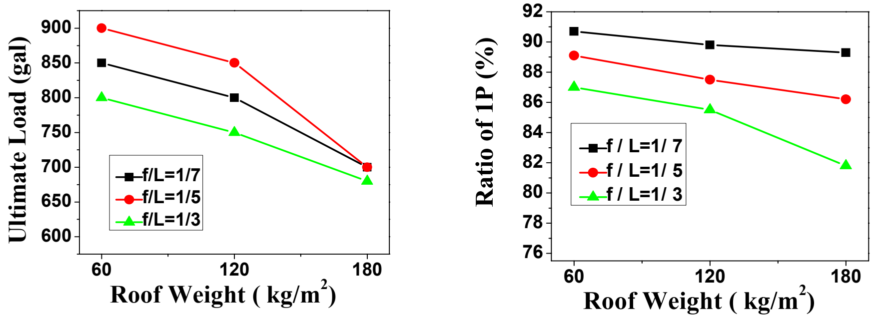


a Ultimate loads. b The ratio of 1P

Figure 5: Influence with different rise-span ratio (Taft earthquake)

5.2 Roof weight

It can be seen from Fig.6 that the roof weight has also an important influence on the structural response. As we known, the ultimate load will decrease as the roof weight increases. But the plastic deformation level makes no apparent difference to the roof weight. These behaviors of single-layer saddle-curve reticulated shells are the same as those of single-layer reticulated domes and cylindrical reticulated shells [6, 7].

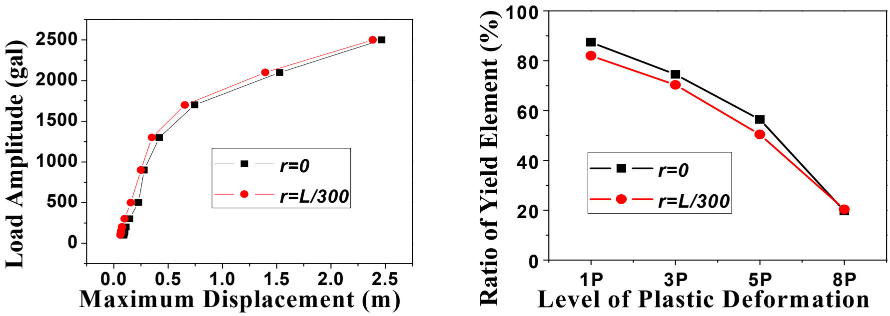


a ultimate loads. b the ratio of 1P

Figure 6: Influence with different roof weight (Taft earthquake)

5.3 Geometric imperfection

Geometric imperfection usually has an important effect on the mechanical behavior of shells. In this paper, the dynamic responses of single-layer saddle-curve reticulated shells are analyzed with or without geometric imperfection. And we consider the maximum value of geometric imperfection as 1/300 of shell span. As shown in Fig.7, with geometric imperfection taken into consideration the critical load makes no evident difference. Moreover, geometric imperfection is taken into account, the distribution of plastic development in single-layer saddle-curve reticulated shells remains unchanged by and large; only the degree of plastic deformation changes slightly. These characteristics are evidently different because the influence of geometric imperfection is much big on other reticulted shells. It should be explained as that geometric imperfection can be minished gradually as the displacement increases, i.e. the influence fades gradually as load intensity increases.



a full-range curves of maximum displacement b ratio of members with different yield levels

Figure 7: Influence with different geometric imperfection

6. Conclusions

The following are the conclusion drawn from the study on the failure mechanism of single-layer saddle-curve reticulated shells under earthquake motion:

(1) A single-layer saddle-curve reticulated shell under earthquake motions will present dynamic strength failure. The shell structure reaches an ultimate state primarily caused by material strength failure. Dynamic instability wouldn't happen, and this is different with single-layer reticulated domes and cylindrical reticulated shells.

(2) The failure critical states of examples are judged based on general judgement of structural responses and practical factors in engineering. Through investigating to the structural responses at critical state, a limited displacement value (1/150 of shell span) is suggested to determin the critical load.

(3) The structural responses are obtained through parametric example simulation. The relations between the structural ultimate responses and the structural parameters including rise-span ratio, roof weight and geometric imperfection are discussed. Partial results can be drown as follows: the single-layer saddle-curve reticulated shell with small ratio of rise to span possesses bigger dissipative capacity and better anti-seismic ability; the ultimate load will decrease along with roof weight increasing, but the plastic deformation level has no apparent difference with different roof weight; with geometric imperfection taken into consideration the critical load and the distribution of yield elements makes no evident difference.

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7. Appendix table

Appendix table.1 Cross-sections and other parameters of single-layer saddle-curve reticulated shells

Numbering of single-layer cylindrical reticulated shell	Span (m)	Roof weight (kg/m^2)	Ratio of rise to span	Cross-section of members (mm)
SD40063	40	60	1/3	60×3.0
SD40065			1/5	68×3.5
SD40067			1/7	76×3.5
SD40123		120	1/3	73×3.5
SD40125			1/5	83×4.0
SD40127			1/7	95×4.0
SD40183		180	1/3	83×4.0
SD40185			1/5	95×4.0
SD40187			1/7	102×4.0