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SEISMIC RESILIENCE OF LARGE-SPAN LATTICE STRUCTURES

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Abstract

Reasonable quantitative performance indicators are extremely important for the assessment and classification of performance levels of structures that experienced strong earthquakes. Seismic resilience is introduced to offer a direct assessment mean for quantifying the ability of highly redundant large-span lattice structures with some degree of damage due to earthquakes to restore or retain their original seismic capacity. A macroscopic global seismic damage model proposed previously with the consideration of multiple vibration modes for lattice structures is adopted to quantify the level of initial damage and to act as a collapse judge criterion. The so-called seismic resilience index is then defined as the ratio of the seismic capacity of an initially intact lattice structure to that of a damaged one. The incremental dynamic analysis is carried out to evaluate the seismic capacity of intact and damaged lattice structures. Lattice structures can be classified as different grades of seismic resilience according to the complete relationship curve between resilience index and global damage index. Five types of single-layer lattice structures are used to study the influence of some factors on seismic resilience. Computational results indicate that failure mode has significant impact on resilience level of a damaged lattice structure. Structurally global instability can lead to substantial loss of seismic resilience. Structures with any level of damage can still have the ability to withstand earthquakes with certain degree if strength failure eventually takes place. Compared with other response-based or damage-based performance indexes, seismic resilience index is advantageous to provide a complete scanned photo of reservation in seismic resistance of structures with certain damage. A parametric study is conducted to investigate the effects of some factors, e.g. structural system, rise-span-ratio, and initial imperfection, etc. on seismic resilience. Seismic resilience has a strong correlation with robustness and integrity of structures. Thus, seismic resilience index can also be regarded as a useful tool more reasonably to quantify the degree of robustness or integrity.

Keywords: seismic resilience; global damage; lattice structures; performance-based seismic design

1. Introduction

The core method of performance-based design is expressed that the structure is required to maintain the certain performance level under various loading effect and disasters [1]. Large-span space structures are divided into the key protection projects in the revision of the 'Standard of construction engineering seismic fortification classification' (GB50223-2008) [2]. It means that the structure cannot collapse or be extensively damaged after an earthquake. Meanwhile, the building function should be able to remain by properly restoration without interruptions. According to the definition of resilience from UN/ISDR [3], which is the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functional and structure, seismic design philosophy based resilience has good applicability in the area of large-span space structures. Numerous institutions and scholars are studying on their research on seismic resilience, which focuses on the capacity of the unstable engineering system return towards it equilibrium after a disaster [4]. Resilience has been defined as the system to mitigate hazards and recover quickly after a disturbance, which combined seismic uncertainty and another variable. A classic mathematical model for resilience was put forward to realize the quantization and assessment of actual engineering system [5, 6, 7, 8]. In the aspect of infrastructure groups, especially the transportation network, there are lots of research work about seismic resilience, whose objects from engineering system turning to complex transportation system [9, 10, 11, 12]. Recently, a framework for measuring community resilience at different spatial and temporal scales has been proposed to help planners in selecting the optimal restoration strategies [13]. In this paper, seismic resilience studies address the specific structure itself. Resilience is considered as a measure of the structural system to absorb change and disturbance and keep the aseismic capacity unchanged. Authors put forward a quantitative approach to structural seismic resilience regarding the ability of highly redundant large-span lattice structures with some degree of damage due to earthquakes to restore or retain their original seismic capacity.

2. Definition and qualification

2.1 Motivation and purpose

There are usually two possible failure modes of large-span space structures under dynamic load, which are dynamic instability due to geometric nonlinearity and dynamic strength failure due to material nonlinearity. Study on failure modes are relatively common, the most important of which is shown in the Fig.1. For the majority of the large-span lattice structure, there is a close inner link between analysis and design. Therefore, the damaged structure cannot be evaluated residual safety by performance level after an earthquake, and the structural design cannot be assessed reasonability according to traditional ductility or intensity index. The resilience combined with global damage can be used as an appropriate indicator to evaluate the structural performance level under hazards as well as alternative defensive ability when local members failed due to seismic damage. Hence, the research strategy proposed in this paper provides a new train of thought to measure structural design rationality and economy, the key issues of which are an evaluation of integral seismic capacity and selection of global damage model.

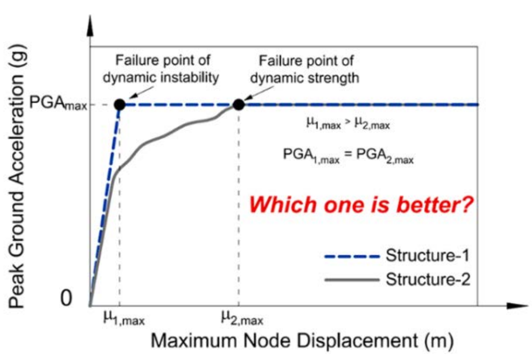


Fig. 1 – Different failure modes of large-span space structures

2.2 Definition and quantification

Since highly redundancy of space grid structures and the ability to avoid the continuation of damage and keep the whole structure stability, seismic resilience in this paper is defined as the ability of a structure to restore or retain their original seismic capacity with some degree of damage due to earthquakes. According to the definition, there are two aspects of assessment work about seismic resilience aiming at damaged structures themselves, which are the verification whether the damaged structures could continue to service and the assessment whether the whole structural design is reasonable. For the former, it can be calculated using Eq. (1):

$$Re = \frac{C_{\text{damage}}}{C_{\text{initial}}} \tag{1}$$

where *Re* is expressed as the seismic resilience level of damaged structures under a certain seismic damage; C_{initial} is the maximum seismic capacity of structures without any incident; C_{damage} is the maximum seismic capacity of structures under certain damage. Especially, for the latter, $\overline{Re}$ is computed by different levels of seismic resilience under the different damage, whose analytical expression is Eq. (2):

$$\overline{Re} = \frac{\int_0^{D_{\max}} Re \cdot dD}{D_{\max}} \tag{2}$$

where D is the damage, $D_{\max}$ is the maximum damage degree before structures collapse. According to the general formulae and concept, a mathematical measure of seismic resilience under varies degree of damage can be expressed, in general, by the graphic illustrated in Fig.2.

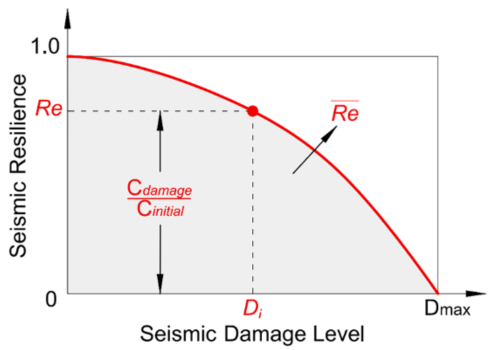


Fig. 2 – Seismic resilience definition based on seismic damage levels

A broad assessment of resilience is shown as Fig.3 below from classical seismic resilience concept[7]:

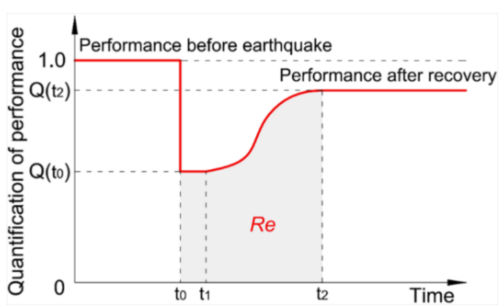


Fig. 3 – Classical seismic resilience definition

where $Q(t)$ =1.0 has been defined as the quality of the manufacturing system performance before an earthquake and $Q(t)$ =0 means the structure collapses. If the hazard happens at time t_0, it would cause performance loss and drop to $Q(t_0)$. Reconstruction after the earthquake is expected to start out at the time t_0 until time t_2 when it is finished. Mathematically, the resilience expression is Eq. (3):

$$Re = \frac{\int_{t_0}^{t_2} Q(t)\,dt}{t_2 - t_0} \tag{3}$$

Because recovery work would not carry out after an earthquake immediately, the period $Q(t)$, from t_0 to t_2, is divided into two parts which are the period of resettlement t_0~t_1 remaining $Q(t)$ unchanged and the period of restoration after disaster t_1~t_2. As the research objective is the damaged structure, it means only considering the immediate resilience of when the earthquake occurs. Thus, there is an overlap between t_1 and t_2; that is $t_2=t_1$. Hence, Eq. (3) can be rewritten as Eq. (4). The final result shows that the numerical structural resilience is equal to the ratio of the residual seismic capacity of damaged structures, which is consistent with the definition proposed in this paper.

$$Re = \frac{Q_1(t)(t_1 - t_0) + \int_{t_1}^{t_2} Q(t)\,dt}{t_2 - t_0} = Q(t_0) \tag{4}$$

2.3 Seismic resistance capacity evaluation

Seismic resistance capacity(C) defined in Eq.(1) is supposed to be the maximum bearing seismic actions of a structure before structural failure. In a practical analysis of seismic resistance capacity, the right evaluation indicator should be chosen according to any specific seismic analysis method. For the time history analysis, seismic resistance capacity could be expressed by the ground motion intensity value that the structure can withstand before collapse [14]. In this paper, the numerical magnitude of seismic resistance capacity is expressed by the value of ground motion acceleration before structure failure referring to the practice of residual capacity ratio expression of ATC3-06 [15]. It has been demonstrated that S_a(T1) doesn't have more efficiency than other ground motion intensity indexes for the large-span structure whose frequencies and spectrums are quite close [16]. So until now, *PGA* is the most choices of the ground motion intensity index in seismic analyses of large-span space structures [17, 18, 19]. Therefore, authors of this paper select *PGA* as the ground motion intensity index and Eq. (1) can be rewritten as Eq. (5):

$$Re = \frac{C_{\text{damage}}}{C_{\text{initial}}} = \frac{PGA_{\text{max,damage}}}{PGA_{\text{max,initial}}} \tag{5}$$

2.4 Global seismic damage model

The research content of this article is based on global seismic damage because there are almost rules in various specifications which state that keeping the whole structure safety under accidental loads based on the overall structure in national architectural design specifications and standards as so far. According to the 3-dimensional characteristic, the global seismic damage model is chosen, which is suitable for large-span space structures to quantify the damage degree [20]. The analytical equation is shown as Eq. (6) and Eq. (7), where D_n is nth-mode damage index; D is global damage index; T_n and $T_{n\text{d}}$ are the vibration periods of the nth-mode of a structural system before and after an earthquake respectively; r is the required minimum number of modes involved in the combination, which can be decided by node displacement modal contribution coefficients.

$$D_n = 1 - \frac{T_n^2}{T_{n\text{d}}^2} \tag{6}$$

$$D = \sqrt{1 - \prod_{i=1}^{r}\left(1 - D_n^2\right)} \tag{7}$$

3. Discussion and extension

3.1 Relationship between seismic capacity and seismic damage

As can be seen from the definition, analysis of resilience needs structural global seismic damage assessment as assistance. Because structural damage caused by the earthquake occurs in some sensitive component or the local structure firstly, the potential safety of damaged structures always is determined by the sensitivity to damaged position. Indeed, it can be seen from the development trend of resilience curves that the relationship between seismic residual capacity and damage development mainly divided into three types: $|\Delta Re|>|\Delta D|$、$|\Delta Re|=|\Delta D|$, and $|\Delta Re|<|\Delta D|$. To avoid disproportionately structural failure caused by the small disturbance, the minimum standards of alternative defensive ability should satisfy the linear relationship, namely $|\Delta Re|=|\Delta D|$, which should be avoided for practice structural seismic design. However, it can be used as assessment standard of seismic resilience whether it could meet the requirement of large-span space structures as key projects. Since the structural components of spatial lattice structures are various, there are a variety of possibilities about the shape of resilience curves. Following, several main kinds of resilience curves are given in this part based on different structural responses and evaluation under earthquakes.

The ideal structure is the one that could maintain or restore higher proportion of secondary seismic capacity with a certain level of damage, which means $|\Delta Re|<|\Delta D|$. When the structure damage degree tends to be 1.0 and the structure is going to collapse, the drop speed of the remaining seismic capacity is greater than the damage development speed. The curve of resilience step into the stage of $|\Delta Re|>|\Delta D|$ after temporary stage of $|\Delta Re|=|\Delta D|$. Once the damages amount to some extent, the level of remaining bearing capacity of the structure falls rapidly as well as the structure loses the value of post-disaster restoration, which is suggested completely dismantled. Therefore, the whole development curve development of the resilience based on various damage degrees is shown in Fig.4(a).

In general, according to the diversity of load-bearing elements of construction arrangements and failure modes, the residual seismic capacity of different structures is often different even though under the same degree of damage besides the above mentioned the ideal structure. The stage of $|\Delta Re|<|\Delta D|$ is still excited when the When the damage is not severely enough for the spread to bearing members since multi-degree of redundancy. With the increase of seismic damage, important load-bearing elements of construction begin to damage when damage level is greater than a certain degree. Immediately, the remaining seismic capacity decreases rapidly which means $|\Delta Re|>|\Delta D|$. That is, the remaining seismic capacity of the damaged structure can be ignored when the seismic structural damage is serious enough that the global damage index tends to be 1.0. So, the whole curve of the resilience, which is the red one, based on various damage degrees is shown in Fig.4(b).

If components or local structures for the whole structure belong to the important parts, the development curve of seismic resilience will immediately enter the stage of $|\Delta Re|>|\Delta D|$ even though the structural bearing components have not happened widespread damage. With the damage increasing, the change of the residual seismic capacity descends into a stationary period. As failure area of bearing components becoming broader, the tendency of the resilience curve changes with damage change is similar to the curve A. In conclusion, the shape of the curve of the resilience based on global damage index is shown as the red one in Fig.4(c).

The most adverse design for structures is that the structure will be destroyed or seriously damaged due to minor damage, which will cause dangerous effects on the state economics and the people's lives and properties. At the moment, the curve of resilience drops rapidly until the remaining bearing capacity of structures almost converges to 0. Note that there are some special cases. On the stage of $|\Delta Re|>|\Delta D|$, the structure would lose overall of its seismic capacity after an earthquake before the global seismic index doesn't reach its maximum 1.0, such as been shown the grey curves in Fig.4(b) and Fig.4(c), which is caused by the different failure modes of large-span space structures. When the structure is falling, with the vibration period changed due to excessive development of plastic deformation and stiffness severely weakened, the global seismic index is close to 1.0 evaluated by the damage model selected in this paper. Besides, structural collapses may occur in the case that plastic development of the whole structures are not serious leading to the global seismic damage index is small, which shows that the final failure mode is dynamic instability.

Above, there are main types of structural resilience according to the conclusions we summarized earlier, which as been shown as curve A to E in Fig.4(d). As a consequence, combined with global seismic damage evaluation, the analysis of seismic resilience can be regarded as a decision basis for the repair or not by the measure of alternative defensive ability after an earthquake. What is more, the whole process analysis of seismic resilience under different degrees of seismic damage can assess the reasonableness of a seismic structural design solution.

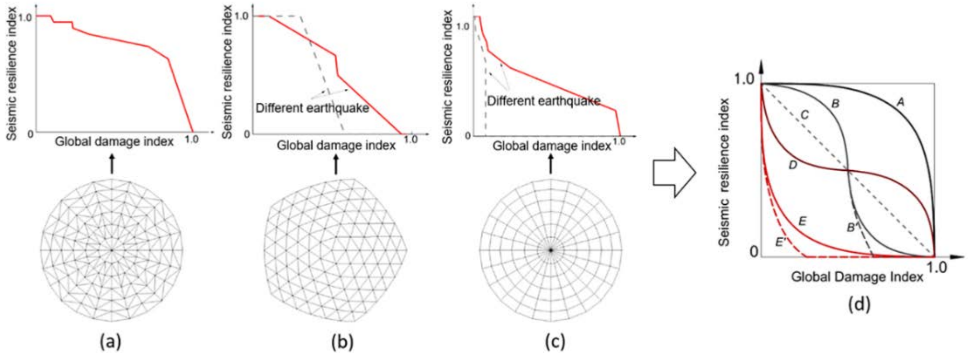


Fig. 4 – Different types of seismic resilience curves

3.2 Characteristics of seismic resilience

Obviously, resilience is an important concept for disaster evaluation of crucial architectures. MCEER's research have identified four dimensions that are robustness, resourcefulness, redundancy, and rapidity [21]. Besides, according to this article, seismic resilience plays a crucial role in post-disaster preparation and represents the seismic capacity of the whole structure, which reflects structural robustness because damaged structures could restore or retain their original seismic capacity. Furthermore, the evaluation of $\overline{Re}$ takes robustness under varies damage extents into consideration. Without the influence of post-disaster restoration time and technological means included, the concept of resilience proposed in this paper focus rapidty on duration of disasters. Because of high redundancy and varies diversification of compoments, the whole structural system has the ability of redistribution of load when the certain components reaching ultimate bearing capacity. From what has been discussed above, seismic resilience presented in this article still has four dimensions just as classical engineering system due to the characteristics of large span space structures.

4. Case study

4.1 Feasibility of indicator considering various single-layer reticulated shells

There are five typical kinds of single-layer lattice shells can be seen in Fig.5, whose informants of sections size and geometric configurations in Table 1. The shells are modeled by using OpenSees [22]. IDA is carried out with a selection of EL-Centro earthquake with consistent incentives on the three main directions of structures according to a percentage of 1:0. 85:0.65.

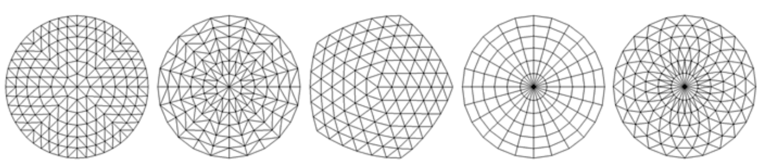


Fig. 5 – Different types of single layer spherical lattice shells

Table 1 – Sections size and geometric configurations of different single layer spherical lattice shell

Structure types	**Sectional dimensions (mm)**	**Rise (m)**	**Span (m)**
Kiewit	Φ70×3.5&Φ68×3.0	6.8	30
Schwedler	Φ70×3.5&Φ68×3.0	6.8	30
Geodesic	Φ45×3.5	6.8	30
Geiger	Φ146×4.5	6.8	30
Lamella	Φ76×3.5	6.8	30

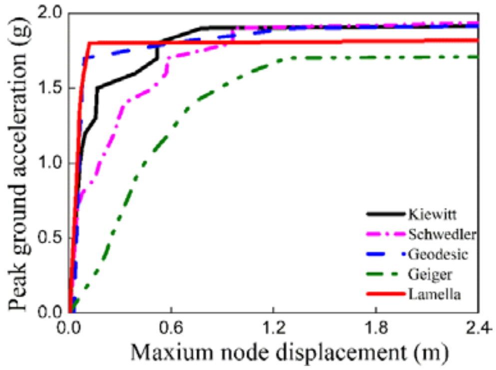


Fig. 6 – Structural response of different models

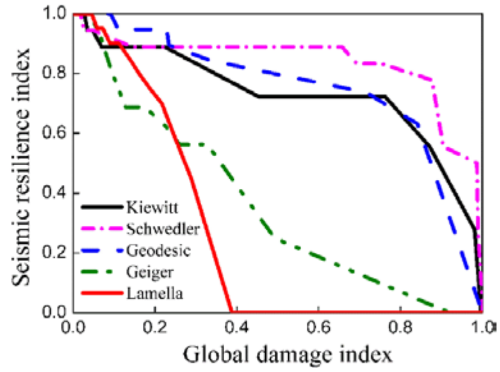
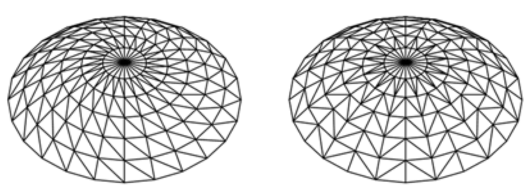


Fig. 7 – Seismic resilience curves of different models

Fig.6 presents the collapse point of five structures according to the maximum node displacements curves. As can be seen from the figure, the maximum seismic intensity of structures can afford 1.7 g to 1.9 g and the failure mode is not the only because of various seismic responses of structures. As for $PGA_{\max}$ or $\mu_{\max}$, it can not be given universally accepted standard to measure structural design. According to Eq. (1), the correlation between global damage and the residual seismic capacity, which is defined as seismic resilience after earthquakes, be implicitly observed from Fig.7. And apparently, there were significant differences in the seismic resilience among the five kinds of structure even if the degree of structural global seismic damage is the same. As can be seen from the curve in the figure, there are two ingle-layer lattice shells, Geiger, and Lamella, whose final failure mode is dynamic instability. The seismic capacity reduced greatly when the damage is small. And the failure mode of three other shells, Kiewit, Schwedler, and Geodesic, belongs to the dynamic strength failure. When the global seismic damage index is about 0.7~0.8, three shells still keep different levels of seismic capacity that much more than the damage degree. After that, the residual seismic capacity of shells is rapidly reduced when the global seismic damage index is beyond the point of 0.7. Until D reaches to 1.0, three shells loss overall of their beating capacity and Re is 0.

4.2 Effects of grid layouts and rise-to-span ratios

Two perfect 30m-span Schwedler single-layer lattice shells with the rise of 6.8m are designed with different grid layouts (see Fig.8). Two sections are adopted for all Q235 steel tubes, i.e. 70mm×3.5mm and 68×3.0mm. The results of global seismic damage of two shells can be seen in Fig.9, and the results of seismic resilience of two shells are shown in Fig.10.



(a) Schwedler-1 (b) Schwedler-2

Fig. 8 – Two types of Schwedler lattice shell

Fig.9 presents the results of global damage indexes of two shells from the IDA of selected ground motion (EL-Centro earthquake), and Fig.10 shows the results of seismic resilience. As mentioned previously, the degradation rates of seismic capacity of damaged structures are different from each other gradually while the level of structural damage increases. When the global seismic damage is not serious, the loss of structural seismic capacity of Schwedler-1 is greater than that of Schwedler-2. And structural collapse can be declared when global damage index level reaches 0.19 for the cases of Schwedler-1 so that the shape of resilience curve is close to curve E' in Fig.4 (d). Conversely, because of considerable redundancy and good robustness, the development trend of resilience of Schwedler-2 can be shown to behave more nearly curve A in Fig.4 (d). As mentioned the example above, the average of seismic resilience per structure is $\overline{Re}_2 > \overline{Re}_1$, which can be a decision fundament to measure whether or not each structure is well-designed. Based on the results of the study, authors further explore the possible causes of these differences from the variable law of internal plastic changes of structures.

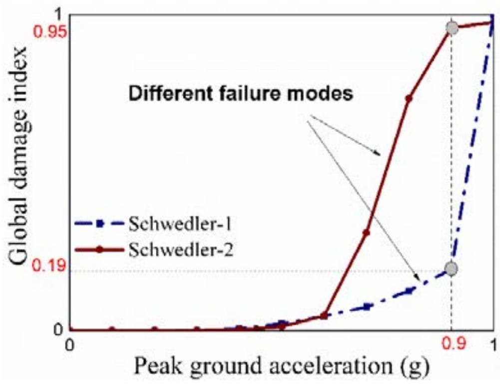


Fig. 9 – Seismic global damage curves

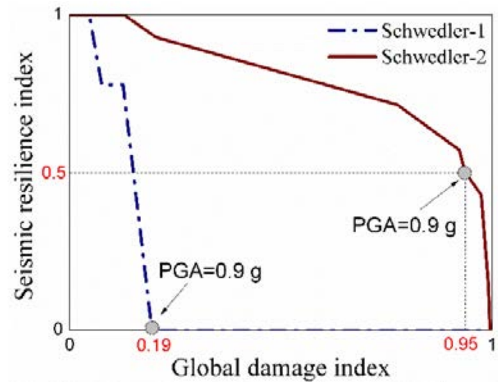
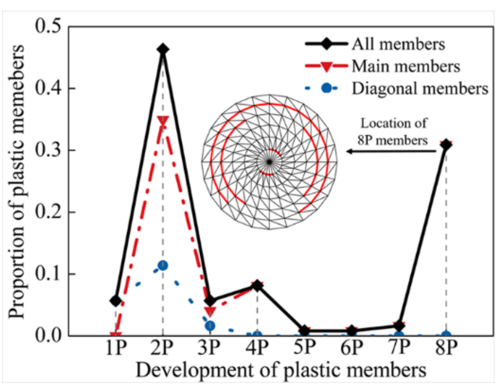
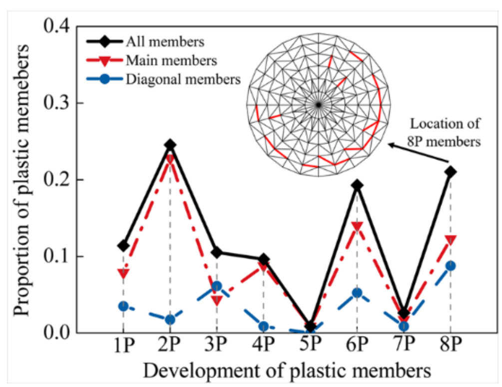


Fig. 10 – Seismic resilience curves

The distribution proportion of two kinds of Schwedler single-layer lattice shells can be intuitively observed from Fig.11(a) and Fig.11(b). Structural components from plastic deformation of Schwedler-1 mainly concentrate in load-bearing members, most of which center on weft members. On the contrary, plastic members of Schwedler-2 are almost equally distributed between load-bearing and non-load-bearing elements. For single-layer lattice shells which have radial and weft members distinctly, stiffness is mainly composed of radial diagonal members so that the global damage index of Schwedler-1 is larger than that of Schwedler-2 under the condition of equal ground motion intensity. For instance, the global seismic index for each other is 0.19 and 0.95 separately when PGA is 0.9g. In this case, the plastic members of Schwedler-1 mainly are concentrated within that spread of the fifth round of weft members. Besides, 8P members leads to an annular section of the vulnerable region. Conversely, 8P members of Schwedler-2 are less than that of Schwedler-1 and broadly dispersed. As a result, there are remaining a considerable proportion of seismic capacity in Schwedler-2. Therefore, the damaged Schwedler-2 structure can maintain a considerable seismic capacity that is much larger than that of the damaged Schwedler-1. This confirms the feasibility and rationality of the seismic resilience assessment method.



(a) Schwedler-1



(b) Schwedler-2

Fig. 11 – The proportion of plastic members in two Schwedler lattice shells

Rise-to-span ratio (*f/L*) is another main reason that the effect on mechanical properties and the total cost, which can result in the shift of structural dynamic failure modes if too small. The model of Schwedler single-layer lattice shell is shown in Fig.5, whose dimension data in Table 1 and the rise is 5m, 6m, and 6.8m. The structure of rise-to-span ratio is too small so that easily causes structural instability as shown in Fig.12. It can reflect the common rule through seismic resilience. In the structure whose *f/L* is 0.167, although the plastic proportion is not large but to form obviously weak area, the reduction of residual seismic capacity is reasonable. Also, due to the significant weak area, the damaged structure repair is more difficult than others. Form this example, a rise-to-span ratio that is far too small can, therefore, result in a shift of dynamic failure mode and a substantial loss of seismic capacity in single-layer lattice shell structures.

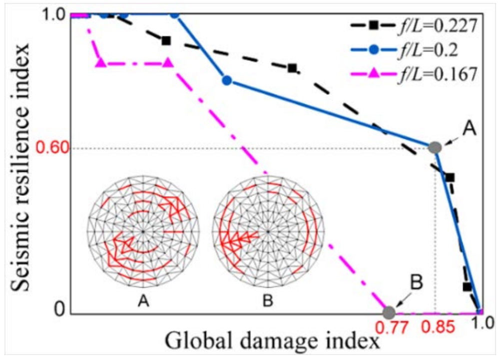


Fig. 12 – Seismic resilience curves of different rise to span ratio

4.3 Effects of geometrical imperfections

Imperfections exist commonly in large-span lattice structures due to various mechanisms, such as initial eccentricities in elements or load positions, material defaults, construction error, etc. For seismic lattice shells, these imperfections will adversely affect their seismic capacity and make failure modes undesirable. It is meaningful to identify the initial damage caused by imperfections at the structural level and its influence on the seismic performance of lattice shells. A single-layer Schwedler shells with a rise-to-span ratio of 0.227 (seen in Fig.5). Two sections are adopted for steel tubes, i.e. 70mm×3.5mm and 68mm×3.0 mm. In this method, the maximum value of the fundamental vibration mode factor is taken as the peak value of geometrical imperfections, e.g. $L/200$ to $L/1000$ (L is span) as discussed in this paper to get the initial damage and residual seismic capacity index.

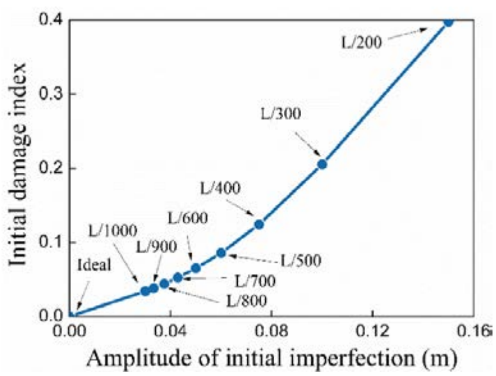


Fig. 13 – Initial imperfection damage curves

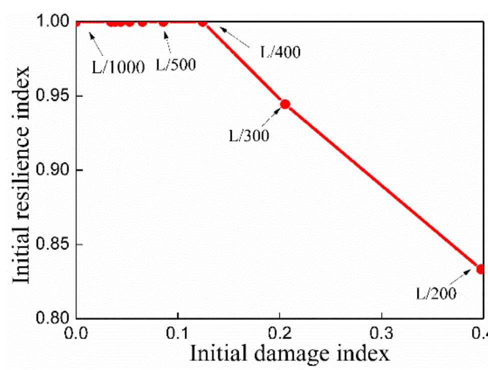


Fig. 14 – Initial resilience curves

Fig.13 shows the initial damage of geometrical imperfections determined by Eq. (6) and Eq. (7). As indicated by Fig.14, initial damage caused by initial geometrical imperfections increases with the imperfections increase. Seismic capacity of an imperfect structure is not smaller than that of ideal structure from Fig.16. When the value of imperfection is $L/300$, the initial damage would begin to increase, and about 7% has reduced seismic capacity. However, when the imperfection is $L/200$, abrupt changes of seismic capacity is about 16%, which is consistent with an idea that $L/300$ is regarded as the acceptable defects in general [23].

5. Conclusion

A new seismic resilience assessment method is developed for lattice shell structures based on global seismic damage evaluation. Some conclusions can be reached from this article as follows,

(1) The proposed method of seismic resilience is mainly studied and simulated based on structures themselves. It is dependent on global seismic damage analysis. Seismic resilience in this paper is defined as the

ability of structures to restore or retain their original seismic capacity with a certain level of damage due to earthquakes, which is different from the classical resilience theory.

(2) Combining with the existing damage model which is fit for large-span lattice structures, there are serious of verification work to demonstrate the feasibility of seismic resilience method which can be used for evaluating the residual seismic capacity and assessing the structural seismic design. Besides, it can characterize the final failure mode through the resilience curve under different damage levels.

(3) The case study on different single-layer lattice shells has clarified that the seismic resilience evaluation is suitable for various structures. Through analyses of different structural parameters, such as the arrangement of components, rise-to-span ratios, and geometrical imperfections, resilience curves can sensitively reflect differences of seismic capacity of damaged structures even though the levels of global damage are the same. This resilience evolution rule can be proved reasonable from the internal plastic distribution of structures.

Synthesize all of above; this study work is based on the selection of seismic damage model, which need to be improved because the proper damage model is crucially important to measure damage degree. Besides, the proposed theory needs a series of experimental validations as well as further numerical simulations.

6. Acknowledgements

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