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CORRELATION BETWEEN MULTI-MODE GLOBAL DAMAGE, MPA STOREY DAMAGE, AND INTERSTORY DRIFT OF RC FRAME

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Abstract

Structural global damage can be obtained either through weighted combination of local damage indexes (called the weighted method), or directly based on the change of vibration parameters (the macroscopic method). Determination of the weighting coefficients of the weighted method sometimes is not physically based, while the macroscopic method generally can not be desirable to localize local damage accurately and assess the degree of damage. But if they are used to assess the same structure damage, some internal connection must be exist. This paper attempts to explore the correlations between story damage, global damage and inter-story drift. A failure mode of RC frame is proposed, which can associate the storey damage with the global damage. The multi-mode global damage model is recommended in this paper. And the upper bound of the weighted storey damage (Park-Ang damage model) is modified (called MPA storey damage model). Through an example of plane RC frame, the relationship between the multi-mode global damage and the MPA storey damage as well as the inter-story drift is studied. By changing the location of the storey damage, the sensitivity of the modal damage to the storey damage is verified. Results show that global damage model, storey damage model and inter-story drift are corresponded well to each other when the location of stroey damage is low. As the location raises, inter-story drift deviate first and then the storey damage model. Simultaneously, proportion of fundamental modal damage decreases. As a consequence, inter-story drift is not suggested to be used as a damage and failure criterion but as a supplement. Further study need to be done on the correlation between modal damage indexes and storey damage location and severity. And the correlations between the damage models, under other failure modes, need to be research.

Keywords: global damage; storey damage; inter-story drift; failure

1. Introduction

A critical step in the damage assessment procedure is the proper choice of a damage model for evaluating the seismic capacity of the structures. Generally, damage models can be classified into material, section, component and structural levels according to their definitions and applicability. In the engineering field, engineers pay more attention to the macro level damages, and its expression or physical meaning. The evolution and migration between different levels of damages are often neglect. The task of this study involves an establishment of a suitable relation between local storey damage and global damage, and attempts to explore correlations between the story damage, the global damage and the inter-story drift.

According to the definition, damage index D should vary within 0 and 1. If the structure does not suffer any damage D equals 0, whilst D should be equal to 1 in the event of total collapse. Structural damage under an earthquake is a gradual process, which begins with local damages and ends up with structure failure. Damages reflected on the integral structural characteristic embody in stiffness and strength degradation. It is common that structures encounter softening when damage increases. This leads to the kind of global damage model which is calculated by comparing the modal properties of the structure before and after the earthquake (the macroscopic method) [1-4]. The softening damage indices provide a promising method of assessing the global state of a structure, but they provide no indication of the distribution of damage [5]. Another kind of global damage model is the weighting of local damage indices (called the weighted method) [6-8]. The use of weighted averages of local damage indices has two limitations. First, the global index can only be as reliable as the local values from which it is derived. Second, the determination of the weighting coefficients sometimes is not physically based, there is no obvious way of determining the weighting that should be given to different structural elements or different levels of damage. In the codes of almost all countries, inter-story drift is used as the seismic damage criterion. In most cases, limits of the drift vary from 1.5% to 3% for design purposes. It’s a very practical tool for engineers to quickly evaluate the damage status of the structures, but inter-story drift cannot provide a clear understanding of accumulative damage induced by hysteretic energy dissipation, and in some cases the evaluation even isn’t proper.

Although, differ in expression, the component based damage model, the global damage model and the interstory drift must have some internal correlation. It is worthwhile to establish the relationship between them. Further, reveal the damage evolution law at different levels and the migration rule from low level to high level damage.

2. Motivation

Generally, the global damage and the local damage are linked to each other by the weighting coefficients. However, ten component-based weighting damage models are compared and studied in a research [9]. Results show that different damage models indicate different damage tendencies, and the same damage state correspond to different damage indexes. So the authors of this paper tried another way round. Attempts have been made to propose a top-down decomposition method to correlate the global damage with the local damage, in which story damage indexes are evaluated directly from global damage indexes through so-called decomposition coefficients originated from the selected global damage model. But after further study, it’s found that the global damage cannot be directly associated with the local damage in a simple form. The formulas are too complicated to have any practical utility. So we decided to deal with the global damage model and local damage model respectively. And then combine the two models at the structural failure point. İn order to achieve this goal, a failure mode of the plane frame is introduced which will be presented in the following part. As mentioned in the introduction, the softening damage indices provide a promising method of assessing the global state of a structure. Further more, accounting for high-order period variations He et al. [4], developed a multi-mode damage model. It can well describe the global damage evolution of a structure. So the He et al. [4] model, which is based on the softening damage indices, is chosen to be the global damage model and also the baseline. According to the failure mode of the plane frame, the weighting method damage model is only adopted up to story level. Most of this kind of models are origin from the Park-Ang damage model [6], which is based on a large number of beam and column experimental data. It can be considered reasonable at component level. But if further weight to get the global damage, results tend to get erratic when the structure approaches collapse. So the weighted storey damage (the Park-Ang damage model) is modified (the MPA storey damage model). Finally, coupled with interstory drift, correlation between the MPA storey damage and multi-mode global damage is studied.

3. Structural failure criterion and damage model

Based on the visible damage phenomenon, many scholars try to combine the damage index with damage description, such as concrete spalling, steel bucking and collapse. Others attempt to associate damage with the repairability of structure, e.g. 1) no damage or minor damage, 2) repairable, 3) unrepairable, 4) collapse. Another method to assess damage is to consider the structure whether collapse or not under the aftershocks. What's in common of these methods are the failure point. But different structures may encounter different failure modes. For the plane frame in this paper the following failure mode, as shown in Fig. 1, is considered, which is called sidesway collapse. Vertical collapse mechanisms, which are not directly simulated in the structural model, are not considered in this assessment.

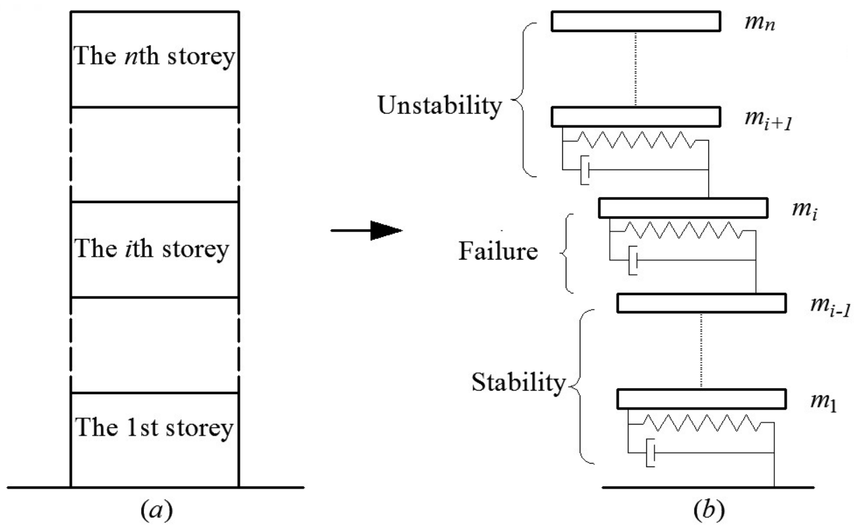

Fig. 1 – Simplified frame model and failure mode

Through the sidesway collapse mode, Storey failure and global failure have been unified. Storey failure in the plane frame means a permanent unrecoverable failure mechanism is formed on the local scale. The whole structure is then divided into two parts by the failure storey. The part which still keep in touch with the ground can be treated according to the normal process, but the part above the failure storey should be treated as an unstable mechanism. That means when any story of the structure is failure – the storey damage index reaches or exceeds 1.0 – the whole structure enters a state of collapse. Simultaneously, the global damage index is approaching 1.0. And for the multi-mode damage index selected in this article the global damage index of failure is > 0.9.

3.1 Modal damage and global damage model

The modal parameters are usually used to indicate and locate structural damage. However, DiPasquale et al. [1] successfully use the modal damage indicators, maximum softening, plastic softening and final softening, to assess the damage level of structures. That's because, the overall effect of all local damages is the stiffness and strength deterioration of a structure, which lead to the elongation of structural periods. Further more, accounting for the multi-period variation, He et al. [4], developed the following damage model,

$$D_i = 1 - \frac{T_i^2}{T_i^{d2}} \tag{1}$$

$$D = \sqrt{1 - \prod_{i=1}^{n}(1 - D_i^2)} \tag{2}$$

Where: D_i is the ith modal damage index, D is the global damage index, T_i is the ith initial natural period, T_i^d is the ith damaged period.

A drawback of the macroscopic-method-global damage model, which is often been pointed out, is that it is not sensitive to the local damages. However, this is also the character that a global damage model should have. Small fluctuation and location change of local damages shouldn't cause significant disturbance of the global damage. That's to say, global damage model should have good robustness. Only by this means can global damage model accurately grasp the damage state from structure level.

As can be seen in Fig. 2, the multi-mode global damage index do not change much as the location of storey damage changes. The evolution curve of the global damage indicates that the global damage positive correlates to the degree of storey damage. When the storey damage reaches 1.0, the global damage index is also approaching 1.0. Many researches indicate that higher modes are more sensitive to local damage. So, as a part of the global damage model, modal damage may be associated with the location of storey damage. The sensitivity of the modal damage to the location of storey damage will be discussed latter.

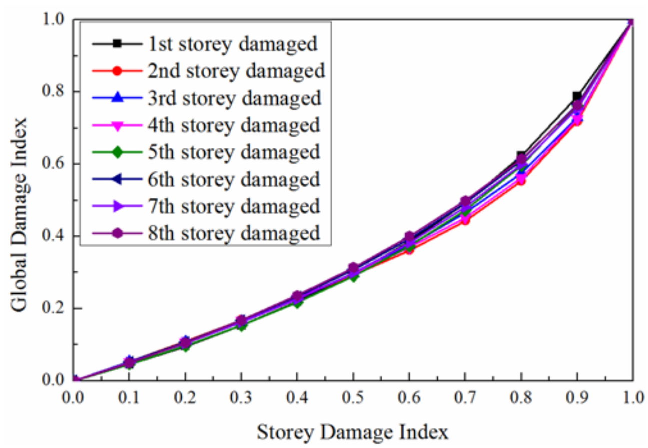

Fig.2 – Global damage under different storey damge

3.2 Modification of the component based storey damage model

Both plastic displacement and plastic dissipated energy can be taken into account in the Park-Ang damage model. And it is supported by a wide correlation with observed damage in the beam and column experiments. However, it gives a positive number even when a structure is still within the elastic range, and the upper bound is not convergence. To improve the model, Kunnath et al. [10] developed the following index,

$$D_{element} = \frac{\varphi_m - \varphi_r}{\varphi_u - \varphi_r} + \frac{\beta}{\varphi_u M_y}\int dE \tag{3}$$

$$D_{storey} = \sum \lambda_i D_{i,element} \tag{4}$$

$$\lambda_i = \frac{E_{i,elment}}{\sum E_{i,elment}} \tag{5}$$

Where: $D_{element}$ is the element damage index, D_{storey} is the storey damage index, λ_i is the weighting factor, φ_m is the maximum rotation attained during load history, φ_u is the ultimate rotation capacity of section, φ_r is the recoverable rotation during unloading, M_y is the yield moment of section, β is the strength degrading parameter, $\int dE$ is the dissipated hysteretic energy.

The improved Park-Ang damage model solves the problem of lower bound, the damage of elastic stage is zero now. But the problem of the upper bound is still remained. The improved element damage index can be used directly to determine damage at each member cross-section. The story level damage index is computed using weighting factors based on dissipated hysteretic energy at component level. But there is still no upper limit for the damage indexes. Results tend to get erratic when a structure approaches collapse which can be seen in Fig. 3. A violent method is used in this study to solve this problem. The cross-section damage index is forced to be 1.0 when it's greater than 1.0 (called the MPA storey damage model hereafter). Because when the index reaches 1.0 it means the failure of the element, and it will no longer contribute more in the subsequent damage process for the storey damage. So it is reasonable to set the cross-section damage index 1.0 when it is greater than 1.0. Through this method, an S-type damage curve is obtained and the failure predication is put off, as shown in Fig. 3.

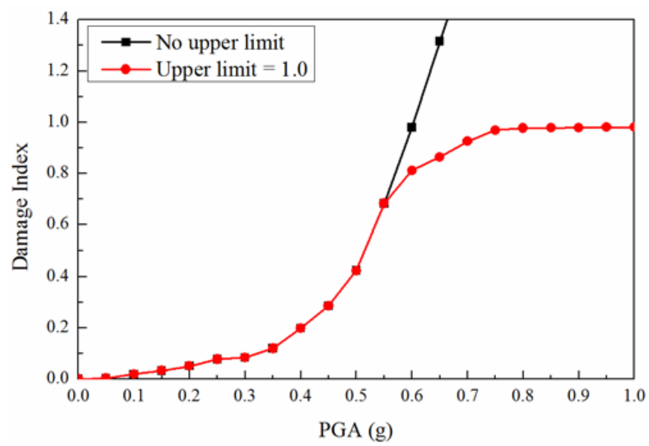

Fig. 3 – Modification for upper limit of the story damage index

4. Correlation between different level of damage models and inter-story drift

An illustration of an 8-story RC frame, which is designed in accordance with current Chinese codes [11-12], is provide in this section, as shown in Fig. 4. It's modeled in the OpenSees program. The fiber-element model with Concrete02 Material and Steel02 Material is selected to model nonlinear beams and columns, and the P-delta effect is considered in the program. Whereafter, different weakened stories are set through out the frame by weakening the column section of each story. That's to say, eight additional different frames are modeled. Incremental dynamic analysis (IDA) is performed to assess the subsequent damage evolution of the nine structures, meanwhile, the inter-story drifts are recorded. The model damage, the global damage and the MPA storey damage are calculated.

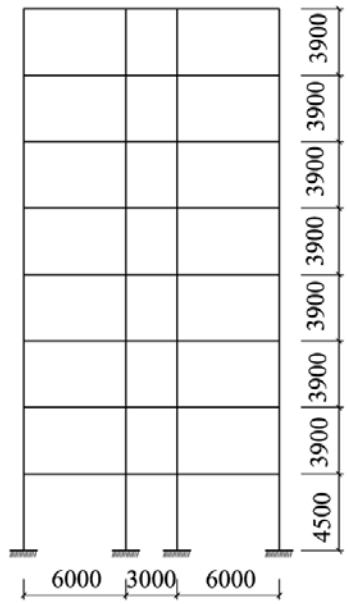

Fig. 4 – Elevation of the 8-story RC frame (unit: mm)

4.1 Global damage index and modal damage sensitivity

The global damage index represents the overall state of the structure. As shown in Fig. 5, the global damage evolution curves equipped with different weakened stories are almost the same. It indicates that damage position does not affect the global damage index much but the severity does. In this calculation, the initial modal parameters are taken from the weakened structure itself. If the original structure is selected to be the initial state, initial damage of the structure will be captured. The following evolution curve of the global damage index won't change much, but the evolution of each modal damage will have different pattern and it may indicate the initial damage position.

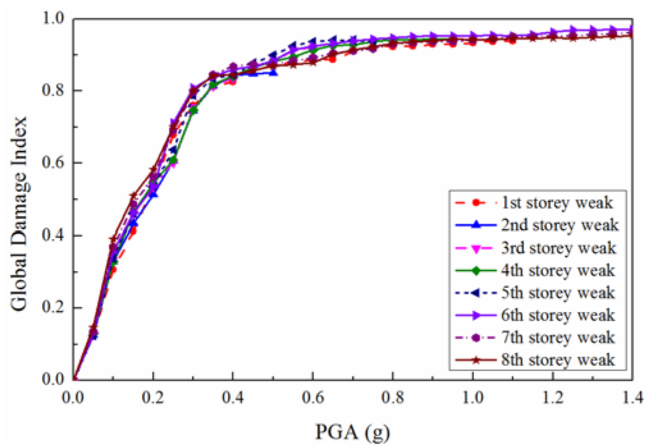

Fig. 5 – Global damage evolution curve

The relation curves of the initial modal damages and position of the damaged story are shown in Fig. 6. It can be seen from the diagram that the value of the fundamental modal damage (1st mode in the figure) decreases as the location of the damaged story rises. Simultaneously, higher modal damages fluctuate heavily. That's because as the location of damaged story rises, higher modes are easy to be excited, and the changes of the higher order periods are severe than the fundamental period. Different order of modal damages are sensitive to different position of damaged stories. For this special example, the 8th modal damage is more sensitive to the third story damage, while the 2nd modal damage is more sensitive to the first and sixth story damage.

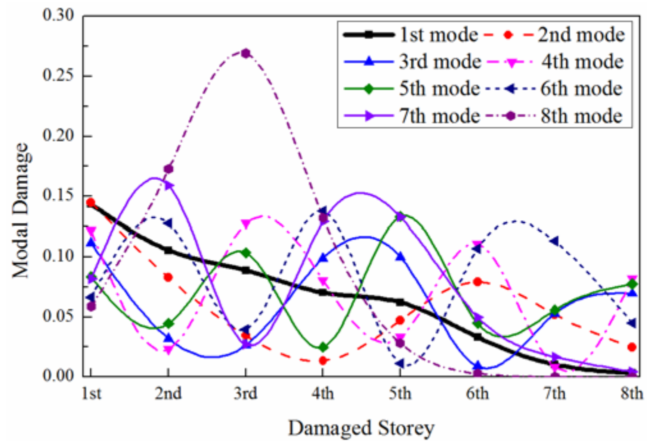

Fig. 6 – Relation between modal damage and damage position

4.2 Correction between different damage criteria

Portion of the MPA storey damage evolution curves and the inter-story drift of the original structure and the weakened structures are shown in Fig. 7 and Fig. 8. Three different methods are used to evaluate the structure failure, 1) the global damage index exceeds 0.9, 2) the maximum MPA storey damage index is greater than 0.95, 3) and the inter-story drift is over 2%. The results are shown in Table 1.

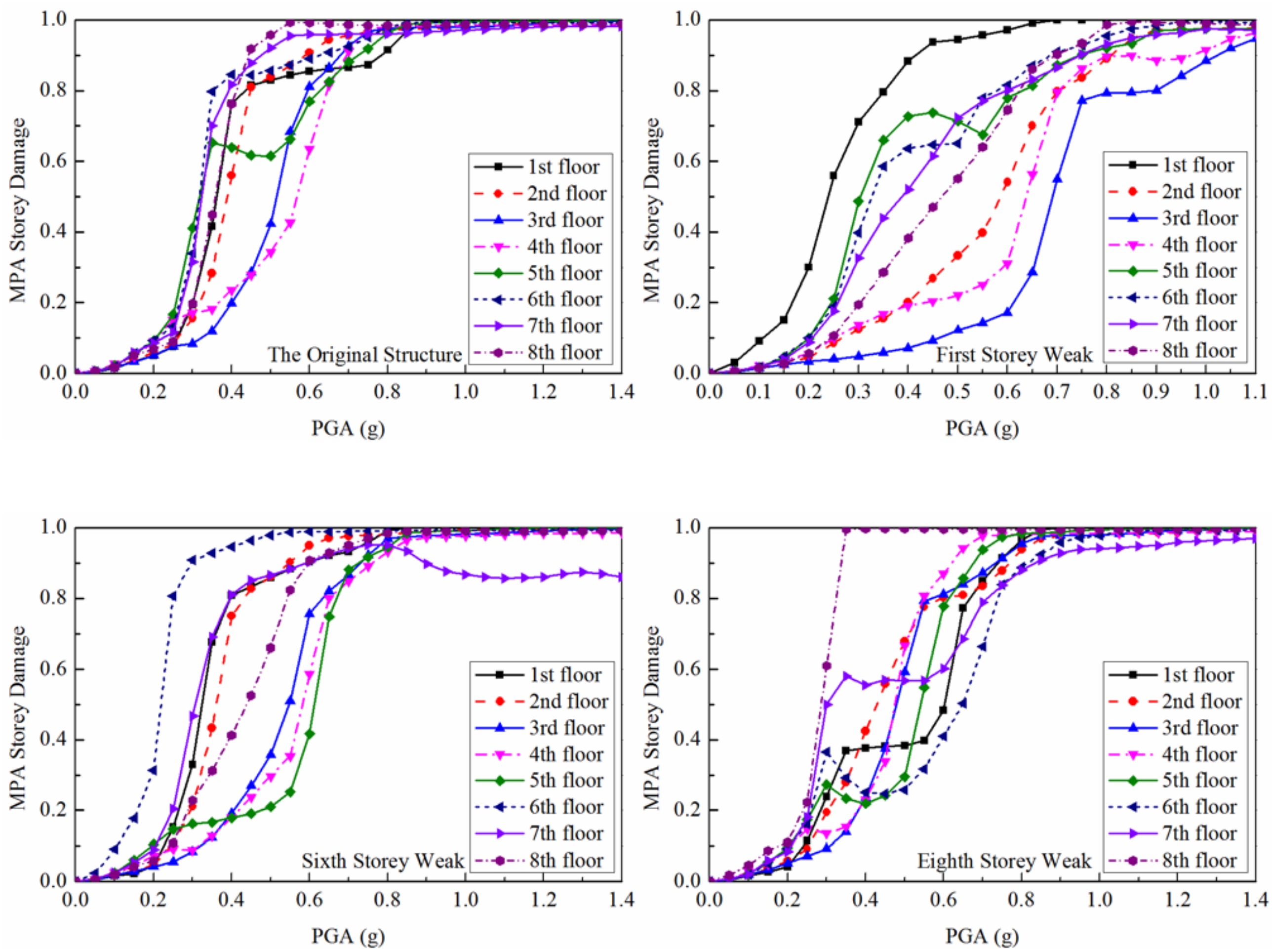

Fig. 7 – MPA storey damage

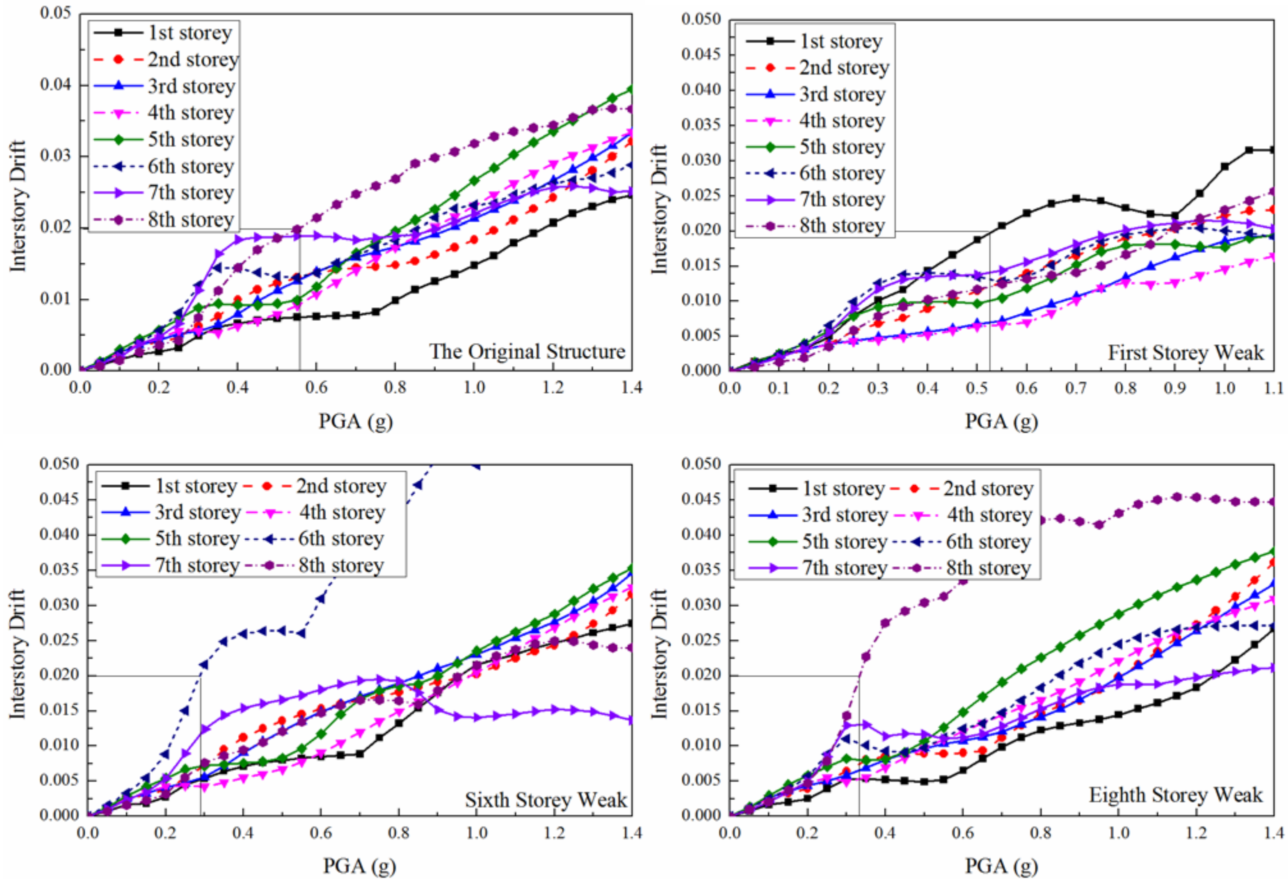

Fig. 8 – Storey drift

As shown in Table 1, the average standard deviation of the three criteria is 0.08 which indicates a good corresponding relationship between the multi-mode global damage, the MPA storey damage and the inter-story drift. Roughly, bigger deviation can be seen as the location of weakened story rises. The MPA storey damage model deviates largely only when the weakened columns are on the 8th story. The assessment of inter-story drift are well related to the other two when the weakened story isn't higher than the 6th floor. That's probably because as the weakened story goes high rigid rotation of top stories increases, which makes the evaluation of inter-story drift deviated. And when the weakened story is the 8th story the MPA storey damage index quickly achieve the threshold value and can not form the failure mode as shown in Fig. 1. So the failure assessment of the MPA storey damage have been advanced.

Table 1 – PGA at the failure point assessed by different criteria

	Global damage (>0.9)	**Storey damage (>0.95)**	**Inter-story drift (>2%)**	**Standard deviation**
Original structure	0.60g	0.55g	0.55g	0.03
1st storey weak	0.45g	0.55g	0.55g	0.06
2nd storey weak	0.45g	0.35g	0.40g	0.05
3rd storey weak	0.45g	0.50g	0.55g	0.05
4th storey weak	0.45g	0.55g	0.60g	0.08
5th storey weak	0.45g	0.55g	0.60g	0.08
6th storey weak	0.50g	0.45g	0.30g	0.10

7th storey weak	0.55g	0.50g	0.35g	0.10
8th storey weak	0.60g	0.35g	0.35g	0.14
Average	0.50g	0.48g	0.47g	0.08

Compared to the original structure, the weakened structures are more vulnerable or at least as equal. The assessment of the multi-mode global damage model and the MPA storey damage model obey this law, but the inter-story drift encounters some contrary.

In addition to the structural response, the influence of hysteretic energy dissipation is also been considered in the MPA story damage model. After controlling the upper bound of the section damage index, the MPA story damage model exhibits a good evolution curve. But some reverse results are obtained by inter-story drift, which indicate that the inter-story drift is not a reliable criterion for damage and collapse assessment. The inter-story drift only reflect the influence of the structure response, and the assessment of the inter-story drift is effective only in certain circumstance. So the inter-story drift is suggested to be used only as a supplement.

5. Conclusion

This paper attempts to explore the correlations between the story damage, the global damage and the inter-story drift. A failure mode of RC frame, which can associate the storey damage with the global damage, is proposed. Vibrational parameters based multi-mode damage model, which reflects the decline of comprehensive structural character, is recommended as the baseline. The upper bound of the weighted storey damage model is modified. And through an example of a plane RC frame, conclusions can be drawn as follows.

1) The global damage model is not sensitive to the location of damaged stories, but to the severity of them.

2) As the upper bound been modified, the MPA storey damage exerts an S-type evolution curve, give a good assessment of the structural damage.

3) The fundamental modal damage indexes decrease as the location of damaged storey rises. The other orders of modal damage indexes fluctuate severely, and are sensitive to different storey damages.

4) When the location of the weakened storey is low, the assessment of the multi-mode global damage, the MPA storey damage and the inter-story drift have a good corresponding relationship. But when the location of weakened storey goes high, divergence appears. Inter-story drift is not suggested to be used as a damage and failure criterion but as a supplement.

Further study need to be done on the correlation between different damage models under other failure modes, and also the correlation between modal damage indexes, location and severity of storey damages.

6. Acknowledgements

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