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Failure mechanism and its control of building structures under earthquakes based on structural system concept

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Abstract: By taking building structures as systems, the difference between the safety margins of a structure and that of its element is clarified and the robustness of the structure to resist unexpected disasters is discussed. The system concept is further used to introduce the concepts of importance levels and functionality levels in structural systems, the designability of structural systems is then pointed out. The local and global failure mechanisms of building structures under earthquake are summarized, and the failure mechanism control method is discussed based on the concepts of system and designability. For global failure mechanism, the desirable seismic performance is put forward, and at last some practical methods to control the seismic failure mechanism and the failure procedures are proposed based on the hierarchy concept of the structural system.

1 Definition of the structural system and its function

In "Unified design standard for reliability of engineering structures GB 50153-2006" (draft for approval)[1], a structure is defined as a system that is composed by a set of elements, can resist certain loads or effects and has appropriate stiffness. This new definition of structures is a great development in the structure engineering and will encourage new theories and methodologies in the study on the structural performance, safety margin and disaster resistance. Based on the system concept, this paper is to provide some new approaches on controlling the failure mechanisms and procedures of building structures under earthquake.

In this paper, a structure is defined as a well-organized load-bearing system composed by a set of properly connected elements. This system has adequate load-bearing capacity, stiffness, deformability and energy-dissipating capacity. It has proper serviceability, adequate safety under design loads, as well as adequate anti-collapse capacity under unexpected loads.

This definition can be further explained as follows:

(1) A structural system should have certain capacities, including load-bearing capacity, stiffness, deformability and energy-dissipating capacity.

(2) A structural system should have proper serviceability under design loads. For seismic design, this demand can be expressed as "undamaged under minor earthquake".

(3) A structural system should have adequate safety margin under design loads, which is usually referred to as the structure safety. For seismic design, this means the structure may experience its capacity limit under design earthquake, but the damage is limited or in other words "repairable under moderate earthquake".

(4) A structural system should have adequate anti-collapse capacity under unexpected loads. For seismic design of building structures, this requires the structure not to collapse under severe earthquakes.

The last item is the main topic of this paper based on the system concept.

2 Safety margin and robustness of structural systems

Based on system methods, the load-bearing capacity, stiffness, deformability and energy-dissipating capacity of a structure are related, but not equal to those of its elements, so is the safety margin.

Generally, a single element or some local elements may fail under expected overloads, but the local failure will not induce the total failure or collapse of the whole structural system if the system is properly designed. The safety margin of individual structural element is thus the "fundamental safety margin" of the structural system, which is to ensure the structure's serviceability and safety during its service life. This is the major design work of current structural design procedures.

For a well designed structural system, the safety margin of the system is higher than that of its element (or fundamental safety margin), even if the safety margins of all its elements are the same. The higher part of the safety margin can be called "additional safety margin", which is very important for the structural system to resist unexpected overloads induced by disasters, such as severe earthquakes and explosions. This capacity is called robustness of the structural system [2], which is **a result of the positive effect when a structural system emerges as a whole as far as the system theory is concerned.**

For a simple structural system, such as statically determinate structure, the safety margin of the system is almost equals to its fundamental safety margin, where the robustness is low, and thus its capacity to resist unexpected disaster is poor. In contrast, for a well designed structural system composed of elements with different structural functions, a bigger additional safety margin, thus higher robustness, can be obtained.

According to the system concept, the failure or collapse of a structural system occurs when the structure loses its whole capacity to achieve its certain function other than that a single element experiences its limit state. Researches on the occurrence of the failure or collapse limit state of structure systems and corresponding safety margin are called "system robustness". If a structure is poorly designed and its safety margin is determined by some of its local elements, the disaster-resistant capacity of the structural system is poor, and thus its robustness is poor. Some principles and methods to improve the robustness of the structural system will be discussed based on the system concept.

Robustness is a specific topic in the study of system safety. More discussions and researches on robustness can be found in Ref. [2]~[5]. The load-bearing behavior, failure limit state and safety margin of a whole structure can only be understood when the structure is taken to be a system. This is also the key concept to improve the robustness and disaster-resistant capacity of structural systems.

3 Hierarchies in structural system

A system is composed by sub-systems, and sub-systems are composed by sub-sub-systems, until the elements that can not or are not worthy to be divided as a structural function. This is an important concept of a system, and also an important step to define the structure as a system. This concept indicates the hierarchies in systems.

In a structural system, different parts of the structure (or sub-systems) have different importance to the whole structural system. In other words, every part in the structural system has its "importance level". Sub-systems or structural elements with higher importance level are more influential to the structure safety and vice versa. In a well-designed structural system, structural elements should have different safety margins according to their importance level. This principle is generally overlooked in current engineering design procedures.

On the other hand, different sub-systems or structural elements have different structural functions in a structure system, or every sub-system has its "functionality level". The functions of structural elements include load-bearing capacity, stiffness, ductility and damping. A well-designed structural system should have proper distributions of load-bearing capacity, stiffness, ductility and damping with the sub-systems or structural elements of different functionality levels.

Based on the concept of hierarchy of importance, the structural elements can be categorized as key, important, common, secondary and redundant elements. For example, the bottom columns are key elements in frame-supported structures; the core tube in frame-core tube structure is also key element; columns in frame structures are important elements, frame beams are common elements and secondary beams secondary elements; coupling beams in shear wall structures are also secondary elements; most of the non-structural elements are redundant elements; dampers for dissipating energy are also redundant elements.

According to the concept of hierarchy of function, the structural elements in seismic designs can be categorized as vertical load-bearing elements, lateral load-bearing elements, potential plastic energy-dissipating elements and special energy dissipating elements. A structural element often has more than one function. For example, the frame columns and shearwalls resist both vertical and lateral loads; frame beams are both vertical load-bearing elements and potential plastic energy-dissipating elements; coupling beams in shearwalls are also potential plastic energy-dissipating elements. From the system's point of view, making the function of a single element as simple as possible is good for taking advantages of elements of different types, and may simplify the element design. For example, dampers are energy-dissipating elements, which can sustain cyclic load with little damage. Were they removed from the structure system, the structure's serviceability and load-bearing capacity will not be obviously influenced. They also greatly enhance the structure's seismic capacity.

In a structural system, the elements of the same importance level can belong to different functionality levels, and the elements of the same functionality level can also belong to different importance levels. The system hierarchies can help structural engineers to better understand the relationships between structure elements and their importance and functions. It can further help structural engineers to determine the role and acceptable damaging degree of each part of the structure and their influences to the whole structural system under various external forces and effects.

4 Designability of structural systems

The safety of a structure system is related, but not equal to those of its sub-systems and structural elements. Meanwhile, the performance of a structural system is related, but not equal to those of its sub-systems and structural elements. As a result, the structural system is much more designable than a single element.

An element is usually designed by firstly choosing proper materials, then determining the cross-section dimensions and reinforcement, according to its load-bearing capacity and deformation demands, which are derived from the total demand of the whole structural system. In such a procedure, little can be done to make the design flexible.

In contrast, for a given performance object, the design of a structural system is much more flexible. Different structure types can be adopted. In other words, different combinations of "hierarchy of importance" and "hierarchy of function" can be used to achieve the same structural object. It is another important character of a structural system, called "designability".

5 Desirable performance of a seismic structural system

Systems should have enough robustness to resist unexpected external actions, especially the disaster actions, such as severe earthquake and explosions. For a robust system, the failure of less important elements or elements with secondary functions will not greatly influence the more important elements or elements with major functions. And more importantly, a system should not breakdown or collapse when local secondary elements fail. For a robust structural system, the failure should initiate and develop from less important elements to more important ones. It'll be better if more important elements don't fail until all or most of the less important elements have failed. And the failure of one sub-system will not greatly affect or propagate to another sub-system. The period of failure procedure should be as long as possible. In order to achieve higher robustness, a structural system should be designed to experience the desirable failure procedure under the external actions. This is the major difference between the system-based and element-based design.

For building structures, the desirable seismic performance can be considered as the following four phases according to the performance-based seismic design object and the "hierarchy of importance" and "hierarchy of function" concepts, as shown in fig.1.

(1) OA, elastic phase. The whole structural system is in its service state. Both the less important elements and the whole structural system can meet the demand of serviceability under design loads. For seismic designs, the structure has no damage under minor earthquakes. Point A is the limit state under minor earthquakes. At this point, local secondary elements and some redundant elements may yield.

(2) AB, hardening phase after yield. All the re-

dundant elements, some secondary and common elements have yielded under expected overloads and earthquakes of design seismic intensity. The structure system suffers from some damage. More and more elements yield with the increase of applied loads. However, the damage of the whole structure is still under control. The structural functions can be restored with some repair after the expected overloads or earthquakes of design seismic intensity.

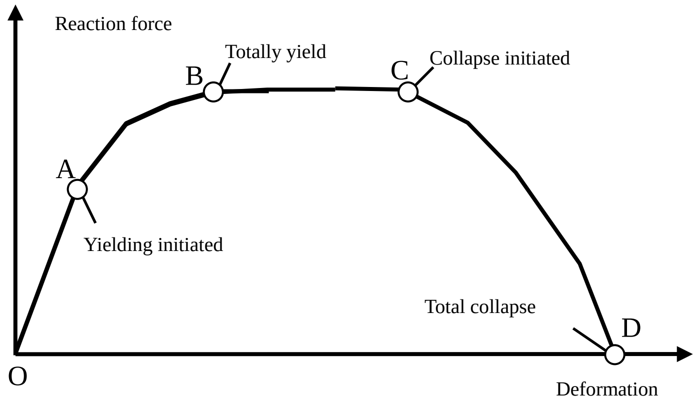


Fig.1 Desirable seismic performance of building structures

(3) Point B, limit state of the hardening phase. Many common elements and some key elements yield so that the structural system forms a failure mechanism. However, the whole structural system will not collapse under dynamic actions of earthquakes. The deformability of the structure failure mechanism is an important part of the structure seismic performance. After point B, the structural system usually suffers from severe damage and the repair is almost impossible.

(4) After Point C, with the development of plastic deformation, the capacity of some structural elements begins to deteriorate. As a result of the second-order effect at the same time, the resistance of the whole structure decreases. The structural system begins to collapse until the loss of all its capacity.

According to the results of numerous nonlinear analyses, the structure seismic response can generally be estimated before Point B. In BC phase, the estimation becomes very difficult because the large plastic deformations make the scatter of seismic response much larger [6].

In the above discussions, all the elements are assumed to be ductile enough to achieve the ductility demand of the whole structural system. In real structures, the ductility capacity of element is not always ensured. The element will be considered to fail and be removed from the structure once its plastic deformation exceeds its ductility limit, and the structural system is thus changed. If this change greatly affects the whole structural system and induces progressive collapse, this structure system is then vulnerable. This is related with another specific topic, the progressive collapse capacity of structure systems.

6 Failure mechanism and its control of a structural system

The designability of structure systems means that the failure mechanism of the structure system under unexpected disasters can be designed. The control of the failure mechanism is to make the structure system fail under earthquake following a desirable failure mechanism. Once the failure mechanism can be controlled, the collapse behavior under severe earthquakes can be predicted and proper measures can be taken to enhance the seismic capacity of the structural systems. Because failure mechanisms are the ultimate states of structural systems, the demands of load-bearing capacity, stiffness, deformability, energy-dissipating capacity and safety margin are also determined by the failure mechanisms. For building structures, the seismic failure mechanisms have two types, the local and the global failure mechanism, as shown in Fig.2.

The following structure types are vulnerable to local failure: frame-supported structure or soft story structure, block structure (masonry structure). In such structures, local damage will induce severe damage or even collapse of the whole structure system. For such structures, the robustness can only be improved by increasing the safety margin of local key elements.

(a) Local failure mechanism with only story failure (b) Local failure mechanism with the whole structure collapse (c) Global failure mechanism

Fig.2 Local and global failure mechanisms

The following structure types are usually to form global failure: ductile frame (strong column-weak beam frame), shearwall structure, tube structure, cluster tube structure and mega frame structures.

6.1 Local failure mechanism and its control

It should be noted that there're two kinds of local failure mechanisms. The first is the soft story failure mechanism, such as the structures with pier columns, as shown in Fig.2(a); another local failure mode will induce progressive collapse of the whole structure system, as shown in Fig.2(b).

For the story failure mechanism in Fig.2(a), the failure is centralized in the soft story while upper stories remain undamaged with little faculties, thus the damage degree may considered not too severe. Actually, the soft story failure mechanism is something like the seismic isolation structures, where a low-stiffness layer is arranged to centralize the earthquake energy input. The difference is that special-designed isolators instead of the soft story columns are used. The isolators are special structure elements that can sustain large deformation and remain elastic with little damage, while the soft story columns often suffer from severe damage under large deformation.

The local failure mechanism in Fig.2(b), which is vulnerable under earthquakes, is another special topic relating to the progressive collapse.

6.2 Global failure mechanism

Generally, the desirable seismic performance of building structures shown in Fig.1 can only be achieved in structures with global failure mechanisms, which are also preferable failure mechanisms for most of the building structures.

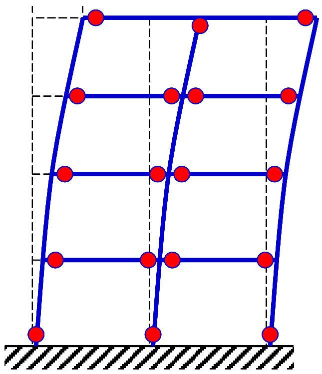
Structural systems with global failure mechanisms usually have well-organized "hierarchy of importance" and "hierarchy of function". Based on the concept of "designability", these can be achieved and the damage degree and damage development can be controlled, the lasting period of damage progress can be maximized.

The ideal failure sequence for the structural systems with global failure mechanisms is: redundant elements, secondary elements, common elements, important elements and at last the key elements. In such structures, important and key elements are always connected with many redundant, secondary or common elements, which should fail prior to the important and key ones. The structural damages progress gradually without sudden collapse in case of the failure of some local elements. Besides, the plastic deformabilities and thus the energy-dissipating capacities of the redundant, secondary and common elements can be fully developed before the failure of important or key elements. This can help minimizing the structural dynamic response under earthquakes.

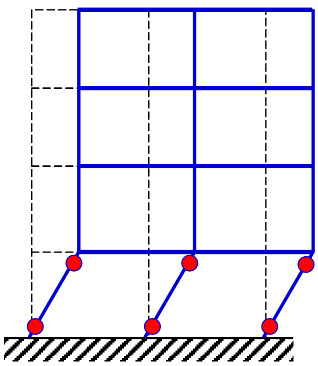
Obviously, the redundant, secondary and common elements are required to have adequate plastic deformability; otherwise the performance of the whole structure will be weakened. In other words, the structure performance is related to but not restricted by the performance of its sub systems and elements. The capacities of sub systems should be designed to meet with the demand of the whole structure system. This is also one of the important principles in the performance-based seismic design. Based on this principle, the load-bearing capacity and ductility of the whole structure system are important to the total seismic capacity. The load-bearing capacity and ductility of the sub-systems must meet the demand of the whole structural system to ensure the total performance object. Demands for the load-bearing and ductility capacities of sub-systems or elements are determined by their connectivity to key elements.

According to the concept of system robustness, the redundancy of key element will be higher if more less important elements are connected to it and fail prior to it. Thus the AB phase in Fig.1 will be longer and the system robustness will be higher.

In structural systems with global failure mechanisms, key elements are global key elements. If a system has more than one global key element, it is called "multi seismic structural system". In such systems, the seismic capacities of the global key elements are different. Thus, when one of the key elements with less seismic capacities is damaged under earthquake actions, the other key elements with larger seismic capacities can still ensure the seismic capacity of the whole structure system. Cluster tubes, tube in tube structures, frame-core cube structures are some examples of such multi seismic systems.



(a) Global failure mechanism

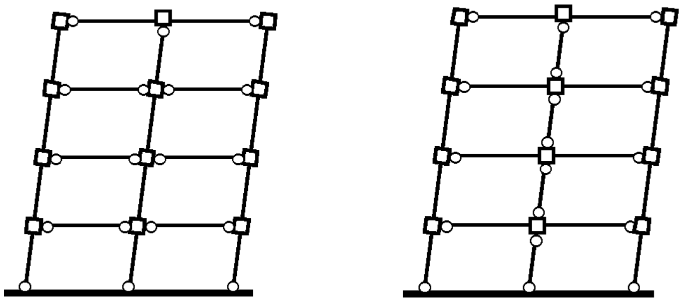


(b) Local failure mechanism

Fig.3 Failure mechanisms of structures with "strong column-weak beam" design

For ordinary frame structures, the global failure mechanism in Fig.3(a) is usually desired. However, plastic hinges at the bottom of the columns are almost inevitable even if the "strong column-weak beam" design is adopted. Besides, plastic hinges may also form at the top of columns as a result of the randomicity of earthquakes. Thus, the designed "strong column-weak beam" can not prevent the occurrence of the soft story failure mechanism shown in Fig.3(b)[8][9], because the current "strong column-weak beam" design is merely based on joint equilibriums without taking into account the system concept. "Story column-beam strength ratio" concept has been proposed recently to overcome this defect and to ensure the global failure mechanism [10][11]. According to the concept of global failure mechanisms and "story column-beam strength ratio", the two failure mechanisms in Fig.4 are both global ones. The plastic hinges in columns in Fig.4(b) are acceptable. This can make the design more flexible. The "strong column-weak beam" condition can be loosened in roof story or in large span, and the bridge capacity of the frame beams can thus be enhanced, which is also important in preventing progressive collapse.

The difference between these two global failure mechanisms is the different demands for element performance. For the traditional "strong column-weak beam" global failure mechanism in Fig.4(a), the demand for structural elements concentrates in the plastic deformability at beam ends. For the failure mechanism in Fig.4(b), there is also demand for some column plastic hinges, thus the columns are also required to have adequate plastic deformablity, which can be implemented by confined concrete or concrete-filled steel tube. Analysis results show that structures with the partial column hinge failure mechanism in Fig.4(b) has similar seismic performance as those with traditional "strong column-weak beam" failure mechanism and can decrease the dimensions of middle columns to release some architectural space.



(a) beam hinge failure mode (b) partial column hinge failure mode

Fig.4 Two global failure modes for frame structures

To achieve the global failure mechanisms based on "strong column-weak beam" concept in Fig.3(a), high strength steel reinforcement is proposed to be used in frame columns to increase their yield strength[8],[9]. Based on the hierarchy concept of structural system, this method can increase the strength of key elements (*i.e.* frame columns) and make the hierarchy of importance of the structure system clearer.

7 Methods to implement global failure mode in seismic structures

Some methods to implement global failure mechanisms in seismic structures are summarized below as the conclusions of this paper:

(1) The structural system should have sub-systems and global key elements in different levels.

(2) Safety margins of elements should be carefully designed according to the system's importance and functionality levels.

(3) Sub-systems in lower levels should be well connected to those in higher levels.

(4) The load-bearing capacity, stiffness, deformability and energy-dissipating capacity of different sub-systems should be designed based on system methods. The yielding procedure of sub-systems should be in a sequence, and sub-systems in lower levels should yield prior to those in higher levels.

(5) Sub-systems in low levels should have adequate plastic deformability and energy-dissipating capacity to meet the demand of the whole system and ensure the overall redundancy of the system before collapse. This is also necessary for reducing the seismic response in the damage phase of the structure system and easing the damage development.

(6) High strength materials are recommended in global key elements to make sure they won't yield until all the less important elements yield.

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