Analysis of Seismic Collapse-Resistant Influencing Factors of RC Frame Structure

Tian Luo*

Department of Civil Engineering and Geomatics, Southwest Petroleum University, Chengdu, China

* Corresponding Author Email: 202122000834@stu.swpu.edu.cn

Abstract. The RC frame structure is widely applied in China due to its flexible layout and good anti-collapse capacity during an earthquake. However, a lot of RC frame structures collapsed in the strong earthquake zone during the Wenchuan earthquake. The collapse resistance of the RC frame structures during an actual earthquake is inconsistent to the designed seismic collapse resistance in a project. So the collapse resistance of reinforced concrete (RC) frame structures during an earthquake and its influencing factors are a hot research topic in the field of earthquake engineering. Based on the research results of scholars in recent years, this paper briefly discusses the evaluation criteria of structural collapse, the structural collapse mechanism during a real earthquake and the influence of nonstructural components. Finally, the influencing factors are summarized in terms of design methods, plastic hinges and nonstructural members, which have certain reference significance for the seismic collapse resistance design.

Keywords: RC frame structure; evaluation criteria; seismic collapse; collapse mechanism.

1. Introduction

Earthquakes are a natural phenomenon caused by the collision of plates that rupture and cause secondary disasters resulting in a large number of injuries. A total of 159 earthquakes of magnitude 6 or above occurred worldwide in 2021, resulting in 2465 deaths and more than 18496 injuries [1]. According to statistics in the 20th century, global earthquake types can be continental and marine earthquakes, while marine earthquakes account for 85% of the global earthquakes and continental earthquakes account for 15%. China, as an earthquake-prone country, totaled about 33％ of the world's continental earthquakes in the 20th century, and it accounted for about 50% of the deaths due to earthquakes in the last century [2]. The main reason of a large number of casualties in earthquake is the collapse of buildings [3], even though the design concept of "no collapse under strong earthquakes" has been proposed in China. However, studies have shown that reinforced concrete frame structures (RC frame structures) based on current Chinese codes are not sufficiently resistant to collapse in strong earthquake region [4]. RC frame structure, as the main form of building structure in China, played a huge seismic advantage in the Wenchuan earthquake. But the design of this structure expected “strong column and weak beam” damage pattern rarely appeared in the strong earthquake zone [5]. Studies have shown that the failure rate of the structure was higher in the strong earthquake zone during the Wenchuan earthquake, and there was a gap between the actual seismic collapse resistance and the design performance. Therefore, the factors affecting the actual seismic collapse resistance have received attention [6]. The evaluation criteria for seismic collapse, the collapse mechanism of the structure during an earthquake and the influence of non-structural components are discussed in this paper, and this paper briefly summarizes the influencing factors in terms of the design methods, the plastic hinges and the nonstructural components, which can be used as a reference for engineers.

2. Evaluation criteria for seismic collapse of structure

Structural components are usually continuously damaged under earthquake action. But how to determine whether the structure will collapse under certain conditions is of concern to researchers, and the choice of reasonable criteria is not conclusive. Structural seismic collapse assessment criteria have an impact on structural collapse resistance design, as the criteria may incorrectly assess the collapse resistance of a structure.

Zhang et al pointed out the drawbacks of seismic collapse assessment criteria for RC frame structure based on the energy principle and the loss of motion stability [7]. Assessment criteria based on the energy principle normally ignores the structural form and material properties. The assessment criterion based on the loss of motion stability is that the RC frame structure loses motion stability after collapsing. However, based on the elastic-plastic properties of materials and the uncertainty of earthquakes, a plastic hinged structure that loses kinematic stability can be recovered. So, the loss of motion stability cannot absolutely indicate the collapse of RC frame structure. Zhang analyzed a RC frame structure with 5-layer and 3-span by using the software Opensees to determine the most reasonable criterion among the criterion based on stiffness, deformation, and incremental dynamic analysis (IDA) and the criterion based on both maximum displacement and energy [8]. The research shows that the two-parameter criterion (maximum displacement and energy) can accurately assess whether the structure collapses or not to some degree. The two-parameter criterion (maximum displacement and energy) is more consistent with the actual situation. While the rest of criteria based on stiffness, deformation, and IDA tend to overestimate the actual seismic collapse-resistant capacity. So, evaluation criteria based on immature theory may lead to a wrong conclusion, which can contribute to a higher or smaller seismic collapse-resistant capacity. Different evaluation criteria for the same structure could result in different conclusions. So, it’s important to apply a method based on software or theory to find the most precise criterion for evaluating the seismic collapse resistance of the structure.

There are many evaluation criteria for the seismic collapse of structures in China and abroad, including evaluation criteria based on a single parameter (energy, displacement, IDA, deformation, etc.) and evaluation criteria based on double parameters. While Chen summarized the evaluation criteria (As shown in Table 1) from 2 aspects [9]. The criterion is based on a single parameter (intensity, deformation, stiffness, energy, and IDA) and based on double parameters (both displacement and energy). The research shows that the criterion based on intensity, which is widely used, takes the demand exceeding the capacity of structure as the evaluation of collapse. But the criterion only considers the linearly elastic state of the structure. In reality, the structure will turn into a state of the elastoplasticity. Because the natural vibration period and stiffness of the structure will change under earthquake action. So, the criterion based on intensity cannot precisely determine the collapse resistance of a structure during an earthquake.

In conclusion, various design methods based on different evaluation criteria may lead to various conclusions based on higher or smaller structural seismic collapse-resistant capacity. So, design method, as a seismic collapse-resistant influencing factor, could determine the structural performance of collapse resistance in a real earthquake. The structure tends to collapse in advance during an earthquake if a structural design with larger seismic anti-collapse capacity is applied in a project. While a structural design with smaller seismic collapse-resistant capacity could result waste of materials in order to enhance the seismic collapse-resistant capacity of structure. Therefore, an accurate design method based on appropriate evaluation criteria can make the capacity of the structure in the design similar to the actual capacity during an earthquake. Then the seismic collapse-resistant capacity of structure can be fully used based on actual needs in a different area.

Table 1. The evaluation criteria based on different parameters

Evaluation criteria	parameters
single parameter	Intensity, deformation, stiffness, energy, and IDA
double parameters	Both displacement and energy

3. The seismic collapse mechanism of RC frame structure

Researchers can better study the factors affecting the seismic collapse of RC frame structures by studying the rules and causes of the collapse of the structure during an earthquake. Then researchers can analyze the common factors that cause the seismic collapse of the most RC frame structures. So seismic collapse-resistant capacity and performance of the structure can be better when the factors are solved.

Xu et al summarized the collapse mechanisms of the structure (As shown in figure 1 and figure 2) in the strong earthquake zone from two aspects: the yield mechanism of the beam hinges and the column hinges [10]. The yield mechanism of the beam hinges indicates that the structure as a whole can resist earthquake action. Ideally, the plastic hinges will be formed at both ends of beams under earthquake action. The beams with plastic hinges can consume the energy of earthquake, so the beams are the first components to collapse during an earthquake. As for the yield mechanism of column hinges, the columns will form plastic hinges at the both ends under earthquake action due to shear and bending moment. Then the columns of the structure tend to rotate. Therefore, the structure consisting of moveable columns may be transformed into a geometrically unstable system. Finally, RC frame structure collapses because the columns with plastic hinges collapse first. While components on other layers may be undamaged.

Wang summarized the collapse mechanisms of the structure during an earthquake from four aspects: the failure of partial layers, the failure of all layers, the failure of the bottom layer, and the failure of the middle layer [11]. The failure of partial layers and failure of all layers indicate that the beams of partial layers and all layer's form plastic hinges, so the beams with plastic hinges can consume the energy of earthquake. Then the columns continue to carry the vertical loads and horizontal loads of the structure, so the whole structure can't collapse easily during an earthquake. The failure of the bottom layer and failure of the middle layer indicate that the columns of the bottom layer and the middle layer form plastic hinges. So, the whole structure collapses due to the collapse of the bottom columns. While the structure is partially collapsed due to the collapse of the middle columns.

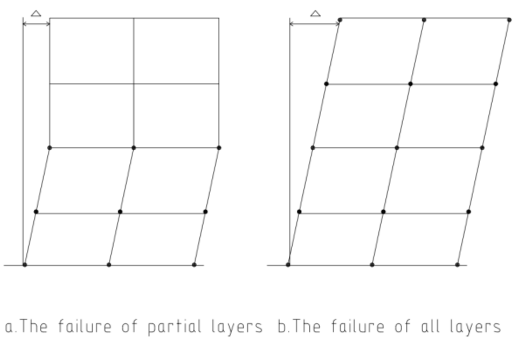

Fig. 1 The yield mechanism of the beam hinges

Figure 1 shows that the beams of partial layers and all layer's form plastic hinges

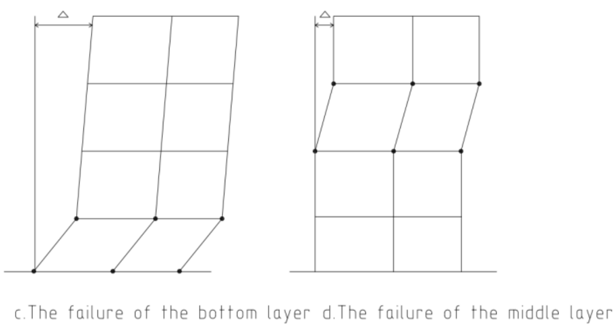

Fig. 2 The yield mechanism of the column hinges

Figure 2 shows that the columns of the bottom layer and the middle layer form plastic hinges

Researchers normally analyzed the factors that cause the collapse of RC frame structures in an earthquake by using software or a shaking table. Cai et al used a finite element software to analyze a completely collapsed RC frame structure with 10 floors during the Wenchuan earthquake [12]. The collapse mechanism was found by dynamic time history analysis. While the seismic collapse resistance of the structure was calculated by incremental dynamic analysis (IDA). The research shows that the completely collapsed structure has weak layers at the bottom and in the middle of the structure. Because the bottom and middle of the structure had multi-story unbraced columns. While the stiffness of structure changes gradually due to different slabs being applied to the structure. Therefore, the weak layers composed of columns without many beams supports tend to collapse firstly during an earthquake. Lian et al analyzed the collapse mechanism of a single-span frame structure during a major earthquake by the means of Pushover [13]. The research shows that the structure collapses due to the mechanism of a “weak column and strong beam”. The damage degree of the column is more serious than that of a beam under earthquake action because more plastic hinges are formed at both ends of columns than at both ends of beams, so columns of the structure are the first to be damaged during earthquake action. Huang studied the collapse mechanism of Xuankou Middle School (RC frame structure) in the Wenchuan earthquake through a shaking table test [6]. The research points out that the cause for the collapse of the structure is that the middle columns at the bottom of the structure are destroyed firstly. Because the columns on the 1st floor form the plastic hinges.

The beams and the columns tend to form plastic hinges at the both ends under earthquake action. According to the analysis of the collapse mechanism of the structure during an earthquake by the above-mentioned researchers. The structure collapses during an earthquake due to the columns collapse firstly. Then the whole structure collapses directly. The seismic collapse mechanism studied by the researchers indicates that the columns are weaker than other components under earthquake action. The actual “weak column and strong beam” mechanism of RC frame structure during an earthquake is contrary to the ideal "strong column and weak beam" mechanism during a design. Actually, the plastic hinges seem to be formed at both ends of the structural columns firstly during an earthquake. So, the actual anti-collapse capacity of columns is smaller. Then the columns under maximum shear and bending moment, especially the columns at the bottom of the structure, tend to collapse first.

In conclusion, the plastic hinges, as a seismic collapse-resistant influencing factor, could result in the columns at the bottom layer or the middle layer collapse firstly. Then the whole structure or part of the structure collapses. While components like beams on other layers may be undamaged. However, the possibility of structural collapse is reduced if the beams form plastic hinges at the both ends first during an earthquake because the plastic hinges can consume the energy of earthquake. Then the column can continue to carry the weight of the structure. So, the collapse mechanism of the structure meets the design goal of “strong column and weak beam”.

4. Influence of non-structural components on seismic collapse of the structure

From the research mentioned above, the researchers almost ignored the Influence of non-structural components (like infilled walls and concrete slab) on the collapse of the structure during an earthquake by analyzing the structural collapse mechanism based on software. However, the non-structural components will affect the anti-collapse capacity of the structure during an actual earthquake. To better study the factors affecting the seismic collapse-resistant performance of RC frame structures in actual earthquakes and analyze the reasons for the "strong beam and the weak column" failure mechanism. Research of taking non-structural components as structural seismic collapse-resistant influencing factors is important.

4.1. Concrete slab

The seismic collapse mechanism of the "strong column and weak beam" of RC frame structure is that the beams form plastic hinges at the both ends first during an earthquake. So, the beams can consume the energy of earthquake and the columns will not collapse firstly. Finally, the structure has a small possibility failure of collapse when the columns can still carry loads from the structure under earthquake action. However, the seismic collapse mechanism of the "weak column and strong beam " is more likely to occur during an actual earthquake.

Researches show that the concrete slab affects the designed collapse mechanism of "strong column and weak beam". Ye et al studied the collapse mechanism of the structure in the Wenchuan earthquake [14]. The research summarized the reason for the collapse mechanism of the " weak column and strong beam " during an earthquake. The research summarized that the concrete slab enhances the load-carrying capacity of the beam. Because reinforcements of concrete slab and reinforcements of beam supports work together. Then the beam can carry larger negative bending moment. The concrete slab is also used as the flange of beam to enhance the load-carrying capacity of beam. Li studied the effect of the thickness of the concrete slab and the flange width of beam on the load-carrying capacity of the beam [15]. The research shows that the concrete slab has a positive effect on the load-carrying of the beam. Wang et al summarized that to better calculate the strengthening effect of the concrete slab on the beam, the cross section of the beam is normally assumed as a “T” shape or an “L” shape [16 17]. So, the calculation of the effective width of the flange can measure the strengthening effect of the concrete slab on the bearing capacity of the beam. The researchers also summarized that the type of structural joints, the stiffness of the transverse beam and the lateral displacement of the structure all can influence the strengthening effect of the concrete slab on the bearing capacity of the beam.

In conclusion, the non-structural component, the concrete slab, can make the bearing capacity of the beam larger because the reinforcements enable the slab and beam to work together. The slab can also be seen as a flange of beams. Then the actual bearing capacity of the beam during an earthquake is larger than the designed capacity. So, it’s not easy for the beams to form plastic hinges and collapse first. Finally, the columns form plastic hinges earlier than the beams and collapse earlier than the beams. The structure then collapses following the mechanism of the “weak column and strong beam”.

4.2. Infilled wall

The paper summarized the effect of infilled walls on the designed collapse mechanism of “strong column and weak beam” during an earthquake from 4 aspects [14]. Firstly, the infilled walls tend to work together with the beams during an earthquake, so the actual beams are “stronger” than the designed beams. Secondly, the infilled walls enhance the stiffness of the structure. Then the structure is subjected to greater seismic action. Thirdly, the uneven distribution of infilled walls leads to the uneven distribution of structural stiffness. Then the bottom layer of the structure may transfer into the weak layer. Finally, the columns collapse firstly due to the effect of continuous half-height infilled walls (As shown in figure 3). The paper summarized that the columns restricted by continuous half-height infilled walls (spandrel walls) will be distributed to greater shear under earthquake action [11]. The lateral stiffness of columns becomes larger when the height of columns can actually be considered to be smaller. So, the plastic hinges are more likely to form at both ends of columns first. Finally, the whole structure collapsed due to the collapse of the key weight-bearing members.

The infilled walls can work together with the beams to bear earthquake load. So, the beams may have better seismic collapse-resistant capacity than the designed capacity. Then the collapse mechanism of the “Weak column and strong beam” is more likely to occur. The column can be subjected to larger seismic shear because the stiffness of column, restricted by continuous half-height infilled walls (spandrel walls), becomes larger. So, the columns tend to collapse firstly during an earthquake.

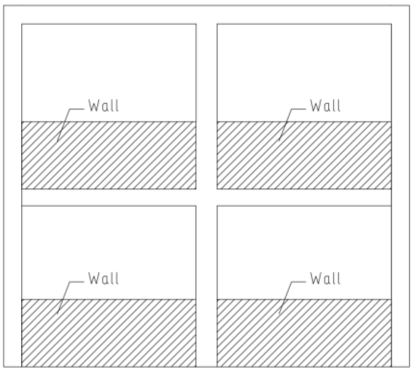

Fig. 3 Continuous half-height infilled walls

Figure 3 shows the columns restricted by continuous half-height infilled walls

5. Conclusion

This paper briefly discussed the assessment criteria for seismic collapse, the seismic collapse mechanism and the influence of nonstructural components on structural collapse during an earthquake. The design methods, the plastic hinges and non-structural components as influential factors are considered as the seismic anti-collapse influencing factors of RC frame structure in this paper. But this paper doesn't provide solutions for enhancing the seismic collapse-resistant capacity and performance. But detailed measures to improve the collapse-resistant and performance of structures in actual earthquakes are issues of interest. In this paper, the factors influencing the seismic collapse-resistant influencing factors are summarized as follow:

1.The design methods of the structure are considered as one of the seismic collapse-resistant influencing factors in this paper. The design methods based on various evaluation criteria can result from different conclusions of determining whether the structure collapses or not under certain earthquake actions. So, an appropriate design method enables the designed seismic collapse-resistant performance of the structure to be similar to the actual performance of the structure in a real earthquake. Then the structure will not collapse in advance or waste materials because of the inaccurate design method.

2.The plastic hinges formed at both ends of columns are taken as one of the seismic collapse-resistant influencing factors in this paper. The RC frame structures mainly follow a collapse mechanism of the "weak column and strong beam" in actual earthquakes from the research mentioned above. Because the plastic hinges are likely to be formed at both ends of columns first during earthquake action. Then the whole structure or part of the structure collapses due to the columns collapse firstly while other components may be undamaged. But the structure follows a collapse mechanism of "strong column and weak beam" when the beams form plastic hinges at both ends first.

3.The nonstructural components are taken as one of the seismic collapse-resistant influencing factors in this paper. From the research mentioned above, the concrete slab and infilled walls both have a positive effect on the anti-collapse capacity of the beams under earthquake action. Then the plastic hinges are less likely to be formed at both ends of beams in an actual earthquake than in a design project. Besides, the columns restricted by the continuous half-height infilled walls (spandrel walls) are more likely to collapse first.

Based on the research results of scholars in recent years, this paper summarizes the factors influencing the collapse resistance of RC frame structure during an earthquake. The design methods that overestimate the anti-collapse capacity of the structure, the plastic hinges that formed at both ends of columns and the nonstructural components all could lead the structural collapse resistance in an earthquake to be different with the designed seismic collapse resistance in a project. So, the structure tends to collapse in a different mechanism of the "weak column and strong beam" during a strong earthquake. However, this paper only considers the influencing factors without providing any solutions. So, solutions that enables the structure to collapse following the mechanism of “strong column and weak beam” are important. Then the collapse resistance of the structure during an earthquake can be fully used and the structure can be safer.

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