Analysis of seismic collapse mechanism of concrete frame structures subjected to near-fault ground motions

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Abstract. The characteristics of near-fault ground motions are significantly different from far-field ground motions. There are also great differences in the damage of concrete structures caused by these two kinds of ground motions. Earthquake damage indicates that the damage of concrete frame structures subjected to near-fault ground motions is more serious and collapse mechanism is more complicated. In this paper, the traditional alternative path method (APM) in the analysis of collapse was improved. Collapse mechanism of reinforced concrete frame was studied by numerical simulation method. A typical ten-story reinforced concrete frame model was established. Three harmonic waves and three practical near-fault ground motions were selected as acceleration time history input. The results show that different damaged parts of structure caused by strong earthquake have little effect on the final collapse mode when the structure is under free vibration. The failure mode of columns subjected to different ground motions is almost the same. Simple harmonic excitation whose period is close to the predominant period of ground motion can approximately simulate the failure mode of structure caused by earthquake.

1. Introduction
Progressive collapse of structures refers to a failure mode in which the final failure mode of the structure is not proportional to initial damage. Progressive collapse of the Ronan Point apartment in England was caused by gas explosion in 1968. This was recognized as starting point for structural collapse resistance studies. In 2001, U.S. World Trade Center completely collapsed due to terrorist attacks. This event has attracted great attention of scholars and engineers on progressive collapse.

In the past two decades, domestic and foreign scholars have conducted a large number of experimental studies and numerical simulations on the mechanism of progressive collapse of reinforced concrete structures. Many research results were obtained based on alternative path method. Weijian Yi completed a pseudo-static collapse test of RC frame with 4 spans and 3 floors using alternative path method[1]. This test revealed the whole process of collapse of framework structure from elastic stage to compressive arching action and then to catenary action. Lew H S found angle limits at the end of beam in column removal monotonic displacement loading pseudo-static test were 7 to 8 times that of dynamic tests[2]. Therefore, it is necessary to consider the influence of dynamic factors in the structural collapse analysis. Sasani M conducted dynamic column removal test to two real concrete buildings[3,4] and Yan Xiao performed side and corner column sudden removal test to large scale reinforced concrete frame model[5,6]. The results of dynamic tests using alternative path method showed that seismic design frame structures had good performance in collapse resistance. The catenary action and vierendeel frame action of structures can effectively prevent frame structures from progressive collapse. However, these static and dynamic alternative path methods only take dead and live load into account. The collapse resistance of structures with initial damage subjected to horizontal loads (like earthquake) has not been fully studied yet. Shuang Li conducted a shaking table test of a
3-story concrete frame structure and analyzed in detail the collapse process of the concrete frame structure[7]. Large-scale shaking table test can obtain valuable test data while scale or full scale shaking table tests have strict requirements on experimental equipment and need huge material, human and financial resources. Therefore, economical and developed numerical simulation method has become one of the most important methods used to study the collapse of structures. Serkan Sbuild a numerical model of a 7-story concrete frame structure and analyzed its collapse resistance using alternative path method. The results showed that the structure was easier to collapse after upper story column was removed[8]. Xiao Lu conducted numerical simulation of collapse process of reinforced concrete structures under extreme ground motions[9]. The result showed numerical method can simulate the collapse process and collapse mechanism of high-rise reinforced concrete structures under extreme ground motions.

Near-fault ground motion is more likely to cause serious damage or collapse to structures and great loss of life safety and property. The alternative path method was initially proposed to simulate the initial damage of structures under explosion and collision. Its operation is simple. It can better evaluate the properties of progressive collapse resistance of structures. However, the damage of structures under earthquake is different from that under explosion and collision. The bearing capacity of components will not be suddenly lost under earthquake which usually cause partial damage on components. When part of structure is damaged, the residual structure will also have different degrees of damage and stiffness distribution of the structure will change greatly. Internal forces will be redistributed within the residual structure. This may cause further damage to other components and cause progressive collapse. However, the destruction of a component or part of structure caused by explosion or collision does not cause damage to residual structure. The subsequent collapse resistance capacity is provided by undamaged residual structure. This is essentially different from the collapse resistance capacity provided by residual structure with degraded stiffness when the structure is under earthquake and weakened parts are damaged. Therefore, it is necessary to conduct further research on the collapse mechanism of structures under strong ground motion.

This paper has improved the traditional alternative path method. In view of the damage characteristics of concrete frame structure subjected to near-fault ground motions, improved alternative path method was used to establish a finite element model. Dynamic analysis was conducted to reveal internal force redistribution patterns and collapse mechanism of concrete frame structures under strong earthquakes.

2. Improved Alternative Path Method

The collapsed structures studied by traditional alternative path method has two characteristics. First, the causes of the initial damage of the structure mainly include explosions, car crashes, terrorist attacks, fire and so on. The initial damage of structure caused by these factors is generally focused on a very small area of overall structure. The damage degree of components is often very serious and the bearing capacity is almost lost. The second is the load causing the structure to collapse. Traditional alternative path method is aimed at studying progressive collapse of structures under vertical load such as gravity loads. After removing columns, the remaining columns are mainly subjected to bending moments and axial forces while the beams are mainly subjected to bending moments and shear forces.

Structural collapse caused by near-fault ground motions can also conclude two characteristics. First, it is believed that the beginning of ground motion (or main shock) causes initial damage to the structure. Earthquake has effects on the whole structure. The structural damage will not be concentrated on a single component. The initial damage occurs in a large area of structure and the components in the damaged area still have some bearing capacity. Secondly, it is considered that the latter stage of ground motion (or aftershocks) causes structural collapse. The shear force in column is much larger.

In order to deal with the differences between the above characteristics, the traditional alternative path method needs to be improved. Improved alternative path method reduces the bearing capacity of frame column qualitatively and remains part of rigidity and strength. The differences between traditional and improved alternative path method proposed are shown in Table 1.
Table 1. Comparison between traditional and improved alternative path method

| Comparing content                  | Traditional APM                      | Improved APM                       |
|-----------------------------------|--------------------------------------|-----------------------------------|
| Cause of initial damage           | Explosions, crashes, terrorist attacks, fire | Beginning of earthquake or main shock |
| Number of components damaged in first stage | Single                              | Multiple                          |
| Damage degree of components in first stage | Completely                          | Partly                            |
| Collapse load                     | Gravity load                         | Earthquake load                   |
| Direction of collapse load        | Vertical                             | Horizontal                        |
| Number of components removed      | Single                               | Multiple                          |
| Degree of components removed      | Completely                           | Partly                            |

The specific operations of improved alternative path method proposed in this paper are as follows: First, determine the weak story of the RC frame structure. Second, determine factor $\alpha$ and select a column at the weak story as the main object for capacity reduction. Last, determine factor $\beta$ ($\beta<\alpha$) and reduce the bearing capacity of other columns at the weak story.

3. Numerical Model

3.1 Basic Information of Frame Structure

This paper selects the 10-story RC frame structure in literature[9] as a basic model. Figure 1 shows basic information of the frame. Table 2 shows column section size and reinforcement area.

![Figure 1. The plane and elevation of the 10-story RC frame](image)

Table 2. The cross sectional parameters of the 10-story RC frame

| Story | Column cross sectional size/mm² | Area of side and corner column longitudinal reinforcement/mm² | Area of middle column longitudinal reinforcement/mm² | Area of beam longitudinal reinforcement/mm² |
|-------|---------------------------------|---------------------------------------------------------------|-----------------------------------------------------|---------------------------------------------|
| 1     | 700×700                         | 5000                                                          | 6000                                                | 8000                                        |
| 2     | 700×700                         | 5000                                                          | 6000                                                | 5000                                        |
| 3     | 700×700                         | 5000                                                          | 6000                                                | 5000                                        |
| 4     | 700×700                         | 3400                                                          | 6000                                                | 5000                                        |
| 5     | 600×600                         | 3400                                                          | 4400                                                | 5000                                        |
| 6     | 600×600                         | 3400                                                          | 4400                                                | 5000                                        |
| 7     | 600×600                         | 3400                                                          | 4400                                                | 5000                                        |
| 8     | 500×500                         | 2200                                                          | 3000                                                | 5000                                        |
| 9     | 500×500                         | 2200                                                          | 3000                                                | 5000                                        |
| 10    | 500×500                         | 2200                                                          | 3000                                                | 5000                                        |
3.2. Basic Information of Material

In this model, the stress-strain relationship of concrete adopts the plastic damage constitutive model and stress-strain curve adopts the uniaxial tension curve proposed in literature[10]. The stress-strain curve is shown in Figure 2. The constitutive model adopted for reinforcement can be seen in Figure 3. Table 3 shows the parameters of concrete and reinforcement materials.

![Stress-strain curve of concrete under uniaxial tension and compression](image)

**Figure 2.** Stress-strain curve of concrete under uniaxial tension and compression

![Stress-strain curve of rebar](image)

**Figure 3.** Stress-strain curve of rebar

**Table 3.** The parameters of concrete and reinforcement

| Material         | Strength | E (GPa) | ρ(t·mm⁻³) | Poisson's ratio γ | σₘ₀(MPa) | σₘ₉(MPa) |
|------------------|----------|---------|-----------|------------------|----------|----------|
| Concrete         | C30      | 30      | 2.4E-9    | 0.2              | 2.5      | 30       |
| Longitudinal rebar | HRB400  | 200     | 7.8E-9    | 0.3              | 540      | 540      |
| Stirrup          | HPB300   | 200     | 7.8E-9    | 0.3              | 420      | 420      |

3.3. Finite Element Model of Frame Structure

The finite element model was established based on software ABAQUS. The concrete frame uses the solid element (C3D8R). The reinforcement uses the line element (T3D2) and the floor adopts the shell element (S4R). Reinforcement is embedded into concrete assuming no relative slip and detachment.

Existing research shows that cast-in-situ slabs have a significant effect on the stiffness of concrete frame beams[11]. The results of the shaking table test also show that columns and beam-column joints are mostly damaged before beams[12]. The earthquake damage survey also shows that in the collapse of many concrete frame structures the "strong beam weak column" failure mode appears[13]. Considering progressive collapse of frame structure mainly caused by the failure of column, this paper mainly studies the damage of frame columns under earthquake and resulting collapse mechanism. The rigid floor assumption is used in the model. The connection between column and floor is bound (Tie).

![Locations of column weakened 50% for each scenario](image)

**Figure 4.** Locations of column weakened 50% for each scenario
3.4. Scenarios Setting
Different scenarios are considered in the analysis. It is currently impossible to accurately predict the damage of structures subjected to near-fault ground motions. Therefore, 12 scenarios of columns of first, fifth and eighth story are set using improved alternative path method. The reduction coefficient $\alpha$ is 50% and $\beta$ is 20%. The naming of each scenario is shown in figure 4.

3.5. Input Load
Simple harmonic wave and second peak period of ground motion are selected as acceleration time history input. The simple harmonic waves are used to simulate the free vibration process of the structure. The period values of the simple harmonic waves are similar to first, second and third natural vibration period in load direction and the values are 0.5s, 0.2s and 0.1s, respectively. The peak acceleration of simple harmonic waves is set to 0.2g and duration is 10s. Intercept 10s of second peak period of El Centro Wave, Wenchuanwolong Wave and Jiangyouhanzeng Wave as acceleration time history input. These three actual earthquake records are used to simulate the seismic load of the structure in the second period of ground motion (or aftershocks). The peak acceleration amplitudes are all adjusted to 0.4g. Figure 5 is acceleration time history of intercepted ground motions and the time on abscissa is corresponding to original ground motion recording time. Figure 6 is Fourier amplitude spectrum of the intercepted ground motions.

![Figure 5. Time history of different earthquakes](image_url)

![Figure 6. Fourier amplitude spectrum](image_url)

4. Analysis

4.1. Response of Structure under Harmonic Vibration
Under simple harmonic vibration with peak value of 0.2g, there is no case where the inter-story displacement ratio exceeded 1/50 meaning no collapse occurred. The harmonic wave with a period of 0.1s does not cause any further damage to the structure. The damage of the structure under harmonic wave with a period of 0.2s is basically similar for each scenario and the eighth story is moderately damaged while the remaining floors are not damaged. Harmonic wave with a period of 0.5s causes the most serious damage to the structure and concrete damage is mainly concentrated at the first story.

Figure 7(a), (b) and (c) are top inter-story displacement ratio under the harmonic wave with the period of 0.5s for four scenarios of the first story, the fifth story and the eighth story, respectively.
It can be seen in figure 7 that in all scenarios of first, fifth and eighth floor the distribution mode of top inter-story displacement ratio is similar. The top inter-story displacement ratio of top floor is the smallest. The top inter-story displacement ratio of four scenarios of the 5th floor and the 8th floor is smaller than the first story. Therefore, compared with the frame columns on the middle floor and the upper floor, the structural stability decreases more seriously when the bottom column is damaged. The top inter-story displacement ratio of the 8th story has a significant increase in all scenarios. However, in the 5th story with changing cross section of frame column, the increase in the top inter-story displacement ratio is not significant. Therefore, the story where the cross section of frame columns is changed is not always the most damaged under strong ground motion. Arrangement of columns with cross section changed has great effects on the response of structure under near-fault ground motions.

Figure 8 shows the process of compression damage of concrete under harmonic wave with period of 0.5s. Because the damage and failure modes of concrete under different scenarios are basically the same, only the process of concrete damage under scenario 1-1 is plotted. Harmonic wave with period of 0.5s causes damage to the first story first. When the damage of first story accumulates to a certain degree, 8th story starts to damage. The 5th story began to be damaged when the damage of concrete of first and 8th story columns aggravates. Finally, first story suffers the most serious damage. Moderate damage occurs in 8th story and minor damage occurs in 5th story.

4.2. Response of Structure under Earthquake

Under El Centro wave with peak value of 0.4g, the top inter-story displacement ratio of the structure has reached 1/50 which means collapse occurred. Wenchuanwolong wave with peak value of 0.4g causes minor damage to the structure while Jiangyouhanzeng wave did not cause further damage.

Figure 9(a), (b) and (c) are top inter-story displacement ratio under El Centro wave for four scenarios of the first story, the fifth story and the eighth story, respectively. It can be seen from Fig. 10 that when first story reaches the critical collapse state under El Centro wave the top inter-story displacement ratio of the remaining floors are small and no serious damage occurs. This indicates that the damage is mainly concentrated at the first story when collapse occurs. The top inter-story displacement ratio of 8th story in each scenario shows a sudden increase but not obvious at 5th story.
This phenomenon means that weak story failure occurs in the structure and does not enter overall yield state under El Centro wave. The ability of energy dissipation of the structure was poor and local yield and damage were prone to occur. Although the reinforcement of the columns at first story has been strengthened, obvious weak story failure mode still occurs. The collapse of the entire structure is caused by the failure of first story column. This measure fails to effectively prevent first floor from becoming weak story. In order to improve the seismic performance of the structure, it requires in-depth study of characteristics of energy dissipation of structures with localized destruction.

![Figure 9. Top inter-story displacement ratio for each scenario](image)

Figure 9. Top inter-story displacement ratio for each scenario

Figure 10 shows the evolution process of compression damage of concrete of scenario 1-1 under El Centro wave. The compression damage process of concrete under all scenarios is almost the same. The beam-column joints of first story are damaged first and then the columns are damaged. When the columns reach a moderate damage state, the damage begins to transmit to the beams of the lower floor. However, when the collapse occurs, the damage of the beams is still slight and the remaining floors and components are almost intact. The damage of structure caused by El Centro wave is similar to that caused by harmonic wave with period of 0.5s. The damage is mainly concentrated at the lower story.

![Figure 10. Damage evolution process of scenario 1-1](image)

Figure 10. Damage evolution process of scenario 1-1

The final state of concrete under compression of the structure under Wenchuanwolong wave. The moderate damage occurs at the end of 8th story columns and the remaining floors are almost intact. Jiangyouhanzeng wave does not cause further damage because its predominant period corresponds to third order natural vibration period of the structure and its contribution is less. The predominant period of El-Centro wave is close to first order natural vibration period of the structure and contributes most. El-Centro wave causes the most damage to structure. The predominant period of Wenchuanwolong wave is close to second order natural vibration period of the structure, so it causes less damage to the structure than El-Centro wave. The high-frequency ground motion is more likely to excite the higher order vibration mode causing structural damage concentrated in the upper part of the structure.
5. Conclusion
In this paper, the traditional alternative path method is improved. The finite element model of a typical concrete frame is established by using the improved alternative path method. Three simple harmonic waves and three actual earthquake waves are selected as acceleration time history input. The seismic response and collapse process of the concrete frame structure are analyzed. The collapse mechanism of the concrete frame structure is studied. The main conclusions are as follows:

1) Although the damaged part of the structure caused by strong earthquakes is different, the initial damage of structure has little effect on its final collapse mode under the free vibration.

2) The failure mode of the frame columns for each scenario is almost the same. The structure is initially damaged by the column whose bearing capacity is reduced 50% and then the damage is transmitted to surrounding columns. When the damage of surrounding columns accumulates to a certain degree, the damage rate of the column whose bearing capacity is reduced 50% suddenly increases until the column failures.

3) Using a simple harmonic excitation that is close to the predominant period of ground motion can simulate the failure mode caused by the ground motion to the structure approximately.

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