Fast assessment method for progressive collapse of RC frame structures

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Abstract. Progressive collapse has attracted enormous research interests since the catastrophic 911 event. However, there is still a lack of fast assessment methods for assessing the damage state of structures suffering a certain initial local failure. In this paper, a newly developed efficient numerical model is introduced for progressive collapse analysis of reinforced concrete (RC) frame structure, and the reliability of the numerical model is verified by a collapse test. Then, the fast assessment method is proposed based on both the numerical model and energy approach. A 6-story RC frame structure is taken as an example, and three different initial failure scenarios are analysed by both the proposed fast assessment method and direct dynamic analysis method. Results indicate that although only one static analysis is required for the proposed fast assessment method, the accuracy is almost identical with that of direct dynamic analysis.

1. Introduction

Once a certain initial local failure is triggered by some extreme loading conditions such as impact, blast and fire, RC structures may be at risk of collapse, causing serious threats to the safety of life and property. A fast assessment method is very essential for collapse resistance design and rescue operation, which requires both efficient numerical model and reliable assessment framework.

Progressive collapse has attracted enormous research interests in recent years, including both experimental and numerical studies. In terms of numerical studies, reduced finite element (FE) models using frame elements were widely adopted for progressive collapse analyses of RC structures due to their computational efficiency [1,2]. However, these numerical simulations neglected the joint failure, bond failure under large deformations and slab effect, etc., such that the results cannot be considered satisfactory. Recently, in order to improve the computational accuracy of reduced FE model, a macro joint model was proposed by to simulate the progressive collapse of RC frame structures [3,4].

A well-known progressive collapse assessment framework proposed by Izzuddin [5,6] mainly considered the ultimate capacity of a damaged structural system. In this approach, the ultimate capacity of a structure with a certain initial local failure (e.g., under sudden column loss scenarios) is evaluated through nonlinear static pushdown analysis over successive levels of structural idealisation. Meanwhile, energy based analysis is used to account for the dynamic effects under sudden column losses. In the authors’ opinion, a more precise and efficient numerical model for progressive collapse analysis is still needed for a better assessment results.

As a consequence, this study aims to develop an energy based fast assessment framework for progressive collapse of RC frame structure. A 6-story RC frame structure is adopted for application of the proposed framework and some important conclusions are drawn in the end.
2. Numerical model for progressive collapse of RC frame structure

2.1 A newly developed efficient numerical model

The RC frame structures generally undergo both strong material and geometric nonlinearities in the process of progressive collapse. Although accuracy of the detailed FE model with solid elements is well guaranteed, the computational time is unacceptable for fast assessment of collapse resistance of RC frame structure under a certain initial local failure. Therefore, an efficient numerical model for progressive collapse of RC frame structures with both accuracy and efficiency is very essential for the fast assessment framework. A reduced model with fiber beam element for beams and columns, rigid beam element and discrete beam element for joint regions, rigid beam element and layered shell element for floor system is developed in this study, as shown in figure 1.

![Figure 1. Scheme of the numerical model for progressive collapse analysis](image)

2.1.1 Verification of the numerical model

In order to verify the proposed numerical model for progressive collapse analysis of RC frame structure, the field test on a 3-bay, 3-story, half-scale reinforced concrete frame by Xiao et al. [7] is simulated here. The plan view, loaded regions and established FE model are shown in figure 2. Geometrical properties and reinforcement details can be found in the reference. The average unconfined concrete compressive strength was 33 MPa. The yield strength, ultimate strength and ultimate strain of reinforcement are provided in table 1.

The sequential removal of columns D3 and D2 are simulated by using the efficient numerical model presented previously. The vertical displacement histories of the points on top of the removed columns obtained from both the test and simulation are compared in figure 3 and figure 4. As can be observed, the proposed model is able to accurately reproduce the test results with the error controlled within 10%. And the vertical displacement contours of the final steady states after removal of columns D3 and D2 are shown in figure 5. As can be seen, the proposed model is able to accurately reproduce the test results, indicating its validity in progressive collapse analysis of RC frame structures.
Figure 2. Plan view and FE model of the tested RC structure

Table 1. Material properties of steel reinforcement

| Bar type | Yield strength (MPa) | Ultimate strength (MPa) | Ultimate strain (%) |
|----------|----------------------|-------------------------|---------------------|
| Ø8       | 453.0                | 657.3                   | 18                  |
| Ø10      | 432.7                | 649.1                   | 18                  |
| Ø12      | 485.8                | 640.7                   | 18                  |
| Ø14      | 456.8                | 627.4                   | 18                  |

Figure 3. Comparisons of displacement history of the point at top of column D3

Figure 4. Comparisons of displacement history of the point at top of column D2
3. Proposed fast assessment method

The fast assessment method proposed for progressive collapse of RC frame structure is based on the energy method proposed by Izzuddin [5], and this method makes an assumption that the structural response is dominated by a single deformation mode. When a certain initial local failure is introduced into the system, the maximum deformation of the structure is set as \( u_0 \), and the work of applied vertical load \( Q_d(u_0) \) is:

\[
W_{ext} = \alpha Q_d(u_0)u_0
\]

Where \( \alpha \) is a dimensionless parameter associated with the deformation mode.

The work done by external forces is assumed completely transformed into the strain energy of the structural system at the moment the maximum structural deformation is reached. The internal energy of the system can be expressed as:

\[
W_{int} = \alpha \int_0^{u_0} Q_s(u) du
\]

Where \( Q_s(u) \) is calculated by nonlinear static analysis using the efficient numerical model presented in section 2. Let the work done by the external force in equation (1) be equal to the internal energy in equation (2),

\[
Q_d(u_0) = \frac{1}{u_0} \int_0^{u_0} Q_s(u) du
\]

As shown in Figure 6, the curve \( Q_s(u) \) is obtained by pushdown analysis using the efficient numerical model presented in section 2, and the curve \( Q_d(u) \) is calculated by equation (3).
4. Numerical example

To illustrate the application procedure of the proposed fast assessment method, a 6-story RC frame structure is taken as an example in this section. Detailed information of this RC frame structure can be referred to the corresponding reference[8]. A total of three different scenarios are designed for validating the proposed fast assessment method, as shown in figure 7. The detailed analysis procedures are: (1) Establish the FE models for the RC frame structure using the newly developed efficient numerical model (2) Introduce the initial local failure by deleting corresponding elements (3) Apply the initial uniform distributed loads on slabs (4) Start static analysis until reaching a balance state (5) Apply an increasing distributed load to the affected areas and calculate until failure of the structure (6) Extract the load versus displacement curve from the result files (7) Calculate the energy based load-displacement curve according to equation 3.

For scenario 1, the corner column C1 is removed to account for the initial local failure of the RC frame structure, and the load-displacement data calculated by direct nonlinear static analysis, energy based method and direct dynamic analysis are all shown in figure 8. As can be observed, the RC frame structure is still in a stable state when the increased distributed loads to the affected areas are 5kPa, 7kPa, 10kPa and even 12kPa, and the coordinate point corresponding to the load and displacement falls on the load-displacement curve obtained by the energy based method. However, once the increased distributed load reaches to 13kPa, the RC frame structure suffers progressive collapse. When the penultimate column C2 is removed in scenario 2, the pattern of load-displacement curve generated from static pushdown analysis is similar to scenario 1. As shown in figure 9, the structure will collapse once the increased distributed load reaches 8kPa. Furthermore, an initial local failure with removal of an internal column B2 is considered in scenario 3. As can be observed in figure 10, the structure still has the ability to redistribute the unbalanced force with an increased distributed load of 5kPa, 8kPa or even 10kPa, while collapse occurs with the distributed load increasing to 11kPa.

An interesting phenomenon is found that the limit collapse state of the RC frame structure is very closely related to the first peak value or the maximum value of the load-displacement curve calculated by static pushdown analysis. And the limit state for scenario 1 and scenario 2 can be generated from the first peak value, while that for scenario 3 is generated from the maximum value. This is mainly because the catenary mechanism can be only developed in scenario 3.
Figure 7. The three calculated scenarios of the numerical example

Figure 8. Collapse assessment of scenario 1

Figure 9. Collapse assessment of scenario 2
5. Conclusions
A fast assessment method for progressive collapse of RC frame structures based on an efficient numerical model and energy approach is proposed and validated in this study. And the proposed method is applied to assess the collapse resistance of a 6-story RC frame structure under three different initial local failure scenarios. Some main conclusions drawn as follows:

1) The efficient numerical model for progressive collapse analysis of RC frame structure is proved reliable with both accuracy and efficiency.

2) The first peak value of load-displacement curve calculated by static pushdown analysis is closely related to the limit collapse state of the structure if the catenary mechanism cannot be developed.

3) The maximum value of load-displacement curve calculated by static pushdown analysis is closely related to the limit collapse state if the catenary mechanism can be developed in the structure.

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