Engineering Structures 141 (2017) 126–143

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Modeling progressive collapse of 2D reinforced concrete frames subject to column removal scenario

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ARTICLE INFO

Article history:
Received 3 April 2016
Revised 2 December 2016
Accepted 13 March 2017

Keywords:
Progressive collapse
Column removal
Reinforced concrete frame
Member and substructure removal
Impact loading during collapse

ABSTRACT

In this study, a new modeling procedure for progressive collapse analysis of 2D reinforced concrete (RC) frames subject to single or multiple column removal scenario is proposed. Different from traditional pushdown analysis, the proposed method incorporates the effects of service loads *before* column removal into the analysis. To trace the collapse sequence of the structure, a member removal algorithm based on combined actions of flexural/shear/axial failures is employed. For detecting substructure collapse mechanisms, a specially designed searching algorithm is developed. Furthermore, the locations and magnitudes of collapse impacts are respectively determined by rigid-body kinematics and energy principle with both inelastic and oblique impact effects considered. Numerical examples with different loading and column removal scenarios are given to validate the suggested damage assessment procedure, the member failures identification procedure and the collapse searching algorithms as well as to demonstrate the effectiveness of the proposed modeling approach.

1. Introduction

Research on progressive collapse of structures subject to column removal scenario has intensified since the collapse of the World Trade Center towers [1]. Physical tests and numerical modeling are two main means to investigate structural resistance against progressive collapse. Due to the high cost of physical tests, progressive collapse modeling is gaining increasing popularity, especially for tracing the collapse sequence of the structures. In general, four kinds of modeling approach, namely linear static analysis, nonlinear static analysis, linear dynamic analysis and nonlinear dynamic analysis could be applied to study the responses of buildings during progressive collapse [2,3]. Static analysis procedures such as pushdown analysis [4–6] are usually load-history independent as they ignore the effects of service loading. In addition, most static analysis procedures [7–9] do not model the impact effects of failed members after the initial partial collapse. Although nonlinear dynamic analysis [10–12] may be able to model of progressive collapse accurately, they are complex to implement and require expensive computational cost. In order to improve the reliability of the modeling procedure, researchers also employed methods such as robustness evaluation [13], uncertainty concept [14] and vulnerability assessment of the structural system [15]. However, in most cases they did not attempt to identify the collapse sequence of the building, nor they attempted to predict the occurrences of impacts and their effects on the structural integrity of the remaining structure.

As a design that could be able to prevent the occurrence of any partial collapse is deemed to be too expensive in practice, it is important that engineers could be able to predict the progress of partial collapse after the initial triggering event of column removal. In practice, it is much more useful and feasible to come up with a performance-based design that could avoid catastrophic collapse by limiting the extent of the progressive collapse to only part of the structure. In this case, a tool for simulating and tracing the progressive collapse sequence in reasonable computational cost and to identify failures and collapse modes of the structure is critical to structural engineers.

Regarding the tracing of progressive collapse sequence, detecting failure of structural members and collapse impact forces generated on other members are core issues that affect the accuracy and reliability of the prediction tool. However, so far only a limited number of publication [16–19] are reported on these issues. The most common approach is to eliminate a failed member's contribution to the structure's resistance by multiplying its stiffness with a small multiplier. However, this approach may lead to numerical instabilities, especially when many failed members are residing in

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http://dx.doi.org/10.1016/j.engstruct.2017.03.018
0141-0296/

the system [17]. A better way to eliminate failed members is to remove them directly from the existing model, and then regenerate a new model in subsequent analyses. Talaat and Mosalam [16,17] developed a direct member removal algorithm in terms of dynamic force equilibrium. Kaewkulchai and Williamson [18] proposed a hinge damage parameter to quantify damages and to identify failed members during dynamic progressive collapse. However, in their work, the assumption that flexural failures at member-ends would cause separation of the affected sections from adjacent members is too conservative as any catenary action [20] in beam is not considered. For the prediction of impact point and forces, Kaewkulchai and Williamson [18] presented a modeling approach for frame structures.

This paper presents a new nonlinear static modeling procedure for progressive collapse analysis of 2D RC frames subject to column removal scenario. Based on a damage assessment procedure [21] that considers the combined effects of flexural/shear/axial forces on structural members, direct removal algorithms are developed at both member and substructure levels to remove failed structural components. Unlike other previous approaches [16–19], the proposed modeling procedure considers catenary action of beams [20] at large deformation. Furthermore, the proposed procedure also considers the effect of service loads on the structure *before* column removal. It should be noted that for RC frames, if heavy service loads on intact structure may produce non-ignorable effects on the structure's performance after column removal. The proposed approach will also incorporate the effects of impacts from failed members. Both vertical impact force due to free fall of members and tangential impact forces due to oblique impact will be taken into account. The whole modeling procedure is implemented with a nonlinear quasi-static finite element solution procedure. Five numerical examples are employed to validate the accuracy of the proposed modeling approach and to demonstrate its effectiveness for tracing the whole progressive collapse process.

2. Terminologies and modeling framework

2.1. Terminologies used

In order to give a clear description of the proposed modeling procedure, a list of self-explanatory terminologies used in this paper is summarized in Table 1.

2.2. Modeling framework

The modeling framework proposed in this study is based on nonlinear quasi-static analysis procedure in which the total loads in the structure are proportionally applied at each incremental step during analysis. A load factor ($0 \leq \lambda \leq 1$) is employed to control the loading level during the incremental analysis such that $\lambda = 1.0$ indicates that the full load is applied. In order to give an overall view of this modeling framework, a flowchart of the analysis is provided in Fig. 1. The analysis can be divided into two main parts corresponding to (1) service load analysis before column removal and (2) progressive collapse analysis after column removal. Firstly, service loads are applied to the intact structure (Fig. 2a), where the load factor λ_1 will be increased gradually from 0 to 1.0 and the damage of the structure under the action of this service load will be determined. The member stress level is usually not critical if the structure has been properly designed to satisfy code provisions. After the full service-loading is applied, progressive collapse analysis will commence by removing the single or multiple columns predefined by the user (Fig. 2b). In Fig. 2b, the solid-line loads denote the equilibrium loads applied at the moment of column removal, while the dash-line loads are reactions to the internal forces at the ends of the removed column. With the equilibrium loads in place, the dash-line loads will then be proportionately applied to the new model (with the column removed) using a new load factor λ_2. During this process, damage assessment will be performed at each load increment. Member removal and model regeneration will be conducted when at least one member has failed in the model. Fig. 2c shows a partial collapse of a substructure in which the corresponding members are identified and removed. Additional loads created after the partial collapse including released forces of removed members and impact loads from collision of members will be determined during model regeneration. In order to continue the analysis, the newly created loads (indicated as dash-line loads in Fig. 2d) will also be proportionally applied to the new model by using yet another new load factor λ_3 (from $\lambda_3 = 0$) while the equilibrium loads from Fig. 2b remain unchanged. The above process will continue until either (1) all the loads in the new model are fully applied (i.e. the new load factor attaining unity) or (2) the whole structure has collapsed.

In this study, a Total Lagrangian (TL) beam element formulation [21–22] is employed to model RC members for large deformation analysis. Comparing with P-Delta method [23], the TL formulation is more accurate and could account for the second-order effects up to collapse with high fidelity [23]. The modified Kent-Park model [24] is adopted to provide tensile and compressive constitutive laws for concrete material, where the hysteretic behavior is predicted based on the rules by Spacone et al. [25]. In addition, a bilinear elastic plastic strain-hardening model [26] is employed for steel in both tension and compression. Fiber discretization for cross-sections at integration points of elements is carried out to characterize the nonlinear behaviors of concrete and steel. Furthermore, the generalized displacement control method [27] is adopted to determine incremental step for the stiffening or softening of the structure.

Table 1
Terminologies and notations used to describe the structural system.

Term	Used in description of the model and the whole algorithm
Element	A finite element of the model.
Member or Edge	A beam or column of the frame. A member (e.g. beam or column) can be discretized into several elements.
Joint	A junction that connects two members (e.g. beam or column) or a member at a support of the structure.
Substructure	Part of the whole structure that consists of more than one member.
Structure	The entire system which includes all the members and joints (and hence all the elements in the model).
Failure	At section/element level, it refers to flexural/shear/axial failures; at member/substructure level, it refers to the ultimate collapse state.
Collapse	The ultimate state of a member or a substructure, at which the collapsed part would fall down and collide to the lower floor.

3. Damage assessment and failure criteria

The damage assessment scheme and failure criteria for RC members [21] will be employed to identify critical damages of RC frames including concrete cracking or crushing, rebar fracture in tension or buckling between stirrups. Flexural-shear-axial interactions will be considered when determining section's final failure. Detailed descriptions of the damage assessment and failure criteria can be found in [21]. In this section, a concise summary is given for completeness.

3.1. Flexural damage and failure criterion

Flexural damage of RC members and frames is quantified by the flexural damage index D_f which considers the reduction of flexural rigidity under axial-flexural interaction and is expressed as