Engineering Structures 123 (2016) 372–378

Contents lists available at ScienceDirect

Engineering Structures

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

Energy-based pulldown analysis for assessing the progressive collapse potential of steel frame buildings

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ARTICLE INFO

Article history:
Received 29 May 2015
Revised 17 March 2016
Accepted 14 May 2016
Available online 11 June 2016

Keywords:
Frame building
Progressive collapse
Nonlinear static analysis
Pulldown analysis
Pushdown analysis
Energy balance

ABSTRACT

This paper presents a new nonlinear static analysis procedure for predicting the peak structural responses of a building frame upon the sudden removal of a column. Based on the pulldown analysis technique that was originally developed using the empirical dynamic increase factors, the present procedure is derived by checking the condition of energy balance between the external work done by the unbalanced gravity loads and the internal energy stored in or dissipated by the deformed frame following the column removal. In contrast to the existing energy-based pushdown analysis that needs to incrementally apply the distributed gravity loads over all directly affected bays at every floor level above the removed column, the new energy-based pulldown analysis only requires the incremental application of a single downward force at the column removal location. As a result, only a single force–displacement response curve is needed in the energy-based pulldown analysis, compared to a large number of force–displacement curves for multiple nodes along all directly affected beams above the removed column, as required in the energy-based pushdown analysis. Hence, the computational complexity and expense is significantly reduced. Taken a steel frame structure as an example, the accuracies of energy-based pulldown analysis and energy-based pushdown analysis in assessing the building potential for progressive collapse after the notional column removal are systematically compared, using the nonlinear time history analysis results as a baseline. Numerical study shows that values of key structural responses (e.g., peak vertical displacement, maximum plastic hinge rotation, peak axial forces and moments) predicted by the energy-based pulldown analysis agree generally well with those by the time history analysis and are at least as accurate as those by the energy-based pushdown analysis. Therefore, the energy-based pulldown analysis holds great promise for fast, reliable assessment of building progressive collapse potential.

1. Introduction

Progressive collapse, also known as disproportionate collapse, of buildings as a disastrous structural problem has regained extensive attention in both academia and industry since the tragic collapses of Murrah Federal Building and World Trade Center in the U.S. [1–7]. For a building that is not intentionally designed against progressive collapse, the potential structural damages could be widespread and highly disproportionate to the initial local damages [8]. In order to mitigate this risk, the structural members of a building must be sufficiently proportioned such that resulting damages can be well confined within a local region of the building [9,10].

The alternate path method (APM) is most widely used for the analysis of building structures subject to postulated scenarios of initial structural damages [9]. As a threat-independent analysis approach, the causes (e.g., explosive loading, vehicular collision) for initial damages are no more a direct concern. Instead, a critical structural element (e.g., a column in a frame building) is instantly removed from the original structure to simulate the sudden loss of the particular element due to extreme loads. The remaining building is then analyzed to check if the deformation levels and/or internal forces of the structural members meet the prescribed criteria for collapse prevention [11]. Clearly, APM offers a tractable, systematic way of assessing the potential of a building structure for progressive collapse.

Because a building upon the sudden element removal would respond dynamically, the nonlinear time history analysis is the most accurate strategy to predict the building behavior [10,11]. However, the associated computational burden and data interpretation requirements can be enormous [12,13], making nonlinear time history analysis very expensive for APM-based progressive

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http://dx.doi.org/10.1016/j.engstruct.2016.05.020
0141-0296/

collapse analysis of large-scale buildings, especially at the preliminary design stage when exact structural responses are not required and approximate solutions are acceptable.

Nonlinear static analysis provides a useful alternative to approximately evaluate the progressive collapse potential while drastically reducing the computational efforts. Specifically, a so-called "pushdown" procedure is widely used for nonlinear static analysis [14–16] and has been adopted in current design guidelines [9,10]. Using this procedure, the gravity loads within all the immediate affected bays at all floor levels above the removed column are appropriately amplified to approximately reflect the dynamic load effect due to the sudden column removal. The static responses under the incremental application of such amplified gravity loads are then calculated to enable the performance evaluation. Apparently, the calculation accuracy of a nonlinear static analysis depends largely on the proper amplification of the unbalanced gravity loads [17].

There are two methods to determine the needed level of such amplification. In the first method, a dynamic increase factor (DIF) is used to multiply all the directly affected gravity loads and incrementally apply the amplified loads on the column-removed building. Empirical DIF equations can be developed for the analysis and design of different types of buildings [18–20]. Although the DIF method is very straightforward to implement and has been adopted in the current progressive collapse design guidelines [9], its apparent drawback is that considerable errors may be introduced by using the empirical DIF equations that are typically obtained from a curve-fitting process [18,19]. The other method is based on the condition of energy balance between the external work and the internal strain and dissipated energy [16,21–23]. The basic concept is that the column-removed building is considered able to avoid progressive collapse provided the external work done by the unbalanced gravity loads passing through the vertical displacements can be entirely absorbed by the building via structural deformation [16].

The salient advantage of such an energy-based method is that the peak structural responses of a column-removed building can be directly obtained without resort to empirical DIF equations that are derived using on a finite number of similar buildings. Its computational expense, however, is still considerable compared with that of the DIF-based method. This is because, in order to calculate the energy terms, the response curves of the unbalanced gravity load vs. the corresponding vertical displacement at the end and selected intermediate nodes of each affected beam at every floor level above the removed column should be established. This requirement can be a formidable task when analyzing buildings with a large number of stories for which multiple column removal scenarios need to be considered in order to comprehensively assess the building potential for progressive collapse.

In order to reduce the computational burden associated with the pushdown analysis, a facile nonlinear static analysis procedure termed "pulldown analysis" has recently been developed based on empirical DIFs to evaluate the progressive collapse potential of frame buildings [24]. Using the pulldown analysis, a structural analyst only needs to apply a single downward point force at the upper node of the removed column while the gravity loads within the directly affected bays are kept original instead of being amplified. Incrementally increased from zero, the final downward force is calculated by multiplying the axial force in the to-be-removed column of the original intact frame by an appropriate DIF. Numerical study has indicated that, compared with the DIF-based pushdown analysis, the DIF-based pulldown analysis is able to predict key structural responses with at least the same level of accuracy [24]. Because it is no longer needed to amplify the gravity loads within all affected bays, the computational burden is thus reduced significantly. Note that empirical DIF equations are still required in order to employ the existing version of the pulldown analysis for progressive collapse assessment.

It should be pointed out that both pushdown analysis and pulldown analysis are based on the same basic idea that the dynamic effect of unbalanced gravity loads (or their equivalent) due to column removal can be approximately accounted for by appropriate amplification of their original static values. It is also interesting to view the pulldown analysis as a special case of the pushdown analysis, provided the unbalanced gravity loads above the removed column of a frame are indeed all concentrated along the affected column line of the frame. However, under a more general situation where the unbalanced gravity loads are typically distributed over all bays above the removed column, the computational advantage of using pulldown analysis becomes apparent.

In this paper, a DIF-free version of pulldown analysis is developed based on the energy balance between the external work and internal strain energy. As a result, the progressive collapse potential of any individual building can be directly assessed without using empirical DIFs, thereby totally eliminating the DIF-related prediction errors. A step-by-step procedure is described to implement the energy-based pulldown analysis for the calculation of peak structural responses upon sudden column removal. Taken a steel moment frame as a numerical example, the prediction accuracy of the new energy-based pulldown analysis is critically compared with that of the existing energy-based pushdown analysis, using the nonlinear time history analysis results as a baseline.

2. Energy-based pulldown analysis procedure

The pulldown analysis was originally developed using the empirically derived DIFs [24], and the pulldown force is applied at the upper end of the removed column while the original unbalanced gravity loads are still applied on the bays directly above the removed column. In the present development of the energy-based pulldown analysis, the goal is to drastically reduce the efforts in the computation of the external work and internal strain energy associated with all the end and intermediate nodes of the beams that are directly above the removed column. Towards this goal, the unbalanced gravity loads are entirely excluded from such directly affected beams. To recover the effects of gravity loads, however, a single downward force needs to be applied to the removed column location, thereby resulting in a single pair of internal strain energy and external work calculation, compared with multiple pairs each corresponding to a node point along a beam within every directly affect bay at every floor level. As a result, the calculation burden associated with the gravity loads on the directly affected bays, as experienced in the existing energy-based pushdown analysis, is reduced to a minimum.

For the progressive collapse evaluation of a frame building subject to a given column removal scenario, the energy-based pulldown analysis procedure takes the following steps (Fig. 1a):

Step 1. Statically apply the original gravity loads to the column-removed frame except the bays directly above the removed column. Set an appropriate value for the force increment and initialize the increment counter $k = 0$.

Step 2. At the kth increment, statically and incrementally apply an increased downward force F_k to the upper node of the removed column. Record the resulting vertical displacement D_k of the force-applying node, and then append the obtained $F_k - D_k$ data pair to the F–D curve.

Step 3. Calculate the internal strain energy E_k as the area under the current F–D curve from Step 2. Also calculate the corresponding external work $W_k = F_0 \cdot D_k$, where F_0 is the axial force in the to-be-removed column of the original intact frame.