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Assessment of dynamic increase factor for progressive collapse analysis of RC structures

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ABSTRACT

Assessment of a building vulnerability against progressive collapse using Nonlinear Dynamic (NLD) analysis has greater accuracy compared to other methods. Yet, the relevant standards and design guidelines allows the use of Linear Static (LS) analysis and Nonlinear Static (NLS) analysis to assess the progressive collapse risks of buildings. To approximately account for the dynamic effects due to sudden element removal, two different dynamic amplification factors namely, the Load Increase Factor (LIF) and the Dynamic Increase Factor (DIF) in linear and nonlinear static analyses, respectively are suggested. The DIF formulation of the current design guidelines of progressive collapse is relied on the material properties of the affected structural members. In this study, the effect of available structural capacity on DIF value in the Reinforced Concrete (RC) structures is investigated and on this basis a new empirical DIF formula is proposed. For this purpose, several three-dimensional RC building structures with different span lengths and number of stories are designed that have different levels of seismic resistance and implemented to derive the new DIF empirical formula. One of the advantages of the proposed formulae is the possibility of predicting stress and deformation in the RC structures' members after column removal.

1. Introduction

One of the most common failures recently considered by different design guidelines is "progressive collapse" in which significant part or whole structure is destroyed due to sudden collapse of a structural element. Based on all definitions, progressive collapse is a kind of replicating failure in which total final collapse is more than primary one. Thus, the term "disproportionate collapse" is used instead of progressive collapse in some countries such as England for describing such collapse.

The progressive collapse issue first began in 1970s following an incident happened in Ronan Point building in England. It was a 22-storey tower block composed of pre-cast panels and bearing unreinforced walls. Gas explosion in 18th floor caused the loss of support of the upper floors. Due to lack of integration between load-bearing members, the upper floors collapse on lower ones and cause destruction. Incidents like relative collapse of Ronan Point tower is a turning point in formation of progressive collapse issue because not only it has been mentioned in global published works repeatedly, but this incident was the stimulus of the first form of supervising standards to prevent progressive collapse by countries such as England and Canada. In recent years, a surge of research activities on the evaluation of progressive collapse have been conducted. Botez et al. [1] considered multiple post flexural resisting mechanisms in the structural analyses of RC structures. The results showed that, in addition to flexural behavior in beams, other supplementary resisting mechanisms will be developed in RC structures to resist abnormal loads. In a research by Formisano et al.

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[2], the robustness assessment methods in steel structures under different column-removed conditions were studied. Also, a number of studies have been carried out to investigate the progressive collapse performance of RC frames [3,4]. Cheng et al. [5], studied the progressive collapse mechanism of excavations retained by cantilever contiguous piles.

There are two standards and design guidelines for evaluating structures against progressive collapse [6,7]. In both guidelines, the main direct design method is alternative path method in which the structure analyzed for failure potential after removal of column. According to this method, a structure is designed so that other alternative paths exist to transfer the load when losing or damaging the original load transferring paths. Analysis methods to evaluate alternative load paths are including LS, NLS and NLD methods. NLD method is more accurate than the other methods [8,9]. However, the current guidelines of progressive collapse design allow the application of the other two analysis methods for evaluating the risks of progressive collapse in buildings. In initial editions of these guidelines, the same increase factor 2.0 was applied to consider the dynamic effects in static analyses. Several studies show that value 2 is more conservative [10,11]. Based on the related references, maximum dynamic displacement of a structure is twice its static displacement when an impact load applied in a linear analysis [12]. Therefore, increase factor 2 can be appropriate for designing structures in elastic mode. In progressive collapse phenomenon, a building mostly responds nonlinearly after removal of critical structural element (nonlinear geometry or nonlinear materials or both). Thus, dynamic increase factor less than 2 is needed for approximating nonlinear dynamic response through NLS analysis method. In edition 2009 of UFC guideline, for consideration of dynamic and nonlinear effects, two different magnification factors called LIF and DIF recommended in LS analysis and NLS analysis, respectively [7,13].

The only effective parameter in the DIF formula recommended in the UFC 4-023-03 guideline is the material properties of the affected structural members. Therefore, it recommends approximately identical values for a specific frame under the same location of column removal at different stories, independent of gravity loading and structural capacity. Consequently, the extraction process of DIF empirical equation in the progressive collapse design guidelines does not properly predict the rate of damage intensity after removal of the column and just predicts collapse or no-collapse. It is obvious that, if the existing structural capacity only results in elastic deformation, the DIF value may be close to 2. Moreover, if the existing structural capacity presents remarkable plastic deformation, the DIF value may be significantly less than 2. Therefore, it is necessary to adjust the DIF in a manner that includes structural capacity and gravity loading.

This paper is an extension of Min Liu paper [14] with one difference; the proposed method is extended to three dimensional RC building structures and a new empirical DIF equation is presented for the nonlinear static alternate path analysis to assess the potential of RC structures in progressive collapse. To this end, several three and ten-storey RC moment frames with different span lengths are modeled. These structures which were designed to have different levels of seismic resistance, are used to derive empirical DIF equations for nonlinear static alternate path analysis of building structures.

2. Progressive collapse in RC structures

The key factors to reduce the risk of progressive collapse in the structures design are over strength, integrity, ductility and energy absorption capacity. All these factors should be considered in first phase of design. The quality of steel reinforcement at the joints of reinforced concrete structures is vital to ensure about concrete plasticity. Considering ductility principles can be effective on reduction of column removal risks when structure elements entering into nonlinear stage. It is very common that a reinforced concrete building, which is designed to resist against gravity loads, have elements incapable of bearing loads after column removal. This is true especially about the buildings in low seismic risk. In this case, since vertical members (e.g. columns & shear walls) usually have symmetrical reinforcement, they show high capacity in any directions. However, horizontal structural members (e.g. beams) may be just reinforced to resist against downward gravity loads. Thus, the reinforcement should be placed at both top and bottom along the beam where different moments emerged due to gravity loads after removal of column. Although the design codes for reinforced concrete buildings recommend minimum percentage of reinforcement at both top and bottom to achieve continuity along horizontal members, this percentage can be insufficient to prevent progressive collapse in short and medium RC structures.

For instance, when a main column removed, not only it causes an additional span but also loss of this column imposes the forces to

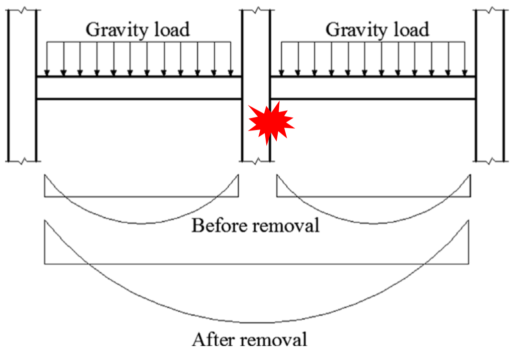

Fig. 1. The removal of middle column in a two-span concrete beam.