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A performance-based design approach for retrofitting regular building frames with steel braces against sudden column loss

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ABSTRACT

Progressive collapse resistance of existing building structures against sudden column loss may be increased with adequate supply of steel braces. A performance-based design approach for retrofitting regular building frames with steel braces is proposed in this study. The retrofit design approach is developed from the pseudo-static response analysis of an idealized elastic–plastic, single degree-of-freedom system. Analytical relationship between the increment of collapse resistance and structural characteristics is derived to determine the design strength and stiffness of added braces. Accuracy of the proposed approach is verified with incremental dynamic analysis. Also, its application to multi-story buildings is demonstrated with three frame models. Conservative performance is obtained with the design approach, especially for a larger resistance increment. An iterative modification technique is suggested to refine the retrofit design and only a few nonlinear static iterations are required for convergence. Nonlinear dynamic analysis results indicate that the column-loss response of the braced frames is approximated to the performance target and thus the proposed retrofit design approach is feasible for practical applications.

1. Introduction

Vulnerability of building structures to accidental loading induced progressive collapse has attracted worldwide attention since the partial collapse of the Ronan Point apartment building in 1968 [1]. As pointed out by the US National Institute of Standards and Technology [2], the accidental loads may vary from unintentional household gas explosions, careless vehicular collision to deliberate terrorist bombing attacks. Perhaps due to low probability and high unpredictability, these abnormal loadings are generally not considered in conventional structural design. However, prevention and mitigation of progressive collapse are undoubtedly an imperative issue in the development of structural design codes. Most current codes highlight the necessity of providing sufficient structural integrity, ductility, and redundancy to indirectly compensate the risk of collapse [3–6]. The General Service Administration (GSA) and the Department of Defense (DoD) of US have issued design and analysis guidelines for progressive collapse evaluation of building structures [7–9]. Practical linear and nonlinear static procedures are recommended to assess the alternative load paths as one or more column members instantaneously lose their load-bearing capacities due to accidental loads.

As compared to prevention of progressive collapse, earthquake resistant design technologies are more well-established and well-developed. Some studies have indicated that seismically designed building structures are less vulnerable to progressive collapse under sudden column loss [10–13]. Moment resisting frames (MRFs) with braces may perform better than ordinary MRFs. Kim et al. [14] compared the progressive collapse resistance of different braced frames and showed that all of them remained stable with less deflection than the MRF after sudden removal of a column. Fu [15] indicated that cross-bracing lateral resisting system is less vulnerable to progressive collapse. Mohamed [16] suggested that adding braces may effectively divert the high force induced by the removed column to the bracing system. Khandelwal et al. [17] showed that eccentrically braced frames may have higher collapse resistance than special concentrically braced frames. These studies reveal that adding braces is an effective option for enhancing the progressive collapse resistance of building frames. Stiffness and strength of structural members are two key factors for promoting the collapse resistance of building frames [18]. Adding braces may have a significant contribution to both factors with proper design.

It is well-known that application of steel braces to building frames has a long history. Nowadays, buckling-restrained-braces (BRB) are more and more popular in practical engineering because of their superior compressive behavior than conventional ones [19]. They may exhibit pretty symmetric elasto-plastic response under cyclic loadings. Performance-based design methods of such yielding-type steel braces have been proposed [20,21]. Effect of tension bracing on the collapse mechanism of steel moment frames under lateral loadings was investigated by Lotfollahi and Alinia [22]. In general, most braced building frames aim at mitigating earthquake-induced damage. Increase of collapse resistance under sudden column loss is rather than a by-product of the seismically designed braces. Nevertheless,

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