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Progressive collapse evaluation of externally mitigated reinforced concrete beams

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ABSTRACT

One of the factors that lead to potential progressive collapse of structures is removal of a load-bearing element such as a column. In this paper, a technique and a numerical procedure are presented for mitigation and evaluation of potential progressive collapse of reinforced concrete continuous beams following removal of interior columns. The procedure presented for mitigating progressive collapse proposes the use of external unbounded Fiber reinforced plastic (FRP) cables attached to the beam at anchorage locations and deviators/saddle point(s) only, without being posttensioned. The cables will be in effect when excessive vertical displacements and deformations occur in the mitigated beam due to removal of the interior column support of the beam. The proposed numerical model evaluates the progressive collapse of such beams using a push-down analysis to simulate column removal. It assumes that the anchorage and deviator locations of the external cables act as rigid arms that connect the external cables to the beam. Parameters such as beam cross-section shape, location(s) of deviator/saddle point(s), area and profile of the external unbounded FRP cables are considered in the proposed model. The model predicts the strength of beams mitigated by the proposed technique and evaluates the effects of the external cables on the beam ductility. Numerical results of the proposed mitigation technique obtained by the proposed numerical model are compared to those in the literature.

1. Introduction

The General Services Administration of the United States defines the progressive collapse as a total damage which is disproportionate to the original cause [1]. While a number of different definitions of progressive collapse coexist, the notion of disproportionality is common to all of them [2–5]. Recently, research and engineering community have increasingly focused on developing systems that can strengthen structure and resist their progressive collapse in the event of losing load-carrying member(s). The challenge is to develop mitigating schemes and concepts that are economical and feasible to implement. A number of research and development projects have been funded to address this problem. The objective of these efforts has been to develop mitigation and protective measures to reduce the damage resulting from progressive collapse.

Astaneh-Asl and his research associates at the University of California Berkeley [6–8], carried out three full-scale experimental projects on reinforced concrete (RC) slabs. The projects were conducted to test a cable-based mechanism that uses steel cables inside slabs to prevent progressive collapse of slab due to removal of one of the exterior columns. Based on their

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full-scale tests, they concluded that using steel cables in the floor slabs of steel structures progressive collapse of steel structures could be prevented. In 1998, the concept of using catenary action of cables in the floors as a hardening measure to prevent progressive collapse was considered by MKA engineers of Seattle in design of a building. The original developer of the concept is not known to the authors. However, to the best of the authors' knowledge, the use of cables in the floors to prevent progressive collapse was first proposed in 1996 by Dr. Joseph Penzien, professor emeritus of the University of California at Berkeley. Hadi and Alrudaini [9] proposed a scheme for retrofitting RC buildings to resist progressive collapse that may result from a first floor column failure. They used finite-element modeling and a nonlinear dynamic analysis following the alternate path method (APM), as recommended by U.S. General Services Administration guidelines, to assess the viability of the proposed scheme on a 10-storey RC building. The proposed scheme is comprised of placing vertical cables connected at the ends of beams and hung on a hat steel braced frame seated on top of the building. In case of a column collapse, the cables transfer the residual loads above the failed column to the hat- braced frame, which, in turn, redistributes these loads to the adjacent columns. They concluded that based on numerical results, their model is efficient in resisting the potential progressive collapse of the sample building used in their study. However, they indicate that before applying the proposed scheme in actual structures, experimental investigations are recommended for future studies to demonstrate the applicability of the proposed scheme in the actual structures. Izadi and Ranjbaran [10] presented analytical investigation of the approach which was presented by Hadi and Alrudaini [9] to provide alternate load path to redistribute residual loads and prevent potential progressive collapse of RC buildings. They adopted nine analytical independent failure scenarios of a ten-storey regular structural building in their investigation, including six external removal cases in different floors and three removal cases in the first floor. A new detail is proposed by using barrel and wedge to improve residual forces transfer to the cables after removal of the columns. Simulation results showed that progressive collapse due to failure of columns located in floors can be efficiently resisted by using this method.

While in most of the recent works the structures are modeled using 2D frames [11–16] full nonlinear 3D dynamic computations with geometrically nonlinear formulations are found in the literature related to steel structures [17,18]. Nevertheless, such detailed approaches are scarce for reinforced concrete structures, partially due to the high complexity involved in the modeling of the sectional response of heterogeneous RC beams, which depends on their design and on the material properties of their constituents in the non-linear range. Hence, most of the progressive collapse related references are focused on steel structures [11,12–14,16,17,19–21]. Few contributions in the literature tackle the dynamic analysis of progressive collapse of reinforced concrete structures [15,22–27]. Recent works [23–25] use explicit finite element formulations, which are mainly adopted in the simulation of blast-induced progressive collapse analyses. Few numerical methods have been introduced that can deal with collapse analysis, like Rigid Bodies Spring Model [28], Extended Distinct Element Method [29], Combined Finite-Discrete Element method (FEM/DEM) [30], and Applied Element Method (AEM) [31–33] and Improved Applied Element Method (IAEM) [34–36]. These are numerical methods for computing the motion and effect of a large number of small particles but they are relatively computationally intensive, which limits either the length of a simulation or the number of particles.

The objective of this study is to investigate the flexural behavior of beams in demonstrating progressive collapse. To analyze the flexural behavior, control beam and mitigated beam models with catenary action in external Fiber Reinforced Plastic (FRP) rods were studied. FRP is a lightweight, high-strength composite material composed of fibers (glass, carbon, or silicon carbide) embedded in a polymeric (epoxy, phenolic, or polyester) matrix. The flexural behavior of both types of beams, control and mitigated, was investigated through the load–deflection responses, ultimate load-carrying capacities, modes of failures, load–strain responses, and energy ratios of the control beam and beam models. The mechanical properties of these FRP cables are provided in Table 1 [37].

2. Proposed mitigation procedure

The proposed mitigation procedure to prevent progressive collapse of existing RC structures is based on installing external unbounded FRP cables attached to the beam at anchorage and deviators/saddle locations only to bridge over the potential removal of interior column and transfer the loads above the failed column to the external FRP cables, which in turn redistribute these loads to the adjacent beams and columns. The objective of these cables is to provide a combination of strength and ductility without being posttensioned. They are installed externally on the tension side of the beam by hanging them at deviator locations along the beam length and anchoring them at the beam end zones, and they may have a straight or deviated profile. The FRP cables will go into effect when interior column fails causing increasing/excessive vertical deflections and deformations associated with increasing rotations of the cable anchorage zones. As the mitigated beam ends undergo increasing rotations, strain in the external cables initiates and resistance force develops in the cables leading the mitigated beam to regain strength. Arapree (or Arapree-8), Leadline, Technora, and CFCC are FRP cables considered in this study. Arapree is a tendon made of aramid fibers embedded in epoxy resin. The anchorage device for this tendon consists of a tapered metal sleeve into which the tendon can be grouted or clamped with two wedges. Leadline is pith-based carbon FRP rod, that is pultruded and epoxy impregnated. There are several types of Leadline, round, indented, and rib shapes rods. Technora is a spirally-wound pultruded rod impregnated with a vinyl ester resin. Technora tendons can use both wedge and potted anchoring systems, but in the research a potted anchor was used. CFCC is the trade name for Carbon Fibre Composite Cable. The cable is formed by twisting a number of small diameter rods. The materials used for this tendon are PAN (polyacrylonitrile)-based carbon fibre and epoxy resin. CFCC anchoring system is classified as resin filling and die-cast methods.