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Extreme response of reinforced concrete buildings through fiber force-based finite element analysis

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ABSTRACT

Recent events showed that buildings designed according to conventional codes are not necessarily able to resist man-made extreme events such as impact or explosions. In the past, safety against disproportionate collapse of key elements has been increased by non-structural protective measures such as barriers, sacrificial elements and limitation or control of public access. Codified procedures emerged in the last decade asking for resistant structural design methodologies to inhibit failure incidents acting on structural components performance.

This paper presents an open access procedure using a fiber-based model in order to reproduce the progressive collapse of reinforced concrete (RC) buildings subjected to blast loading in an urban environment that leads to the loss of one or more bearing elements. Member removal in this fashion represents an event that happens when extreme situations or abnormal loads destroy the member itself. Two- and three-dimensional models of frame structures have been created and compared using three different numerical tools: an open source program such as OpenSees and two different commercial codes, SeismoStruct and Ls-Dyna. The first two are more classical fiber-based software, while the last one is a well-established general purpose finite element (FE) package. Removal of critical elements is assumed to occur in the building studied and a special purpose routine has been developed, within OpenSees and SeismoStruct, to create a fiber model capable of simulating overall structural response due to their failure. In this computational routine, one or more vertical members are instantaneously removed from the model and the ability of the building to successfully absorb member loss is investigated. The results obtained have been compared and validated by using the transient dynamic FE program Ls-Dyna.

The numerical and modeling outcome of this research on progressive collapse behavior of RC buildings may be immediately applied to the design, vulnerability assessment and strengthening of different structural typologies ranging from residential frames to strategic and military facilities.

1. Introduction

In order to ensure resistance against progressive collapse phenomena, a structure should respect five main requirements [1]: robustness, integrity, continuity, redundancy and ductility. According to the definition given by Starossek [2], robustness is purely a property of the structure in contrast with a more general definition given in Eurocode UNI EN 1991-1-7 [3] that refers to a broader triggering accidental actions (i.e. the Eurocodes do not include a separate "structural" standard for progressive collapse, but include it in the Accidental Action code). Integrity regards the ability of the structural connections between members to carry loads after the presence of abnormal events. The document published by NIST in February 2007 [4] offers an overview of approaches for structural integrity [5], and a review of available standards for design against progressive collapse, such as GSA [6] and DoD [7]. Continuity defines the interconnectivity between structural elements such as beams, columns and slabs. ASCE 7-02 [8] requires that the structural integrity be achieved by providing sufficient continuity, redundancy, and ductility in the members of the structure. The existence in a building of alternative load path for forces is usually referred to as redundancy: this simply implies the capability of "other" structural members, different from the one collapsed, to carry extra load. The term ductility refers to the ability of a structural system, elements, section or material to deform beyond elastic limits without excessive strength or stiffness degradation [9].

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2. Direct vs. indirect design methods

Therefore, in designing (or verifying) a structure to be considered as less vulnerable to progressive collapse it must be considered the comprehensive aspects of the five main requirements listed above by following two main methods: direct and indirect. The direct design method explicitly provides resistance to the structure by enhancing the strength of key elements [4] (by preventing local failure assuming specific local resistance [2]) or by designing the skeletal frame in order to bridge across collapse (by assuming local failure using alternative load paths [6,7]). While the direct approach relies explicitly on structural analysis and design [10], the indirect method considers resistance to progressive collapse implicitly through prescriptive design rules, intended to provide minimum levels of ductility and continuity [7,8,11,12]. According to the review done by Dusenberry and Juneja [13] and the description commented by Starossek [2], the following common prescriptive rules must be reached in building design:

1. according to UNI EN 1991-1-7 [3] and ACI 318 [14] horizontal and vertical tie elements (such as ordinary steel cables or post-tensioned strands) should be provided to transfer tensile forces and enhance overall integrity [15];
2. in case of intermediate column failure a transition from flexural to tensile load transfer happens. Beam-catenary (or slab-membrane) action should be enabled in order to activate a bridge over the failed column and, consequently, provide continuity within structural members [16,17]. In RC sections this could be done by using composite section or more classical seismic details such as the continuity of top/bottom reinforcements over a failing column;
3. when a major abnormal load imposes large deformation, the structure should be capable of sustaining a high proportion of the initial strength. This ability of the building or its elements or its sections or its materials to be beyond the elastic limit is usually referred to be ductility [9].

2.1. Numerical analysis approaches

In both direct and indirect procedures, four analyses can be used according to the classification described by Marjanishvili [18]:

1. linear static analysis;
2. nonlinear static analysis or pushover analysis;
3. linear dynamic analysis;
4. nonlinear dynamic analysis.

The disadvantage of linear analyses, both static and dynamic, is the inability to include material and geometric nonlinearities such as large displacements/rotations (i.e. beam-catenary action), second order effects, inelastic behavior and plastic hinge formation (i.e. strength or stiffness degradation and ductility). Nonlinear static analysis is relatively simple and gives a capacity curve that, similar to a seismic analysis, provides insight whether a building has adequate capacity to resist the extreme loading condition or not, in a static fashion. One determining factor in considering that a local portion of the structure has failed is the highly dynamic effect produced when a structural element is rapidly removed from the frame. As demonstrated by Pretlove et al. [19] there are structures which are statically safe, but dynamically unsafe due to the fact that time-dependent overloads, induced by the element removal, may cause the progressive fracture of other elements before a new equilibrium state is reached (i.e. cascade or domino effects). This requires the nonlinear dynamic behavior of a structure to be taken into account in progressive collapse simulations.

Considering the aforementioned observations regarding the five main requirements [1] (robustness, integrity, continuity, redundancy and ductility), two methods (direct and indirect) and two sources of nonlinearity (geometry and material), the flowchart in Fig. 1 has been built in order to describe the numerical open tool developed within OpenSees [20] and SeismoStruct [21].

Nonlinear fiber-based implicit dynamic analyses applied to two- and three-dimensional RC frames are carried out and then compared with a Hughes–Liu [22] FE Ls-Dyna [23] model, analyzed in explicit dynamic fashion, to prove the ability of the proposed approach. One of the final objectives for this paper is the development of a computational methodology for structural design against progressive collapse to be implemented into an open source platform.

3. Progressive collapse numerical models

To withstand abnormal loading that may cause progressive collapse, there are several characteristics to be fulfilled in progressive collapse simulations. Many commercial software packages can be used for this purpose and some of them have specific options for progressive collapse simulations. In the last two decades, several modeling applications have been done, e.g.:

- three-dimensional models using four-node quadrilateral shell elements in ABAQUS [24,25];
- macromodels based on nonlinear springs to obtain the nonlinear static response of single beams as a consequence of the column removal, using code ADAPTIC [26];
- two-dimensional boundary-element models coupled with two-dimensional FE models using ADINA [27];
- three-dimensional solid elements coupled with 3D Euler flux-corrected transport (FCT) for the air volume using AUTODYN [28];
- 20-node brick elements with a total Lagrangian formulation to model beam–column subassemblies in DIANA [29];
- finite difference approach to reproduce structural concrete and steel connections using DYNA3D [30];
- multi-body models based on bricks and continuum-based multi-layer shell elements in FEAP and Ls-Dyna [31,32];
- solid and shell elements to simulate a three-storey two-span RC frame with initial damage to structural members using Ls-Dyna [33];
- macromodels based on rigid elements and inelastic shear links to model concentrically and eccentrically steel braced frames using Ls-Dyna [34];

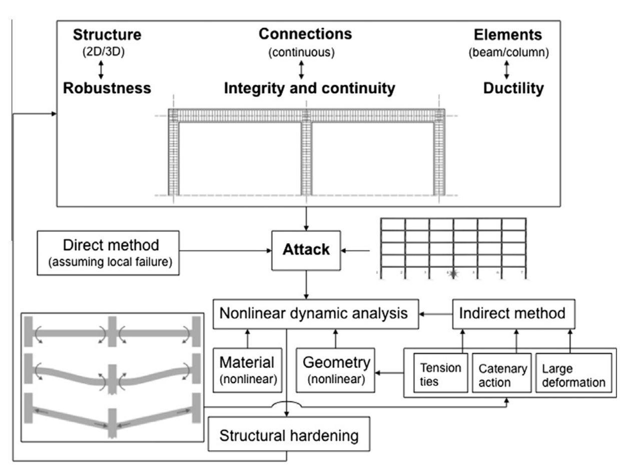

Fig. 1. Proposed approach for progressive collapse resistance assessment and strengthening strategy.