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Nonlinear Dynamic Analysis of Frame Elements Subjected to Blast Explosions

Serhan Guner*

University of Toledo, 2801 W. Bancroft St. MS 307, Toledo, OH 43606, USA

Abstract

A finite element method was recently proposed for performing nonlinear analysis of plane frames subjected to blast loads. This method uses an explicit three-parameter time integration method within a total-load, secant-stiffness analysis framework. Rigorous nonlinear sectional analyses are undertaken, considering the strain rate effects and utilizing nonlinear concrete and reinforcement hysteresis models. Shear effects are included through a 2D implementation of the Disturbed Stress Field Model, which is based on a smeared rotating crack conceptualization. In this study, numerical modeling of 18 previously-tested specimens was undertaken to verify the accuracy, reliability, and practicality of this method for blast load conditions. Some specimens were subjected to multiple blast loads, resulting in 24 simulations in total. Most specimens were subjected to very high peak reflected pressures in the range of 0.35 MPa and exhibited significant damage and nonlinearity. Analysis results (obtained from this method and two other methods from the literature) are compared to the experimental responses in terms of peak displacements, stiffnesses, residual displacements, and crack widths. The three advantages of the proposed method were demonstrated: more accurate modeling of reinforced concrete behaviour, simpler modeling requirements, and shorter analysis times. The proposed method was found to simulate the experimental behaviours of the specimens examined with a high degree of accuracy. The solution algorithm provided unconditional numerical stability, and required much shorter analysis times than continuum finite element methods.

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Keywords: blast; finite elements; fiber sections; nonlinear analysis; numerical modeling; reinforced concrete shear; simulation.

* Corresponding author. Tel.: +1-419-530-8133; fax: +1-419-530-8116
E-mail address: serhan.guner@utoledo.edu

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1. Introduction

Structural resilience to blast explosions has become a crucial design requirement for government and high-profile public buildings due to increased levels of terrorism. Analysis methods available in the literature for blast loads range from simplified "single-degree-of-freedom" (SDOF) methods to sophisticated "continuum finite element analysis" (FEA) procedures. While the SDOF methods are easy to use and directly provide the required design parameters, they are only suited for the analysis of single structural elements and do not consider many important influences such as the interaction of shear, axial, and bending responses, membrane action, and hysteretic material response. On the other hand, FEA tools, such as LS-DYNA [1] and ABAQUS [2], are more comprehensive but demand extensive knowledge and experience, require a large number of input parameters, and take significant time. To fill this critical gap, an analysis method was recently proposed by Guner and Vecchio [3] and implemented into the procedure VecTor5 [4] for impact, blast, and seismic load conditions. In addition to accurately modeling the concrete response, it sought to eliminate the need for pre-analysis material model calculations and the selection of the analysis options, and provide a single solution for a given problem. The objective of this study is to demonstrate the application and verification of this method, and numerically study the dynamic behaviour of previously-tested frame elements. The specimens examined include ten singly- and four doubly-reinforced panels, two wall strips, one square slab, and one prestressed panel. Some of the specimens were tested multiple times, thereby providing a total number of 24 simulations. The materials modelled include both high-strength and normal-strength concrete in combination with high-strength vanadium reinforcing bars, normal-strength deformed reinforcing bars, and low-relaxation prestressing tendons.

2. Overview of the proposed analysis method

The proposed method employs six-degree-of-freedom elements, as shown in Fig. 1(a), within a distributed-plasticity frame analysis algorithm using an iterative, total-load, secant-stiffness formulation. The nonlinear sectional analysis algorithms provide a comprehensive and accurate representation of the concrete response, including the shear effects coupled with axial and flexural responses, based on the Disturbed Stress Field Model [5]. A fiber discretization is employed as shown in Fig. 1(b). Each concrete and longitudinal reinforcing bar layer is defined as discrete elements; the transverse and out-of-plane reinforcement is smeared within the concrete layers. The out-of-plane reinforcement provides confinement to concrete layers. The main sectional compatibility requirement is that 'plane sections remain plane,' while the sectional equilibrium requirements include balancing the axial force, shear force, and bending moment. To compensate for the clamping stresses in the transverse direction, a shear protection algorithm is developed to prevent premature failures of D-regions. The effects of the strain rates follow the fib Model Code [6] formulations for concrete, and the Malvar [7] formulations for the reinforcement as discussed in Guner and Vecchio [3]. An explicit three-parameter time integration method was developed and implemented, which allows the use of either Newmark's Average Acceleration, Newmark's Linear Acceleration [8], or Wilson's Theta [9] methods. Structural damping is primarily taken into account through the nonlinear concrete and reinforcement hysteresis models, as presented in Guner and Vecchio [10]. The method allows the analysis of frames with unusual or complex cross-sections, and considers significant second-order mechanisms such as the membrane action, concrete out-of-plane confinement effects, reinforcement buckling, and reinforcement dowel action. Refer to Guner and Vecchio [3, 10-12] for the formulation details.

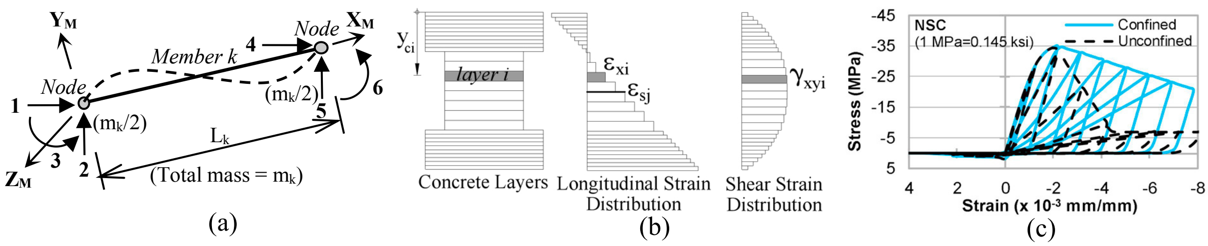

Fig. 1. (a) Frame element proposed; (b) layered section method proposed; (c) concrete hysteresis model.