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Behavior of reinforced concrete columns under combined effects of axial and blast-induced transverse loads

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ABSTRACT

The results of numerical studies on the dynamic response of reinforced concrete (RC) columns subjected to axial and blast-induced transverse loads utilizing an advanced single-degree-of-freedom (SDOF) model are presented in this paper. The main variables considered in this study were the level of axial force and longitudinal reinforcement ratio. This work addressed the effect of various levels of axial compressive load on the resistance function, time-history response, and load–impulse diagram when the columns were subjected to transverse loads due to blast. The blast loads were idealized as triangular pulses and the effects of flexural, diagonal shear, and tension membrane behaviors were included in the RC column response. The results from the SDOF analyses were validated using the commercial finite element (FE) program ABAQUS. The results of the parametric study indicated that the level of axial compressive load has a significant influence on the behavior of RC columns when subjected to transverse blast-induced loads.

1. Introduction

Progressive collapse of a building is typically initiated by an abrupt failure of one or more of the load bearing structural members, such as columns. Therefore, the endurance of such members under severe short duration loads is essential for the survivability of the building. The primary objective of this paper is to investigate the blast response of reinforced concrete columns with various levels of axial compressive loads and idealized boundary conditions using both fast running nonlinear SDOF and high fidelity continuum based finite element approaches, and show how the response of the column varies as the axial load level is changed using moment–curvature, resistance function, and pressure–impulse diagrams. While beams are normally subject only to transverse loads, columns are always exposed to both transverse and axial loads. In practice, it is often assumed that lateral responses are normally larger than the vertical ones for columns under the above mentioned combined loading conditions, and that the failure of columns are normally caused by transverse, rather than axial, loads [1]. While the failure of the column will most likely be induced by the transverse loads, the effect of axial loads on the response should also be considered. The column resistance may be reduced due to the axial loads, and the column may fail sooner than if no axial loads were applied [2]. Furthermore, RC columns may undergo large deformation if the axial load increases enough to create a stability failure, and/or the transverse load combined with the axial load increases enough to cause a flexural failure. If the transverse deflection is sufficiently large (e.g., larger than the cross-sectional depth) the column may exhibit a tensile membrane response that has been observed for RC beams and slabs. Certain conditions must exist for a column to enable tension membrane behavior. The longitudinal steel reinforcement must be continuous through the entire length of the column and be well anchored into the supports. Also, once the transition into a tension membrane occurs, the axial compressive load acting on the column cannot be resisted, and it must be redistributed to other structural elements in the building. At that point, although the column no longer has the capability to carry axial compressive loads, it continues to have the ability to carry transverse loads. Fig. 1 shows the deformed shape of an RC column following a blast test in which the column exhibited a tension membrane behavior [3]. This capability of the column could be significant for structures that must provide protection against various explosively-induced lateral loads [4].

2. Numerical approach

In this study, the Dynamic Structural Analysis Suite (DSAS) is used to perform numerical analysis of RC columns under blast loads. DSAS is a multifunctional dynamic analysis suite, capable

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Fig. 1. RC column following a blast test [3].

of performing time-history analyses of a wide range of structural components [2,4,5]. DSAS is based on an equivalent SDOF analysis concept [1], and it utilizes a layered section analysis approach and strain compatibility to determine the moment–curvature relationship of a structural component. Then, a displacement controlled nonlinear FE analysis, using Crisfield's cylindrical arch length method [6], is carried out to establish the resistance function and the equivalent load and mass characteristics. The resulting resistance function is then used to perform a SDOF time-history analysis of the structural component. DSAS is also capable of plotting physics-based load–impulse diagrams [7]. The details of the approach used in obtaining the resistance function for different degrees of freedoms (DOF) are described below.

2.1. Equivalent SDOF system

In order to perform an SDOF analysis of a structural component, one must establish the relationships that relate the continuous system, such as the one shown in Fig. 2, to a simple mass-damper system. Furthermore, the load function under consideration should be separable into time dependent and spatial components as shown in Eq. (1), where $p^t(x)$ is the load function, λ^t is the time dependent portion of the load function, and $\bar{p}(x)$ is the spatial distribution of the load.

$$p^t(x) = \lambda^t \bar{p}(x) \tag{1}$$

The evaluation of the equivalent SDOF properties, including the resistance function, is accomplished by using a static nonlinear analysis. The reference displacement for the SDOF system is defined as the displacement of the continuous system at the point of interest (e.g., midspan) for each load increment i as shown in Eq. (2). The normalized displacement field is defined, as shown in Eq. (3):

$$u_m^i = u^i\left(\frac{L}{2}\right) \tag{2}$$

$$\varphi^i(x) = \frac{u^i(x)}{u_m^i} \tag{3}$$

In which $u^i(x)$ is the displacement field at increment i. u_m^i is the midspan displacement field at increment i. $\varphi^i(x)$ is the normalized displacement field at increment i.

The equivalent resistance value for the load increment i can be written as shown in Eq. (4), to ensure that the strain energies of both the continuous system and the lumped SDOF system are identical.

$$F_e^i = \int_0^L p^i(x) \cdot \varphi^i(x) \cdot dx \tag{4}$$

In which F_e^i is the equivalent load at increment i. $p^i(x)$ is the load function at increment i.

Similarly, the equivalent mass value for the load increment i is determined by setting the kinetic energies to both systems equal to each other and assuming that the acceleration field normalized with respect to the midspan acceleration is the same as the normalized displacement field. The final equation for the equivalent mass at load increment i, M_e^i, is shown in as follows:

$$M_e^i = \int_0^L m(x) \cdot [\varphi^i(x)]^2 \cdot dx \tag{5}$$

In which $m(x)$ is the mass function of the continuous system.Once the static analysis is completed and the equivalent SDOF system properties are established, the Newmark-Beta method [8] is employed to solve the dynamic equilibrium equation, as shown in Eq. (6), and to determine the component's response time history.

$$F_e^t = M_e^t \ddot{u}_m^t + C\dot{u}_m^t + R_e^t \tag{6}$$

In which $R_e^t = R_e(u_m^t)$ is the equivalent resistance at time t. $M_e^t = M_e(u_m^t)$ is the equivalent mass at time t. $F_e^t = \frac{F_e(u_m^t)}{\lambda(u_m^t)}\lambda^t$ is the equivalent external force at time t. $\ddot{u}_m^t, \dot{u}_m^t, u_m^t$ is the midspan acceleration, velocity, and displacement at time t. C is the Damping coefficient.

2.2. Flexural and tension membrane resistance

Most RC components will respond to dynamic lateral loads in a flexural behavior mode. One may determine the equivalent load and equivalent mass for elastic and plastic ranges using closed form solutions, as described by Biggs [1]. This, however, may lead to some inaccuracies, since the ratio of the equivalent load to the applied load, defined as the load factor, and the ratio of the equivalent mass to total mass, defined as the mass factor, vary continuously as the nonlinearities in the member progress. In DSAS, a specific purpose FE analysis using structural type elements and a solution algorithm based on Crisfield's cylindrical arc-length method [6] are used to evaluate the equivalent resistance and mass values in Eqs. (2) and (3) at each load increment, respectively. Each of the structural element's behaviors is determined from the moment–curvature relationship of the section, considering the nonlinear material behavior of concrete and reinforcing steel. These material models account for crushing of concrete layers and fracture of steel layers. The moment–curvature function assigned to each element is derived using a layered section analysis and strain compatibility,

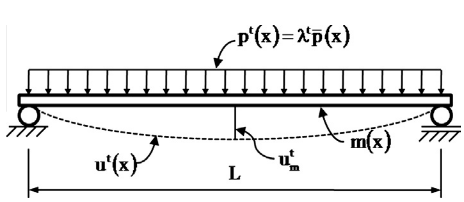

Fig. 2. Continuous structural member.