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The feasibility of passive controlled structural mechanism method to the design of structures

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ABSTRACT

Passive control of structures to sustain blast loads is extremely important; however, the current research literature and existing technologies are rather limited. The major challenge lies in the fact that the control system should operate rapidly during a very short period of time. In this work it is proposed to overcome this difficulty by changing the structure into a mechanism and by using shear and moment passive control devices attached to the structural members in a sophisticated manner to form "Passive controlled structural mechanism (PCSM)". The friction devices are located at the joints of the structural members, they are designed so that under mundane loading they are locked and fully transfer the forces and moments acting between the members, while in the case of blast loadings, they transfer predetermined force Fr and moment Mr between the members. Thus, the blast response of the structure is defined by the forces and moments induced by the friction devices. These forces and moments are designed so that they do not exceed the elastic capacity of the structural members, and no damage or collapse will occur. The blast energy is absorbed mainly by the rigid body movement of the structural members and not by the structural members' flexure. The blast response of a PCSM reinforced concrete (RC) column and frame are investigated by using an analytical model and a finite elements method (FEM) model. It is shown that the PCSM structure remains intact in the elastic regime while regular structures are losing their stability for the same impact.

1. Introduction

Structures are traditionally designed to sustain both service and irregular loads, e.g. wind and seismic loads, respectively. The increasing number of explosions due to terrorist activities has raised the demand to protect critical structures and infrastructures from blast. Failure of structures' main load-bearing members due to explosion causes human casualties and economic losses [1].

The commonly used methods of passive control for structures exposed to explosions comprise two types: strengthening the structure or shielding it [2]. Strengthening methods, such as column jacketing, toughening connections, and the addition of supports that lead to span reduction, increase structural resistance and/or ductility. Advanced solutions of this type include polymeric coating, concrete field tubes, and high strength materials, fiber strips or mats made of concrete, glass, carbon, Kevlar® or aramid fibers embedded in a polymer matrix such as an epoxy resin, which are attached to structural elements or masonry walls. These retrofits enhance shear and flexure capacity and elements confinement, and the structural members can deform extensively while maintaining (or even increasing) their load-bearing capacity [3–11]. Shielding methods are based on the addition of external cladding layers designed to absorb the blast. The cladding layer can be applied locally or added all over the building. Its absorption capacity is achieved by its special geometrical design or by using specific materials such as aluminum foam [12–17].

Passive control devices are widely used in retrofitting structures addressing seismic events [18]. There are few attempts to use these passive control devices to consider blast. Ewing et al. [19] proposed a combination of semi-active devices with passive yielding tendons. The tendon reduces the first peak of the structural displacement and the semi-active devices mitigate the free-vibration phase. Monir [20] proposed a new unidirectional passive damper that solves the re-centering problem, which might appear while using regular passive dampers. These solutions mitigate the interstory drifts but do not overcome the bearing structural member failure. Su et al. [21] proposed a piston-cylinder assembly that can cover the external surface of a structure for blast effect mitigation. Chen and Hao [22] suggested a sandwich panel with a core consisting of a rotational friction hinge device and a spring, which absorbs blast energy and restores the panel to its original shape. The general concept of these methods is adding a cladding layer to the

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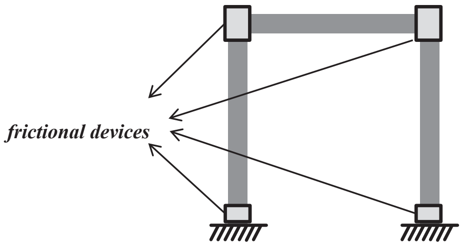

Fig. 1. Scheme of a PCSM frame.

structure.

In this work it is proposed to use shear and moment passive control devices between the structural members. In the case of mundane loading (gravitational or wind loads) the structure is fully constrained, while in the case of blast loading the structure is transformed into a passive controlled structural mechanism (PCSM) structure, and the forces and moments induced into the members are within their elastic capacity.

2. Basic concepts of the proposed method

The blast resistance of a PCSM is based on friction forces and moments induced by passive control devices. Each is located between structural members, as shown in Fig. 1. The frictional control device is based on commercially available products with two modes: locked and slip. In the slip mode the device allows relative slipping or rotation of the two structural members with a constant force *Fr* or moment *Mr* acting between them. In the case where the forces and moments acting between the two members are below *Fr* and *Mr* the device is in a locked mode. In this case no relative slipping or rotation between the members takes place. The frictional control devices are designed so that under mundane loading the structure is a fully constrained structure; *Fr* and *Mr* are larger than the forces and moments acting between the members and the devices are locked. In the case of blast loadings, where the forces and moments acting between the members exceed *Fr* and/or *Mr*, the structure is transformed into a PCSM, and the friction device slips. It is designed so that the forces and moments induced in the structural members are within their elastic capacity. In this study the friction devices are located only at points *A* and *B*, as shown in Fig. 2. Under mundane loads the frame is clamped at points *A* and *D*. In the case of blast (the blast pressure $p(t)$ is assumed to act uniformly and it is time dependent only), the loads and moments acting at points *A* and *B* are *Fr* and *Mr* due to the friction devices. It is possible to refer to structural member *AB* as an "inertial blast mitigation device (IBMD)". The drag resistance of the air behind member *AB* helps to reduce the response but it is ignored in this study. A detailed response analysis is presented in Sections 3–5.

3. Analytical study

Consider a structural member with Young's modulus (E), moment of inertia (I), mass per unit length (m), and with negligible damping, gravitational force and its related reaction. The member is subjected to impact at $t = 0$. It has only two simple supports, which allow the member to move laterally and to rotate. The movement is passively controlled by frictional devices (Fr_A, Fr_B, Mr_A, and Mr_B) at the members' joints.

The solution approach is based on basic structural engineering theory regarding designing structures that are fully constrained to dynamic loading [23]. The general equation governing the transverse vibration of a straight member without damping subjected to an external force, $P_{fr}(x,t)$, is given in Eq. (1).

$$m(x)\frac{\partial^2 u}{\partial t^2} + \frac{\partial}{\partial x^2}\left[EI(x)\frac{\partial^2 u}{\partial x^2}\right] = P_{fr}(x,t) \quad (1)$$

In order to simplify the analytical solution, it is assumed that the load duration, t_d, is much smaller than the natural period of the structure, Tn; thus, the initial velocity (V_0) according to Eq. (2) can replace the actual blast loading [24].

$$V_0 = I_r/M \quad (2)$$

where I_r is the reflected impulse generated by the explosion (can be obtained using [25]), and M is the total mass of the structural member.

By this simplification, the blast loading induced an initial velocity, V_0, and therefore the external forces acting on the member, $P_{fr}(x,t)$, consists only the forces generated by the frictional devices. A schematic diagram of the investigated problem can be seen in Fig. 3.

The movement of the structural member, presented in Eq. (3), is composed from rigid body motion, $u_{rigid}(x,t)$, and local vibration motion, $u_{vibration}(x,t)$, determined by the member characteristics such as geometry and supporting conditions. The rigid body motion component is derived from the unique supports of the structural member in this problem, and does not exist in the solution approach for the full constrained structure.

$$u(x,t) = u_{rigid}(x,t) + u_{vibration}(x,t) \quad (3)$$

The rigid motion is given by Eq. (4)

$$u_{rigid}(x,t) = u_{c.g.0} + \dot{u}_{c.g.0}t + 0.5\ddot{u}_{c.g.}t^2 + \theta_{c.g.0}x + \dot{\theta}_{c.g.0}xt + 0.5\ddot{\theta}_{c.g.}xt^2 \quad (4)$$

where *c.g.* represents the member center of gravity, θ is the rotation angle, and an overdot denotes differentiation with respect to time.

For a uniform member, where $m(x) = \text{const} = m$, $E(x) = \text{const} = E$, and $I(x) = \text{const} = I$, substituting Eq. (4) into Eq. (1) and integrating it over the length of the member yields

$$\int_{-H/2}^{H/2} m\ddot{u}_{c.g.}dx + \int_{-H/2}^{H/2} m\ddot{\theta}_{c.g.}xdx = \int_{-H/2}^{H/2} P_{fr}(x,t)dx \quad (5)$$

which implies

$$M\ddot{u}_{c.g.} = -(Fr_A + Fr_B) \quad (6)$$

where $M = \int_{-H/2}^{H/2} mdx$, and, accordingly,

$$\ddot{u}_{c.g.} = -\frac{Fr_A + Fr_B}{M} \quad (7)$$

Substituting Eq. (4) into Eq. (1), multiplying by x, and integrating yields

$$\int_{-H/2}^{H/2} m\ddot{u}_{c.g.}xdx + \int_{-H/2}^{H/2} m\ddot{\theta}_{c.g.}x^2dx = \int_{-H/2}^{H/2} P_{fr}(x,t)xdx \quad (8)$$

which implies

$$J\ddot{\theta}_{c.g.} = Mr_A + Mr_B + \frac{H}{2}(Fr_B - Fr_A) \quad (9)$$

where $J = \int_{-H/2}^{H/2} mx^2dx$, and, accordingly,

$$\ddot{\theta}_{c.g.} = \frac{Mr_A + Mr_B + \frac{H}{2}(Fr_B - Fr_A)}{J} \quad (10)$$

Substituting Eqs. (10) and (7) in Eq. (4), with the initial conditions of $u_{c.g.0} = \theta_{c.g.0} = \dot{\theta}_{c.g.0} = 0$ and $\dot{u}_{c.g.0} = V_0$ (Eq. (2)), the rigid part of Eq. (3) is obtained.

For the vibrational motion part, the natural vibration frequencies and modes of an unsupported uniform member end were developed. For the homogeneous problem Eq. (1) becomes

$$m\ddot{u} + EIu^{IV} = 0 \quad (11)$$

Eqs. (11)–(16) are part of the common modal solution of the homogeneous problem which can be found in [1], and are presented here for convenience.