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A modal approach to determine direct shear of beams subjected to impulse

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ABSTRACT

Protecting important structures against blast loading is vital. Most engineering practitioners use either a Single Degree of Freedom (SDOF) approximation of the dynamic response to blast loading or a computationally expensive numerical model. In this paper, a modal approach is proposed that provides a more accurate and less conservative estimate of direct shear, the transient dynamic shear response developed within a few milliseconds of pressure wave arrival, than the estimate based on SDOF. By way of example and via the proposed approach, simple analytical expressions to estimate the direct shear are developed for simply-supported beams. The estimates are compared with the results of a series of dynamic analyses of a refined finite element model of the beam, performed using LS-DYNA. Very close agreement between the results of numerical modeling and analytical estimates are observed. In addition, the estimated direct shear is significantly lower than the value obtained from the SDOF method. The proposed approach, thus provides an efficient and accurate estimate of the direct shear to be used in structural design.

1. Introduction

Terrorist attacks have highlighted the importance of incorporating the risk from blasts into the design of important facilities in large metropolitan areas. Failure of an individual structural element subjected to blast could trigger disproportionate collapse of a large portion of the structure. This calls for design of buildings and structural components against blast loads to minimize the risk to human life as well as socioeconomical damage. Many new important structures are required to be designed to withstand different levels of intentional or accidental explosions. In addition, some existing structures that are vulnerable to blast must be re-analyzed and retrofitted, to protect against different levels of possible threat. Examples of such structures include densely populated commercial structures, government buildings, financial institutions, and landmarks. To address these challenges, standards and design methods are developed to guide the analysis and design of structures against blast loads [39,38].

Some analytical methods such as using SDOF response assumptions to estimate the direct shear—shear developed within a few milliseconds of shock wave arrival—demand on structural members can be very conservative. Refined numerical methods, such as dynamic finite element analysis [15], can provide more realistic estimates of the transient response of structure at both component (e.g. members, connections and supports) and system level [22–24,34]. In addition more advanced numerical tools have also been developed and used to study the damage and fracture due to dynamic blast load [30,31,18]. While these models are more informative and provide more realistic estimates, they are computationally expensive. Herein, a simple but not too conservative method is proposed to estimate direct shear demand for beams under blast loading. The method is based on modal analysis of the shear force, and takes into account the impact of higher modes that are essential for calculating the transient dynamic response, i.e. direct shear. The simplified analytical expression developed for direct shear response provides accurate estimates that agree well with finite element simulations. The estimates for direct shear are significantly lower than the values obtained using a SDOF approach [4].

2. Blast loading

Detonation of high explosive charges causes blast, which occurs over a very short period of time. Blast generates a high-pressure detonation wave of hot gasses that rapidly expands and displaces the surrounding air in the atmosphere. As a result the elevated pressure (overpressure) travels out from the source of detonation in form of a shock wave and when it hits the structure at the arrival time t_a leads to an abrupt rise of pressure from the ambient pressure P_0 to the peak pressure P_s, as illustrated in the blast pressure profile in Fig. 1. The peak pressure depends on the distance from the source (standoff distance),

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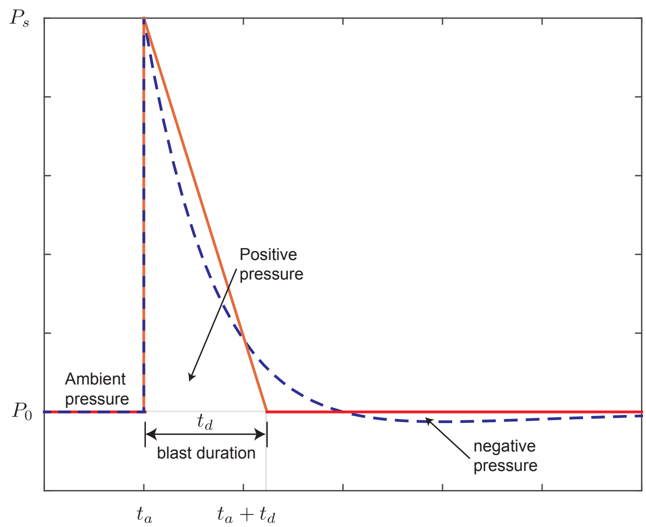

Fig. 1. Blast pressure time history.

property and weight of the detonation material. After time t_a the evacuation of the air leads to an approximately exponential attenuation of pressure to the ambient pressure over a time period t_d. The pressure continues to decrease to sub-ambient pressure after time $t_a + t_d$, creating suction and returns to the ambient pressure afterwards. Baker [2] proposed the following equation for pressure time history:

$$P(t) = P_s\left(1-\frac{t-t_a}{t_d-t_a}\right)\exp\left(-\alpha\frac{t-t_a}{t_d}\right) \quad \text{for} \quad t > t_a \tag{1}$$

with α the waveform number that accounts for the pressure attenuation rate. The total specific impulse is expressed as the area under the pressure versus time curve with positive pressure:

$$I = \int_{t_a}^{t_a+t_d} P(t)dt \tag{2}$$

The main structural damage is verified to be related to the positive phase of blast pressure. Furthermore, the produced negative pressure is small compared to the positive one and is applied in the opposite direction. Hence in practice only the positive pressure is taken into account and the negative phase is typically ignored [20]. With this assumption, blast loading is idealized as a linear approximation of the pressure time history given in Eq. (1) for many structural engineering applications [35]. The approximate blast pressure time-history is plotted in Fig. 1 with a solid line. The positive pressure of the time history at $t_a < t < t_a + t_d$ is approximated by a triangular function with the area $P_s \times t_d/2$ equal to the impulse load, and the negative phase is disregarded (see Bodner and Symonds [5], Humphreys [17], Symonds and Mentel [36], Florence and Firth [9], Micallef et al. [28], Fallah et al. [8] among other references for more detailed discussions on impulsive loads).

2.1. Blast wave front parameters

Let the peak pressure occur at time zero, i.e. $t_a = 0$. The two main parameters of the pressure time history shown in Fig. 1 are the peak overpressure P_s and the duration of blast positive pressure t_d. The maximum blast pressure P_s depends both on the charge mass W and the standoff distance from the charge center R. Researchers have proposed approximate functions for P_s in functions of scaled distance $Z = R/\sqrt[3]{W}$ [6,32,29]. As an example Mills [29] estimated the peak overpressure for free-air explosion in kPa as:

$$P_s = \frac{1772}{Z^3} - \frac{114}{Z^2} + \frac{108}{Z} \tag{3}$$

where Z has the units of $[\mathrm{m}/\sqrt[3]{\mathrm{kg}}]$. It is noted that, these equations can be used for far-field blast and are not suitable for providing realistic load for close-range explosive charges where localized behavior is of interest and the assumption of uniform spatial pressure is not valid [23,27,26].

Held [14] provided the following approximate formula for impulse in Pa·s, to approximate impulse due to free-air explosion:

$$I_0 = 300\frac{W^{2/3}}{R} \tag{4}$$

Blast duration is then obtained based on the approximate triangular function $t_d = 2I_0/P_s$.

When the blast incident pressure wave hits a structure with higher density than the environment transmitting the wave (air), part of the incident wave is reflected. The reflected pressure P_r is the most destructive component of blast loading to structures. The magnitude of P_r depends on the angle between pressure wave and the surface. For an incident wave normal to the surface the reflected pressure reads [35]:

$$P_r = 2P_s\frac{7P_0 + 4P_s}{7P_0 + P_s} \tag{5}$$

For a small charge, or at a distance far from the charge P_s is much smaller than the ambient pressure and the reflected pressure approaches $2P_s$. Conversely for large values of P_s, the reflected pressure can reach $8P_s$.

3. SDOF method to estimate direct shear

When studying the structural response due to blast, three different response regimes are typically considered based on the ratio of the duration of blast t_d to the first natural period of the structural component T_1, i.e. (1) the impulsive regime for $t_d/T_1 < 0.4$, (2) the dynamic regime for $0.4 < t_d/T_1 < 2$ and (3) the quasi-static response regime for $t_d/T_1 > 2$ [37]. Columns and beams of typical major structures being designed against blast typically have natural frequencies that fall into the impulsive regime. Hence the impulsive response is studied in this paper.

A triangular blast loading time-history is typically used for design of structural components [35,33]. This load is given by:

$$F(t) = \begin{cases} F_r(1-t/t_d) & \text{for } 0 < t < t_d \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

The above equation is used for design of structural components against blast with peak load F_r, function of the reflected pressure P_r. In practice the blast load is assumed to be uniform throughout the length of the structural component when the scaled distance is greater than $3.0\ \mathrm{ft}/\sqrt[3]{\mathrm{lb}}$ [25].

Structural components subjected to blast can have failure modes due to both global and local response. Local failure modes are generally due to close threats and are manifested in the form of localized punching and spalling. Global responses can be associated with the flexural response and relating shear after a long duration of blast pressure arrival. They can also correspond to the transient dynamic response shortly after the incident waves hit the structural component and before there is a meaningful flexural deformation. The shear force in the latter case-direct shear-can reach values that are much higher than the flexural failure mode (see Fig. 5 for beam deformation at different times) and thus are the focus of this paper.

Fig. 2(a) shows a simply-supported beam of length L subject to a uniform blast pressure $P(t)$. Here, the SDOF method to estimate the direct shear is briefly described [10–12,16,1,5]. The structural component is modeled as a generalized SDOF system, for which the structural response, i.e. beam displacement $y(x,t)$, is expressed as the product of a shape function $\phi(x)$, that satisfies the boundary conditions, and a generalized coordinate $q(t)$. The inertia force due to vibration is proportional to the shape function $\phi(x)$ as $I = m\phi(x)\ddot{q}(t)$, where m is mass per unit length of the beam and the superposed dot denotes time