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Response of roof beams in buildings subject to blast loading: Analytical treatment

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ABSTRACT

Among the lateral loads that a building structure may experience is that produced by blast from an explosion. The analysis of the response of building structure to blast loads is traditionally carried out on a member-by-member basis. The magnitude and variation of blast load with time depends on the position of the member being considered in the building. The nature of such loads is different for the front face, the side faces, the roof, and the rear face of the building. In particular, loads for the roof and side face members that span in a direction perpendicular to the shock front vary both spatially and temporally in a complicated manner. In the current practice, such loads are represented by an equivalent load that is spatially uniform but varies with time. The roof or the side face member along with the load acting on it is then converted to a single-degree-of-freedom system, whose analysis provides the desired response parameters, such as deflections and stresses. It is shown in this paper that the current methodologies provide widely differing results whose accuracy is suspect. A method that provides a better representation of the load variations and a more accurate procedure of analysis is presented. The implementation of the method is carried out through a computer program developed for the purpose and it is demonstrated that the entire process is as simple as the present techniques based on a single-degree-of-freedom representation.

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1. Introduction

The structural elements of the roof in a building structure that resist the blast loads can be categorized into two groups. As shown in Fig. 1, the first group is comprised of beams that span in a direction parallel to the blast shock front. The blast overpressure on these members can be assumed as being uniform across the span since the distance from the center of explosion to different points on the beam is not significantly different. Analysis of these roof beams may be carried out in the same way as of the columns on the front face of the building, where the blast loads are assumed uniformly distributed along the length of the member. The other group is comprised of beams that span in a direction perpendicular to the blast shock front. With these beams, the blast pressures and loads may vary significantly along the span. This paper deals with the challenges in the analysis of beams that are perpendicular to the blast wave shock front. Throughout the remainder of this paper, this type of members is meant when roof beams are mentioned.

The theory that governs the propagation of the blast wave along the roof span has been discussed in several different Refs. [1–3]. When the blast wave from an explosion reaches the front face of a building, it is reflected from the surface. The reflected overpressure decays to the stagnation pressure within the clearing time. After a while, the blast wave diffracts around the structure, and exerts pressure on the roof as well as on the side walls. For a flat roof, blast wave reflection does not occur and the pressure instantaneously rises to the incident overpressure. The net pressure on the roof is a combination of the incident overpressure and the dynamic wind pressure. The latter, also referred to as drag pressure, is caused by air movement as the blast wave propagates through the atmosphere and is negative in the case of a roof member [1,2].

As the blast wave propagates along the span of the roof, the peak incident pressure decays while the wavelength and positive phase duration increase. This is illustrated in Fig. 2. It is evident that the distribution of pressure along the length of the beam varies with both space and time. Also, at any specific time, only a portion of the roof may be loaded, depending on the length of the beam, location of the shock front, and the wavelength of the travelling wave.

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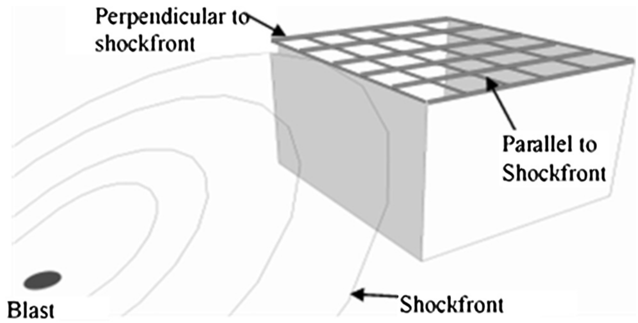

Fig. 1. Different members in the roof subject to blast loading.

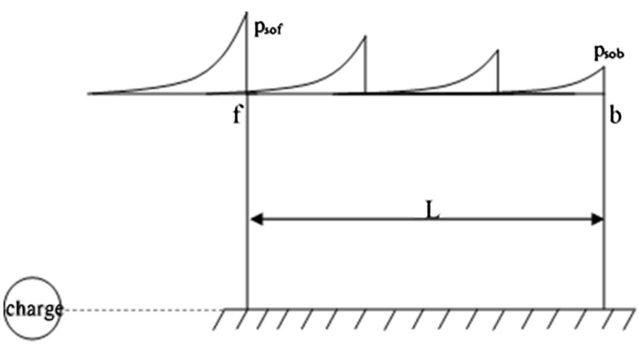

Fig. 2. Shock wave propagation along the roof span.

The total pressure at any point on the surface can be determined from Eq. (1).

$$P(t) = P_{so}(t) + C_D q_o(t) \quad (1)$$

where $P_{so}(t)$ is the side-on (incident) pressure, $q_0(t)$ is the dynamic pressure, and C_D is the drag coefficient, which can be obtained from the data presented in Table 1 [2].

As stated earlier, an accurate calculation of the blast forces that act on the roof of a structure is complicated because the blast pressure varies both spatially and temporally. In order to develop a simple methodology for the design and analysis of the buildings and structures subject to blast, it has been suggested that the blast pressure be assumed as being spatially-uniform over the span, but varying with time.

There are, however, differences in how the magnitude of the uniform load and its variation with time are defined by different sources. UFC 3-340-02 [2] uses the pressure values at the front point of the roof ("f" in Fig. 2), P_{sof} and q_{0f} along with a uniform load equivalent coefficient C_E in the determination of the maximum pressure, as shown in Eq. (2).

$$P = C_E P_{sof} + C_D q_{of} \quad (2)$$

Coefficient C_E depends on the ratio of the length of the blast wave at the instant it arrives at point f, L_{wf} to the span length of roof, L. The dynamic pressure q_{0f} is related to the modified peak overpressure $C_E P_{sof}$. The time it takes for the uniform pressure on the surface to rise to its maximum value, t_d, and also the duration of the load, t_{0f}, are expressed as functions of the blast wavelength to beam span ratio. All of the parameters are obtained from charts given in UFC 3-340-02. The variation of P with time is shown in Fig. 3(B).

Table 1
Drag coefficient for roof beams [2].

Peak dynamic pressure, q_0 (kPa)	Drag coefficient, C_D
0–170	−0.40
170–350	−0.30
350–1000	−0.20

In another manual, TM 5-855 [4], an expression similar to Eq. (2) is used for determining the maximum pressure, but instead of the front point pressure and wavelength, the parameters corresponding to the rear point ("b" in Figs. 2 and 3(A)) are used, as shown in Eq. (3).

$$P = C_E P_{sob} + C_D q_{ob} \quad (3)$$

The time history of the uniform pressure P is shown in Fig. 3(C), where d is a point along the span, such that, when the shock front arrives at the point it causes the greatest deflections and stresses in the beam (see Fig. 3(A)). The location of point d is related to wavelength to roof span and can be determined from empirical charts given in TM5-855. Charts are also available for the other parameters.

Another design methodology suggested by ASCE [3] suggests the same blast load magnitude and time variation as that given in UFC 3-340-02.

In the time-histories shown in Fig. 3, t_f and t_b are the arrival times of the blast wave at points f and b respectively. Parameters U_b, U_d and U_f are the shock front velocities at points b, d, and f, respectively, while t_{db} and t_{df} are the positive phase durations of the blast wave calculated from parameters at points b and f.

The charts given in UFC 3-340-02 and TM5-855 for determining the equivalent load coefficients C_E are compared in Fig. 4. It should be noted that the reference points for calculating the wavelength of the blast are different in the two methodologies, as discussed in the previous paragraphs.

The methodologies given in UFC 3-340-02 and TM 5-585 have been used for many years in protective design and analysis of buildings; however, there are several research studies in which the moving blast loads are used instead of the equivalent uniform distributions. Recognizing the availability of high performance computing in the recent years, some research studies [5–7] estimate a more accurate response of the building structure using comprehensive models based on the theories of Computational Fluid Dynamics (CFD). In all of the referenced studies, the loading obtained from CFD is used in association with a Finite Elements Method (FEM) of analysis.

A relatively recent research study has attempted to verify the validity of the equivalent blast loading of the roof systems by means of numerical simulation and experimental tests [8]. In that study, the roof beams were modeled by beam elements and analyzed by FEM in ANSYS software package. The blast properties were obtained by using CONWEP [4] software, and the loads were applied to the beams both as code-specified equivalent uniform loads and dynamic moving loads. The peak deflections of the beams, in simply supported conditions, were derived for the two sets of loads and compared to the results of field tests.

The comparison of the numerical results obtained from the moving blast load and the equivalent uniform loadings of the beam with the field tests showed some important observations. First, the response of the beams in the moving loading simulations matched the experimental results, except after the first peak. After the first peak, the analytical deflections were higher than in the tests, since the effect of damping was neglected in the simulations. Second, the equivalent uniform load method was unable to predict the maximum deflection; in some cases, it gave values that were up to 50% higher than that produced by the moving loads.

An important objective of the present study is to develop a method of blast load analysis of a roof beam, which while retaining the simplicity of the equivalent load method, would provide a more accurate and reliable estimate of the response. Considering

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