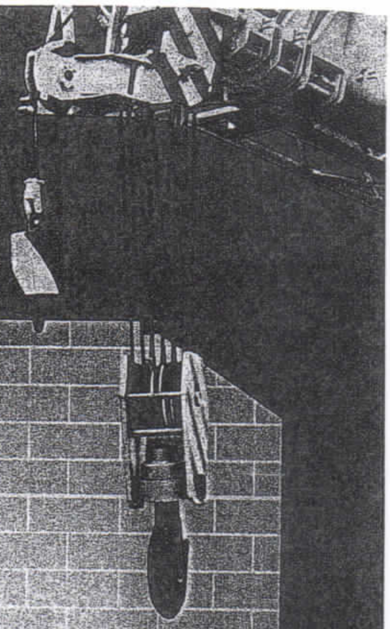

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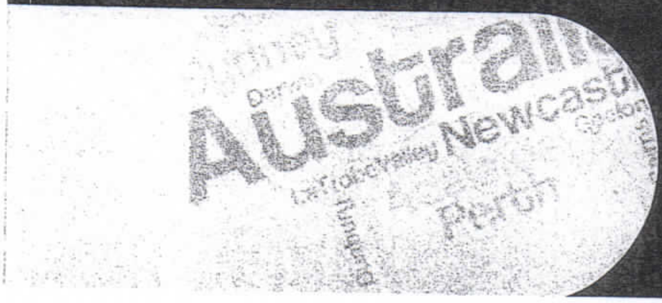

RESEARCH PUBLISHING

RESPONSE OF ORTHOTROPIC PLATES TO LOCALIZED BLAST LOAD

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The dynamic response of various plate structures subjected to blast loads is analyzed in this paper in particular fully rigid supported orthotropic plates using the method of modal superposition. The analysis procedure is used to quantify the linear transient response of such plates subjected to localized blast loads. Many studies are currently available, in which the blast load is considered to be spatially uniform across the plate with a temporal distribution described by a Dirac delta function. The novel aspect considered here is the case for which the blast load is modeled as a step triangular function and the orthotropic plate is fully fixed along its edges. A Mathematica program is used to solve the values of the natural frequencies of the system from the transcendental equations. The results presented here are collected from the results of analyses performed on blast loaded plates for a variety of parameters important with regard to the dynamic response. Conclusions are drawn concerning the influence of the various parameters on the nature of the plate response.

Keywords: Orthotropic plates, Modal superposition, Dirac delta function, Step triangular function, Transcendental equations.

1. Introduction

The response of orthotropic plates to localized blast loads had been the subject of a great deal of research. In particular, the behavior of plates under blast loads was investigated in theoretical as well as numerical studies (Bonorchis and Nurick 2009, Langdon *et al*, 2002, Kadid and Abdelkrim, 2008, Alisjahbana and Wangsadinata, 2012). Although this research had some overlapping results, the methods of analysis were quite different. Therefore the focus in this paper will be on the response of orthotropic plates subjected to localized blast loads. The theoretical formulation of the idealized blast loads is either a zero period or rectangular, uniformly distributed pressure impulses, which may be accompanied by simplified constitutive laws, as was investigated by Bahei-El-Din and Dvorak (2007). The theoretical formulations for the response of rigid-plastic circular plates with clamped supports were investigated by Wang and Hopkins (1957) for a zero period impulse and by Florence (1966) for a rectangular impulse. In their work, bending kinematics were assumed to be linear and membrane stretching was neglected. Houlston and DesRochers (1987) compared the numerical and experimental results of uniformly blast loaded square and quadrangular plates. Good numerical and experimental agreement between the plate and stiffener midpoint displacement histories was found. The study of blast loaded stiffened orthotropic plates subjected to localized blast loads modeled as a triangular blast load was intensively studied by Alisjahabana and Wangsadinata (2012). In this work the plate was stiffened by longitudinal stiffeners and the effect of stiffeners configurations on the dynamic responses of the plate was studied intensively. The aim of this paper is to investigate the effect of introducing the time duration of the step triangular blast load on the dynamic responses of the stiffened orthotropic plate. The inclusion of the effect of time duration of the localized blast load is intended to introduce the idealization of the condition that might occur in practice.

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2. Vibration Analysis

In the first part of this paper the free vibration analysis of orthotropic stiffened plates with fully fixed condition along its support is studied first using the Levy's solution. By using the method of separation of variables the free vibration response of the system can be expressed as:

$$w(x,y,t) = W(x,y)\sin\omega t \tag{1}$$

where $W(x,y)$ is a function of the position coordinates only, and ω is the circular frequency. The undamped free vibration equation of motion of the system can be expressed as:

$$\begin{aligned} D_x\frac{\partial^4 W(x,y)}{\partial x^4} &+ 2B\frac{\partial^4 W(x,y)}{\partial x^2 \partial y^2} \\ &+ D_y\frac{\partial^4 W(x,y)}{\partial y^4} - \rho h\omega^2 W(x,y) = 0 \end{aligned} \tag{2}$$

where D_x and D_y are the flexural rigidities in the x and y direction respectively, B is the torsional rigidity, ρ is the mass density of the plate.

The boundary conditions of the orthotropic stiffened plate for fully fixed condition along its support are as follow:

Along $x = 0$ and $x = a$:

$$W(x,y) = \frac{W(x,y)}{\partial x} = 0 \tag{3}$$

Along $y = 0$ and $y = b$:

$$W(x,y) = \frac{W(x,y)}{\partial y} = 0 \tag{4}$$

The natural frequencies of the system with the boundary conditions according to Eqs. (3) and (4) can be found from the solution of two auxiliary Levy's type problems that can be solved by using Mathematica program as follow:

$$(\omega_{mn})^2 = \frac{\pi^4}{\rho h}\left(D_x\frac{p^4}{a^4} + 2B\frac{p^2q^2}{a^2b^2} + D_y\frac{q^4}{b^4}\right) \tag{5}$$

where p and q are real numbers to be solved from two transcendental equations (Pevzner *et al* 2000).

3. Dynamic Response

The orthotropic stiffened plate is assumed to be subjected to a normal blast loading $p(x,y,t)$ on the upper surface. By using the modal participation method, the dynamic response of the system can be expressed in the following form:

$$w(x,y,t) = \sum_{m=1}^{m}\sum_{n=1}^{n} X_{mn}(x)Y_{mn}(y)T_{mn}(t) \tag{6}$$

where $X_{mn}(x), Y_{mn}(y)$ are eigen functions, and $T_{mn}(t)$ is a function of time which must be determined through further analysis.

4. Idealization of Blast Loading

To determine of the exact blast loading is almost unrealistic, considering the complicated process of the interaction of the blast wave with the target concerned (Bing Li *et al.*, 2009). In order to reduce this complex problem of blast loading to reasonable terms, the localized blast load $p(x,y,t)$ can be expressed by the following equation:

$$p(x,y,t) = P(t)\delta[x - x_0]\delta[y - y_0] \tag{7}$$

where $\delta[..]$ is the Dirac delta function, x_0 is the position of the localized blast load in the x direction and y_0 is the position of the localized blast load in the y direction.

The blast loading $P(t)$ as a stepped triangular function can be expressed as:

$$P(t) = P_0\left(1 - \frac{t}{t_3}\right) \text{ for } 0 \le t \le t_1 \tag{8}$$

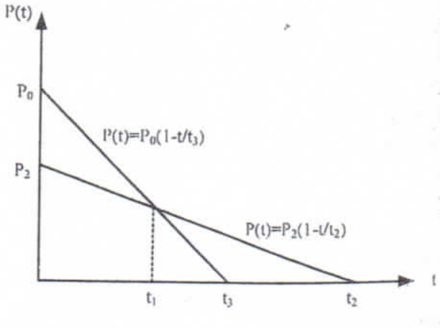


Figure 1. Pressure time history for a stepped triangular loading.

$$P(t) = P_2\left(1 - \frac{t}{t_2}\right) \text{ for } t_1 \le t \le t_2 \quad (9)$$

$$P(t) = 0 \text{ for } t > t_2 \quad (10)$$

The general solution for the forced response deflection of the orthotropic stiffened plate to a stepped triangular load $P(t)$ can be solved further by using the Duhamel integration method as follows:

$$w(x,y,t) = \sum_{m=1}^{m}\sum_{n=1}^{n} X_{mn}(x)Y_{mn}(y)$$
$$\left[\int_0^t \frac{P(\tau)\delta\left[x - x_0\right]\delta\left[y - y_0\right]}{\rho h Q_{mn}} \int_0^a X_{mn}(x)dx \int_0^b y_{mn}(y)dy \frac{e^{-\gamma\omega_{mn}(t-\tau)}}{\omega_{mn}\sqrt{1-\gamma^2}} \sin\omega_{mn}(t-\tau)d\tau\right] \quad (11)$$

where Q_{mn} is the normalization factor of the Eigen vector, and γ is the damping ratio. Once the response deflection has been obtained, the internal forces of the plate (moments and shear forces) can be computed, using derivatives of those equations.

5. Numerical Results

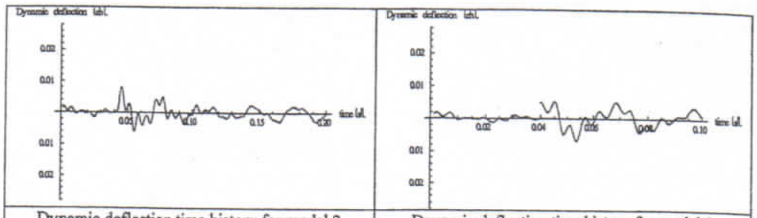
An orthotropic rectangular damped concrete plate stiffened by longitudinal beams along the x axes is considered. The data for the plate and blast load are: a = 8 m, b = 4.75 m, h = 0.12 m, $E_c = 2.35 \times 10^{10}$ N/m^2, $v = 0.23$, $\rho = 2,400$ kg/m^3, t_1 =1.56 ms, $t_2 = 40$ ms, $t_3 = 3$ ms, $P_0 = 3 \times 10^4$ N/m^2, $P_2 = 12 \times 10^4$ N/m^2. The boundary conditions are fully fixed along the x and y edges and the damping ratio (γ) is varied from 0% to 10%. In the following discussion the position of the blast load is at $x_0 = 1$ m and $y_0 = 1$ m. The absolute maximum dynamic deflection at the mid plate subjected to a stepped triangular blast load has been calculated by using 5 modes in the x direction ($m = 1, 2, \ldots, 5$) and 5 modes in the y direction ($n = 1, 2, \ldots, 5$). By using the Mathematica program the values of p and q and the natural frequencies of the orthotropic plate for three models, model 1 (without stiffeners), model 2 (1 stiffener) and model 3 (2 stiffeners) are computed.

The absolute maximum dynamic deflection has been computed for 3 different stiffeners configurations. The introduction of stiffeners decreases the mid-point displacement significantly. The mid-point displacement for model 1 is 12.27 mm, while for model 2 and model 3 are 8.04 mm and 6.83 mm respectively, all computed for the value of damping ratio of 2%. Thus, the configurations of stiffeners can have an important influence on the response of the stiffened orthotropic plates as shown in Table 1.

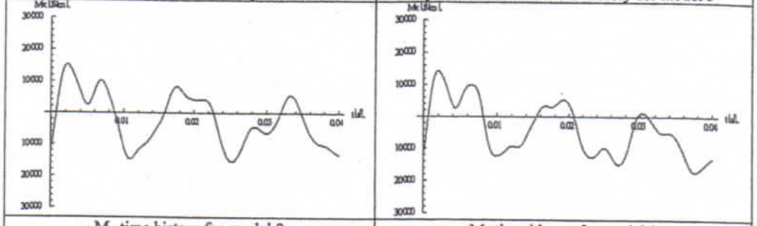
For model 2 with the value of damping ratio 2% increasing the time duration of the step triangular load (t_2) by a factor of 1.5 has resulted in a decrease in the mid-point displacement by a factor of 1.51. This has occurred due to the fact that the response in the first region ($0 \le t \le t_1$) has already decreased before it is amplified by the response in the second region ($t_1 \le t \le t_2$). Therefore, the time duration of the blast loading plays an important role in determining the level of response of the orthotropic plate.

Table 1. The absolute maximum dynamic deflection of damped orthotropic stiffened plates subjected to a stepped triangular blast load.

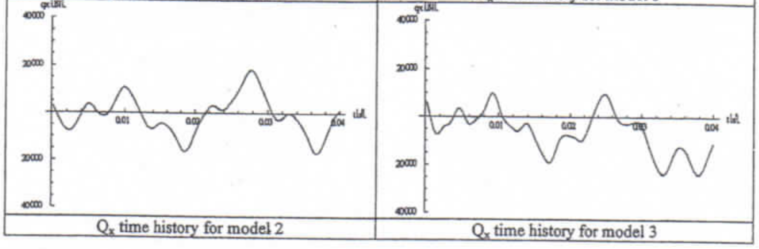
Damping ratio (γ)	Model 1 (without stiffener) w_{max} (mm) $t_2 = 40$ ms	Model 2 (1 stiffener) w_{max} (mm)		Model 3 (2 stiffeners) w_{max} (mm) $t_2 = 40$ ms
		$t_2 = 40$ ms	$t_2 = 80$ ms	
2%	12.27	8.04	3.82	6.83
5%	7.87	4.41	1.52	3.40
10%	4.43	2.11	0.61	1.79



Dynamic deflection time history for model 2 | Dynamic deflection time history for model 3

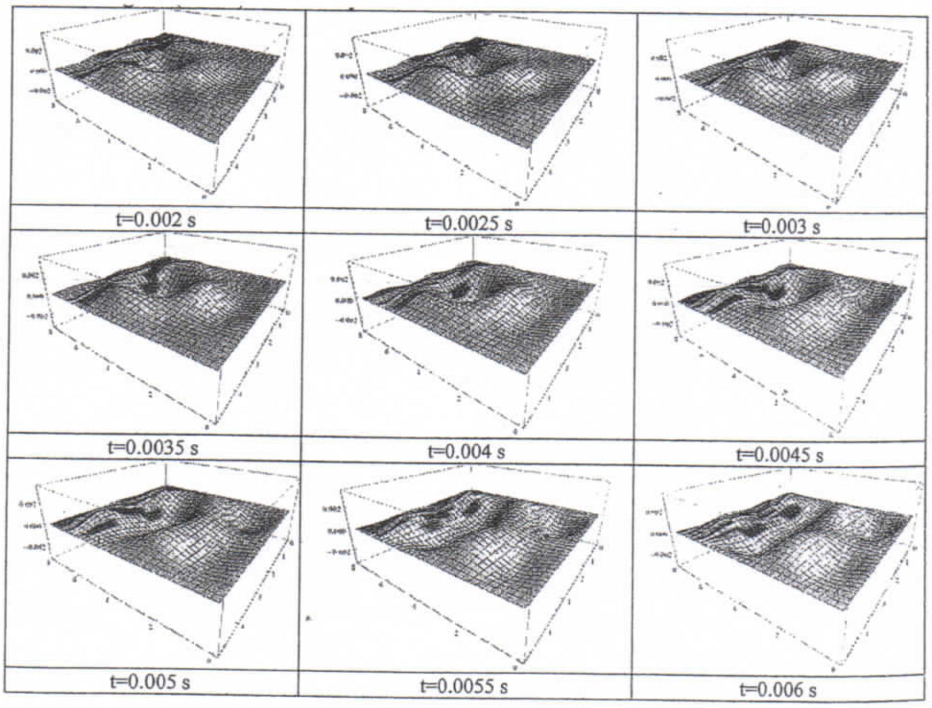


M_x time history for model 2 | M_x time history for model 3



Q_x time history for model 2 | Q_x time history for model 3

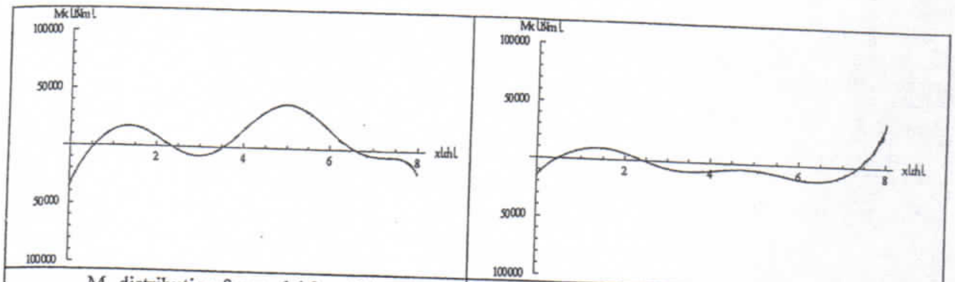
Figure 2. Time history of damped orthotropic plate for model 2 (1 stiffener) and model 3 (2 stiffeners) subjected to a step triangular blast loading, $\gamma = 2\%$.


t=0.002 s | t=0.0025 s | t=0.003 s

t=0.0035 s | t=0.004 s | t=0.0045 s

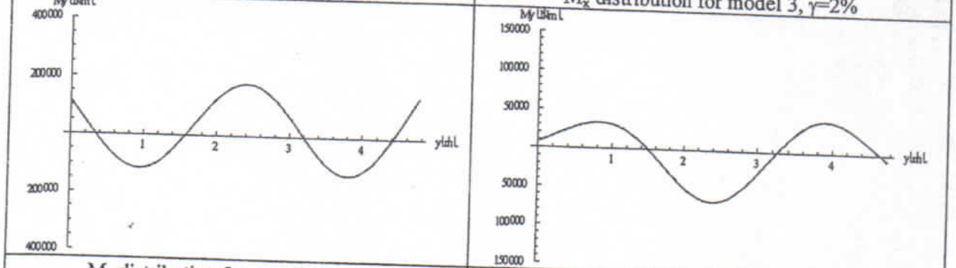
t=0.005 s | t=0.0055 s | t=0.006 s

Figure 3. The deformation of the damped orthotropic plate for model 3 with the value of damping ratio 2% subjected to a stepped triangular load.



M_x distribution for model 2, γ=2%

M_x distribution for model 3, γ=2%



M_y distribution for model 2, γ=2%

M_y distribution for model 3, γ=2%

Figure 4. M_x and M_y distribution along x axes and y axes for model 2 subjected to a stepped triangular blast load, $\gamma = 2\%$.

6. Conclusions

It can be seen that stiffener configuration has a significant effect on the overall dynamic response of the orthotropic plate. A stiffener located along the mid length of the plate (model 2) significantly reduces the overall plate dynamic deflection. The time duration of the blast load is one of the important parameter, since it has an influence on other responses, such as moment distribution, shear distribution and the maximum dynamic deflection of the system.

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