International Journal of Impact Engineering 61 (2013) 36–47

Contents lists available at SciVerse ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Investigation of effect of negative phase of blast loading on cable net curtain walls through the linearized stiffness matrix method

Mijia Yang*, Saeed Ahmari

Department of Civil Engineering, North Dakota State University, Fargo, ND 58108-6050, USA

ARTICLE INFO

Article history:
Received 21 October 2012
Received in revised form
27 May 2013
Accepted 7 June 2013
Available online 19 June 2013

Keywords:
Cable net
Blast load
Negative phase
Linearized stiffness matrix
Nonlinear analysis

ABSTRACT

Safety of cable net structures has been threatened due to rising conflicts and the possibility of exposure to blast load. Pre-tensioned cable nets are geometrically nonlinear problems and the nonlinearity can be addressed by using the linearized stiffness matrix method (LSM). On the other hand, the effect of negative phase pressure of blast wave is usually ignored in practice while the research indicates its significance on the dynamic response of the system. In this paper, LSM method is used to study the effect of negative phase pressure and other factors such as charge weight, standoff distance, pretension level, and modal frequency on cable net structures. The effect of glass panel failure on the system response is also studied by removing the corresponding wave pressure acting on the failed glass panels. Accuracy of the LSM method is evaluated through comparison between the proposed numerical and closed-form solution. The results indicate the significance of the effect of negative phase pressure on the system response, which is pronounced at lower TNT weights and more flexible structures. The major effect of negative phase pressure is on the outward displacements, which exhibits up to 25% more displacements for the studied cable net when the negative phase pressure is considered. Failure of glass panels and consequent pressure release in negative phase can cause increase in the subsequent displacements. LSM method can reliably predict the system response as far as displacements are not too large. However, at very large displacements, LSM method significantly overestimates the predicted displacements.

1. Introduction

Blast loading has been a challenging concern for structural designers. The recent growing local and international conflicts have elevated the risk of structural damage and threatened the safety of structures. Cable net facades are one of the structures that can cause life loss and experience detrimental structural damage if exposed to blast loading. The structure comprises a network of pre-tensioned cables, which holds glass panels. Due to architectural aesthetic of the cable net curtain walls, their application in different private and public areas such as airports and shopping malls is rapidly growing [1–3]. Therefore, it is important to implement a rigorous structural design in order to maintain the cable net's safety related to blasting.

Due to life threatening consequences of the failure of glass panels and the resulted glass fragments, researchers have attempted to study failure of glass panels and enhanced behavior of composite glass panels under blast loading [5–10]. Essentially, the glass panels and their attachments are designed to resist low blast loading while they are expected to fail at moderate and high loads [11]. However, the cable net is required to remain sound at intense blast loading. Therefore, a number of researchers have studied dynamic response of the bare cable net when exposed to blast load [12–15]. Some research studies have considered the entire system by accounting for the interaction between the glass panels and the cable net [16,17]. In this study, the blast load is considered to be directly applied to the cable net on the connecting nodes and dynamic responses of the structure are determined through the derived displacements, stiffness, and modal frequencies.

Structural analysis of cable net is quite different from regular structures such as concrete since this type of structure is far flexible and thus highly deformable. High flexibility of cable net results in geometrically nonlinear response of the structure, especially under extreme loads such as blast load. In order to incorporate geometrical nonlinearity in the analytical approaches, different techniques have been developed. The proposed methods, in general, can be divided into the following three categories [13]:

1 Linearized stiffness matrix (LSM), which is similar to the linear stiffness matrix and modified for nonlinearity by introducing a

* Corresponding author. Tel.: +1 701 231 5647; fax: +1 701 231 6185.
E-mail addresses: uamijia@gmail.com, mijia.yang@ndsu.edu (M. Yang).

0734-743X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijimpeng.2013.06.004

second term to the equation. The second term contains out-of balance loads generated due to nonlinearity.
2 Assuming continuum behavior of the wall and solving the governing differential equations using the plate theory.
3 Nonlinear analysis based on the energy method.

Kwan [18] suggested an LSM method for statically loaded cable nets by accounting for the nonlinearity through equilibrium, compatibility, and constitutive equations. This method is further extended to dynamic response analysis in Ref. [12]. However, the derived LSM is based on the assumption that the displacements are so small that the higher orders of displacements can be neglected and a constant level of pretension is assumed in the derivation. While due to highly nonlinear behavior of the system, especially at high blast loads, the internal forces might noticeably change, which leads to altered stiffness matrix. This in return leads to the change of modal frequencies.

Accurate formulation of blast load is another issue. Basically, blast load involves two phases, positive and negative phase. The positive phase is associated with the motion of wave front away from the source of blast, which eventually causes displacement of the structure in the direction of motion (inward displacement). The positive phase is followed by a suction negative phase, which will cause displacement of the structure pointed to the explosive location due to creation of cavity behind the air wave front. The effect of negative phase is usually ignored by structural design specifications such as US GSA (2001) and ISO (2007). However, many researches showed that the impulse generated by the negative phase can have significant effect on the dynamic behavior of the system [4,8,16]. Krauthammer and Altenberger [4] studied the dynamic responses of glass panel walls under blast loads considering both their positive and negative phase. They argued that the outward (in the opposite of wave direction) displacements are always larger than the inward displacement and this is pronounced when the negative phase is included in the analysis. Wei et al. [8] simulated laminated architectural glazings by FEM and reported that the displacement of midpoint at negative phase is twice that at positive phase and geometrical nonlinearity at the negative phase cannot be neglected. As discussed earlier, stiffness of the system changes during loading and this can be more severe when negative phase effect is considered.

In this paper, the LSM method proposed by Kwan [12] is adopted to study the effect of negative phase of blast load on the dynamic responses of cable net. For accurate analysis, higher orders of displacements are included in the derivation of the stiffness matrix. A parametric study is performed to study the effect of different factors such as negative phase of loading, TNT mass, standoff distance, pretension level, and glass panel failure on the peak inward and outward displacements. The effect of glass panel failure is also investigated through progressive failure, which releases the load applied on the broken panels at different time sequences. A closed-form solution is also suggested to evaluate the effect of negative phase of blast load by approximating the nonlinear time history of the blast load to a linear relationship. To study the accuracy of the LSM method in predicting the dynamic responses of cable net, the developed code is modified to update the LSM based on the altered configuration of the structure. A nonlinear closed-form analysis aligned with the numerical model is also conducted, which confirms LSM over-predicts the displacement responses.

2. Background and theory

2.1. Blast load

Theoretically, blast load produces a hemispherical surface burst when an explosive charge detonates on or very near the ground. The energy released is concentrated over a small area and modifications must be applied to the airburst equations in order to quantify the peak overpressure [19]. Instead of developing new functions for surface burst, airburst relations can still be used if twice the charge weight (2MTNT) is substituted for MTNT in the equations provided the ground is perfectly unyielding [20]. Since in reality ground can absorb some amount of energy, a modification factor between 1.7 and 1.8 exhibits better correlations with the experimental results [21].

Standoff distance and charge weight are two key parameters for the blast load. The blast pressure is inversely proportional to the cube power of the standoff distance. Although there is a decrease in reflected blast pressure with height due to the increase in distance and angle of blast incidence, the blast pressure remains nearly constant at its fully reflected value for small angle of incident (less than 45°) [22].

Blast design requires that the actual loads be quantified from risk analysis and that the structural performance requirements be established based on the building function. Generally the bombs associated with vehicles can be kept away from buildings by appropriately built vehicle barriers. The key aspect of structural design of cable net facade to resist blast effect lies in the nature and magnitude of blast load. The details of blast pressure analysis can be found in Ref. [22]. Following a similar procedure in Refs. [26], a typical spherical airburst pressure–time curve of an incident blast wave can be written as [23]:

$$P_i(t) = \widehat{P}_i \cdot \varphi(t) \tag{1}$$

where $\widehat{P}_i$ is the peak overpressure (gauge pressure) and $\varphi(t)$ is the shape function, which can be determined from the Friedlander approach [24]:

$$\varphi(t) = \left(1 - \frac{t}{t_{\mathrm{d}}^{+}}\right) \cdot e^{-\alpha\left(t/t_{\mathrm{d}}^{+}\right)} \tag{2}$$

where t_{d}^{+} and α are time duration of the positive phase and the shape parameter, respectively. α can be obtained from the following equation for Z_{g} between 0.1 and 30 m/kg$^{1/3}$ [25].

$$\alpha = 1.5 \cdot Z_{\mathrm{g}}^{-0.38} \tag{3}$$

where Z_{g} with a unit of m/kg$^{1/3}$ is the scaled ground distance and calculated from:

$$Z_{\mathrm{g}} = \frac{R}{M_{\mathrm{TNT}}^{1/3}} \tag{4}$$

where R and M_{TNT} are the standoff distance and the charge weight, respectively. The peak overpressure can also be expressed in terms of the scaled distance.

$$\widehat{P}_i = P_0 \frac{808 \cdot \left[1 + \left(\frac{Z_{\mathrm{g}}}{4.5}\right)^2\right]}{\sqrt{1 + \left(\frac{Z_{\mathrm{g}}}{0.048}\right)^2} \cdot \sqrt{1 + \left(\frac{Z_{\mathrm{g}}}{0.32}\right)^2} \cdot \sqrt{1 + \left(\frac{Z_{\mathrm{g}}}{1.35}\right)^2}} \quad [\mathrm{kPa}] \tag{5}$$

where $P_0 = 101.3$ kPa (ambient pressure).

The duration of positive (t_{d}^{+}) and negative phases (t_{d}^{-}) can be obtained from the following equations [26]: