DYNAMIC ANALYSIS OF STIFFENED SHALLOW SHELL ON NONLINEAR ELASTIC SUPPORTS SUBJECTED TO BLAST LOADING

PHÂN TÍCH ĐỘNG LỰC HỌC VỎ THOẢI CÓ GÂN GIA CƯỜNG TRÊN LIÊN KẾT ĐÀN HỒI PHI TUYẾN CHỊU TÁC DỤNG CỦA TẢI TRỌNG NỔ

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ABSTRACT

Covered structures (as roof tunnels) affected by short-term loads, like impulses or shock waves from an explosion, typically require solutions to dissipate energy and reduce the load on the structure. The most common solution involves using flexible pillows, which can be linear elastic supports, nonlinear elastic supports, viscoelastic supports, etc. The paper presents the problem of stiffened shallow shell on nonlinear elastic supports subjected to blast loading. Therefore, it addresses a specific case, evaluating the effectiveness of using nonlinear linkage model.

Keywords: *Blast loading; Impulse; Shell; Nonlinear elastic; Nonlinear restraints.*

TÓM TẮT

Các kết cấu dạng mái che (như mái che đường hầm) chịu tác động của tải trọng ngắn hạn, như xung lực hoặc sóng xung kích từ vụ nổ, thường yêu cầu các giải pháp để phân tán năng lượng và giảm tải trọng lên kết cấu. Giải pháp phổ biến nhất là sử dụng liên kết giá đỡ (gối đỡ), có thể là giá đỡ đàn hồi tuyến tính, giá đỡ đàn hồi phi tuyến, giá đỡ đàn nhớt, v.v. Bài báo trình bày lời giải cho bài toán tính kết cấu vỏ thoải có gân gia cường trên liên kết đàn hồi phi tuyến chịu tải trọng nổ. Bài báo giải quyết một trường hợp cụ thể, đánh giá hiệu quả của việc sử dụng mô hình liên kết phi tuyến trong tính toán.

Từ khóa: *Tải trọng nổ; Xung lực; Vỏ; Đàn hồi phi tuyến; Liên kết phi tuyến.*

1. INTRODUCTION

With outstanding features such as lightweight, and good coverage, the shell structures are widely used in many fields with many shapes. When the structure is required to withstand the impulse load, the solution of using the elastic restraints is often thought of. Research on the problem of shell structure affected by shock waves has received the attention of many scientists. Susler et al. [1] investigated the geometrically nonlinear dynamic behavior of tapered laminated composite plates supported and subjected to air blast loading. Cheng Zheng et al. [2] study the large deformation of reinforced plates under shock waves through experimental testing and numerical simulation. The results allow to evaluate the effects of material deformation rates and boundary conditions on the dynamic response of the plate. H. Türkmen [3] uses analytical methods to establish the governing equation of composite shell subjected to three-layer blast loading. Nguyen Duc Thang [4] focused on solving the problem, in which a single shock wave affected shallow cylindrical shells on linear and nonlinear elastic supports. However, the shell structures in these models did not have stiffeners. Calculation of the plate and shell structures on the elastic links bearing the effect of mechanical and heat load are presented in the studies of Nguyen Dinh Duc et al. [5, 6]. The stiffened shallow shells under the influence of multiple layers of shock waves were shown by Nguyen Thai Chung, Le Xuan Thuy [7].

This paper presents further development of the research direction regarding stiffened shallow shells on nonlinear elastic supports subjected to blast loading. It focuses on incorporating the nonlinear component of the bond into the oscillator differential equation and the solving algorithm. The issues related to shell structures on softening pillow systems or hardening support systems are also discussed.

2. DYNAMICS MODEL OF SHELL WITH FLEXIBLE PADS

The shell is supported by flexible pads with cross-sectional dimensions $b_e \times h_e$ and Young's modulus E_e at its four edges. The flexible edge supports of the shell can be modeled as translational springs (Fig. 2). The constitutive equation of the hardening system [8, 9] is typically expressed as:

$$F = k.u \tag{1}$$

$$k = k_0 + \alpha k_0 u^2 \tag{2}$$

Where F denotes constrained force, k denote stiffness constants, u denotes displacement, and α is a small parameter.

To describe the spring with the force-displacement curves characteristic outlined above in the ANSYS software, we utilize the COMBIN39 element [10]. COMBIN39 is a unidirectional element with a nonlinear generalized force-deflection capability that can be employed in any analysis. The element offers longitudinal or torsional functionality in 1-D, 2-D, or 3-D applications. The longitudinal option is a uniaxial tension-compression element featuring up to three degrees of freedom at each node: translations in the nodal x, y, and z directions. No bending or torsion is taken into account. The torsional option is a purely rotational element with three degrees of freedom at each node: rotations about the nodal x, y, and z-axes. No bending or axial loads are accounted for. The element possesses large displacement capability, allowing for two or three degrees of freedom at each node. It has no mass or thermal capacitance.

To describe the shell and ribs in the model, the SHELL93 and BEAM188 elements are utilized. SHELL93 is particularly well-suited for modeling curved shells. The element features six degrees of freedom at each node: translations in the nodal x, y, and z directions, as well as rotations about the nodal x, y, and z-axes. The deformation shapes are quadratic in both in-plane directions. BEAM188 is based on Timoshenko beam theory, incorporating shear deformation effects. It has six degrees of freedom at each node.

3. THE EQUATION OF MOTION WITH AN ADDITIONAL LOAD VECTOR

To solve the nonlinear transient response of the shell supported by nonlinear elastic restraints, the nonlinear restoring forces of the restraints are treated as additional applied loads [8].

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+[K]\{u(t)\}=\{p(t)\}+\{N(u)\} \quad (3)$$

Where vectors {p(t)} and {u(t)} denote applied nodal loads and system displacements, respectively, being functions of time.

The vector {N} denotes the nonlinear forces supplied by nonlinear elastic restraints, depending on the displacements {u}, which can be treated as additional applied loads. The nonlinear equations are solved by using the load increments scheme in conjunction with Newton-Raphson iteration. A complete description of the numerical procedure used to solve the nonlinear problem is given in Figure 1.

For geometrically nonlinear problems, the system of equations needs to be solved multiple times to track the behavior of the deformed structure. Nonlinear variations can result from changes in shape or loading. The stiffness of the structures varies and must be taken into account by regenerating the stiffness matrix during a nonlinear analysis.

The element stiffness is:

$$[K]=\frac{\partial}{\partial u}\int_V [B]^T\{\sigma\}dV=[K]^m+[K]^d \quad (4)$$

Where $[K]^m$ and $[K]^d$ refer to the material and the differential stiffness, respectively.

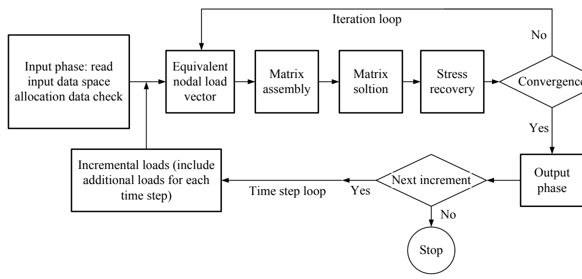

Figure 1. Diagram of nonlinear solution with additional loads.

4. NUMERICAL EXAMPLES

Consider a shallow cylindrical shell with a rectangular plan view. The dimensions of the plate L = 2.0 m, W = 1.0 m, curved radius R = 1.5 m and thickness t = 0.01 m. The shell includes stiffeners with a height of 0.02 m and a thickness of 0.01 m. There are 6 stiffeners in each direction. The material parameters for the shell and ribs are: Young's modulus E = 2.0 x 10^{11} N/m^2, Poisson's ratio ν = 0.31, and density ρ = 7800 kg/m^3. The applied load is due to a shock wave characterized by the load law $p(t) = p_{max}F(t)$, where p_{max} = 3 x 10^4 N/m^2, $F(t)=\begin{cases}1-\frac{t}{\tau} : & 0 \le t \le \tau \\ 0 : & t>\tau\end{cases}$, the load time ☞

τ = 0.025 s, and the calculation time τ_t = 0.08 s. The four sides of the shell are supported by restraints. These geometric and load parameters are shared by three examples in this study.

In this example, the force-displacement relation of restraints is calculated according to the formula $F = k_0u + \alpha\, k_0u^3$. Evaluating the influence of the bearing and the linear and nonlinear restraints model, the author addresses the problem with the following cases:

Case1: k_0 = 1.0 x 10^4 N/m, α = 0 (linear model).

Case2: k_0 = 1.0 x 10^4 N/m, α = 1.8 (nonlinear model).

The results of displacements and stresses at point A, spring compression at point B (Fig. 2):

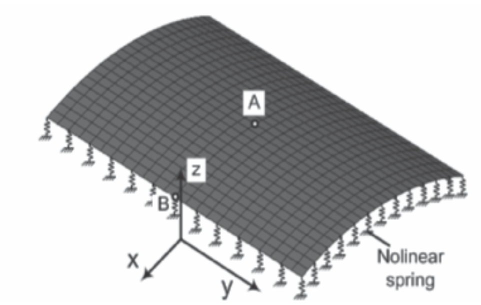

Figure 2. Model of shell supported by flexible pads at 4 edges

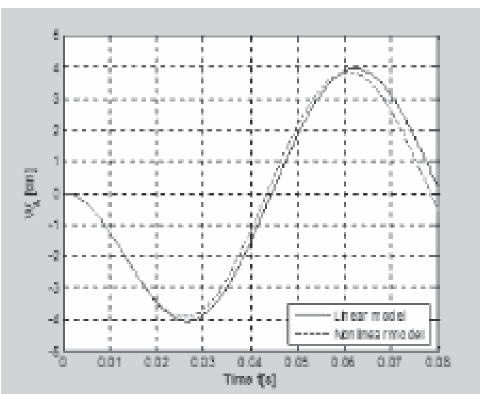

Figure 3. Vertical displacement WA over time

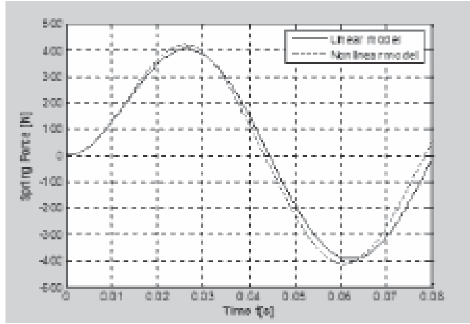

Figure 4. Spring force over time

Table 1. The extreme value is at the point A, B

Method	**W_A^{max} [cm]**	**$\sigma^A_{x\,max}$ [N/m²]**	**$\sigma^A_{y\,max}$ [N/m²]**	**F^B_{spring} [N]**
Linear model	4.047	5.779 x 10^6	8.780 x 10^6	404.694
Nonlinear model	3.938	5.990 x 10^6	9.120 x 10^6	421.672

• Comment:

In the first stage (t < 0.02s), the results in both cases are quite similar (the graph is almost identical). This may be due to the deformation of the springs being too small for the nonlinearity to have much impact. The difference becomes evident in the later stage when the deformation of the spring is substantial. The extreme value of the displacement at A decreases, while the stress at A and the compression of the spring increase. This is understandable when the nonlinear restraints are utilized as a hardening system.

5. CONCLUSIONS

In this paper, the simulation program of stiffened shallow shells supported by nonlinear elastic supports subjected to blast loading was developed, thereby solving specific examples with various support patterns. With the program established, it is possible to perform calculations for different types of nonlinear elastic restraint systems when the force-displacement relation diagram is known.

Compared to the linear elastic support model, the results obtained using the nonlinear elastic pillow model are more noticeable when the spring displacement is sufficiently large. The use of a softening support system that is preferable for reducing damage from pulse load, rather than using a hardening support system, is also presented.❖

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