VIBRATION CHARACTERISTICS OF A SHIELD PLATE REINFORCED WITH TRAPEZOIDAL RIBS

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Abstract: A finite element analysis of the vibration characteristics of a stiffened structure subjected to lateral compression and uniformly distributed load on the surface was performed to identify potentially dangerous frequencies and to minimize the severity of failure frequencies. The natural frequencies and vibration modes can be further ap-plied to the design of stiffened plates for dynamic loading conditions, such as transient forced vibrations due to suddenly applied pressure. The dimensions of the plates investigated in this study, obtained from strength calculations, have been optimized for a cost function that includes material and fabrication costs associated with gas metal arc welding (GMAW) technology. Numerical calculations using finite element software based on the application of the Lanczos iteration method are presented to perform vibration tests considering the geometric parameter variations of the structure.

Keywords: plate stiffening, trapezoidal rib, natural frequency, resonance

1. INTRODUCTION

Reinforced plates are a solution for achieving an optimum design of load-bearing shell structures in a wide range of applications, including mining, construction, aerospace, automotive and marine structures. The most effective way to increase the load-bearing capacity of plates is to incorporate stiffeners of various cross-sections. The simplest way is to use longitudinal ribs, but in hull construction, for example, the plates are reinforced by a pattern of longitudinal and transverse ribs. The sizing and optimization task thus leads to a mechanical analysis of a plate supported at the edge. The loading condition of the plate may be uniaxial or multiaxial compression, bending, shear, hydrostatic pressure at the plate surface, concentrated or uniformly distributed

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loading, and the temperature difference during operation may be taken into account. In addition to the plate thickness, the favorable optimized properties of the rib design and layout can be exploited to reduce manufacturing costs in addition to strength aspects. The design of the ribs also plays an important role in influencing the audible noise effects from vibrations during operation, which in mines must also comply with health and safety and environmental regulations [1]. An example is the safety shields in deep mines, where ribs play an important role in reinforcing the shields (Fig. 1).

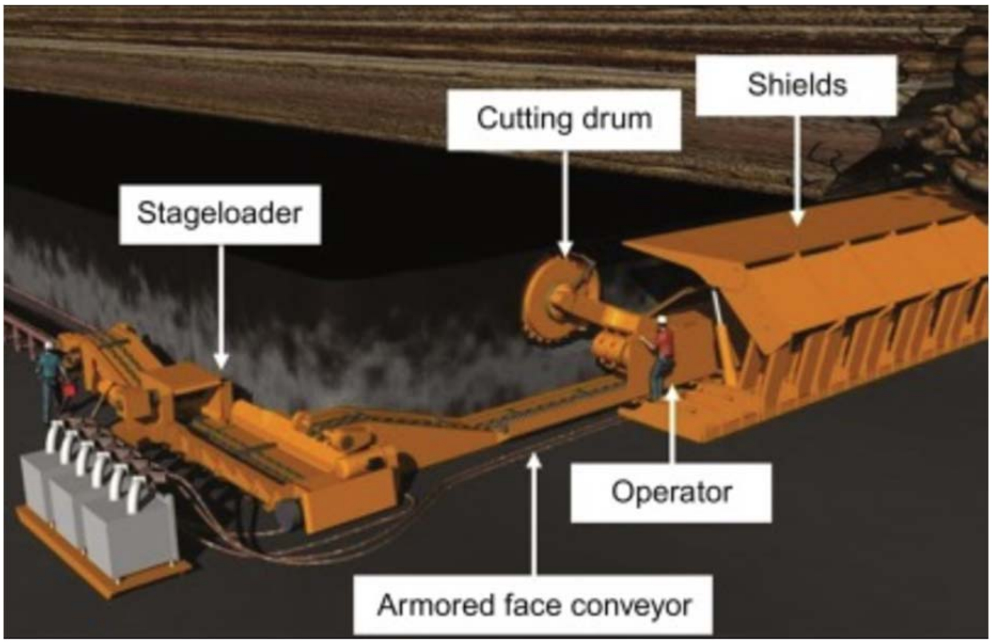

Fig. 1. The environment of longwall mining [1]

Modal analysis by generating eigenfrequencies and mode shapes provides a means of modelling the dynamic effects on structures during operation using different mode superposition methods. The solution of the eigenvalue problems is concluded by the generation of mode shapes corresponding to the eigenfrequencies in ascending order after the numerically more accurate eigenvalue calculation. The established procedures for the numerical solution of eigenvalue problems of structures are the subspace iteration and the Lanczos method. Numerical experience has shown that, when the problem is large or the nature of the problem warrants it, the generally more efficient Lanczos method is the most appropriate choice among the options offered by software [1, 2]. In the imaging of the eigenvalues, the location of the maximum displacement on the color scale is usually marked in red and its magnitude is chosen to be unity.

The direct benefit of the calculations is to prevent resonance catastrophes caused by excitation frequencies coinciding with one of the natural frequencies of the structures subject to excitation, thus avoiding problems during operation. Because of the potential dangers of resonance catastrophes, studies are being carried out in various industrial fields, e.g., in excavators used in mines [2, 3]. Damage to the plate structure [4] or the implementation of a structure with different parameters than those designed [5] will result in a change in the eigenvalues of the structure, which is unfavorable.

2. PLATE GEOMETRY

The buckling condition of a plate reinforced with trapezoidal ribs, i.e. the effect of the residual welding stress during plate manufacture and the initial imperfections of the structure, and the limitation of the amount of deformation due to the welds along the whole length of the plate, can be estimated from calculations based on the deformation condition of the plate length, where the objective function to be minimized is cost, the number of ribs and their characteristic dimensions. The objective function is the summary of K_m material cost and K_f fabrication cost, which is determined by

$$K = K_m + K_f = k_m \rho V + k_f (T_1 + T_2 + T_3) \tag{1}$$

where k_m and k_f are cost factors, ρ is density, V is volume, and T_1 is time of assembly, T_2 is time of welding and T_3 time of other fabrication activities. Details on (1) can be found in [6].

The given data of the trapezoidal stiffened plate are width B = 6000 mm, length L = 4000 mm, the compressive force is $N = 1{,}974 \times 10^7$N in the direction of the ribs, while it has a p lateral pressure as shown in Figure 2.

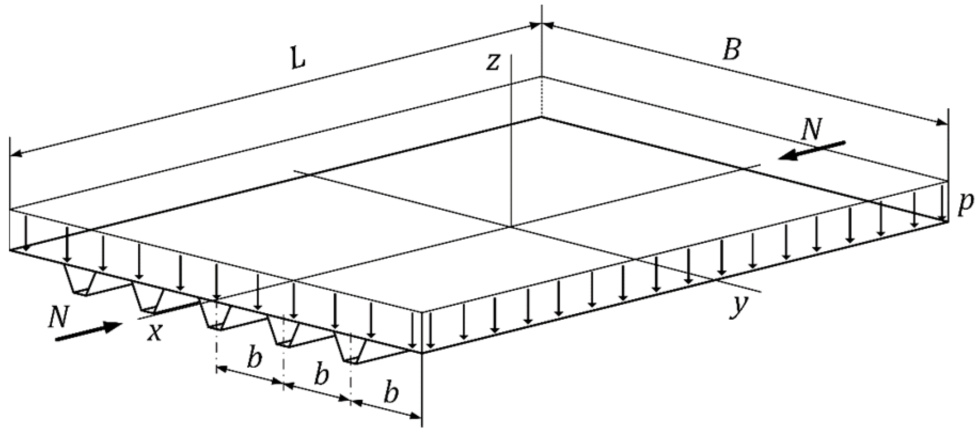

Fig. 2. The trapezoidal stiffened plate and its load condition

The data of the material of the plate are Young modulus $E = 2.1 \times 10^5$ MPa, Poisson ratio $\nu = 0.3$, density $\rho = 7.85 \times 10^{-9}$ t/mm^3 and yield stress $f_Y =$ 355 MPa. In the optimization procedure [5], the base plate thickness t_f and the rib thickness t_s, the rib height h_s and the number of stiffeners $\varphi - 1$ are considered unknown, whose values can only vary within certain limits.

Table 1. Geometric dimensions of the optimized plate

No.	p [MPa]	t_f [mm]	t_s[mm]	$\varphi - 1$ [db]	a_1[mm]	a_2[mm]	a_3[mm]	h_s[mm]
1.	0.02	17	10	4	90	309.17	300	290.79
2.	0.01	18	8	4	90	247.34	300	223.95
3.	0.005	15	8	5	90	247.34	300	223.95

For the selected pressures on the non-ribbed surface of the base plate with p = 0.02, 0.01 and 0.005 MPa, the structural design for the dimensions summarized in Table 1 is shown to be optimal according to Equation 1. These dimensions are interpreted as shown in Figure 3.

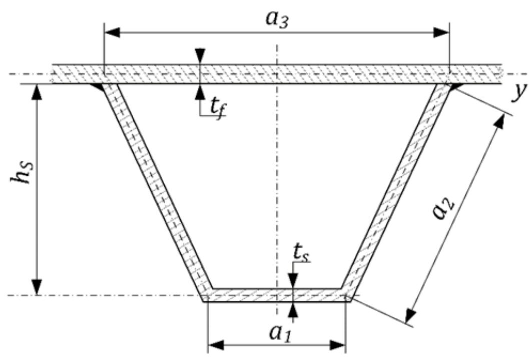

Fig. 3. Typical geometric dimensions of the trapezoidal rib

Using the geometrical dimensions from Table 1 for the strength and vibration analysis of the reinforced structural design, it is sufficient to examine a 3D model of a quarter of the plate, taking advantage of the geometric and load symmetry.

3. COMPARISON OF NATURAL FREQUENCIES

In the 3D finite element modelling of the ribbed plate quarter, a well-established conventional element family, a 4-node shell element, S4R, was used [7, 8]. In dynamic studies, the use of linear element families is usually more appropriate [7]. Repeatedly exploiting the symmetries of the plate design, simple support boundary conditions were imposed on the free edges of the plate piece and symmetry boundary conditions were on the edges obtained along the symmetry axes of the base plate.

The strength calculation for the trapezoidal stiffened plate was performed with the parameters shown in Table 1. In the modal analysis of the model shown in Figure 2, the natural frequencies and corresponding mode shapes were determined. This was done using the Lanczos method in software, where the eigenfrequencies can be displayed as part of the solution [7]. Table 2 shows the first 6 eigenfrequencies for the unloaded structure.

Table 2. Natural frequencies [Hz]of the plate for unloaded case

p [MPa]	1.	2.	3.	4.	5.	6.
0.02	22.767	39.282	93.510	124.02	129.55	153.36
0.01	16.910	35.761	35.761	114.92	129.39	136.65
0.005	18.349	36.071	66.014	121.43	132.88	143.82

Table 2, the first six natural frequencies of the unloaded structure, can be compared with the natural frequencies of the structure subjected to preload given in Table 3. Firstly, the static calculation is applied by taking into account a preload in the form of the axial compressive and surface loads on the structure. The deformation, as the initial geometry, from the previous static step should be taken into account in the subsequent frequency calculation, i.e., the eigenvalue extraction is performed in two analysis steps.

Table 3. Natural frequencies [Hz]of the plate loaded by compressive force $N = 1.974 \times 10^7$N and given lateral pressure p

p [MPa]	1.	2.	3.	4.	5.	6.
0.02	18.630	37.557	92.042	120.97	125.08	137.26
0.01	10.264	33.852	91.378	107.34	123.13	135.56
0.005	11.505	33.338	64.719	119.86	126.16	137.70

The results in the tables show that axial pressure leads to a decrease in natural frequencies as expected, with values of 16.24 %, 24.85 % and 26.05 % for the first natural frequencies. While the smallest dead load is associated with the design for load p = 0.005 MPa and it suffers the largest decrease in natural frequencies caused by the smaller trapezoidal curvature. The models obtained provide an opportunity for further dynamic studies of the plate using the defined vibration patterns. It is also possible to model the damage and corrosion of the plate. The simplest way to do this is to carry out geometric modifications to the 3D geometry after the corrosion effects have been assessed. For plates reinforced with longitudinal ribs, this can be done by omitting the stiffeners, i.e., excluding ribs or multiple ribs from the model. After the series calculations have been performed, comparisons can be made to show the effect of the damage on frequencies and load carrying capacity [4].

4. CONCLUSIONS

A modal analysis of the plate reinforced with trapezoidal ribs was performed. The use of advanced simulation tools and finite element software allows much more complex problem formulations and investigations. This can be exploited to determine the natural frequencies of the preloaded structure. The geometry of the base plate and its stiffener is optimized for cost, so different base plate and rib dimensions were calculated for different surface pressures. In the modal analyses, the vibration characteristics of the unloaded and loaded plate were determined. Structural reinforcement of plates with ribs also reduces the adverse noise emission of the vibrating flexible structure, which is also investigated based on the modal calculation performed. The results can be used to propose different stiffenings and mass reductions, which can now be considered from a vibration point of view. The effect of dynamic loads on stiffened plates can be further investigated by using the mode superposition technique using the results of the mode calculations.

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