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Original Article

FREE VIBRATION ANALYSIS OF PERFORATED PLATE WITH SQUARE PENETRATION PATTERN USING EQUIVALENT MATERIAL PROPERTIES

MYUNG JO JHUNG [a,*] *and KYEONG HOON JEONG* [b]

[a] *Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon 305-338, Republic of Korea*
[b] *Korea Atomic Energy Research Institute, 989 Daedeok-Daero, Yuseong-gu, Daejeon 305-353, Republic of Korea*

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ABSTRACT

In this study, the natural frequencies of the perforated square plate with a square penetration pattern are obtained as a function of ligament efficiency using the commercial finite-element analysis code ANSYS. In addition, they are used to extract the effective modulus of elasticity under an assumption of a constant Poisson's ratio. The effective modulus of elasticity of the fully perforated square plate is applied to the modal analysis of a partially perforated square plate using a homogeneous finite-element analysis model. The natural frequencies and the corresponding mode shapes of the homogeneous model are compared with the results of the detailed finite-element analysis model of the partially perforated square plate to check the validity of the effective modulus of elasticity. In addition, the theoretical method to calculate the natural frequencies of a partially perforated square plate with fixed edges is suggested according to the Rayleigh–Ritz method.

1. Introduction

Perforated plates are used in various industrial applications such as sorting and screening materials. They are also utilized extensively in heating and ventilating installations, balustrade infilling, and acoustics proofing. In architecture, they are often used as internal and external cladding. Perforated plates have also been used for liquid submerged reactor internal structures in nuclear engineering fields. The perforated structures usually support equipment or a component, and a reactor coolant flows through the perforated plates. The reactor internals should be designed to withstand not only normal operating loads but also seismic loads. To check the design requirements, the dynamic responses of the reactor

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* *Corresponding author.*
E-mail address: mjj@kins.re.kr (M.J. Jhung).

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internals due to the forcing functions of a normal operation and earthquakes are computed by commercial computer codes. The adequacy of seismic loadings used for the design of the reactor internals is confirmed by the methods of dynamic analysis using time history or response spectrum techniques. Before the time-history or response spectrum analysis, finite-element modal analyses of the reactor internals are performed for the appropriate equivalent lumped-mass stick models [1]. It is necessary to idealize a mathematical model consisting of lumped masses connected by elastic massless members to reduce computation time and storage memory. Because the perforated structures of the reactor internals require many elements for a finite-element modal analysis, the finite-element model for the perforated structures cannot be constructed as they currently are. The application of equivalent properties of the perforated structures for the finite-element analysis can be an effective analysis method.

There are many potential applications where perforated materials could be used. In many of these uses, however, the strength and stiffness properties of the perforated plate are very important. Because perforated structures can potentially be used in so many applications in reactor internals involving different geometries, materials, and loading conditions, the equivalent material properties for a design data will be given in a general form. The ratio of the effective elastic modulus of the perforated material, E^*, to the elastic modulus of the imperforated solid material, E, will be given, but Poisson's ratio, and υ, is assumed to be constant regardless of the ligament efficiency.

The concept of an equivalent solid material is widely used for design analyses of perforated structures that are assumed to have homogeneous material properties, because circular holes in the perforated plate have an identical diameter with a square pattern. As applied herein, the equivalent stiffness of the perforated material is used in place of the stiffness of the solid structures. By evaluating the effect of the perforations, the equivalent effective elastic modulus of the perforated material, E^*, was obtained as a function of the elastic modulus of the solid or imperforated material, E. In addition, the effective Poisson's ratio, υ^*, of the perforated material was also suggested. Poisson's ratio may be used in cases where correction for the load biaxiality is important. The effective elastic constants presented herein are for plane stress conditions and are also applicable for the in-plane loading of the thin perforated sheets of interest. However, the suggested equivalent properties are based on the in-plane loading. The plane stress effective elastic constants given by O'Donnell [2] and Slot and O'Donnell [3] may be conservatively used for all loading conditions, which are adopted by the American Society of Mechanical Engineers Pressure Vessels and Piping Code [4]. Using these effective elastic properties, the designer is able to determine the deflections of the perforated sheet for any geometry of application and any loading conditions using available elastic solutions. However, the effective elastic constants given by O'Donnell [2] are not confirmed for the modal analysis of the perforated plates. It is not convincing that the effective elastic modulus is constant regardless of vibration modes and structural boundary conditions. In addition, the suggested effective Poisson's ratio, υ^*, is > 0.5 in the small ligament efficiency, which is approximately < 0.2. In general, it cannot be applicable in the commercial finite-element analysis computer codes for a modal analysis. Therefore, this report will suggest the mode-dependent elastic modulus (E^*) for the perforated square plates with various boundary conditions as a function of the ligament efficiency. Finally, an example of a partially perforated square plate will be given to check the validity of the newly suggested elastic modulus (E^*).

2. Natural frequency and elastic constant

2.1. *Fully perforated model*

A mathematical model of a square perforated plate with a square penetration pattern is shown in Fig. 1, where a and h are the width and thickness of the plate, respectively. The equivalent material properties for the square plate are the equivalent modulus of elasticity (E^*), the equivalent mass density (ρ^*), and Poisson's ratio (ν). To apply the Rayleigh–Ritz approach to the free vibration analysis of the perforated structure, each wet mode shape is approximated by a combination of a finite number of admissible functions, $W_{mn}(x, y)$, and an appropriate unknown coefficient, q_{mn}:

$$x(x,y,z) = \sum_{m=1}^{M}\sum_{n=1}^{M} q_{mn} W_{mn}(x,y)\exp(i\omega\, t) \tag{1}$$

where $i = \sqrt{-1}$ and ω is the circular natural frequency of the perforated square plate. The indices m and n indicate the mth order polynomial in the x direction and nth order polynomial in the y direction, respectively. The transverse modal function can be defined by a multiplication of the x- and y-directional admissible functions, $X_m(x)$ and $Y_n(y)$, as follows:

$$W_{mn}(x,y) = X_m(x)Y_n(y) \tag{2}$$

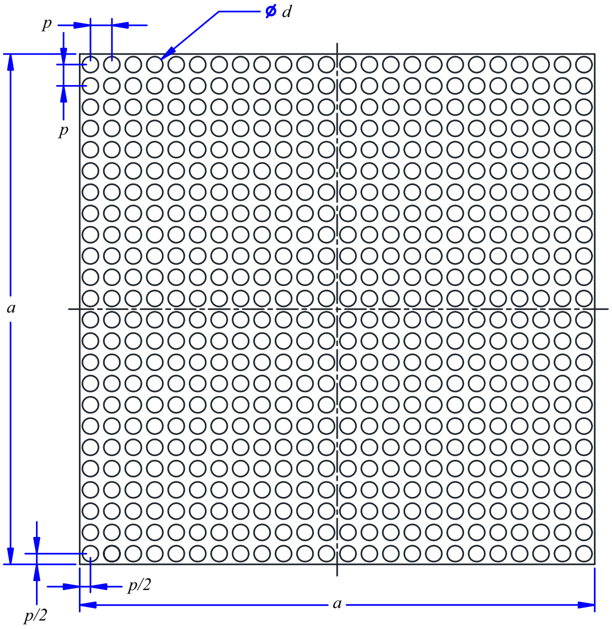

Fig. 1 – Perforated plate model with a square penetration pattern.