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Proposed Formulas for Evaluation of the Equivalent Material Properties of a Multiholed Structure

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Abstract

It is widely known that the development of fine mesh in the immediate vicinity of the holes in a multiholed plate is a challenging issue. In practice, due to the amount of time consumed and the quality of the modelling, it is not desirable to model the structural characteristics of a multiholed plate in detail. In this regard, an effective means by which to avoid the unnecessary work of simulating a multiholed plate is to replace it with an equivalent solid plate while considering the decrease in stiffness associated with the increasing area of the holes. The objective of this study is to numerically and experimentally investigate the equivalent material properties of a multiholed plate of stainless steel 316L with respect to ligament efficiencies. Simple design formulas are proposed to determine the equivalent material properties of a multiholed plate that is completely perforated with closely spaced circular holes in a square or diagonal pattern by means of nonlinear finite-element method computations. It is concluded that the proposed formulas are accurate for prediction of the equivalent material properties of multiholed structures for their design and engineering.

Key words: Proposed design formulas; multiholed plate; equivalent material properties; stainless steel; finite element analysis

Nomenclature

A	Original cross-sectional area of specimen
A_{nom}	Nominal cross-sectional area of effective region for multiholed specimen
d	Diameter of circular hole

E	Young's modulus
E^*	Equivalent Young's modulus
h	Ligament width
K	Strength coefficient for Swift constitutive equation
L_o	Gauge length of extensometer
n	Plastic strain hardening exponent for Swift constitutive equation
P	Measured force applied by testing machine
p	Pitch
t	Thickness of plate
TPR	Thickness-pitch ratio
δ	Displacement
ε	Engineering strain
ε_r	Rupture strain in true stress-strain curve
ε_{F}	Fracture strain in engineering stress-strain curve
ε_{un}	Uniform true strain before onset of necking
$\varepsilon_{\mathrm{F}}^*$	Equivalent fracture strain
η	Ligament efficiency
σ	Engineering stress
σ_r	Rupture stress in true stress-strain curve
σ_n	Necking stress in stress-strain curve
σ_{av}	Average true stress after onset of necking
σ_{un}	Uniform true stress before onset of necking
σ_{T}	Ultimate tensile strength in engineering stress-strain curve
σ_{Y}	Yield strength
σ_{T}^*	Equivalent ultimate tensile strength the engineering stress-strain curve
σ_{Y}^*	Equivalent yield strength

1. Introduction

In this study, a multiholed plate is regarded as a single plate with numerous circular holes that are regularly arranged across it. Multiholed structures are used extensively in various engineering fields. In offshore structures, multiholed structures are used as heat shields against fire action and as perforated blast walls that function as a passive mitigation system by disrupting explosive pressure. In the nuclear field, multiholed structures express their structural characteristics in nuclear reactors and are mainly used to provide structural support and to facilitate the flow-passage of coolants. In civil engineering, multiholed structures are used as building components for various engineering purposes.

The application of multiholed structures is limited because their failure can directly affect system operation failure. Therefore, many engineers and designers continue to perform structural analysis and assessment of multiholed structures and focus upon numerical analysis of the nonlinear response and stress concentration of multiholed plates for safety design and operation. In the design of multiholed structures, it is necessary to define equivalent material properties to structural behaviour. However, limited information is available in the literature to determine the equivalent material properties of multiholed structures.

A theoretical method was developed to determine the equivalent elastic properties of a perforated plate, and several validation experiments were carried out (Bailey & Hicks, 1960). They successfully obtained design curves to determine the equivalent elastic properties of the perforated plate. However, the nonlinear equivalent material properties of the perforated plate were not considered. Choi et al. (1997) presented a finite-element (FE) modal analysis of a perforated plate with diagonal and square penetration patterns, and an attempt was made to put the equivalent elastic constants into the solid plate using modal analysis to compare the behaviour of the perforated plate with its original properties. However, the method for determination of the equivalent material properties was not mentioned. Although Appendix A to Section III of the ASME A-8000 (2004) contained a method for calculating the equivalent elastic constants of multiholed plates, the methods for determining the equivalent yield strength, equivalent ultimate strength and equivalent fracture strain for each specified multiholed plate were not presented. The imperfection of the ASME rule for modal analysis was realised, and several new formulas were developed to determine the equivalent Young's modulus of a thin multiholed plate by means of modal analysis (Jhung & Jo, 2006). A series of FE analyses for a triangular perforated circular plate were numerically performed using an axisymmetric model. Based on the simulation results, several equations were proposed to determine the equivalent elastic material properties and nonlinear equivalent material properties of the perforated plate. Kasahara et al. (2007) also clarified that the equations were only geometric functions and that they were independent of both the constitutive equation and the material type without experimental investigation. The buckling strength of steel plates with a circular hole were analysed numerically under axial compressive loading along their short edges by varying the hole size and performing compression with elastic buckling strength with plasticity correction (Paik, 2007). However, in this paper, only one hole on the plate was considered. Meanwhile, the buckling and ultimate strength of perforated plate panels with an opening were investigated experimentally and numerically subject to axial compression, and new design-formula solutions with important parameters of influence were derived (Kim et al., 2009). However, only one opening on a plate was considered for analysis of the compressive strength of perforation. The stability of a biaxial loaded square plate with a single central hole was numerically studied (El-Sawy & Martini, 2010), and the families of the design curve were generated to define the buckling stress for the various hole sizes, but the necessary experimental validation was not presented.

In this study, the linear and nonlinear equivalent material properties of a multiholed plate of stainless steel 316L with either a diagonal or square pattern were mainly examined by means of quasi-static analysis using both experimental and numerical methods. A series of nonlinear FE computations were performed with varying thicknesses, pitch ratios and ligament efficiencies. The sensitivity of the specified geometry parameters on the equivalent material properties was then analysed and is discussed in detail in this paper. Finally, eight types of formulas derived as a function of the ligament efficiency are proposed.

This paper also presents six groups of experimental investigations conducted with various types of multiholed plates. One set of experiments was used to validate the modelling technique, and the remaining experiments compared the proposed formulas to enhance their reliability. Meanwhile, the proposed formulas were also compared with the current rules and studies on the equivalent material properties of a multiholed plate to further improve their applicability. This series of validations with various methods demonstrated that the proposed formulas provide some useful support for the nonlinear analysis of large perforated structures. These proposed formulas will be very useful for structural designers for easy determination of the additional thickness of perforated structure that is required to provide the same properties as an unperforated plate at the same scale.

2. Experimental modal investigations

A series of experimental investigations of the tensile properties of the multiholed specimen were carried out at the Korea Ship and Offshore Research Institute at Pusan National University to determine the equivalent material properties of the multiholed structure.

2.1. Material and dimensions of the test specimens

Six sets of multiholed specimens were used to investigate the equivalent material properties. Each set of multiholed plates was examined twice. The test results for the same specimen types were then compared to determine the accuracy of the experimental results.

In ship and offshore manufacturing industries, stainless steel 316L is used to manufacture heat shields, perforated blast walls and the corresponding structural components for ships and offshore installations due to its excellent mechanical properties. Accordingly, a multiholed structure of stainless steel 316L was used in the following experimental and numerical investigations. The thickness-pitch ratio and ligament efficiency were both considered to effectively express the opening distributed characteristics of the multiholed plate. These two parameters, illustrated in Figure 1, are defined as follows:

$$TPR = t / p \tag{1}$$

$$\eta = h / p = (p - d) / p \tag{2}$$

Fig. 1. Schematic diagram of the parameters of the thickness-pitch ratio and ligament efficiency.

To effectively investigate the influence of the distributed characteristics of various circular openings on the equivalent material properties, the effective area of the multiholed specimens was fixed at 500 × 500 mm. Figure 2 shows the design of the quasi-static tensile multiholed plate test specimens and the distributed characteristics of the circular openings, which are displayed inside the dotted line. It is noted that the staggered direction of the diagonal pattern is along the direction of tensile loading. The thickness of the multiholed specimens is fixed at 1 mm.

Fig. 2. Design of the quasi-static tensile multiholed plate test specimens (mm).

Detailed information on the tensile test specimens is presented in Table 1. Each type of multiholed specimen was prepared to repeat the same tests twice. The specimens were identified in the order of material, opening arrangement type, porosity, thickness-pitch ratio, ligament efficiency and repetition number. A total of 12 experimental investigations was carried out.

Table 1
Detailed information of the multiholed specimen preparation.

2.2. Experimental setup

The experimental setup is described in Figure 3. The test jig is a type of fixed device that can sustain the load produced by the test apparatus. The MTS is a tensile testing machine that can provide up to 500 KN to the specimen. The supporting device mainly supports the spindle of the MTS to ensure axial movement without any longitudinal vibration. Moved gripping is mainly used to evenly transmit the measured force applied by the MTS to the multiholed specimen. Fixed gripping is applied to the other end of the specimen in static status. A high-speed camera was positioned to capture the quasi-static displacement of the specimen. A tensile speed of 1.0 mm/s was applied in the experimental investigations for the quasi-static behaviour of the multiholed plate.

(a) Schematic diagram of the specimen installation.

(b) Status of the test.

Fig. 3. Experimental setup.

2.3. Test results

The fracture of the specified multiholed specimen under quasi-static tensile speed is shown in Figure 4. Comparison of the test results for the same specimen types shows that the fracture occurred along the smaller effective cross-section area in the gauge length and that both types showed similar fracture behaviour. These results can be explained by the effects of greater stress in the smaller effective cross-sectional area, which was perpendicular to the increasing axial tensile loading. As would be expected, the smaller effective cross-sectional area is also weaker than the other parts.

(a) SUS316L-60°-20%-0.12-0.53-01

(b) SUS316L-60°-20%-0.12-0.53-02

Fig. 4. The fracture status.

Figure 5 shows the stress-strain curves of a series of multiholed tensile tests with various opening distributed characteristics, in which the engineering stress is expressed as the measured load applied by the testing machine divided by the nominal cross-sectional area of the effective region of the multiholed specimen, as illustrated in Eq. (3).

$$\sigma = P/A_{nom} \tag{3}$$

Figure 5 shows that porosity caused a reduction in the mechanical properties of the multiholed plate and reduction of the fracture strain. The greater discrepancy in the fracture strain for SUS316L-60°-40%-0.17-0.34, for which it can be explained that the misalignment of the measured point on the surface of the specimen could have caused the difference in strain, is a result of the digital character of high-speed cameras, which is a function of pixel size. A rapid termination time was observed in the fracture, which is caused by the localised necking phenomenon on the necked surface of the specimen. However, for the different opening arrangements, it was observed that the mechanical properties of a diagonal perforated plate are more outstanding features than the staggered pattern on the multiholed plate.

(a) Material properties of the diagonal pattern.

(b) Material properties of the square pattern.

Fig. 5. Comparison of the test results for each set of multiholed specimens.

Several of the main mechanical properties of each specimen type are presented in Table 2. The yield strength was determined by the offset method, with the value of the offset set at 0.2%.

Table 2

The mechanical properties of the multiholed specimens measured in the experimental investigations.

3. Numerical modelling

3.1. Target specimen

A multiholed specimen of SUS316L-60°-20%-0.12-0.53-01 was used as the target specimen to verify the numerical model. The detailed configuration of the target specimen is shown in Figure 6. The thickness of the specimen is set at 1.0 mm.

Fig. 6. Detailed dimensions of the target specimens used for validation.

3.2. Material modelling

Stainless steel 316L is an austenitic stainless steel that is widely used in offshore installations and ship structures. This type of stainless steel is also extensively used in many engineering applications for its resistance to corrosion, improved welding capability and predominant toughness. To characterise the quasi-static material properties of stainless steel, tensile coupon tests were performed with a 500-kN MTS machine. The dimension of the specimens was determined on the basis of the ASTM standard, as shown in Figure 7. From Figure 7, it can be seen that the gauge length is 50 mm. The tensile speed of the specimen is also set at 1.0 mm/s.

Fig. 7. Detailed dimensions of the tensile coupon test specimen (unit: mm).

The gauge length of the extensometer was fixed at 50 mm. The load and displacement data were then recorded with an extensometer and were converted to an engineering stress-strain curve using Eq. (4a) and Eq. (4b), respectively.

$$\sigma = P/A \tag{4a}$$

$$\varepsilon = \delta/L_o \tag{4b}$$

$$\sigma_{un} = \sigma_{Y}(1+\varepsilon) \tag{4c}$$

$$\varepsilon_{un} = \ln(1+\varepsilon) \tag{4d}$$

$$\sigma_{av} = K(\varepsilon_r)^n \tag{4e}$$

For application of the measured stress-strain curve, the uniform true stress-strain curve must be obtained by converting the engineering stress and strain using Eq. (4c) and Eq. (4d). The average true stress-strain curve is determined after the first necking because the stress state in the necked section after the first necking changes from uniaxial stress to triaxial stress. Figure 8 presents the engineering stress-strain curve and the converted average true stress-strain curve.

(a) Engineering stress-strain curve

(b) True stress-strain curve

Fig. 8. Stress-strain curves of the stainless steel 316L.

The uniform true strain corresponding to the necking point is 0.36, as shown in Figure 8(b), and the rupture length is 75 mm (Figure 9). In addition, the true plastic rupture strain is approximately 0.5 as derived by Eq. (4b). Therefore, the uniform stress-strain curve before the first necking can be used in the numerical investigations.

Fig. 9. The rupture length for stainless steel 316L.

To solve this problem, the Swift constitutive equation illustrated in Eq. (4e) was used to extend the average true stress-strain curve until the true plastic rupture strain was achieved. The strength coefficient (K) and the plastic strain hardening exponent (n) involved in the Swift constitutive equation can be obtained by fitting the uniform true stress-strain curve before the first necking.

The true stress-strain curve for stainless steel 316L was applied to the series of numerical analyses introduced in Figure 8(b). Although the material type is the same, there is some variation in the material properties according to the geometric characteristics of the target structure. Therefore, the material was assumed to have a constant value (rupture strain of 0.5), which was used as the assumed value in FE material modelling. The effects of dynamic hardening can be considered in the simulation of the multiholed specimen; however, the dynamic loading mode of the standard specimen was the same as that of the multiholed specimen, and their strain rates were similar. Therefore, the effects of dynamic hardening are ignored in this study.

3.3. Boundary and loading conditions

In this study, the target specimen was modelled in 1/4 scale in consideration of the symmetric conditions. The boundary conditions and loading conditions are shown in Figure 10. The circular opening is distributed inside the dashed line. The loading speed is applied in the same manner as the test condition (1 mm/s) in the FE analysis.

Fig. 10. Boundary conditions and loading conditions for the 1/4-scale multiholed plate.

3.4. Mesh convergence study

A mesh convergence study is an empirical process for determination of the successive levels of mesh refinement by comparison with the simulated results of a meshed model. In this mesh convergence study, multiholed specimens of SUS316L-60°-20%-0.12-0.53-01 were analysed. The four-node shell element type of 4 nodes shell 181 (ANSYS/LS-DYNA, 2014) with reduced integration scheme in ANSYS was applied in the simulation. The specimen can be treated as an elastoplastic material with bending, membrane and large strain structural behaviour. Therefore, the selected element can be suitable for these simulations. Figure 11 shows different mesh sizes for different parts of the plate. Region A is the critical plate; therefore, the mesh convergence study was carried out in Region A with different element sizes as shown in Figure 12. The results of the mesh convergence study show that an approximate element size of 1.0 × 1.0 mm can be suitable for multiholed FE modelling.

Fig. 11. Finite-element model of the multiholed plate.

Fig. 12. Results of the mesh convergence study.

3.5. Validation of FE modelling

The fracture of the multiholed specimen of SUS316L-60°-20%-0.12-0.53-01 for comparison of the numerical and experimental results is shown in Figure 13. The numerical and experimental methods are in agreement. The fracture positions of the multiholed plate as determined by the two different methods are near the midline of the specimen plane.

(a) Fracture for the numerical investigation (one quarter).

(b) Fracture for the experimental investigation (full).

Fig. 13. Fracture of the target multiholed specimen.

The results of FE analysis with the experimental results are presented in Figure 14. The main mechanical properties given by the numerical and experimental methods are also listed in Figure 14. The experimental result for the material behaviour near the plastic strain of 0.002 is slightly greater than the numerical result. Based on this result, it is assumed that an inertial effect occurred once the tensile force was applied by the testing machine. The force-induced inertial effect can result in overestimation of the material's related mechanical properties (Choung, 2013). Therefore, FE modelling can be the appropriate modelling method and will be used in development of the design formula.

Fig. 14. Validation study for comparison of the numerical and experimental results.

4. Proposed multihole formulas based on numerical results

In this section, the geometric parameters of the multiholed plate are considered, and the influence of each geometric parameter on the structural behaviour of the multiholed plate is investigated with the verified FE model. Finally, the proposed formulas are derived as a function of the ligament efficiency by fitting the curve, which can determine the equivalent Young's modulus, the equivalent yield strength, the equivalent ultimate strength and the equivalent fracture strain of the multiholed plate with diagonal or square penetration patterns.

4.1. Target structure

The most likely models to be used in a multiholed plate were selected for the parametric study. All possible practical scenarios are presented in Table 3. It is well known that the diagonal penetration pattern possesses structural directionality, including better structural properties along the direction of the stagger. In the parametric study, only the equivalent material properties were considered along the direction of the stagger, which means that the direction of the stagger was arranged along the tensile direction.

Table 3.
Considered geometric parameters of the multiholed plate.

4.2. Results and discussion

The equivalent material properties are widely used in the structural analysis of perforated structures. If the equivalent material properties of the perforated plate are applied to the material properties of the solid plate, the applied solid plate can express a response similar to that of a perforated plate of the original material under various loading conditions. Based on the simulation results, several investigations can be observed; these are defined as the ratio of the equivalent material properties of the perforated plate to the original material properties. The material properties (yield strength, ultimate tensile strength, fracture strain and Young's modulus) with their ligament efficiency are expressed in Figure 15.

(a) Young's modulus constant of the perforated plate with a diagonal penetration pattern.

(b) Yield strength constant of the perforated plate with a diagonal penetration pattern.

(c) Ultimate strength constant of the perforated plate with a diagonal penetration pattern.

(d) Fracture strain constant of the perforated plate with a diagonal penetration pattern.

(e) Young's modulus constant of the perforated plate with a square penetration pattern.

(f) Yield strength constant of the perforated plate with a square penetration pattern.

(g) Ultimate strength constant of the perforated plate with a square penetration pattern.

(h) Fracture strain constant of the perforated plate with a square penetration pattern.

Fig. 15. Specified constant versus ligament efficiency for the diagonal and square penetration patterns.

The thickness-pitch ratio tends to affect the equivalent material properties of the multiholed plate, but the ligament efficiency exercises more influence, as shown in Figure 15. Moreover, the ligament width between two adjacent holes is perpendicular to the tensile loading, which directly influences the mechanical properties of the perforated plate.

Only the two geometric tests showed difficulty in the statistical validation of the proposed formulas. Therefore, to enhance the reliability of the proposed formulas obtained from the numerical analysis, a literature review was performed to compared the results regarding the equivalent material properties of the perforated plates. Some general methods for determination of either the equivalent Young's modulus or the equivalent yield strength are provided for multiholed plates with diagonal or square penetration patterns, as shown in Figures 15(a), (b) and (e) (Bailey & Hicks, 1960; Slot et al., 1971; ASME A-8000, 2004; Jhung & Jo, 2006; Kasahara et al., 2007). In addition, the equivalent Young's modulus and equivalent yield strength of a perforated plate with a diagonal pattern according to porosity are provided in the handbook of the Industrial Perforators Association, as shown in Figures 15(a) and (b) (IPA, 2015). From the results of these observations, the trend of the equivalent material properties according to the ligament efficiency is given to similar results, with deviation between the proposed formula and the design curve proposed by previous researchers, although the deviation can be within an acceptable range. The results for the formula proposed in this study also agree well with the solution of ASME A-8000, as illustrated in Figure 15(a). According to the IPA handbook (IPA, 2015), for the equivalent material property of a perforated plate with a diagonal penetration pattern depending on the loading directions, the values of $\sigma_{\mathrm{Y}}^{*} / \sigma_{\mathrm{Y}}$ along the direction of the straight row of spaced holes is approximately less than 0.05 the direction of the stagger (IPA, 2015). It should be noted that the equivalent material properties of a perforated plate with the diagonal pattern used this study are along the direction of the stagger.

The proposed formulas in this study focus on a relatively larger ligament efficiency zone, approximately 0.3 to 0.8. Figure 15 presented that comparisons of the proposed formulas and the current literature in this ligament efficiency range can yield considerable results. However, the higher ligament efficiency zone displays the nonlinear relationship between the material properties and the ligament efficiency as in the lower ligament efficiency zone, as shown in Figure 15(a). Therefore, more convincing formulas must be developed to also take into consideration the lower and higher ligament efficiency zones in future studies.

The proposed formulas for evaluation of the mechanical properties of multiholed plates with diagonal or square penetration patterns can be expressed as follows:

For the diagonal penetration pattern

$$E^{*}/E = 1.2446\eta - 0.0704 \tag{5a}$$

$$\sigma_{\mathrm{Y}}^{*}/\sigma_{\mathrm{Y}} = 1.1006\eta + 0.0493 \tag{5b}$$

$$\sigma_{\mathrm{T}}^{*}/\sigma_{\mathrm{T}} = 0.9769\eta + 0.0515 \tag{5c}$$

$$\varepsilon_{\mathrm{F}}^{*}/\varepsilon_{\mathrm{F}} = -2.1424\eta^{3} + 2.1816\eta^{2} - 0.3083\eta + 0.2472\,. \tag{5d}$$

For the square penetration pattern

$$E^{*}/E = 1.018\eta + 0.1221 \tag{6a}$$

$$\sigma_{\mathrm{Y}}^{*}/\sigma_{\mathrm{Y}} = 1.0952\eta + 0.0572 \tag{6b}$$

$$\sigma_T^* / \sigma_T = 1.0174\eta + 0.0379 \quad (6c)$$

$$\varepsilon_F^* / \varepsilon_F = -0.1937\eta^2 + 0.387\eta + 0.1824.$$

The proposed simple formulas express the influence of perforations on the equivalent material properties by inputting the structure's original material properties. The proposed formulas provide a useful guideline for the structural design of perforated plates and can be used to effectively determine the safety margins for any geometric type of structure and loading type.

4.3. Validation of the proposed formulas with the experimental results

The accuracy of the proposed formulas was validated by comparing the experimental results with the results obtained using the proposed formulas. Table 4 presents the comparisons of the equivalent material properties between the experimental method and the proposed formulas. The results obtained with the proposed formulas agree well with the experimental results. However, the experimental results and the proposed formulas tend to vary significantly in their predictions of the yield strength and fracture strain of the multiholed plate. This difference can be explained by the inertial effect produced by the testing machine; the experimental yield strengths are usually higher than the yield strengths obtained with a numerical method.

The stress triaxiality is an important factor in determining the structural fracture strain, which is mainly distributed in the necked cross section. However, the state of stress triaxiality differs as the geometric details vary, even when the structure is made from the same material (Choung, 2012). In this study, a constant fracture strain criterion was used in the simulation instead of the fracture strain criterion, which is a function of the stress triaxiality. This finding can also explain the difference between the experimental results and the results of the proposed formulas in determining the fracture strain. Finally, the discussion above verifies that the formulas developed in this study can be used to effectively determine the equivalent material properties of a multiholed plate with a diagonal or square pattern.

Table 4.
Comparison of the results of the proposed formulas and the experiment.

5. Conclusions

Modelling the details of large-scale perforated structures and the construction of fine mesh around the circular holes is quite complex. Moreover, the relative simulation requires significantly more time to run for a perforated structure than for an unperforated structure. Therefore, it is necessary to study the equivalent material properties of a multiholed plate with diagonal or square penetration patterns and to derive formulas to effectively predict the equivalent material properties of a multiholed plate with respect to the ligament efficiency.

The proposed formulas are a function of geometry and are independent of materials, and parametric study is most likely to be used in a limited range of structural applications involving various geometric shapes, different material properties, various constitutive equations of base metals and different loading types. As concluded above, the behaviour of a perforated structure with the original properties is in agreement with that of a solid structure with equivalent material properties determined by the formulas proposed in this study. These proposed formulas are very useful for structural designers because they can be used to easily determine the additional thickness of a perforated structure that is required to provide the same properties as an unperforated plate of the same scale.

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