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Strength tests of axially symmetric perforated plates for chemical reactors: Part 2—Experiments

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Abstract

The aim of the present paper is to elaborate the methodology of empirical studies, which would allow establishing stress histories in perforated plates centrally loaded by a concentrated force. The other objective is to empirically verify the mathematical model proposed in a companion paper (Part 1). The diameter of the holes, as well as the geometry of their distribution in the plate prepared for the study, provided for the constancy of section-weakening coefficients. Some resistance strain gauges were placed in between the holes in order to measure the strains. The axially symmetric perforated plate was subjected to bending with a concentrated force applied centrally. Additionally, bending of the plate was monitored with a dial gauge during the measurements of the strains. On the basis of the measured values of the strains we were able to establish radial, circumferential and equivalent stresses in the plate. The empirical research corroborated the correctness of the adopted model of calculating the stress states in the perforated plate.

Keywords: Perforated plate; Heat exchanger; Test methods; Strain gauges; Reduced stress

1. Introduction

The aim of empirical research is the assessment of the correctness of solving a given construction with respect to its strength. The basis for such an evaluation is the effort of the material defined by stress and strain states in the considered structural elements. Both real objects and their models made of different materials can be used to test these states [1–7].

The conducted study yielded the data, which permitted us to

- verify the adopted mathematical paradigm for the description of stress states of the designed construction element,
- check its performance under service loading.

Parallel to the mathematical modeling, which describes the stress state and strains of the perforated plates, the methodology of empirical research was also developed, which was subsequently used to corroborate the validity of the adopted models.

In the 1960s such research was initiated, among others, by Bailey and Hicks [1], Duncan and Upfold [2] and Sampson [3]. Specimens in the form of perforated plates underwent stretching. Next, the graphs of stress–strain were calculated. Based on the strain graphs the substitute elastic constants (i.e. the substitute Young's modulus and the substitute Poisson's ratio) were determined. Hexagonal and square distributions of holes were used. To determine the strain and the stress state in the specimens (perforated plates) subjected to tension elastic–optical methods were adopted in [4,5,7].

Lee and Chen [6] conducted empirical studies on specimens in the form of perforated plates in the elastic–plastic regime. Specimens with a hexagonal distribution of holes were subjected to stretching. The aim of the research was to calculate the mechanical anisotropy caused by the distribution of the holes in the specimen. In some cases, the results of empirical research served to corroborate calculations obtained through finite element methods [6,7].

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Nomenclature

C_r, C_ϑ	coefficients of section weakening in radial and circumferential directions
R_i	hole radii ($i = 1, 2, \ldots, 10$)
d_i	hole diameters ($i = 1$ to N)
N	the number of holes in the plate
R_z	the external radius of the plate
R_p	the radius of support spacing
P_0	preliminary load of the plate
P_n	calculation load of the plate ($n = 1, 2, 3, \ldots, 5$)
P_j	total load of the plate ($j =$ I, II, III, …, V)
f_0	preliminary plate deflection
h	plate thickness
v	Poisson's ratio
σ_r, σ_ϑ	radial and circumferential stresses
E	the modulus of longitudinal elasticity for the plate material
σ_{eq}	equivalent stress
ε_r, ε_ϑ	radial and circumferential strains
ρ_i	the dimensionless value of the current plate radius
p_{ri}, $p_{\vartheta i}$	the dimensionless values of radial and circumferential stresses
p_{eq}	the dimensionless value of the equivalent stress
Δr	finite increment of radial coordinate corresponding to the pitch of the hole distribution in radial direction
$\Delta\vartheta$	finite increment of circumferential coordinate
$R_i\Delta\vartheta$	the pitch of the hole distribution in the circumferential direction
$\hat{R}$	the estimator of correlation coefficient
P	probability function

The above research implies that models of perforated plates were tested under stretching only. Empirical studies where specimens underwent bending seem to be missing. The novelty of the present work is to fill this research gap. Our objective was the empirical analysis of the stress state in a perforated circular-symmetric plate, which is subjected to bending, and the corroboration of the correctness of the suggested model of the substitute plate.

2. Testing methods for the circular-symmetric plate

2.1. The analyzed perforated plate

The plate for the tests (Fig. 4) was made of steel sheet S235JR G2 according to EN (A 570 Gr.36 acc. ANSI) with the thickness of $h = 5\,\text{mm}$. A disk was cut out from the steel sheet with a laser torch, with a suitable allowance. Next, the disk was subjected to preliminary machining in order to obtain the required diameter, i.e. $2R_z = 300\,\text{mm}$. Afterwards, in such a circular-symmetric plate, holes were made with a numerically controlled boring machine. To make sure that in the whole perforation zone of the plate the values of weakening coefficients both in the radial direction C_r and in the circumferential direction C_ϑ (similarly to [11]) were constant, the following method for calculation of the diameters of holes d_i and radii of circumferences R_i where the centers of the holes were located (Fig. 1) was used.

1. The initial data for designing the plate for empirical research:
   $n_1 = 20$—the number of holes in the inner (the smallest) circumference with the radius R_1;
   $d_1 = 3.5\,\text{mm}$—the diameter of holes on the circumference with the radius R_1;
   $C_r = 0.50$—the value of the section weakening coefficient in the radial direction; and
   $C_\vartheta = 0.55$—the value of the section weakening coefficient in the circumferential direction.
2. The calculation of the finite value of the circumferential coordinate increment $\Delta\vartheta$:
   $$\Delta\vartheta = \frac{2\pi}{n_1} = 0.314\,\text{rad}, \tag{1}$$
   which corresponds to the angular pitch 18° (Fig. 1).
3. The calculation of the radius R_1 of the smallest circumference (Fig. 2)
   $$R_1 = \frac{d_1}{\Delta\vartheta(1 - C_r)} = 22.5\,\text{mm}. \tag{2}$$
4. The radius of the second circumference R_2 and the diameter of the holes d_2 on this circumference was established from the relation (Fig. 2)
   $$R_2 = R_1 + \Delta R_1 = 27.75\,\text{mm} \;\; (\text{assumed } R_2 = 27.5\,\text{mm}), \tag{3}$$
   $$d_2 = R_2\Delta\vartheta(1 - C_r) = 4.35\,\text{mm} \;\; (\text{assumed } d_2 = 4.5\,\text{mm}), \tag{4}$$
   where the increment of the radius was determined from the relation $\Delta R_1 = kd_1 = 5.25\,\text{mm}$, $1 \leqslant k \leqslant 2$, k—the constant dependent on the plate construction assumptions (assumed $k = 1.5$).

The radii R_i of the subsequent circumferences as well as the diameters of subsequent holes d_i located on these circumferences was established, respectively, through the formulae

$$R_i = R_{i-1} + \Delta R_{i-1}, \tag{5}$$

$$d_i = R_i\Delta\vartheta(1 - C_r), \tag{6}$$