RESEARCH OF MAXIMUM STRESS ZONES IN CIRCULAR PLATES WITH LOADES CONCENTRATED FORCE

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Abstract: The paper presents numerical and experimental analysis of the state of stress in a circular perforated plate, free supported or fixed on entire premier and loaded concentrated force. This type of plate have found applications in the field of chemical equipment, pressure tanks and box conveyors. The use of the finite element method for numerical calculations enables accurate location of stress concentration zones in a perforated plate and allows to determine stress values around these hole.

KEYWORDS: Perforated plate, reduced stresses, numerical calculations, experimental research

1 Introduction

Present engineering constructions are characterized by a decrease of the safety factor, which is why calculations of strength, stiffness and stability of thin-walled construction elements are becoming some of the important aspects in all branches of technology, especially such as chemical engineering. There are many applications of perforated plates e.g. in pressure vessels, chemical equipment (heat exchanger tube screens) [1], oil refineries, box conveyors [2] or as elements of loose material screens, which can be subjected to a load that varies over time. This type of girders (perforated plates) can also act as mounting plates in which holes are made for various operational reasons [3,4].

Fig. 1 Box conveyors [2]

In practical design issues, it is often necessary to determine stresses and deflections in such plates, which are loaded with static forces acting perpendicular to their surface. Due to the wide application of perforated elements in many branches of industry, it is advisable to undertake studies involving the analysis of the state of stress regarding such elements subjected to a normal load. Knowledge of the state of stress will offer optimal design; and thus, safe operation of devices in which these types of components are used has been made more feasible [5,6,7,8,9].

In literature, many attempts were made to analyze stress concentration, deflections, strains, stress concentration factor and stress intensity factor in perforated plates weakened because of openings in them. The analytical method [10,11], the experimental method [12,13] and the numerical method [14,15,16,17,18,19,20,21] were used to evaluate the parameters of perforated plates. In the work [12], the authors developed a methodology of experimental research that which allow to determine the stresses histories in perforated plates centrally loaded by a concentrated force. 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. Resistance strain gauges were placed between the holes in order to measure the strains. The axially symmetric perforated plate was subjected to bending with a concentrated force applied centrally. On the basis of the measured values of the strain, radial, circumferential and equivalent stresses in the plate were determined. The experimental research corroborated the correctness of the adopted model of calculating the stress states in the perforated plate. However, in the work [22], optimum hole size and shape of perforated plates with round and staggered holes investigated using mid-point deflections of perforated plates under their self-weights. Analysed plates are free supported on their four sides. The ANSYS program was used for research. The square perforated plates were examined in terms of mid-point deflections by changing numbers, radii and locations of their holes. The results obtained can be useful for determine the design parameters and perforation operations of perforated square plates with round and staggered holes.

The purpose of the study reported in the present paper is to locate the zones in which maximum stresses occur in a circular axisymmetric perforated plate, free supported or fixed and loaded with concentrated force P_i applied in the geometric center of the plate. Tests of stress concentration zones were performed numerically using the finite element method.

2 Model and material of the perforated plate

The calculation was based on a circular axisymmetric perforated plate with the dimensions: diameter $D = 300$ mm, thickness $h = 5$ mm. 200 holes with different radii placed on the plate. These holes were arranged in 10 circles with 20 holes in each circle, as shown in Figure 2. As a plate material, S235JR steel sheet with the following mechanical parameters was adopted: $E = 205$ GPa, Poisson's ratio $\nu = 0.3$. In the first variant, the perforated plate was free supported (Fig. 3a) over the entire perimeter and loaded with concentrated force P_i applied in the geometric center of the plate, and in the second variant the perforated plate was fixed (Fig. 3b) over the entire perimeter and loaded with concentrated force P_i applied in the geometric center of the plate (Fig 3). The following values of the load were assumed P_i : $P_1 = 410$ N; $P_2 = 875$ N; $P_3 = 1365$ N; $P_4 = 1925$ N; $P_5 = 2510$ N. With two variants on the axisymmetric perforated plate, ten measurement zones were marked, i.e. from Z1 to Z10 (Fig. 2).

Fig. 2 Model of perforated plate with ten measuring zones, i.e. from Z1 to Z10 [12]

Fig. 3 A circular axisymmetric perforated plate loaded with concentrated force P_i applied in the geometric center of the plate with the following boundary conditions: a) free supported over the entire perimeter; b) fixed over the entire perimeter

3 Numerical calculation

The subject of numerical calculations of the state of stress applied a circular axisymmetric perforated plate, which geometry, i.e. the dimension, the method of restraint and the load method were outlined in section 2 of this paper. Numerical calculations were carried out using the ANSYS program [23]. ANSYS is a program for numerical calculations using the finite element method (FEM). It allows solving complex tasks with high accuracy. ANSYS uses a range of advanced and universal technologies that enable quick, efficient and simple preparation of the calculation model.

The plate solid was modelled using cubic spatial finite elements (3D) with square sides containing twenty nodes (eight nodes in the corners and twelve on the edges of the element sides), i.e. W20, described by a square shape function (Figures 4 and 5). The computational model contained the total number of finite elements 130620, while the total number of nodes was 596310. The plate solid had 6 layers of finite elements.

a)

b)

Fig. 4 a) A cubic spatial element (3D) with a square shape function with twenty nodes, i.e. from W1 to W20; b) Division of the plate into finite elements

For example, in Fig. 5, the distribution of reduced stresses σ_{red} is given, calculated according to the von Mises hypothesis in a circular axisymmetrical perforated plate, free supported and loaded with concentrated force P_i applied in the geometric center of the plate with the value $P_5 = 2510$ N.

Fig. 5 Distribution of reduced stress σ_{red} given in MPa for an axisymmetric perforated plate free supported and loaded with concentrated force P_i applied in the geometric center of the plate with the value $P_5 = 2510$ N, $\sigma_{red \max} = 416.79$ MPa

However, the location of stress concentration zones in the tested plate is shown in Figure 6. The figure illustrates the distribution of reduced stresses given in MPa in two sample measuring zones (in the first zone Z1 – the closest to the edge of the plate and in the tenth zone Z10 – the

closest to the central part of the plate), (Fig. 2). Points T1 and T10 define the values of reduced stresses obtained numerically at control measuring points, and P1 and P10 are points of identification of the maximum numerical values of stress. In square brackets the values of three coordinates, i.e. x, y, z coordinates, are given.

Fig. 6 Reduction stress zones σ_{red} given in MPa for an axisymmetric perforated plate free supported and loaded with concentrated force P_i applied in the geometric center of the plate with the value $P_5 = 2510$ N: a) zone Z1: $\sigma_{red \max} = 131.28$ MPa; b) zone Z10: $\sigma_{red \max} = 416.79$ MPa

For example, in Fig. 7, the distribution of reduced stresses σ_{red} is given, calculated according to the von Mises hypothesis in a circular axisymmetrical perforated plate, fixed and loaded with concentrated force P_i applied in the geometric center of the plate with the value $P_5 = 2510$ N.

Fig. 7 Distribution of reduced stress σ_{red} given in MPa for an axisymmetric perforated plate fixed and loaded with concentrated force P_i applied in the geometric center of the plate with the value $P_5 = 2510$ N, $\sigma_{red \max} = 241.9$ MPa

However, the location of stress concentration zones in the tested plate is shown in Figure 8. The figure illustrates the distribution of reduced stresses given in MPa in two sample measuring zones (in the first zone Z1 – the closest to the edge of the plate and in the tenth zone Z10 – the closest to the central part of the plate), (Fig. 2). Points T1 and T10 define the values of reduced stresses obtained numerically at control measuring points, and P1 and P10 are points of identification of the maximum numerical values of stress. In square brackets the values of three coordinates, i.e. x, y, z coordinates, are given.

Fig. 8 Reduction stress zones σ_{red} given in MPa for an axisymmetric perforated plate fixed and loaded with concentrated force P_i applied in the geometric center of the plate with the value $P_5 = 2510$ N: a) zone Z1: $\sigma_{red \max} = 102.56$ MPa; b) zone Z10: $\sigma_{red \max} = 241.9$ MPa

5 Experimental research

The aim of experimental research was to verify, i.e. assess the accuracy associated with solving a given design with respect to its strength. The basis for such an evaluation involves the study of the effect exerted on 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. As a result of these tests, it is possible to verify the results derived numerically.

The subject of the experimental research of the state of stress was a circular axisymmetric perforated plate, which geometry, i.e. the dimension, the method of restraint and the load method were outlined in section 2 of this paper. The strain gauges were stuck on the previously prepared plate surface at the points shown in Figure 9. Foil strain gauges type TF - 1/120, TFw - 2/120, TFP - 2/120 were used for the measurement of strains in the perforated plate. For

practical reasons, the strain gauges were placed in eight circles, meaning with radii $R_3, R_4, \dots, R_{10}$. Since the tested perforated plate was axially symmetric, the strain gauges were placed in the first and fourth quarter as shown in Figure 9.

Fig. 9 The arrangement of extensometers on a circular axisymmetric perforated plate - schematically (numbered 1-8) [12]

The perforated plate with the collocated strain gauges was subsequently mounted on a suitable annular support, concentric in relation to the loading mandrel of the strength test stand. A schematic of the plate mounting and the applied concentric load application P are shown in figure 10. In order to control the plate deflection, a dial gauge was used with an accuracy of 0.001 mm. The gauge was installed so that the axis of the gauge plunger coincided with the axis of the loading mandrel [9].

During the first stage of the study, a preload P_0 was applied to the perforated plate. This caused a preliminary deflection in the plate center, $f_0 = 1$ mm. This deflection corresponded to the force $P_0 = 570$ N. Having obtained the preliminary loading and deflection, the readings of the strain gauges were taken in each measuring region in radial and circumferential directions. Next, the plate was loaded with a force P_i , which caused the deflection $f_i = 1.5$ mm. The readings of the strain gauge were taken again and they were marked with the index “k” standing for the “final readings”. The value of force P_n and the ensuing deflection f_n were calculated from the relations:

$$P_n = P_i - P_0, \quad (1)$$

$$f_n = f_i - f_0, \quad (2)$$

where: n – successive natural numbers, i.e. 1, 2, 3, 4, 5; $i = I, II, III, IV, V$.

Fig. 10 A scheme of support of a circular axisymmetric perforated plate loaded with concentrated force P_i applied in the geometric center of the plate, where R_p - radius of supports distribution, h - plate thickness [12]

The successive loads applied by forces: $P_I, P_{II}, P_{III}, P_{IV}, P_V$ were used so as to obtain deflections equal to $f_{II} = 2 \text{ mm}$, $f_{III} = 2.5 \text{ mm}$, $f_{IV} = 3 \text{ mm}$, $f_V = 3.5 \text{ mm}$, respectively. In this case, loading values were $P_I = 410 \text{ N}$, $P_{II} = 875 \text{ N}$, $P_{III} = 1365 \text{ N}$, $P_{IV} = 1925 \text{ N}$, $P_V = 2510 \text{ N}$. The deformations of the perforated plate subjected to the above loadings were measured in the radial and circumferential directions, at points along the x - and y -axes. Finally, the strain gauge readings and the calculated radial and circumferential strains, ε_r and ε_θ , were used for the determination of the radial stresses σ_r and circumferential stresses σ_θ in the investigated perforated plate.

It was assumed that in the tested perforated plate, a plane stress state occurs. Having determined empirically the strains ε_r and ε_θ the principal stress components in the radial and circumferential directions, σ_r and σ_θ , were defined on the basis of the following relations [24]:

$$\sigma_\theta = \frac{E}{1-\nu^2} (\varepsilon_\theta + \nu \varepsilon_r), \quad (3)$$

$$\sigma_r = \frac{E}{1-\nu^2} (\varepsilon_r + \nu \varepsilon_\theta), \quad (4)$$

The reduced stress was determined using the relations:

$$\sigma_{red} = \sqrt{\sigma_r^2 + \sigma_\theta^2 - \sigma_r \sigma_\theta}, \quad (5)$$

6 Results of the research

Based on numerical calculations using the finite element method (FEM) and experimental research, the results that were obtained could be compared. Table 1 presents the values of reduced stresses σ_{red} in the zones of accumulated stresses for a circular axisymmetric perforated plate, free supported and loaded with concentrated force P_i applied in the geometric center of the plate, numerically and experimentally determined in eight measuring points and the difference between the results obtained methods $\delta\sigma_{red}$.

Table 1 The values of reduced stresses σ_{red} numerically and experimentally determined.

P_i [N]	σ [MPa]	R_n [mm]							
		33,0	40,5	49,0	60,0	72,5	88,0	107,5	130,5
410	σ_{red}^n	26.25	22.62	18.61	15.31	13.67	10.54	9.39	7.87
	σ_{red}^e	34.17	28.84	23.92	18.68	17.59	12.07	8.63	5.32
	$^{*)}\delta\sigma_{red} \%$	-30.17	-27.50	-28.53	-22.01	-28.68	-14.52	8.09	32.40
875	σ_{red}^n	56.03	48.29	39.72	32.66	29.18	22.50	20.06	16,82
	σ_{red}^e	72.07	60.31	50.71	39.25	33.71	25.37	17.97	12.62
	$^{*)}\delta\sigma_{red} \%$	-28.63	-24.89	-27.67	-20.48	-15.52	-12.76	10.42	24.97
1365	σ_{red}^n	87.41	75.33	61.96	50.96	45.52	35.10	32.29	26.23
	σ_{red}^e	102,25	88,09	17,96	59.22	47.27	37.02	27.73	18.65
	$^{*)}\delta\sigma_{red} \%$	-16.98	-16.94	-16.14	-16.21	-3.84	-5.47	14.12	28.90
1925	σ_{red}^n	123.28	106,23	87.38	71.86	64.19	49.51	44.13	37.00
	σ_{red}^e	131.18	113.22	93.26	75.45	58.42	47.79	38.79	27.40
	$^{*)}\delta\sigma_{red} \%$	-6.41	-6.58	-6.73	-2.00	8.99	3.47	12.10	25.95
2510	σ_{red}^n	160.74	138.51	113.93	93.97	83.70	64.55	57.54	48.24
	σ_{red}^e	160,03	138.62	114.62	93.18	73.17	59.52	55.62	36.14
	$^{*)}\delta\sigma_{red} \%$	0.44	-0.08	-061	0.55	12.58	7.79	3.34	25.08
$^{*)} \delta\sigma_{red} = \frac{\sigma_{red}^n - \sigma_{red}^e}{\sigma_{red}^n} * 100\%$									

In the case of a circular axisymmetrical perforated plate, free supported and loaded with concentrated force P_i applied in the geometric center of the plate, the obtained results of calculations indicate that the highest value of reduced stress σ_{red} at control measuring points occurred when the perforated plate was loaded with a concentrated force P_i with the value $P_5 = 2510$ N, both in the case of experimental calculations, as well as numerical calculations, which was $\sigma_{red}^e = 160.03$ MPa and $\sigma_{red}^n = 160.74$ MPa (Tab, 1). The relative difference, in this case, was 0.44%. Comparison of all results obtained experimentally with numerically calculated results showed that the maximum calculation error was less than 33%. It follows from the above that the numerical results obtained by the finite element method (FEM) for the case of perforated plates can be considered sufficiently accurate for engineering calculations.

Based on numerical calculations using the finite element method (FEM), the results that were obtained could be compared. Table 2 presents the values of reduced stresses σ_{red} in the zones of accumulated stresses for a circular axisymmetric perforated plate, free supported σ_{red}^S or fixed σ_{red}^F and a percentage difference between results obtained for these cases $\delta\sigma_{red}$ and loaded with concentrated force P_i applied in the geometric center of the plate.

Table 2 The values of reduced stresses σ_{red} numerically determined.

P_i [N]	σ [MPa]	R_n [mm]									
		22,5	27,5	33,0	40,5	49,0	60,0	72,5	88,0	107,5	130,5
410	σ_{red}^S	33.87	32.83	26.25	22.62	18.61	15.31	13.67	10.54	9.39	7.87
	σ_{red}^F	20.31	18.65	13.68	10.19	7.16	5.82	6.42	7.28	10.05	12.31
	$^*)\delta\sigma_{red} \%$	40.04	43.19	47.85	54.95	61.53	61.99	53.04	30.93	-7.03	-56.42
875	σ_{red}^S	72.29	70.08	56.03	48.29	39.72	32.66	29.18	22.50	20.06	16,82
	σ_{red}^F	43.34	39.82	29.23	21.76	15.30	12.41	13.70	15.54	21.46	26.27
	$^*)\delta\sigma_{red} \%$	40.05	43.18	47.83	54.94	61.48	62.00	53.05	30.93	-6.98	-56.18
1365	σ_{red}^S	112.77	109.33	87.41	75.33	61.96	50.96	45.52	35.10	32.29	26.23
	σ_{red}^F	67.61	62.12	45.60	33.94	23.87	19.37	21.37	24.25	33.48	40.98
	$^*)\delta\sigma_{red} \%$	40.05	43.18	47.83	54.94	61.48	61.99	53.05	30.91	-3.69	-56,23
1925	σ_{red}^S	159.04	154.18	123.28	106,23	87.38	71.86	64.19	49.51	44.13	37.00
	σ_{red}^F	95.35	87.60	64.31	47.86	33.66	27.31	30.14	34.20	47.22	57.79
	$^*)\delta\sigma_{red} \%$	40.05	43.18	47.83	54.95	61.48	62.00	53.05	30.92	-7.00	-56.19
2510	σ_{red}^S	207.37	201.03	160.74	138.51	113.93	93.97	83.70	64.55	57.54	48.24
	σ_{red}^F	124.33	114.22	83.85	62.41	43.89	35.61	39.30	44.59	61.57	75.35
	$^*)\delta\sigma_{red} \%$	40.04	43.18	47.84	54.94	61.48	62.00	53.05	30.92	-7.00	-56.20
$^*) \delta\sigma_{red} = \frac{\sigma_{red}^S - \sigma_{red}^F}{\sigma_{red}^S} * 100\%$											

However, based on numerical calculations using the finite element method (FEM), the results that were obtained could be compared. Table 3 presents the values of maximum reduced stresses $\sigma_{red max}$ in the zones of accumulated stresses for a circular axisymmetric perforated plate, free supported $\sigma_{red max}^S$ or fixed $\sigma_{red max}^F$ and loaded with concentrated force P_i applied in the geometric center of the plate.

Table 3 The values of maximum reduced stresses $\sigma_{red max}$ numerically determined.

P_i [N]	σ [MPa]	R_n [mm]									
		22,5	27,5	33,0	40,5	49,0	60,0	72,5	88,0	107,5	130,5
410	$\sigma_{red max}^S$	68.07	62.35	55.38	50.72	46.63	41.51	36.61	34.29	28.75	21.44
	$\sigma_{red max}^F$	39.51	37.98	34.30	28.35	25.61	19.61	15.92	9.98	12.58	16.75
875	$\sigma_{red max}^S$	145.33	133.07	118.20	108.26	99.53	88.59	78.15	73.20	61.36	45.76
	$\sigma_{red max}^F$	84.33	81.05	73.21	60.50	54.65	41.87	33.98	21.35	26.86	35.75
1365	$\sigma_{red max}^S$	226.72	207.59	184.39	168.88	155.27	138.20	121.91	114.19	95.72	71.39
	$\sigma_{red max}^F$	131.56	126.44	114.20	94.38	85.25	65.31	53.01	33.25	41.90	55.77
1925	$\sigma_{red max}^S$	319.73	292.76	260.04	238.16	218.97	194.89	171.92	161.03	135.00	100.68
	$\sigma_{red max}^F$	185.54	178.32	161.06	133.10	120.22	92.11	74.76	46.90	59.09	78.66
2510	$\sigma_{red max}^S$	416.79	381.73	339.06	310.54	285.51	254.12	224.17	209.97	176.02	131.28
	$\sigma_{red max}^F$	241.90	232.51	210.00	173.55	156.76	120.10	97.48	61.15	77.05	102.56

The boundary conditions of the perforated plate support have a significant influence on the distribution and values of stresses. The free support of the circular axisymmetric perforated plate on the whole circumference causes markedly increased values of the reduced stresses in relation to the perforated plate fixed on the entire circumference. In the case of free support of a circular axisymmetric perforated plate and loaded with a concentrated force P_i applied in the geometric center of the plate in the first zone Z1 with the radius of the hole $d_{I0} = 20.5$ mm and the radius of the circle on which the hole $R_{I0} = 130.5$ mm is located. The reduced stress σ_{red} was $\sigma_{red max} = 131.28$ MPa (Fig. 6a and Tab. 3) and in the tenth zone Z10 with the radius of the hole $d_I = 3.5$ mm and the radius of the circle on which the hole $R_I = 22.5$ mm is located (the nearest central part of the perforated plate) maximum value of the reduced stress σ_{red} was $\sigma_{red max} =$

416.79 MPa which is the most dangerous place in the plate (point with the coordinates x, y, z [mm], i.e. P10 [-69.9, 72.5; 0.0]), (Fig. 6b and Tab. 3). However, in the case of fixed the perforated plate in the first zone Z1 with the radius of the hole $d_{I0} = 20.5$ mm and the radius of the circle on which the hole $R_{I0} = 130.5$ mm is located, the maximum value of the reduced stress σ_{red} was $\sigma_{red\ max} = 102.56$ MPa (Fig. 8a and Tab. 3) and in the tenth zone Z10 with the radius of the hole $d_I = 3.5$ mm and the radius of the circle on which the hole $R_I = 22.5$ mm (the nearest central part of the perforated plate) the maximum value of the reduced stress σ_{red} was $\sigma_{red\ max} = 241.90$ MPa which is the most dangerous place in the plate (point with coordinates x, y, z [mm], i.e. P10 [1.71, 23.0; 0.0]), (Fig. 8b and Tab. 3). It follows from the above that not only the boundary conditions of the plate support have a significant influence on the distribution of stresses in the perforated plate, but also the diameter of the perforation hole. Significant values of reduced stress σ_{red} are usually the cause of the formation of microcracks in the area of the perforation hole. In the case of variable (fatigue) loads, microcracks start to develop and, as a consequence, they may lead to the destruction of the machine element or the construction element in which the perforated element occurs. In connection with the above, it is very important to determine the value and location of stress concentration in machine components containing the reasons for their occurrence. Numerical calculation of circular axisymmetric perforated plates using the finite elements method ones allow to get an exact distribution stresses on the entire tested surface, especially in areas holes where there are significant stress gradients.

CONCLUSION

The following conclusions can be drawn from the above analysis:

1. The present study has demonstrated that the way a circular axisymmetric perforated plate is loaded and the diameter of perforation has a significant impact on the distribution of stresses on the entire surface of the plate, in particular in the area of holes and on the bridges between the holes;
2. The most hazardous place in a circular axisymmetric perforated plate, free supported and loaded with concentrated force P_i applied in the geometric center of the plate with the highest stress concentration is located in zone Z10 with the hole radius $d_I = 3.5$ mm and the radius of the circle on which the hole $R_I = 22.5$ mm is located, the reduced stress is $\sigma_{red\ max} = 416.79$ MPa (point with the coordinates x,y,z [mm], i.e.. P10 [-69.9; 72.5; 0.0]), (Fig. 6b, zone Z10);
3. The most hazardous place in a circular axisymmetric perforated plate, fixed and loaded with concentrated force P_i applied in the geometric center of the plate with the highest stress concentration is located in zone Z10 with the hole radius $d_I = 3.5$ mm and the radius of the circle on which the hole $R_I = 22.5$ mm is located, the reduced stress is $\sigma_{red\ max} = 241.82$ MPa (point with the coordinates x,y,z [mm], i.e.. P10 [1.71; 23.0; 0.0]), (Figure 8b, zone Z10);
4. Maximum relative disaggregations expressed in terms of the values of reduced stresses σ_{red} obtained by the numerical method using the finite element method and the experimental method, in a circular axisymmetric perforated plate, with free edge support, did not exceed 33% in the present research.
5. The use of numerical methods (MES) leads to the development of topography of stress distribution over the entire surface of a perforated plate, in particular in the perforation holes area so as to offer details regarding the location of stress concentration zones.

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