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Determination of optimal parameters for perforated plates with quasi-triangular cutout by PSO

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Abstract. This study tries to examine the effect of different parameters on stress analysis of infinite plates with central quasi-triangular cutout using particle swarm optimization (PSO) algorithm and also an attempt has been made to introduce general optimum parameters in order to achieve the minimum amount of stress concentration around this type of cutout on isotropic and orthotropic plates. Basis of the presented method is expansion of analytical method conducted by Lekhnitskii for circular and elliptical cutouts. Design variables in this study include fiber angle, load angle, curvature radius of the corner of the cutout, rotation angle of the cutout and at last material of the plate. Also, diagrams of convergence and duration time of the desired problem are compared with Simulated Annealing algorithm. Conducted comparison is indicative of appropriateness of this method in optimization of the plates. Finite element numerical solution is employed to examine the results of present analytical solution. Overlap of the results of the two methods confirms the validity of the presented solution. Results show that by selecting the aforementioned parameters properly, less amounts of stress can be achieved around the cutout leading to an increase in load-bearing capacity of the structure.

Keywords: particle swarm optimization; infinite plates; quasi-triangular cutout; analytical solution

1. Introduction

Stress distribution intensity in areas of plate which have sudden changes in geometry is known as stress concentration. Stress concentration plays an important role in evaluating reliability of engineering structures. It is observed that 80 percent of failures in aircraft structures have happened in fastened joints having high stress concentrations (Gao, Xiao *et al*. 2014). Nowadays, design of metal and composite plates with cutouts is of a great importance due to their extensive application in different industries. For instance, designing vehicles with purpose of weight reduction in order to decrease fuel consumption and utilize engines with lesser powers are some applications of these plates. In this study according to the extensive usage of different types of

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cutouts and their applications in different industries and also long process of trial and error to find their optimum design, particle swarm optimization algorithm is employed for the integrity of the search process in obtaining the optimum and economic design. Savin (1961) performed some investigations on infinite isotropic plates with different cutouts and anisotropic plates with only elliptical and circular cutouts using complex variable method. Anisotropic plates with circular and elliptical cutouts were investigated by Lekhnitskii (1968). Rezaeepazhand and Jafari (2005, 2010), represented the analytical solution of isotropic and anisotropic plates with cutout using Savin's complex variable method and Lekhnitskii's expansion and by defining stress functions which satisfy compatibility equations. Batista (2011) investigated stress concentration around polygonal cutouts with rather complex geometries. Banerjee, Jain *et al*. (2013) studied stress distribution around circular cutout on isotropic and orthotropic plates under transverse loading using numerical method. They investigated effects of plate thickness, cutout diameter and materials on the amount of stress concentration in orthotropic plates.

Sivakumar, Iyengar *et al*. (1998) studied the optimization of laminate composites containing an elliptical cutout by genetic algorithm method. In this research design variables were the stacking sequence of laminates, thickness of each layer, the relative size of cutout, cutout orientation and ellipse diameters. The first and second natural frequencies were considered as cost function. Cho and Rowlands (2007) showed GA ability to minimization of tensile stress concentration in composite laminates containing cutout. In this study was used the genetic algorithm and developed finite element program. By using the finite element method, Liu, Jin *et al* (2006) investigated the optimization of the composite plates with multiple cutouts. At first, they considered the effect of the number of cutouts and cutout spacing relative to each other. The Tsai-Hill failure criterion for a composite plate was used to evaluate cost function. Sharma and Patel (2014) conducted the optimal design of the symmetrical laminates containing an elliptical cutout by using the genetic algorithm method. They obtained optimum fiber angle in symmetrical laminated composites with an elliptical cutout under in-plane loading conditions. Cost function was calculated by using the Tsai-Hill failure criterion. Design variables were stacking sequence of laminates. Zhu, He *et al*. (2015) considered the optimization of composite strut using the genetic algorithm method and Tsai-Hill failure criterion. Their attention was paid to minimize the weight of structure and increase buckling load. Fiber volume fraction and stacking sequence of laminates were considered as design variables.

In this research relying on Lekhnitskii's analytical solution and expanding this solution to the quasi-triangular cutout it is tried to introduce optimum values of the aforementioned parameters for uniaxial tensile loading in order to obtain the minimum normalized stress. It is worth mentioning that the normalized stress value around the cutout is considered as cost function (C.F.) for particle swarm optimization algorithm. Normalized stress is defined as the ratio of the maximum stress around the cutout to the applied stress.

2. Problem definition

A plate with a cutout in the center is available. Plate dimensions are very large compared to cutout dimensions (infinite plate). The plate is under uniaxial tensile loading at a distance from the cutout. Cutout can rotate relative to the *x*-axis. Stress-Strain relationship is linear. By applying boundary conditions ($\tau_{r\theta} = \sigma_r = 0$) the only stress induced around the cutout is σ_θ. According to Fig. 1, cutout is rotated equal to angle β relative to *x*-axis. The traction-free boundary conditions

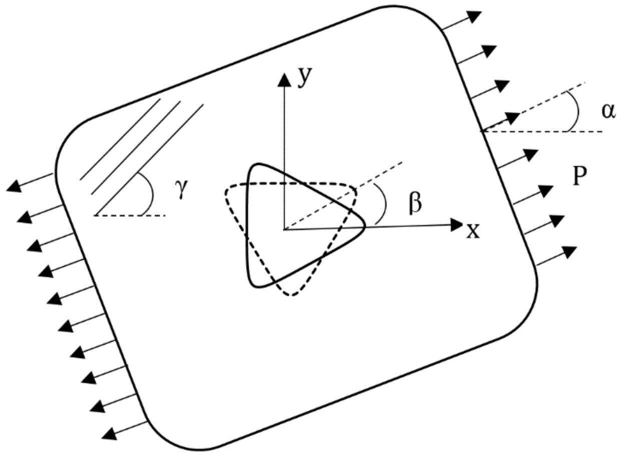


Fig. 1 Orthotropic perforated plate with central cutout

on the edge of the central cutout are assumed.

Analytical method used in this study is retrieved from expansion of analytical solution method by Savin (1961), Lekhnitskii (1968). In this method, stress function converts to an analytical expression with unknown coefficients. After determining the stress function, displacements and stresses can be calculated. Equilibrium equation will be satisfied by introducing $F(x,y)$ as stress function according to Eq. (1).

$$\sigma_x = \frac{\partial^2 F}{\partial y^2}$$
$$\sigma_y = \frac{\partial^2 F}{\partial x^2} \tag{1}$$
$$\tau_{xy} = -\frac{\partial^2 F}{\partial x \, \partial y}$$

By replacing stress-strain relations in compatibility relations and rewriting the resultant equation in terms of stress functions and with the assistance of Eq. (1) in absence of volumetric forces, according to Eq. (2) we will have (Lekhnitskii 1968)

$$R_{11}\frac{\partial^4 F}{\partial y^4} - 2R_{16}\frac{\partial^4 F}{\partial x\,\partial y^3} + (2R_{12} + R_{66})\frac{\partial^4 F}{\partial x^2\,\partial y^2} - 2R_{26}\frac{\partial^4 F}{\partial x^3\,\partial y} + R_{22}\frac{\partial^4 F}{\partial x^4} = 0 \tag{2}$$

Eq. (2) is compatibility equation for anisotropic material where R_{ij} are members of reduced stiffness matrix. Thus solving 2D elasticity problems will lead to presentation and solution of fourth-order differential equation which is expressed by four first-order linear derivative operator and for orthotropic material it is expressed as Eq. (3). Lekhnitskii proved that this characteristic equation associated with orthotropic material generally has four imaginary roots which are mutually conjugated.

$$R_{11}\mu^4 - 2R_{16}\mu^3 + (2R_{12} + R_{66})\mu^2 + 2R_{26}\mu + R_{22} = 0 \tag{3}$$

Characteristic equation shown in Eq. (2), for isotropic materials is in the form of Eq. (4). Eq. (4) contains two conjugated double roots ($\mu = \pm i$) where μ's are roots of the below equation.

$$R_{11}\mu^4 + (2R_{12} + R_{66})\mu^2 + R_{22} = 0 \tag{4}$$

Finally, stress components in terms of two potential functions of $\Psi(z_2)$ and $\varphi(z_1)$ are expressed according to Eq. (5) by Rezaeepazhand and Jafari (2005, 2010).

$$\begin{aligned} \sigma_x &= 2\mathrm{Re}[\mu_1{}^2\varphi'(z_1) + \mu_2{}^2\Psi'(z_2)] \\ \sigma_y &= 2\mathrm{Re}[\varphi'(z_1) + \mu_2{}^2\Psi'(z_2)] \\ \tau_{xy} &= -2\mathrm{Re}[\mu_1\varphi'(z_1) + \mu_2\Psi'(z_2)] \end{aligned} \tag{5}$$

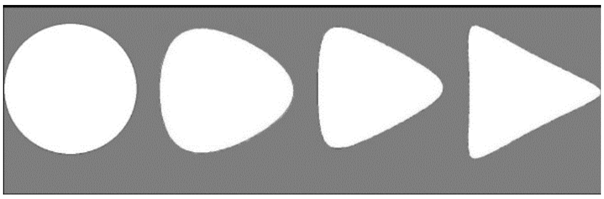
Where in the above equation Re [ ] indicates the real part of the expression inside the brackets and $z_i = x + \mu_i y, i = 1,2$.. $\Psi(z_2)$ and $\varphi(z_1)$ are arbitrary functions that are obtained by defining shape of the cutout and applying stress boundary conditions around the cutout. $\varphi'(z_1)$ and $\Psi'(z_2)$ are derivatives of $\varphi(Z_1)$ and $\Psi(Z_2)$ functions with respect to z_1 and z_2 respectively. Finally, σ_r ،σ_θ and $\tau_{r\theta}$ stresses can be obtained by transferring the Cartesian coordinates to polar coordinates system. As it was mentioned earlier; stress distribution around the circular cutout was investigated by Savin and Lekhnitskii using complex variable method. In order to expand their solution to other cutouts, points on boundary of the cutout with particular shape (contour) should be transformed outside the unit circle using a simple mapping function ($z_i = x + \mu_i y$) first, where x and y are obtained from Eqs. (6) and (7) by Rezaeepazhand and Jafari (2010).

$$\begin{aligned} x &= \lambda(\cos\theta + w.\cos(n\theta)) \\ y &= -\lambda(\sin\theta + w.\sin(n\theta)) \end{aligned} \tag{6}$$

In the above equation, there are different parameters that various cutouts could be modeled by changing them, *n* shows geometry of the cutout; in a way that *n* equal number of cutout sides minus 1. λ shows that how large is the cutout. In the above equation, for quasi-triangular cutout with sides of equal length (equilateral) *n* should be equal to 2. *w* is a measure of cutout sharpness or softness. Effect of the amount of *w* on shape of triangular cutout is shown in Fig. 2, according to this figure for a triangular cutout when *w* decreases, corners of the cutout become smoother until *w* reaches its minimum value, (becomes zero), in this case, cutout converts to a circle.

3. Particle swarm optimization

Particle swarm optimization algorithm is an optimization technique based on laws of probability which the basic idea of it was presented by Eberhart, computer scientist and James



w=*0* *w*=0.1 *w*=0.2 *w*=0.3

Fig. 2 Effect of *w* on the cutout geometry ($\lambda = 1$)

Kennedy, psychologist of social issues at 1995. This algorithm uses bird social behavior while searching for food to guide bird flocks to the promising area in the search space. For this purpose series consisting of a set of particles are formed that each particle is representative of a bird in the search space. Aim of this technique is to find a place having the best fitness value in the search space. This fitness value has a direct impact on direction and velocity of movement of these birds (problem answers) toward location of food (optimum answer). This algorithm starts to work with a number of initial answers which are determined randomly, and it looks to find an optimum answer by moving these answers through consecutive iterations. In each iteration, position of each particle in the search space is determined based on the best position obtained by itself and the best position obtained by the whole particles during the searching process. In each iteration, each particle updates its position and velocity as in Eq. (7) by Yang, Yuan *et al*. (2007).

$$\begin{gathered} V_i(t+1) = \omega V_i(t) + r_1 c_1 \big(p_i - x_i(t)\big) + r_2 c_2 \left(p_g - x_i(t)\right) \\ X_i(t+1) = X_i(t) + v_i(t+1) \end{gathered} \tag{7}$$

Where $V_i(t+1)$ and $X_i(t+1)$ are velocity and position of the particle respectively in the new iteration. $V_i(t)$ and $x_i(t)$ are current velocity and position of the particle respectively, ω is weight factor, c_1 is personal learning factor, c_2 is collective learning factor and r_1 and r_2 are random numbers between zero and one. P_i is particle's best performance itself, and P_g is the best position achieved among all particles. Choosing the appropriate values for c_1, c_2 and ω results in an acceleration in convergence and leads to find the absolute optimum and prevents premature convergence in local optimizations. Here c_1 and c_2 parameters update as in Eq. (8) that described by Ratnaweera, Halgamuge *et al*. (2004). Where $c_{1,f}$,$c_{2,f}$,$c_{1,i}$ and $c_{2,i}$ are constant values. Also, Eq. (9) is considered by Ratnaweera, Halgamuge *et al*. (2004) for ω operator which ω_i and ω_f are initial and final values of weight factor respectively. iter is the number of particle's current iteration and maxiter is the number of the greatest iteration.

$$\begin{gathered} c_1(t) = \left(c_{1,f} - c_{1,i}\right)\frac{\text{iter}}{\text{maxiter}} + c_{1,i} \\ c_2(t) = \left(c_{2,f} - c_{2,i}\right)\frac{\text{iter}}{\text{maxiter}} + c_{2,i} \end{gathered} \tag{8}$$

$$\omega = (\omega_i - \omega_f)\left(\frac{\text{maxiter}-\text{iter}}{\text{maxiter}}\right) + \omega_f \tag{9}$$

4. Simulated annealing

Simulated annealing is a method based on calculations which tries to solve complicated problems and find appropriate answers through randomized controlled selection technique. Algorithm of this technique which is based on Metropolis criteria, was first presented by Kirkpatrick *et al*. in 1983. Since then, this algorithm was widely used in many optimization problems by Geng, Xu *et al*. (2007). As a beginning SA algorithm starts with an initial solution and then in an iteration loop it moves toward the neighboring solutions. If the neighboring solution is better than the current solution, algorithm replaces it as the new current solution, otherwise, algorithm admits that solution with Boltzmann probability function from a random number between 0 and 1 as the current solution according to Eq. (10).

$$\exp\left(-\frac{\Delta \mathrm{f}}{\mathrm{T_i}}\right) \geq \mathrm{rand} \tag{10}$$

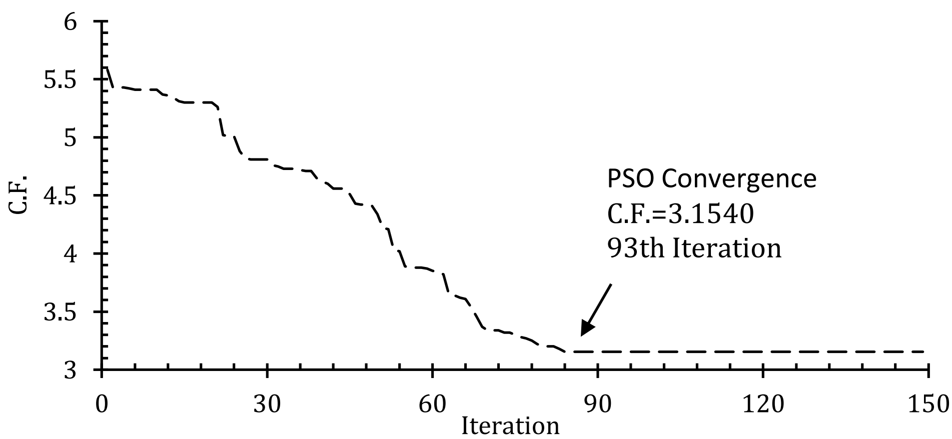
Where Δf is difference of fitting functions of the answers, T_i is temperature at iteration i and rand is a random number between zero and one. Algorithm stop condition was set to reach the temperature of $T_k = 10^{-4}$ or 1000 iterations, and initial temperature was chosen equal to 100. At each temperature, several iterations run and then the temperature decreases slightly. In first steps temperature is set to be very high in order to be more likely to accept worse solutions. With the gradual reduction of temperature, final steps will be less likely to accept worse solutions and thus the algorithm will converge to a good solution.

5. Testing convergence

The constraints contain upper and lower boundaries which can be changed based on shape of the cutout. For the quasi-triangular cutout, range of constraints is as in Eq. (11).

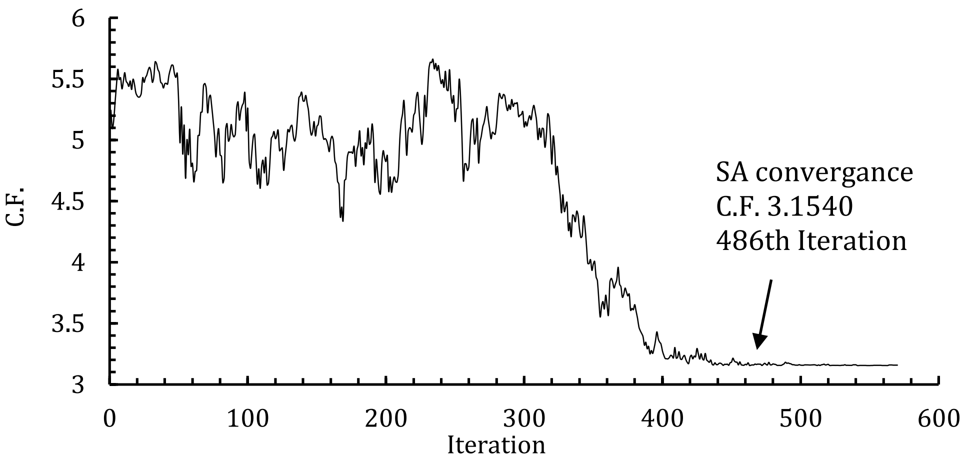
$$0 < \alpha < 90\,; 0 < \beta < 180\,;\; 0 < \gamma < 90\,; 0 < \mathrm{w} < 0.5 \tag{11}$$

Fig. 3 shows convergence diagrams for PSO and SA algorithms respectively for Glass/Epoxy composite plate in one of the optimum conditions of (w=0.1 α=30). In Fig. 3, in addition to viewing the convergence for the intended condition, it can be seen that PSO algorithm at almost iteration 93th and SA algorithm at 500th iteration remains constant permanently for previous and further successive generations. Also, duration of problem solving of these two algorithms was compared to each other and after several runs it turned out that PSO algorithm is capable of finding the absolute optimum value in a very short time compared to SA algorithm.



(a)

Fig. 3 Convergence diagram (a) PSO method (b) SA method



(b)

Fig. 3 Continued

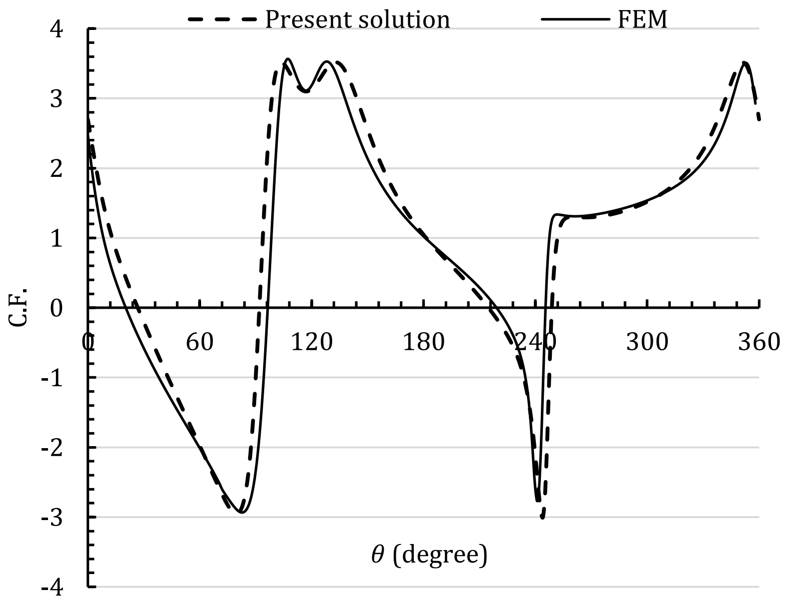


Fig. 4 Comparison of FEM and present solution for Boron/Epoxy (w=0.15)

6. Solution verification

In order to examine results obtained from the present optimization method, finite element method (ABAQUS software) was employed. For this purpose, first, using PSO program code, optimum parameters associated with quasi-triangular cutout were determined for a specific material. Then the cutout geometry was modeled in accordance with optimum parameters obtained from program execution in ABAQUS software. In order to achieve optimum mesh number and

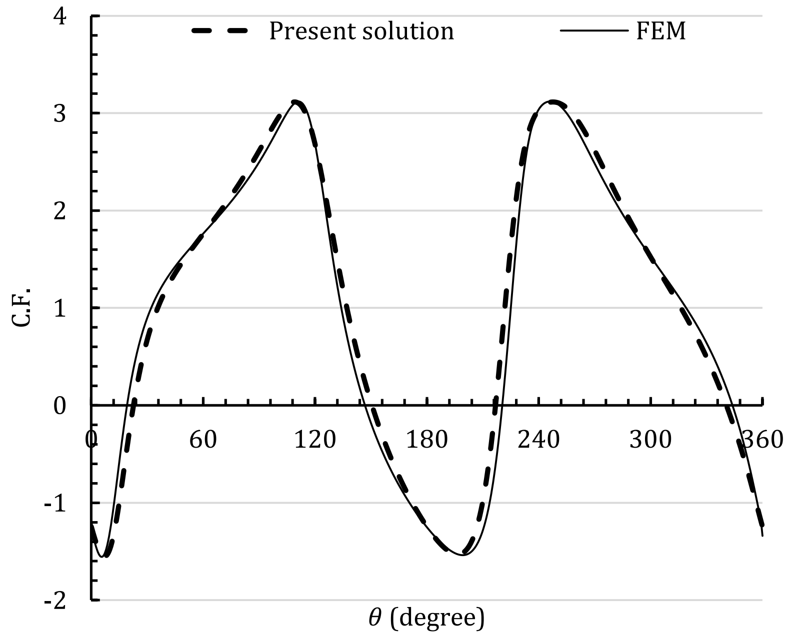


Fig. 5 Comparison of FEM and present solution for Glass/Epoxy (w=0.15)

Table 1 Material properties of the plate. Rezaeepazhand and Jafari (2005, 2010)

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	v_{12}	Material
47.4	16.2	7	0.26	Ce9000 Glass/Epoxy
207	207	79.3	0.3	Steel
294	6.4	4.9	0.23	GY-70/934 Carbon/Epoxy
204	18.5	5.59	0.23	Boron/Epoxy

increased accuracy in results obtained from finite element numerical solution, meshing was finer around the cutout than external boundaries of the plate. Comparison of the obtained values of the cost function from analytical solution method in this case and numerical solution in one of the optimized cases of ($\alpha = 0°, \beta = 53°, \gamma = 69.6°$) for Boron/Epoxy material is shown in Fig. 4. Also, Fig. 5 displays results of optimum mode ($\alpha = 0°, \beta = 0°, \gamma = 68.6°$) obtained by two analytical and numerical methods for Glass/Epoxy material. Angle of θ, specifies angle of points on the edge of the cutout with respect to horizontal axis. It can be seen that results of two methods are close to each other in Fig. 5 and Fig. 6 and this confirms validity of presented results.

7. Results

Mechanical properties used in this study are presented in Table 1. According to the fact that in isotropic materials, the type of material doesn't affect stress concentration, only results associated with steel are presented. Therefore, it is first tried to examine optimum values of other design parameters and minimum amount of stress distribution around the cutout in each loading angle,

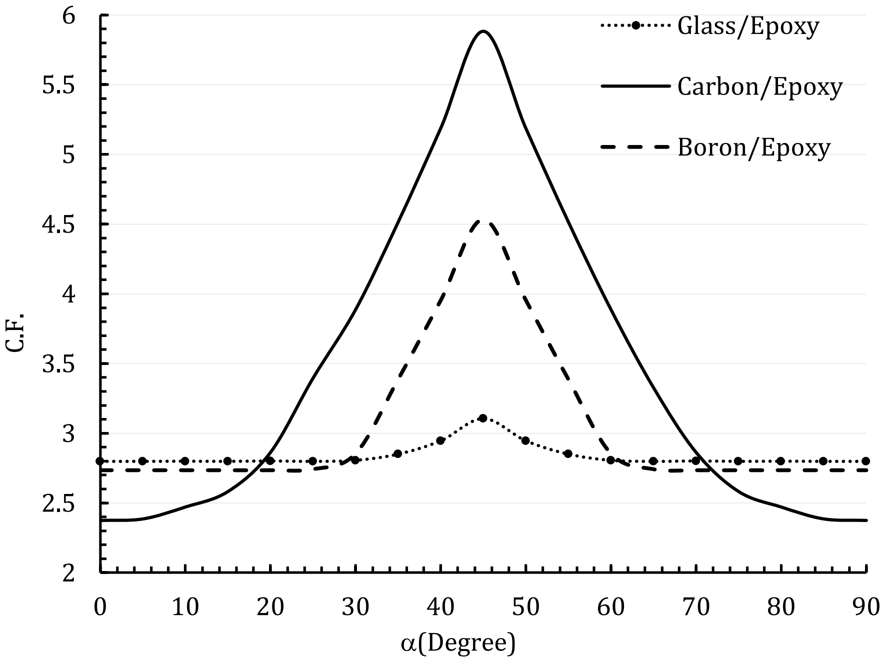


Fig. 6 Variation of the cost function with load angle in optimum rotation and fiber angles (Orthotropic plate)

Table 2 Optimum values of different parameters for Glass/Epoxy (in Degree)

w=0.05					*w*=0				
C.F.	β	$\lvert\alpha-\gamma\rvert$	γ	α	**C.F.**	β	$\lvert\alpha-\gamma\rvert$	γ	α
2.8060	0-60-120-180	62.7	62.7	0	2.6595	-	59.4	59.4	0
2.8060	33.5-93.5-153.5	60	90	30	2.6595	-	59.3	89.3	30
3.1051	30-90-150	45	0	45	2.6595	-	45	90	45
	0-60-120-180		90			-			
2.8060	56.5-116.5-176.5	60	0	60	2.9595	-	59.4	0.6	60
2.8060	30-90-150	62.5	27.5	90	2.6595	-	59.5	30.5	90
w=0.15					*w*=0.1				
C.F.	β	$\lvert\alpha-\gamma\rvert$	γ	α	**C.F.**	β	$\lvert\alpha-\gamma\rvert$	γ	α
3.5821	0-60-120-180	68.8	68.8	0	3.1147	0-60-120-180	66.3	66.3	0
3.6647	35.5-95.5-155.5	60	90	30	3.1540	35-95-155	60	90	30
3.9289	31-91-151	45	0	45	3.1540	30-90-150	45	0	45
	59-119-179		90			0-60-120-180		90	
3.6638	54.5-114.5-174.5	60	0	60	3.1537	55.5-115.5-175.5	60	0	60
3.5790	30-90-150	68	22	90	3.1145	30-90-150	66	24	90

using PSO algorithm, for an anisotropic infinite plate containing a particular cutout.

Fig. 6 shows the effects of loading angle on amount of cost function by considering fiber angles and cutout orientation simultaneously as design variables for the discussed three types of anisotropic materials with w=0.05. Values of Fiber angle and rotation angle in this case, are optimum values obtained by PSO algorithm. According to the above figure, for all used materials,

Table 3 Optimum values of different parameters for Carbon/Epoxy (in Degree)

w=0.05					*w*=0				
C.F.	$\boldsymbol{\beta}$	$\boldsymbol{\lvert\alpha-\gamma\rvert}$	$\boldsymbol{\gamma}$	$\boldsymbol{\alpha}$	**C.F.**	$\boldsymbol{\beta}$	$\boldsymbol{\lvert\alpha-\gamma\rvert}$	$\boldsymbol{\gamma}$	$\boldsymbol{\alpha}$
2.3747	0-60-120-180	90	90	0	2.2614	-	90	90	0
3.8870	2-62-122	60	90	30	3.7551	-	60	90	30
5.8798	20-80-140	45	0	45	5.6833	-	45	0	45
	10-70-130		90			-			
3.8867	28.3-88.3-148.3	60	0	60	3.7554	-	60	0	60
2.3747	30-90-150	90	0	90	2.2614	-	90	0	90
w=0.15					*w*=0.1				
C.F.	$\boldsymbol{\beta}$	$\boldsymbol{\lvert\alpha-\gamma\rvert}$	$\boldsymbol{\gamma}$	$\boldsymbol{\alpha}$	**C.F.**	$\boldsymbol{\beta}$	$\boldsymbol{\lvert\alpha-\gamma\rvert}$	$\boldsymbol{\gamma}$	$\boldsymbol{\alpha}$
3.0653	0-60-120-180	90	90	0	2.6500	0-60-120-180	90	90	0
5.0236	1-61-121	60	90	30	4.2929	1.5-61.5-121.5	60	90	30
7.5858	20.7-80.7-140.7	45	0	45	6.4920	20.2-80.2-140.2	45	0	45
	9.3-69.3-129.3		90			9.8-69.8-129.8		90	
5.0193	29-89-149	60	0	60	4.2944	28.6-88.6-148.6	60	0	60
3.0652	30-90-150	90	0	90	2.6499	30-90-150	90	0	90

Table 4 Optimum values of different parameters for Boron/Epoxy (in Degree)

w=0.05					*w*=0				
C.F.	$\boldsymbol{\beta}$	$\boldsymbol{\lvert\alpha-\gamma\rvert}$	$\boldsymbol{\gamma}$	$\boldsymbol{\alpha}$	**C.F.**	$\boldsymbol{\beta}$	$\boldsymbol{\lvert\alpha-\gamma\rvert}$	$\boldsymbol{\gamma}$	$\boldsymbol{\alpha}$
2.7347	51.7-111.7-171.7	65.15	65.15	0	2.5656	-	62	62	0
2.8875	0-60-120-180	60	90	30	2.7614	-	60	90	30
4.5328	20-80-140	45	0	45	4.3864	-	45	90	45
	10-70-130		90			-			
2.8533	28.8-88.8-148.8	60	0	60	2.7614	-	60	0	60
2.7350	38.3-98.3-158.3	65.15	24.85	90	2.5656	-	62	28	90
w=0.15					*w*=0.1				
C.F.	$\boldsymbol{\beta}$	$\boldsymbol{\lvert\alpha-\gamma\rvert}$	$\boldsymbol{\gamma}$	$\boldsymbol{\alpha}$	**C.F.**	$\boldsymbol{\beta}$	$\boldsymbol{\lvert\alpha-\gamma\rvert}$	$\boldsymbol{\gamma}$	$\boldsymbol{\alpha}$
3.5159	53-113-173	69.6	69.6	0	3.0484	52.5-112.5-172.5	67.5	67.5	0
3.7548	0-60-120-180	59.2	89.2	30	3.2197	2.4-62.4-122.4	60	90	30
5.7218	21-81-141	45	0	45	4.9727	20.5-80.5-140.5	45	0	45
	10-70-130		90			9.5-69.5-129.5		90	
3.7596	28-88-148	60	0	60	3.2120	27.5-87.5-147.5	60	0	60
3.5156	37-97-157	69.6	20.4	90	3.0484	37.5-97.5-157.5	67.5	22.5	90

the maximum value of the cost function occurs at loading angle of 45°, and Carbon/Epoxy material has the highest amount of stress amongst the three others. Tables 2 to Table 4 show optimum values of rotation angle (β), fiber angles (γ) and minimum normalized stress corresponding to each loading angle (α) in different values of bluntness parameters. As it can be seen for this case in w=0 which is representative of circular cutout, we will have the minimum amount of cost function for all of the materials and the lowest amount of it, is equal to 2.2614 which belongs to Carbon/Epoxy material. By increasing w, cost function value increases.

Also Table 5 shows overall optimum results for the isotropic material. In this case for different values of w, optimization process takes place for design variables of loading angle and rotation

Table 5 Optimum values of different parameters for isotropic plate

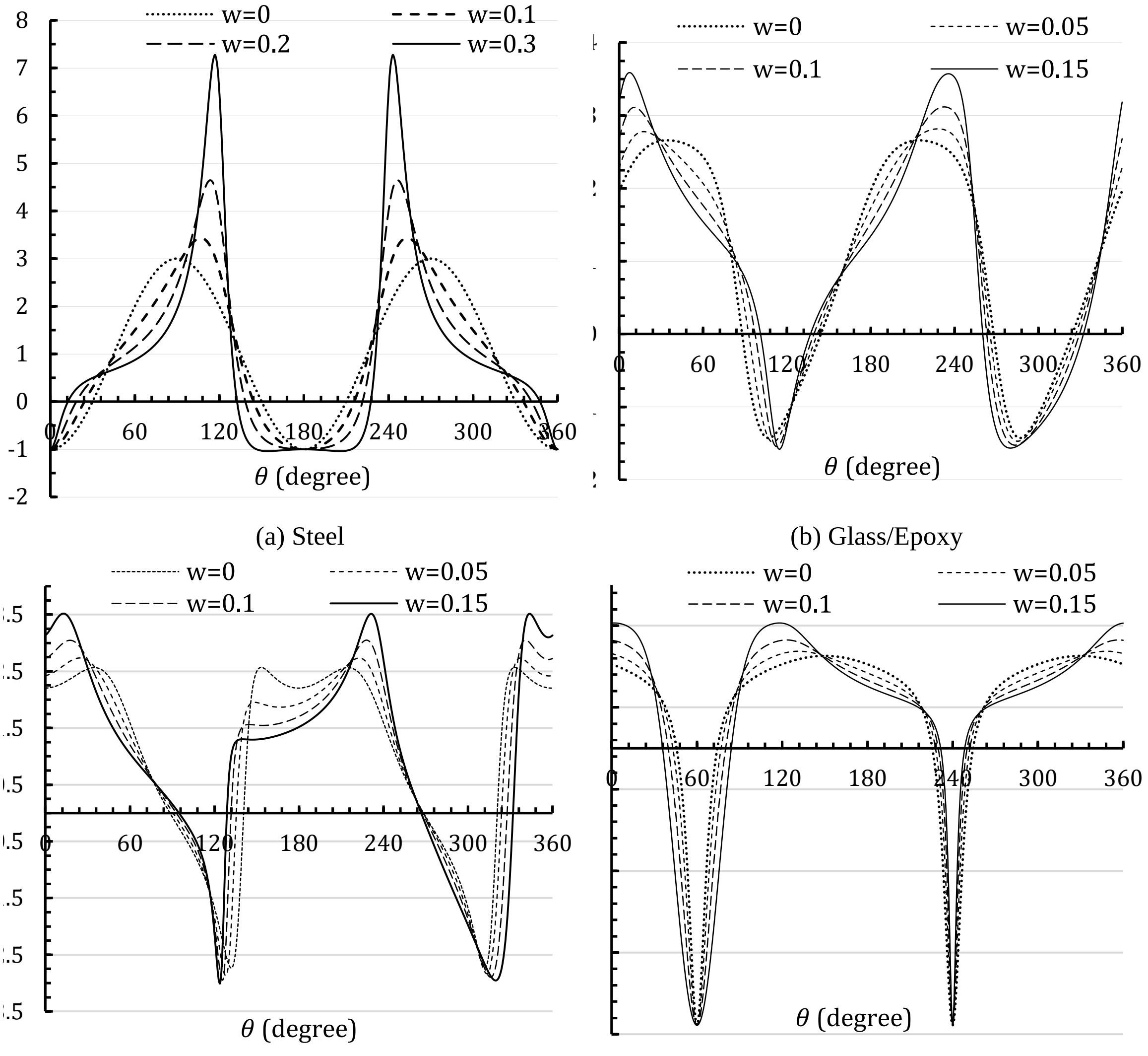
$\|\alpha-\beta\|$	C.F.	β	α	No. of program run	w
-	3.0022	-	-	1	0 (Optimum)
60	3.1132	94.5	34.5	1	
60	3.1127	110.64	50.64	2	
180	3.1175	180	0	3	0.05
0	3.1125	44.94	44.94	4	
60	3.1126	101.5	41.5	5	
180	3.4326	180	0	1	
60	3.4308	73.2	133.2	2	
0	3.4326	42.11	42.11	3	0.1
60	3.4374	105	45	4	
120	3.4326	120	0	5	
60	3.9238	110.11	50.11	1	
120	3.9238	167.2	47.2	2	
0	3.9187	45	45	3	0.15
180	3.9237	180	0	4	
60	3.9195	115.77	55.77	5	
180	4.6472	180	0	1	
60	4.6472	0	60	2	
120	4.6472	172	52	3	0.2
0	4.6472	0	0	4	
60	4.6472	27	87	5	

angle. As it can be seen, in w=0 which is representative of circular cutout, we will have the minimum cost function value which is equal to 3. Presented results were sorted out based on specific curvatures to determine relations between loading angle and rotation angle for the quasi-triangular cutout. In this case, for this type of cutout for every executions of PSO algorithm, different values for loading and rotation angles are obtained. Although these are angles of different values, but absolute difference between cutout rotation angle and loading angle displays specific values. In other words, according to this table, absolute differences at angles of 0, 60, 120 and 180 degrees, have allocated the minimum values of cost function to themselves that means that, this process with 60 degree period repeats for this cutout. Finally, trend of cost function changes in different curvatures and in optimum conditions for anisotropic and isotropic materials in the case that absolute difference of rotation angle and loading angle is 180 degrees (ratio of angles in an optimized mode) is shown in Fig. 7.

8. Conclusions

In this study using particle swarm optimization algorithm, optimum parameters affecting normalized stress around quasi-triangular cutout at different loading angles located in orthotropic plates and also overall optimum parameters in isotropic plates containing this type of cutout were determined. Design variables in this study are loading angle, rotation angle, fiber angle and curvature of the corner of cutout.

Desired cost function of this study, was extended to quasi-triangular cutout using conformal



(a) Steel (b) Glass/Epoxy

(c) Boron/Epoxy (d) carbon/Epoxy

Fig. 7 Variations of cost function in optimal mode

and complex variable mapping, based on Lekhnitskii's solution which was only for circular and elliptical cutouts. Finite element method was employed to verify presented solution results; comparison of results of the two methods confirms validity of presented outcomes. Results revealed that radius of curvature of cutout corners is not the only effective parameter on stress concentration reduction, but also proper rotation angle of the cutout, loading angle and fiber angle affect this stress reduction significantly. By selecting optimum values of mentioned parameters in a specific curvature, stress concentration can be decreased significantly. Because in present optimizing problem, the overall optimum value is not specified, applied optimization program was repeated several times for successive generations or was compared with other programs. Therefore, in this study convergence and solution duration of the problem in particle swarm algorithm were compared with simulated annealing algorithm; results were indicative of high efficiency and output of particle swarm algorithm compared to simulated annealing algorithm.

References

Batista, M. (2011), "On the stress concentration around a hole in an infinite plate subject to a uniform load at infinity", *Int. J. Mech. Sci*., **53**, 254-61.

Banergee, M., Jain, N.K. and Sanyal, S. (2013), "Stress concentration in isotropic & orthotropic composite plate with center circular hole subjected to transverse static loading", *Int. J. Mech. Ind. Eng*., **3**,109-13.

Cho, H.K. and Rowlands, R.E. (2007), "Reducing tensile stress concentration in perforated hybrid laminate by genetic algorithm", *Compos. Sci. Technol*., **67**, 2877-83.

Gao, C.Y., Xiao, J.Z., Ke ,Y.L. (2013), "FE analysis of stress concentrations in composite plates with multiple holes for zigzag multi-fastened joints", *Mater. Sci. Forum*, **770**, 17-20.

Geng, X., Xu, J., Xiao, J. and Pan, L. (2007), "A simple simulated annealing algorithm for the maximum clique problem", *Inf. Sci.*, **177**, 5064-71.

Kennedy, J. and Eberhart, R. (1995), "Particle swarm optimization", *Proc. ICNN'95 - Int. Conf. Neural Networks*, **4**, 1942-8, doi:10.1109/ICNN.1995.488968.

Lekhnitskii, S.G. (1968), Anisotropic Plates. Gordon and Breach Science Publishers;.

Liu, Y., Jin, F. and Li, Q. (2006), "A strength-based multiple cutout optimization in composite plates using fixed grid finite element method", *Compos. Struct*., **73**, 403-12.

Savin, G. (1961), *Stress Concentration Around Holes*, Oxford Pergamon Press.

Ratnaweera, A., Halgamuge, S.K, and Watson, H.C. (2004), "Self-organizing hierarchical particle swarm optimizer with time-varying acceleration coefficients", *IEEE Tran. Evol. Comput*., **8**, 240-55.

Rezaeepazhand, J. and Jafari, M. (2005), "Stress analysis of perforated composite plates", *Compos. Struct*. **71**, 463-8.

Rezaeepazhand, J. and Jafari, M. (2010), "Stress concentration in metallic plates with special shaped cutout", *Int. J. Mech. Sci*., **52**, 96-102.

Sharma, D.S. and Patel, N.P. (2014), "Trivedi RR optimum design of laminates containing an elliptical hole", *Int. J. Mech. Sci*., **85**, 76-87.

Sivakumar, K., Iyengar, N.G.R. and Deb, K. (1998), "Optimum design of laminated composite plates with cutouts using a genetic algorithm", *Compos, Struct*., **42**, 265-79.

Yang, X., Yuan, J., Yuan, J. and Mao, H. (2007), "A modified particle swarm optimizer with dynamic adaptation", *Appl. Math. Comput*., **189**, 1205-13.

Zhu, X., He, R., Lu, X., Ling, X., Zhu, L. and Liu, B. (2015), "A optimization technique for the composite strut using genetic algorithms", *Mater. Des*., **65**, 482-8.

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