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Sensitivity Analysis of Perforated Plate using Design of Experiments for Weight Optimization

Sujith Kumar C
M.E. (Design) Mechanical Engineering Department
Vishwakarma institute of technology
Pune, India

Prof. Dr. M.V.Walame
Mechanical Engineering Department
Vishwakarma institute of technology
Pune, India

***Abstract* - In today's world, speed to market and cost are major drivers for every product development process in an organization. Utilization of tools like Design of experiments, Topology optimization combined with finite element analysis will help in reducing the complexity, cost and product life cycle of structural components without compromising the structural strength. Perforated plates have found variety of applications in structural members and various studies have been conducted on perforated plate with lateral load and effect of cut out shapes on the strength. As the cutouts in such plates induces stress concentration, it is important to study the effect of parameters like plate thickness, hole diameter, spacing of perforation on the strength of these plates. The objective is to study the effect of mainly three parameters, hole diameter, plate thickness and hole pattern on stress. Design of experiment methodology is applied to list out all possible combinations for these parameters. FEA results for all 144 combinations is analyzed and experimental verification is done for 3 combinations. From the results of DOE and Finite element analysis, a generalized equation was established correlating effects of hole diameter, plate thickness, hole pattern for sensitivity analysis. It is found that plate thickness has major effect on stress and deformation followed by hole spacing in direction perpendicular to bolting face. The effect of hole diameter is minimal.**

Keywords—Perforated Plate; Design Of Experiments; Stress Analysis; Sheetmetal; Optimization

1. INTRODUCTION

Structural optimization [1] has gained high prominence in recent years, thereby increasing need for lightweight structures without compromising the structural efficiency. One such structural member is perforated sheet metal plates. These plates are easily manufactured and are widely used in many engineering applications such as platforms in various agricultural and earth moving machines, offshore platforms, ship decks and hulls, box sections of bridge girders and air craft industries. There is an often need for cut-outs in plates for services, dirt drain, inspections, maintenance and majority of times to reduce weight of structure.

The presence of holes on the plate changes the stress distribution and cause reduction in its strength [2] [3]. Hence proper combination of hole size, plate thickness, hole spacing is crucial in maintaining the strength of the plate.

In this study a typical perforated plate to be used in stairs of an agricultural machinery is studied. Design of Experiment is used to identify the important interactions of plate thickness, hole size and hole spacing on perforated plate, effect of them on strength and specimen selection for performing detailed FEA and experiment.

2. LITERATURE SURVEY

Various studies have been carried out related perforated plate with lateral loads as well as axial loads.

Jae-Hoon Kang[4] investigated Exact solutions for stresses, strains, and displacements of a perforated rectangular plate by a central circular hole subjected to linearly varying in-plane normal stresses on two opposite edges by two-dimensional theory of elasticity using the Airy stress function.

M. Aydin Komur [2] investigated the elasto-plastic buckling behavior of simply supported square and rectangular thin steel plates having elliptic cut-outs.

Jinho Woo [5] investigated stress concentration of perforated plates with cur out, orientation of cut out and bluntness.

EmanueleMaiorana [6] analyzed linear buckling of square and rectangular plates with circular and rectangular holes in various positions subjected to axial compression and bending moment.

D.B.Kawadkar [7] studied the stress concentration in plate with various cutouts and bluntness with different cutout orientation.

J. Rezaeepazhand [8] conducted analytical stress analysis of plates with different central cutout. Particular emphasis was placed on flat square plates subjected to a uni-axial tension load.

Venkatachalam G. [9] investigated the influence of holes on the flexural strength of Aluminium 8090 alloy sheets. They carried out various experiments to study the influence of hole size, % of open area and hole arrangement pattern.

O.R. Nandagopan [10] investigated perforated plate with lining to determine the static deflection of the plate.

Very less references is found for effects of perforated plate parameters when vertical loaded.
Application of design of experiments on sheet metal plate optimization.

3. DESIGN OF EXPERIMENTS AND PARAMETERS OF PERFORATED PLATE

Experiment is an integral part of optimization. Experiments are performed in all fields and are used to study the performance of processes and systems [11].

One of the issue in the conventional CAD based design development is that the number of iterations required for finalizing the design in which each iterations output of finite element analysis. In addition the time taken for actual testing considering all variables. The impact is time consuming and high process cost.

DOE techniques provide guidance to choose the experiments to be performed in an efficient way [12] and hence the technique is utilized in this study to minimize the experimental specimens to three from the available combinations.

The objectives of the experiment include: determining the variable that has highest influence on response, determining where to set the influential controllable variables so that the response is almost always near the desired optimal value, which in turn will result in minimizing the variations in response and the effect of uncontrollable variables.

Perforated sheet metal plates has manually or mechanically punched holes where the hole shapes can be round, square, triangle, diamond, oval, hexagonal etc. It is generally advisable to have the hole size larger than material thickness.

The parameter that effects the stress and deformation of a perforated plate are: Plate thickness, Hole size, Pattern (Linear or scattered), Pitch (distance between the hole centers), Open area (total area of holes divided by total area of sheet), Margins (blank area along the edges of the sheet), Material property, Manufacturing process.

4. GEOMETRY AND MATERIAL PROPERTIES

Geometry of the specimen for study is shown in Fig 1
Assumptions (based on practical application):

- Plates size 250mm x 250 mm
- Hole pattern is square
- Bolted on two sides

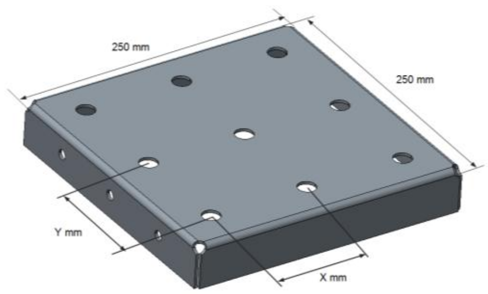

Fig. 1. Geometry

Material properties:
The material specifications of the specimen is listed in table 1 [13].

TABLE I. MATERIAL DATA

Material	MS IS 513 CR2
Yield Stress	240Mpa
Density	7.85e-6 kg/mm^3
Modulous of elasticity	210GPA
Poisons's ratio	0.3

Load:
General weight for large operator 114.1Kg [14] with a bag of seed 25Kg.

Design load considered is 278 Kg (2724N) (including factor of safety-2) [15].

5. FINITE ELEMENT MODELING

Ansys 16.2 is used to carry out finite element analysis and design of experiments [16].

5.1. Finite element modeling:
Meshing element type is 4 node quad shell 181
Mesh size is 1mm
Node population count 186932
Element population count 92331
Design load of 2724 N applied centrally on a surface of 145mm diameter
Load Behavior is taken as Rigid which resembles the practical case.
Boundary condition- blotted on two faces with three bolts and hence the holes surfaces were fixed.
Figure 2 shows the distribution of stress in perforated plate.

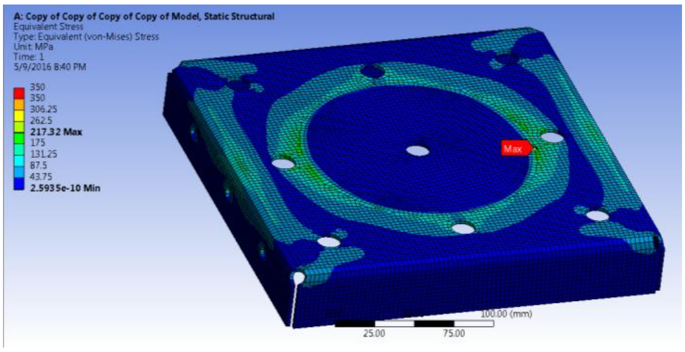

Fig. 2. FEA model set up

Strain gauge location is picked on the basis of vector principal strain direction shown in figure 3.The maximum strain location happens to be at the point below the load which is impractical to gauge. So the next high strain area (close to bolted side) was chosen as gauge location for correlation.

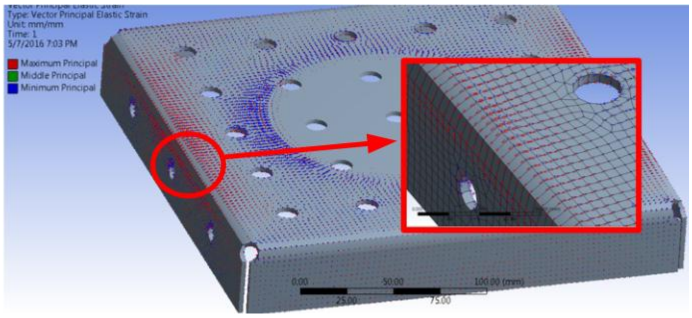

Fig. 3. Vector principal strain direction

5.2. DOE set up:
The parameters and their range considered in the study are shown below
Input parameters: Plate thickness-2, 2.5, 3, 4 mm, Hole spacing in X direction-40, 70, 90 mm, Hole spacing in Y direction-40, 70, 90 mm, Hole diameter-12,16,20,24mm
Output Parameter: Mass (Kg), Maximum equivalent stress (Mpa), Strain (µstrain), Deformation (mm).
Input/output parameters and resulting design point example is shown in figure 4 and 5.

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Outline of Schematic A8: Parameters

	A	B	C	D
1	ID	Parameter Name	Value	Unit
2	Input Parameters			
3	Copy of Copy of Copy of Copy of Model, Static Structural (A1)			
4	P27	thickness1	2.5	mm
5	P28	X	90	mm
6	P29	Y	90	mm
7	P30	dia	16	mm
*	New input parameter			
9	Output Parameters			
10	Copy of Copy of Copy of Copy of Model, Static Structural (A1)			
11	P31	PRT0005 Mass	1.8519	kg
12	P32	Total Deformation Maximum	0.47503	mm
13	P33	Equivalent Stress Maximum	274.04	MPa

Fig. 4. Desing of experiment in Ansys

Table of Design Points

	A	B	C	D	E	F	G	H
1	Name	P27 - thickness1	P28 - X	P29 - Y	P30 - dia	P31 - PRT0005 Mass	P32 - Total Deformation Maximum	P33 - Equivalent Stress Maximum
2	Units	mm	mm	mm	mm	kg	mm	MPa
3	DP 0 (Current)	3	45	45	12	2.1897	0.27598	184.06
4	DP 1	2	45	45	12	1.4712	0.91019	395.92

Fig. 5. Desing of experiment in Ansys

Fig. 6.

The data from DOE was analyzed (144 design points) and 3 specimens were picked to perform experiment for validation as per below table.

TABLE II. TEST SPECIMEN

	THICKNESS (mm)	HOLE SPACING (mm)		HOLE DIA (mm)	NO OF HOLES
		X	Y		
SPECIMEN 1	3	45	45	12	25
SPECIMEN 2	2	45	45	24	25
SPECIMEN 3	2.5	90	90	16	9

Specimen 1- The combination with lowest stress and lowest mass was picked.

Specimens 2- Lowest mass picked. All combinations were failing for equivalent stress. It was added to correlate the fea results

Specimen 3-This plate was already available. Hence used for correlation.

The DOE data was utilized to establish an equation and the values of coefficients was found. This was for interpolation between the limits of the parameters studied. A sensitivity analysis of the variables was studied using this equation.

Equation for deformation:

$$\delta = 1.57-5.195\ (t) +0.0\ (u)-0.0012(v) +0.08(d) +5.914(t^2) -0.01(u^2) -0.0(v^2) +0.023(d^2) +0.021(tu) +0.014(tv)-0.08(td) +0.03(uv)-0.14(ud)-0.02(vd)-2.27t^3$$

Equation for stress:

$$\sigma = 2.154-7.036\ (t) +0.535(u) +0.4167(v) +0.343(d) +7.007(t^2) -0.28(u^2) -0.31(v^2) -0.025(d^2) -0.004(tu) +0.09(tv)-0.16(td) -0.03(uv)-0.14(ud)-0.02(vd))-2.4t^3$$

Where:

t- Plate thickness

u- Hole spacing in X direction (perpendicular tol bolting face)

v- Hole spacing in Y direction

d- Hole Diameter

δ -Deformation

σ- Max equivalent stress.

6. EXPERIMENTATION

6.1. *SPECIMEN AND GAUGE LOCATION*

Figure 6 shows the specimens and the gauge locations.

Two gauges were laid, one on the side near the bolt on faces as per FEA vector principal direction and the other underneath the load.

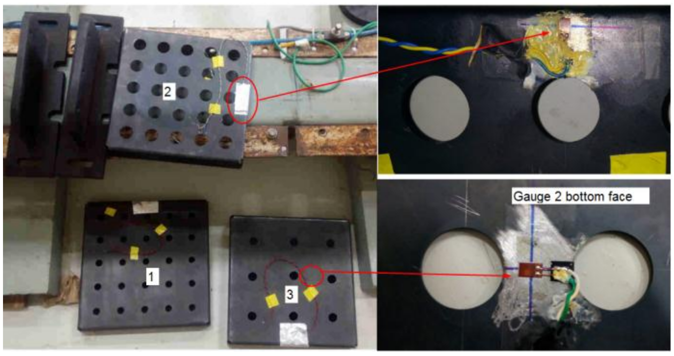

Fig. 7. Specimen and gauge location

6.2. *EXPERIMENTAL SET UP AND PROCEDURE*

The specimen was held between the side plates (fixture) as shown in the figure 6. The load is gradually varied from 50kg to 400 kg in increments of 50 using a hydraulic actuator.

A load cell and a load plate (145mm diameter plate to replicate FEA model) is placed on the actuator. The gauge readings are recorded through eDAQ. Figure 7 shows the output format.

Fig. 8. Fixture and experimental set up

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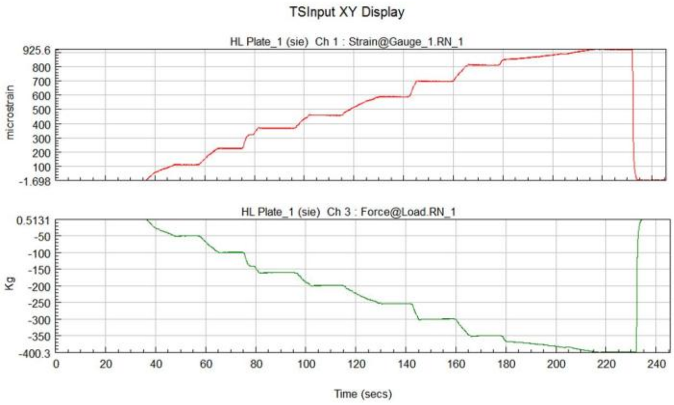

Fig. 9. eDAQ output file

7. RESULTS AND COMPARISONS

7.1. FEA VS EXPERIMENTAL RESULTS

FEA of 3 specimens was carried with 8 steps load ranging from 50 Kg to 400 Kg with increment of 50.

Maximum equivalent stress from FEA for the design load 2724N are:
Specimen 1: 176 Mpa
Specimen 2: 458 Mpa
Specimen 3: 274 Mpa
From the maximum stress values it is found that specimen 1 meets the acceptance criteria.
Strain comparison for gauge1 between FEA and experiment for all 3 specimens are shown in figures 9, 10, 11. Gauge 2 was ignored as the value was negligible.

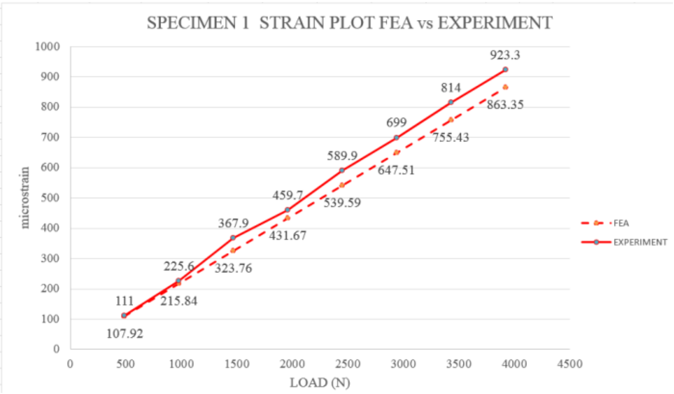

Fig. 10. Specimen 1 fea vs experiment

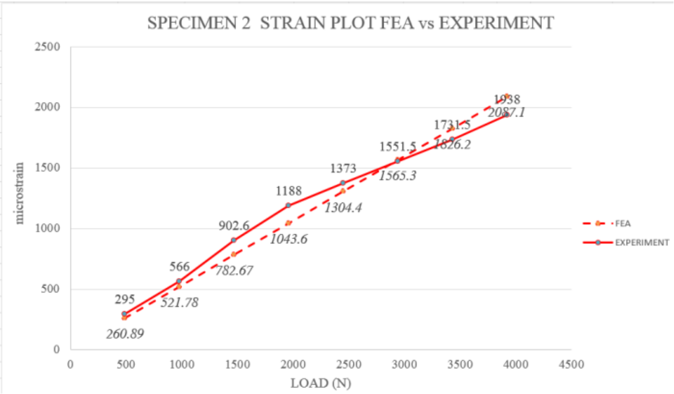

Fig. 11. Specimen 2 fea vs experiment

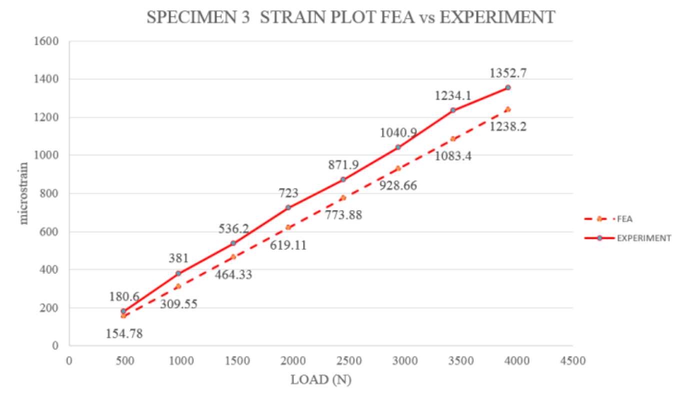

Fig. 12. Specimen 3 fea vs experiment

7.2. DOE DATA ANALYSIS

Sensitivity of hole size, plate thickness and hole spacing to stress is plotted in figure 12.

Deformation is mainly sensitive to thickness.

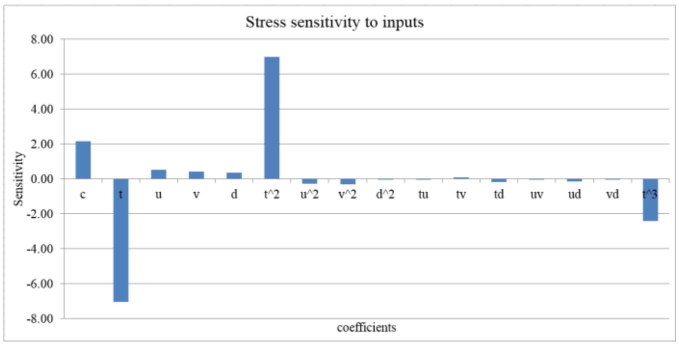

Fig. 13. Stress sensitivity

Figure 13 shows the deflection fit that was done to compare the deformation values from FEA with the values from the equation. It is eveident from the graph that both values are close.

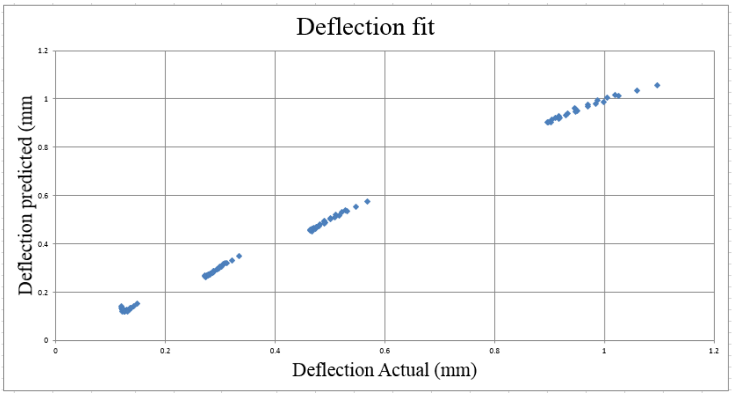

Fig. 14. Deflection fit between actual (FEA) and predicted (curve fir)

It is evident from figure 14 and 15 that as the hole diameter increases, there is increase in deformation and stress.

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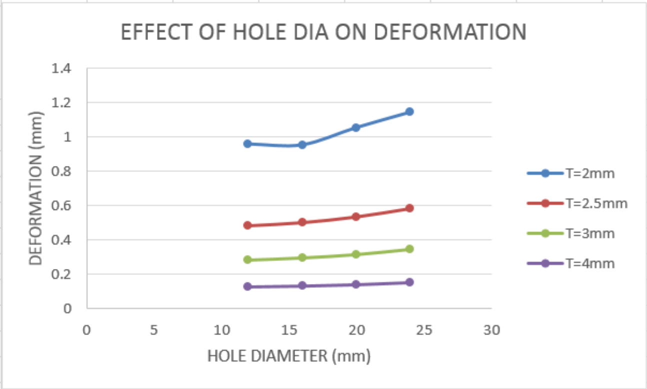

Fig. 15. Deformation sensitivity

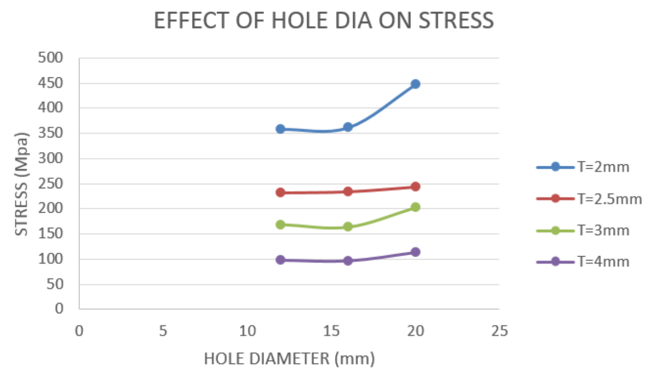

Fig. 16. Stress sensitivity

The behavior of stress in comparison with X spacing for different Y spacing is ploted in figure 16.

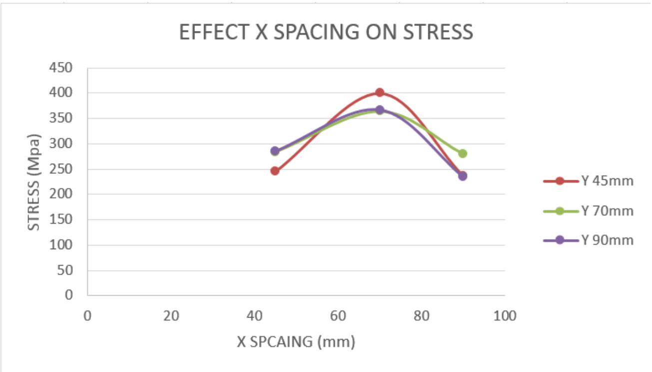

Fig. 17. Stress sensitivity

8. CONCLUSION AND REMARKS

- Experimental Validation of the specimens was done and the variation when compared to between FEA is around 11%.
  Considering 11% variation between FEA and experiment, specimen 1 is the solution.

Form the analysis of FEA data for all the combinations, it was found that:

- Deformation and stress are mostly effected by thickness of the plate.
- The next parameter effecting stress is X spacing.

Detailed analysis revealed that:

- Stress and deformation increases as the hole diameter is increased but the variation is minimum as compared to thickness and X spacing change.
- It is also seen that as X spacing is increased from 45mm to 70mm, stress increases but later with 90mm it falls(Y spacing is kept same as X). This is because at 70mm, the holes fall right below the outer edge of the load creating stress concentration and in addition X direction is the load path due to the boundary condition. In Y direction stress does not increase significantly even if the hole falls under the outer edge of load as it is not the load path.

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