Optical analysis of T-shaped stiffened plate under compressive loading using central composite design scheme

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Abstract. The buckling and post-buckling strength of stiffened panels subjected to compressive loads largely depends upon type and dimensions of stiffeners used. The current research investigates the use of T shaped stiffener in vertical configuration in rectangular plate with square opening for improving strength and buckling characteristics. The static structural analysis is conducted using ANSYS FEA software and dimensions of T shaped stiffeners are optimized using Taguchi response surface optimization. The design points are generated using CCD (Central Composite Design) scheme of response surface method and corresponding responses of optimization variables are captured in 3D plots. The sensitivity chart is generated to determine the effect of optimization variables on parameters of interest which are stress, strain, deformation, buckling load and safety factor. The optimization technique has successfully provided set of values for different parameters for which buckling and stresses are minimum and maximum.

1. Introduction

The stiffened panels possess high structural efficiency and therefore it is used in aircraft fuselage as it demands higher strength and demands higher load bearing capability. In case of heavy loading where web enter post-buckling regime the stiffener and skin tend to separate. In plate like buckling, longitudinal edges of the stiffened steel plates are considered as simply supported. The advantage of such design is development of local buckling prior to global/web buckling of entire panel and the optimized dimensions of stiffeners could significantly increase the buckling resistance of stiffened plate. N. Raghu Prasad, Jeeoot Singh [1] conducted FEA analysis on stiffened plates with and without openings. The boundary condition involved simply supported ends with edge compression. The numerical results shown minor variations in magnitude and pattern of stress with opening as compared to plate without opening. Ali Reza Pouladkhan, Jalil Emadi, Majid Safemehr [2] conducted FEA analysis on thin plate using Abacus software. The buckling loads were evaluated from equilibrium equation with mesh convergence studies. Figure 1 shows application of longitudinal and transverse stiffener in rectangular plate.
The analytical results were in close agreement with FEA results. Sang-Rai Cho, Hyun-seung Lee [3] conducted experimental study of 33 stiffened plate subjected to lateral collision. The buckling pattern was evaluated and the kinetic energy and potential energy obtained for experimental results were validated with analytical results. Ghania Ikhenazen, Messaoud Saidani [4] investigated buckling behavior of isotropic plate subjected to patch loads using total energy concept. The results obtained are validated with FEA results and graph was generated for buckling factor vs aspect ratio.

Byklum et al. [5] devised a computational model for analysing local buckling of stiffened panels and is more accurate than finite element method which takes into account any combination of biaxial loads (both tensile and compressive). Houlston et al. [6][7][8] investigated the application of finite strip method on stiffened panels and validation is made using results obtained from ADINA software and experimental data. Nurick et al. [9] and Rudrapatna et al. [10] conducted testing on fully built-in stiffened square plates subjected to blast loading. The experimental analysis has shown tearing of plates at fixed boundary for smaller stiffener. Louca and Pan [11][12] have analysed stiffened plate using DYNA 3D finite element software to determine local and global response of stiffened plate when subjected to blast loading. The results have shown that structural response of stiffened plate is not influenced by direction of blast loading and type of stiffeners.

2. Optimize design of dimensions of T shaped stiffeners

The objective of this research is to optimize design of dimensions of T shaped stiffeners used in rectangular plate subjected to vertical loading conditions. The material used for shear plates is structural steel and optimization parameters are beam lower with and beam upper width of T shaped stiffeners. The optimization is done using Taguchi response surface method and structural analysis is conducted using Finite Element Method [13].

The structural analysis of rectangular plate is done using finite element method (FEM) which is based on discretization of domain. The analysis has three stages i.e. pre-processing, solution and post-processing. The first stage is CAD modelling using ANSYS software. ANSYS design modeller is specific tool used for designing and editing operation. The CAD model of rectangular plate is modelled in ANSYS design modeller from schematic as shown in figure 2.
The 2-dimensional CAD model is developed and the opening is changed from circular to square and stiffeners modelled is T shaped as shown in figure 3.

The model is meshed using tetra elements of appropriate size and shape as shown in figure 4 below. After meshing, appropriate loads and boundary conditions are assigned. The bottom face is fixed and top face is applied with 900kN vertical load as shown in figure 5.

The simulation is run with sparse matrix solver and values of output variables are determined in solution stage.
3. Results and discussion

The contour plots of output parameters (deformation, principal stress, principal strain and safety factor) generated from FEA analysis to get distribution pattern. These contour plots showed critical regions of rectangular plate. The top most beam of rectangular plate structure has maximum deformation as shown in figure 6 and top left end of bottom plate has maximum principal stress as shown in figure 7.

![Figure 6. Deformation plot for square opening with T beams](image1)

![Figure 7. Max Principal stress for square opening with T beams](image2)

The safety factor is high for vertical members, horizontal members lowest is observed for bottom left and bottom right portion of plate as shown in figure 8.

![Figure 8. Safety factor for square opening with T beams](image3)

The deformation load multiplier plot is generated to determine critical buckling load of structure as shown in figure 9. The plot shows the region immediately above bottom plate opening are susceptible to buckling (shown by red colour).

![Figure 9. Total deformation load multiplier for square opening with T beams](image4)
The responses which are output variable are optimized on the basis of input variable which are independent. The independent variables are denoted by $x_1$, $x_2$, $x_3$…..$x_n$. These variables are independent and controlled by experimenter with negligible error. The relationship between independent variable and dependent variable can be expressed as-

$$Y = f(x_1,x_2,x_3……x_n) + \epsilon$$ (1)

Where $\epsilon$ is error observed in the response $y$. The two variable regression model of quadratic response is given by

$$y=\beta_0 + \beta_1x_1 + \beta_2x_2 + \beta_3x_1^2 + \beta_4x_2^2 + \beta_5x_1x_2$$ (2)

Where $\beta_0$, $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$ and $\beta_5$ are the regression coefficients. The response surface optimization of the current research deals with 2 design parameters which are side width ($x_1$) and lower width ($x_2$). To establish the cause and effect relationship design of experiments (DOE) is performed using ANSYS software. These experiments are conducted using central composite design method or CCD. The design points are generated from DOE is shown in table 1 below.

| A | Name | B | C | D | E | F | G | H | I |
|---|------|---|---|---|---|---|---|---|---|
|   |      | P17- sidewidth (mm) | P18- lowerwidth (mm) | P1- Total Deformation Load Multiplier | P5- Total Bending moment max (N mm) | P10- Total Deformation max (mm) | P11- Max Principal Stress (MPa) | P12- Max Principal Elastic Strain max mm | P13- Safety Factor Min |
| 1 | 159  | 161 | 70.479 | 1.0223E+07 | 1.9358 | 247.99 | 0.0012282 | 0.30915 |
| 2 | 158  | 161 | 7.0241 | 1.0227E+07 | 1.9128 | 248.65 | 0.0012316 | 0.30811 |
| 3 | 160  | 161 | 7.0714 | 1.0219E+07 | 1.9592 | 247.33 | 0.0012249 | 0.31019 |
| 4 | 159  | 160 | 7.0436 | 1.0197E+07 | 1.9567 | 248.63 | 0.0012309 | 0.30798 |
| 5 | 159  | 162 | 7.0522 | 1.0249E+07 | 1.9153 | 247.36 | 0.0012555 | 0.31033 |
| 6 | 158  | 160 | 7.0198 | 1.0201E+07 | 1.9333 | 249.29 | 0.0012343 | 0.30693 |
| 7 DP 0 | 160 | 160 | 7.0702 | 1.0935E+07 | 1.9803 | 247.92 | 0.0012273 | 0.30999 |
| 8 | 158  | 162 | 7.0285 | 1.0253E+07 | 1.8925 | 248.01 | 0.001289 | 0.30929 |
| 9 | 160  | 162 | 7.0757 | 1.0284E+07 | 1.9384 | 246.7 | 0.0012222 | 0.31136 |

The graph of deformation vs side width as shown in figure 10 depicts an increase in total deformation load multiplier or buckling load with increase in side width of T beams up to maximum value of 160mm.

![Figure 10. Deformation vs side width of square opening with T beams](image)

The graph of deformation vs lower width as shown in figure 11 depicts increase in total deformation load multiplier or buckling load with increase in lower width of T beams up-to maximum value of 16mm.
Figure 1. Deformation vs lower width of square opening with T beams

The 3D response surface plot of load deformation multiplier is shown in figure 12. The deformation load multiplier has highest value for side width range from 160mm to 162mm and lower width ranging from 160mm to 162mm and has lowest value for side width range from 158mm to 158.5mm and lower width ranging from 161.5mm to 160mm.

Figure 2. 3D Response Surface Plot of square opening with T beams

The graph of deformation vs side width as shown in figure 13 depicts the decrease in total bending moment with increase in side width of T beams up-to maximum value of 160mm.

Figure 3. Bending moment vs side width of square opening with T beams

The graph of deformation vs side width as shown in figure 14 depicts the increase in total bending moment with increase in lower width of T beams upto maximum value of 162mm.
Figure 14. Bending moment vs lower width of square opening with T beams

The 3D response surface plot of bending moment is shown in figure 15. The total bending moment has highest value for side width range from 158mm to 162mm and lower width ranging from 161.5mm to 162mm and has lowest value for side width range from 158mm to 160mm and lower width ranging from 160mm to 160.5mm.

Figure 15. 3D Response Surface Plot of square opening with T beams

The graph of deformation vs side width as shown in figure 16 depicts increase in total deformation with increase in side width of T beams up-to maximum value of 160mm. The graph of deformation vs lower width is shown in figure 17 depicts decrease in total deformation with increase in lower width of T beams up-to maximum value of 162mm.

Figure 16. Total deformation vs side width of square opening with T beams
The 3D response surface plot of total deformation is shown in figure 18, which shows highest value of deformation for side width range from 159.5mm to 160.62mm and lower width ranging from 160mm to 160.5mm and has lowest value of deformation for side width range from 158mm to 158.5mm and lower width ranging from 161.5mm to 162mm.

The graph of Maximum principal stress vs side width as shown in figure 19 depicts the decrease in Maximum principal stress with increase in side width of T beams up to maximum value of 160mm. The variation of Maximum principal stress vs lower width shows the decrease in maximum principal stress with increase in lower width of T beams up to maximum value of 162mm.

The 3D Response Surface Plot of principal stress is shown in figure 20. The plot shows the maximum principal stress has highest value for side width range from 158mm to 158.5mm and lower width ranging
from 160mm to 160.5mm and has lowest value for side width range from 159.5mm to 160mm and lower width ranging from 161.5mm to 162mm.

Figure 20. 3D Response Surface Plot of square opening with T beams

The graph of Maximum principal stress vs side width shows decrease in Maximum principal strain with increase in side width of T beams up-to maximum value of 160mm.

Figure 21. Maximum principal stress vs side width of rectangular opening with T beams

The graph of Maximum principal stress vs lower width as shown in figure 22 depicts decrease in maximum principal stress with increase in lower width of T beams up-to maximum value of 162mm.

Figure 22. Maximum principal strain vs lower width of square opening with T beams

The 3D Response Surface Plot of principal elastic strain with T beams is shown in figure 23. The plot shows maximum principal strain has highest value for side width range from 158mm to 158.5mm and
lower width ranging from 160mm to 160.5mm and has lowest value for side width range from 159.5mm to 160mm and lower width ranging from 161.5mm to 162mm.

**Figure 23.** 3D Response Surface Plot of square opening with T beams

The graph of safety factor vs side width as shown in figure 24 depicts increase in safety factor with increase in side width of T beams up-to maximum value of 160mm. The variation of safety factor vs lower width depicts increase in safety factor with increase in lower width of T beams up-to maximum value of 162mm.

**Figure 24.** Safety factor vs side width of square opening with T beams

The safety factor plot generated is shown in figure 25. The plot shows that the highest value of safety factor for side width range from 159.5mm to 160mm and lower width ranging from 161.5mm to 162mm and lowest value of safety factor for side width range from 158mm to 158.5mm and lower width ranging from 160mm to 160.5mm.
Figure 25. 3D Response Surface Plot of square opening with T beams

The sensitivities of different optimization variables are studied to determine its effect on output variables as shown in figure 26. This would enable designer/engineer to identify the optimization variable which could cause maximum variation in output variable (the one having higher sensitivity percentage).

Figure 26. Sensitivity plot of various parameters for square opening with T beams

4. Conclusion

FEA analysis conducted on stiffened rectangular plates with square opening. The stress distribution and buckling characteristics of rectangular plate has shown critical areas of failure. The dimensions of I shaped stiffeners are optimized and specific set of optimization variable values are generated. The sensitivity plots of variables are also generated which shows the effect of different optimization variables on output variables. The detailed conclusion points are as follows:

1. For total deformation load multiplier variable both beam lower width and beam side width shows positive sensitivities. Beam lower width sensitivity percentage is 13.32 (positive) and beam side width sensitivity percentage is 86.52 (positive). Therefore, beam side width has higher effect on deformation load multiplier or buckling load.

2. For bending moment beam side width sensitivity percentage is 12.61 (negative) and beam lower width sensitivity percentage is 87.38 (positive). Therefore, beam lower width has higher effect on sensitivity of bending moment.
3. For total deformation beam lower width sensitivity percentage is 47.09 (negative) and beam side width sensitivity percentage is 52.89 (positive). Therefore, beam side width has higher effect on total deformation of beam.

4. For maximum principal elastic strain beam side width sensitivity percentage is 51.15 (negative) and beam lower width sensitivity percentage is also 48.76 (negative). Therefore, beam side width has higher effect on maximum principal elastic strain.

5. For safety factor beam side width sensitivity percentage is 47.44 (positive) and beam lower width sensitivity percentage is also 52.53 (positive). Therefore, beam lower width has more effect on safety factor.

6. The optimum results are obtained for beam side width ranging from 159.5 to 160mm and beam lower width ranging from 161.5mm to 162mm.

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