

RESEARCH ARTICLE

Finite element–based parametric analysis and geometric optimization of stress concentration in semicircular notched plates

Sangram S. Bhosale^{1,*} , Sachin M. Bhosle² 

¹Ph.D. Scholar, Vidya Pratishthan's Kamalanayn Bajaj Institute of Engineering & Technology, Baramati, Affiliated to Savitribai Phule Pune University, Pune, 413133, India

²Professor, Vidya Pratishthan's Kamalanayn Bajaj Institute of Engineering & Technology, Baramati, Affiliated to Savitribai Phule Pune University, Pune, 413133, India

Abstract

The main objective of this study is to optimize the geometry of a tension strip with opposite semicircular edge notches in order to reduce the stress concentration factor (K_t) by using computational techniques. An ABAQUS finite-element model was developed, and a full-factorial design of experiments was used to test the effects of four independent geometrical variables: width, notch radius, thickness, and length. The analytical workflow was automated through a MATLAB-ABAQUS interface, enabling a systematic parametric exploration of sixteen configurations. The inverse relationship between thickness and K_t was the strongest with the notch radius and width showing positive correlation. The lowest K_t was obtained with $H=16\text{mm}$, $r=2\text{mm}$, $h=2\text{mm}$ and $L=28\text{mm}$, resulting $K_t=1.73$. This combined interface system is very effective and dependable process for notched components stress optimization.

Keywords: Stress concentration factor; finite element analysis; semicircular notches; parametric analysis; geometric optimization; design of experiments; structural stress distribution

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1. Introduction

Stress concentration is a critical factor in mechanical design since localized stress peaks often determine the failure modes and fatigue life of structural elements. These magnified stresses are due to notches, holes, grooves, and sudden geometric discontinuities. It often leads to increase in the local stress marginally beyond the nominal values and cause early material degradation or fracture (Carpinteri, 2021). To avoid such degradation or failure, thorough knowledge and management of such stress raisers are necessary to ensure the stability of load-bearing components in industries such as aerospace, automotive, and energy. Recent studies emphasized that accurate modeling of local stress distributions is very critical in predicting fatigue performance and preventing disastrous failure [1].

Optimization of notch geometry has proven effective in reducing stress concentration. Modern design approaches combine

experimental evidence with computational aids to find geometries that balance structural performance and manufacturability [2] which enhances the axial strength without impacting the notch failure during separation. However, few studies have focused on such extreme stress concentration-free designs of a single-side notch on a shell because the asymmetrical structure under common eccentric loading brings much difficulty for theoretical analysis, while numerical approaches can hardly meet the requirements of highly efficient rapid optimal designs. In this paper, a theoretical and experimental study toward extreme stress concentration-free designs of single-side-notched thin cylindrical shells is presented. The general stress concentration factors (SCFs). Existing experimental research on complex notch designs emphasize that in order to reduce stress concentration factor K_t , different notch radii or customized curvature shapes can be used [3]. However, much of the

*Corresponding Author

E-mail Address: profsangram@urownteacher.com

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current literature is based on fixed, geometric analyses instead of flexible, automated models that can efficiently search large parametric spaces.

Analytical and computational approaches to deduce stress concentration factors in notched components have been widely studied in existing literature. Ding et al. [4] suggested an empirical relationship based on an adapted Inglis theory to determine the stress concentration factor (SCF) of semi-elliptical notches formed during crack grinding. It is focused on the geometric effects of depth and thickness. Pan et al. [5] proposed a model of stress-gradient impact factor to mathematically model the notch stress field. It estimates fatigue life during multiaxial loading. Kumar and Goyat [6] investigated functionally graded material layers in the areas surrounding semi-circular notches. A marginal decrease in stress concentration was obtained by means of extended finite element analysis. In other similar research, Hazizi et al. [7] combined experimental and numerical methods to assess the fatigue behavior of carbon steel specimens with semicircular edge notches. Active control methods, such as those illustrated by Abuzaid et al. [8], and notch interaction analysis by Magar [9] also contributed to the knowledge in stress control in which authors highlights the current innovation to streamline the design of notched components.

A significant research gap is observed in the automated parametric optimization of tension strips for the simultaneous effects of multiple geometric variables on stress behavior. Despite the effectiveness of finite-element methods in predicting local stresses, not many studies have integrated simulation tools with automated statistical design to optimize the multivariable optimization systematically [10]. The current research fills this gap by developing a MATLAB-ABAQUS coupled model to simulate and optimize stress concentration in a notched tension strip, using a full-factorial Design of Experiments (DOE). It provides a solid process as well as data-driven approach to geometric optimization in structural design.

2. Methodology

This section explains the methodology used to investigate and optimize the stress-concentration properties of a tension strip with opposing semicircular edge notches. The process involves computational simulation, statistical design of experiments, as well as automated parametric analysis.

2.1. Overview of the study

The study focuses on optimizing a tension strip with conflicting semicircular edge notches using a parametric-based finite-element methodology. The addition of notches causes localized stress concentrations that can significantly reduce fatigue life and structural integrity. In order to reduce this effect, the effect of four geometrical parameters such as width (H), notch radius (r), thickness (h) and length (L) on the stress concentration factor (K_t) were examined by means of a finite element analysis in ABAQUS and followed by a

full factorial design of experiments (DOE). All the parameters were studied at two distinct levels, resulting in a total of sixteen simulation cases. The nominal stress was calculated using the following relation:

$$\sigma_{\text{nom}} = \frac{P}{h \times H} \quad (1)$$

and the corresponding stress concentration factor was obtained from

$$K_t = \frac{\sigma_{\text{max}}}{\sigma_{\text{nom}}} \quad (2)$$

where σ_{max} is the maximum principal stress from FEA results. To make the process automated, MATLAB was used with Abaqus. Extracted Python code from Abaqus is then modified for each case and the run the simulations on each design-of-experiments combination and K_t values are extracted. Figure 1 clarifies the methodological framework of this study, which combines MATLAB automation, finite element analysis, and design-of-experiments (DOE). This combined methodology will provide an effective, consistent, and precise assessment of stress-concentration behavior. It generalizes traditional analytical models, such as that of Peterson (Peterson, 1974).

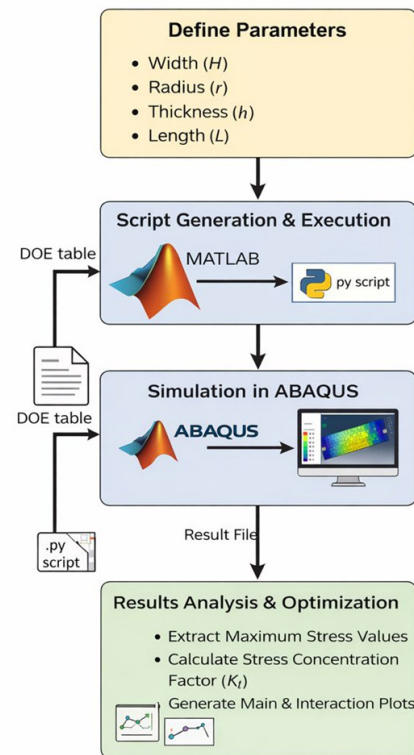


Figure 1. Workflow of the integrated MATLAB-ABAQUS-DOE approach used for the optimization study.

2.2. Geometric model description

The geometric model discussed in this paper consists of a tension strip with opposite semicircular edge notches. It is often designed to model a common structural part used in mechanical and aerospace industries. These notches create a geometric discontinuity which creates stress concentration around their edges, which has been well-documented in classical texts like Peterson (1974). The geometry was modelled in ABAQUS/CAE and parametrically characterized by four key variables: width (H), notch radius (r), thickness (h), and length (L). All the variables were varied systematically within predefined lower and upper limits, thereby creating a complete factorial design for the experiment. A tensile force of 1000N was applied along the longitudinal axis. One side of the strip fixed to prevent rigid-body movement and to provide a uniform load. Nominal stresses for each configuration were calculated using Equation (1). The largest von-Mises stresses were obtained from the finite-element analysis results.

The resultant geometry and boundary conditions are shown in Figure 2. It represents a schematic representation of the notched strip and the applied loading configuration.

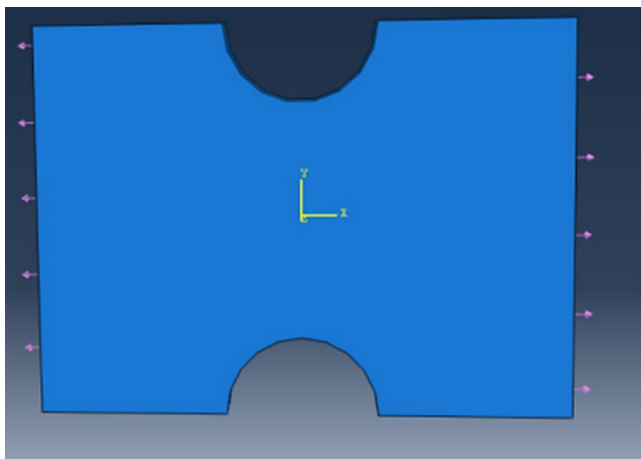


Figure 2. Geometric configuration and loading conditions of the notched tension strip model.

2.3. Design of experiments (DOE)

The stress concentration factor (K_t) of a tension strip was evaluated using a full-factorial design of Experiments (DOE). The effects of four geometric parameters — width (H), notch radius (r), thickness (h), and length (L) both individually and in combination is determined. Assessing all factors at two levels resulted in sixteen simulation cases. This method allows exhaustive interaction analysis of the variables, without any significant combination left out (Montgomery, 2017). The stress concentration factor for each simulation was calculated using equation (2), where the numerator (max) represents the maximum principal stress and the denominator (nom) represents the nominal stress. The combinations of parameter levels obtained are presented in Table 1.

Table 1. Full factorial design matrix for four control parameters (H, r, h, L)

Run No.	Width (H) (mm)	Notch Radius (r) (mm)	Thickness (h) (mm)	Length (L) (mm)
1	16	2	2	24
2	16	2	2	28
3	16	2	4	24
4	16	2	4	28
5	16	4	2	24
6	16	4	2	28
7	16	4	4	24
8	16	4	4	28
9	20	2	2	24
10	20	2	2	28
11	20	2	4	24
12	20	2	4	28
13	20	4	2	24
14	20	4	2	28
15	20	4	4	24
16	20	4	4	28

2.4. Finite element analysis setup

ABAQUS/CAE was used to perform Finite Element Analysis (FEA) to identify the stress distribution in a tension strip subjected to tensile loading. Sixteen geometric configurations, based on a complete factorial design, were incorporated using a parametric Python script that was generated and executed via MATLAB automation. The strip was modeled as a three-dimensional deformable solid with semicircular edge notches keeping modifiable control parameters (width, radius, thickness, and length). It was assumed to be isotropic structural steel with a Young's modulus of 209 GPa and a Poisson's ratio of 0.30. A strip was clamped at one terminal face, and a tensile force of 1000N was applied to the other face to maintain a constant axial tension in the strip.

The discretization (meshing) used C3D8R eight-node, reduced-integration hexahedral elements with an approximate characteristic length of 1mm (mesh size), thereby ensuring that the stress gradients around the notches were well captured.

2.5. MATLAB-ABAQUS integration and automation

A MATLAB-ABAQUS integration was used to automate the analysis and efficiently perform numerous simulations associated with the sixteen experimental runs. An original MATLAB script was created to alter the ABAQUS Python input file for each parameter combination in the full-factorial DOE. This automation enabled dynamic editing of geometric variables such as width, radius, thickness, and length. The sequential execution of ABAQUS analyses is processed without human intervention. The workflow was controlled by MATLAB, in which Python scripts produced, followed by ABAQUS runs. Once simulation completed, results such as the maximum stress values were extracted from the output database (ODB) files. These values were then used to compute the respective stress concentration factors for each case. The integration greatly reduced computation

time, human effort resulting minimization of human error, giving consistent results for all runs. The automated procedure enabled direct visualization of data and statistical analysis in MATLAB, giving output as main-effect and interaction plots.

2.6. Data extraction and analysis

After completion of the ABAQUS simulation, the output database (ODB) files were post-processed to obtain the maximum principal stress values in the notch region. The values were imported into MATLAB and combined with corresponding nominal stress values to calculate the stress concentration factor (K_t) for all sixteen cases. The obtained dataset was presented as a matrix. It then subjected to statistical analysis, which allowed the identification of the prevailing parameters and their interaction effects. Built-in functions in MATLAB were used to generate main-effect and interaction plots. These plots provided a visual representation of each factor's effect on K_t . They enabled determination of the relative importance of width, radius, thickness, and length, resulting in the most effective geometric configuration.

2.7. Validation against analytical model

Peterson's (1974) analytical stress-concentration factors calculated by the theoretical model of notched tension members were used to validate the numerical findings of finite-element simulations. Peterson's findings provide empirical correlations (Figure 3) of K_t values in variety setups with semicircular edge notches loaded with uniaxial tension. A comparative study deduce that the finite-element findings were in good agreement with the analytical forecasts. The slight differences were due to mesh discretization and influences of three-dimensional modelling. The high level of agreement between the analytical and finite-element findings supports the validity of the computational model.

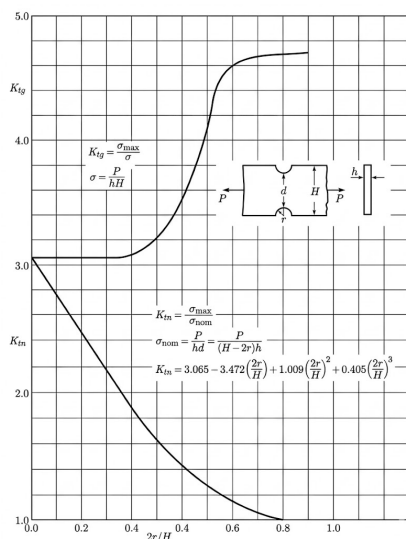


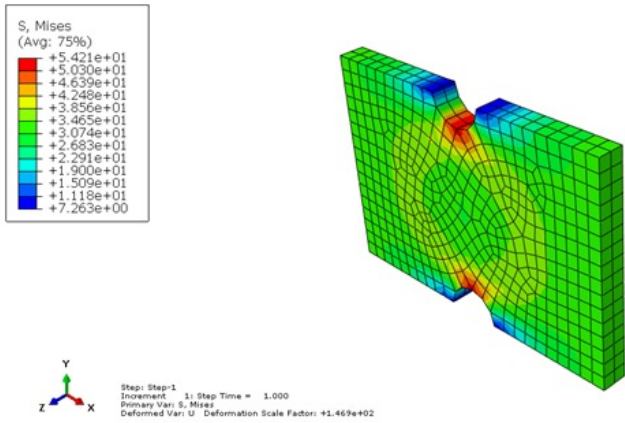
Figure 3. Peterson Model for tension strip with opposite semicircular edge notches

3. Results and discussion

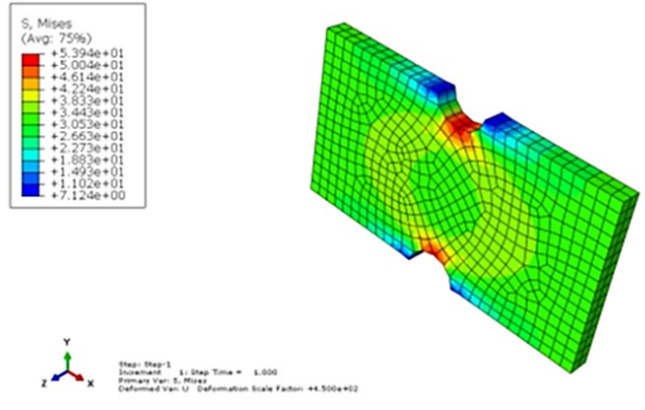
The current section overviews and explains the findings of finite element simulations and related statistical tests. In this section, the influence of the geometrical control parameters on stress concentration is highlighted, identifying the configuration that gives best and most optimized stress concentration factor (K_t).

3.1. Stress contour analysis

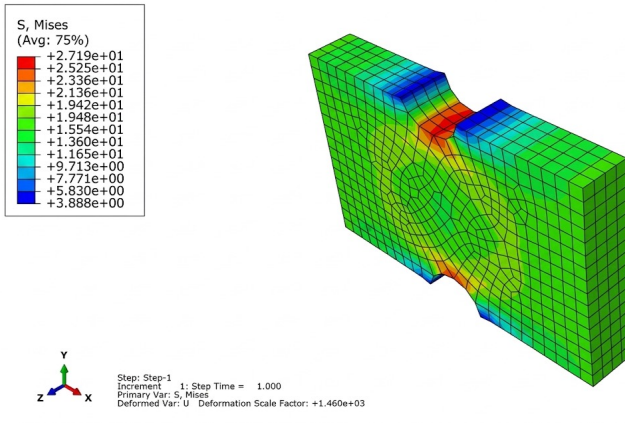
The contour plots of the sixteen geometric configurations defined in the DOE matrix (Table 1). Plots extracted from ABAQUS (Figure 4(a)–4(p)) show the distribution of the maximum von-Mises stress in the tension strip with the opposite semicircular edge notches. The peak stress intensity occurs at the curved edges of the notches in both configurations, which validates the use of these regions as crucial stress-concentration regions due to geometric discontinuities. Areas remote from notch interfaces exhibit a nearly homogeneous stress distribution. It emphasizes the effectiveness of the tensile loading and the imposed boundary constraints. When the notch radius (r) and width (H) increase, the area of localized stress concentration increases, and consequently the peak stresses increase. Conversely, increasing the thickness (h) reduces the level of stress by increasing the load-bearing cross-section and enhancing the homogeneity of stress distribution. The change in length (L) has negligible effect on stress patterns. The validity of the imposed boundary conditions is supported by symmetric stress contours about the specimen mid-plane. These findings are in agreement with the theoretical forecasts made by Peterson (1974), justifying the accuracy of the simulation.



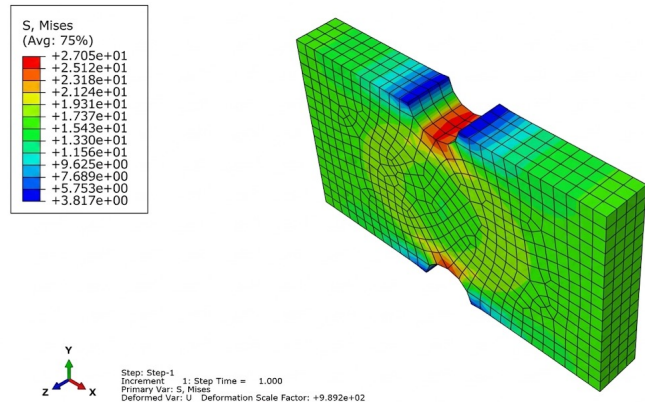
(a)



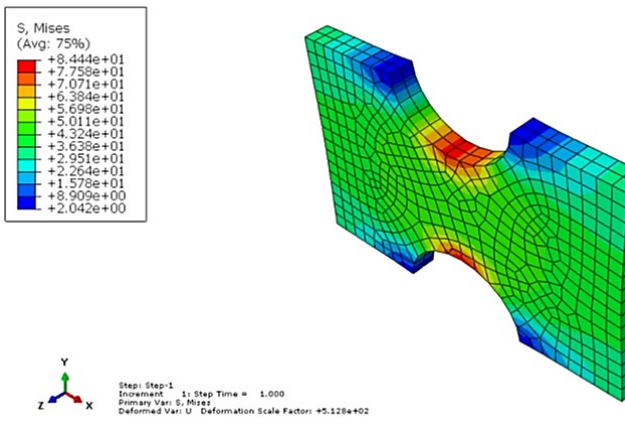
(b)



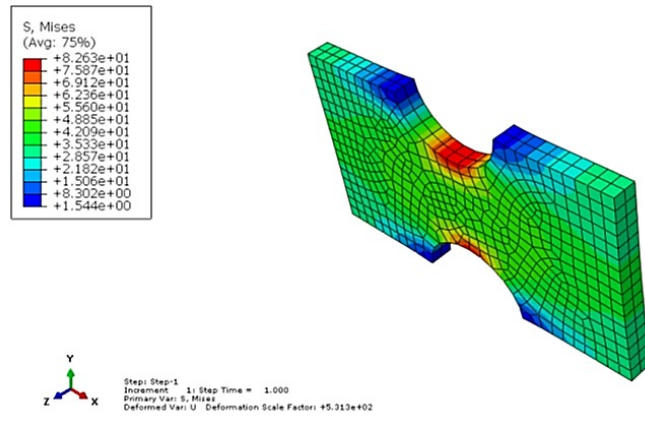
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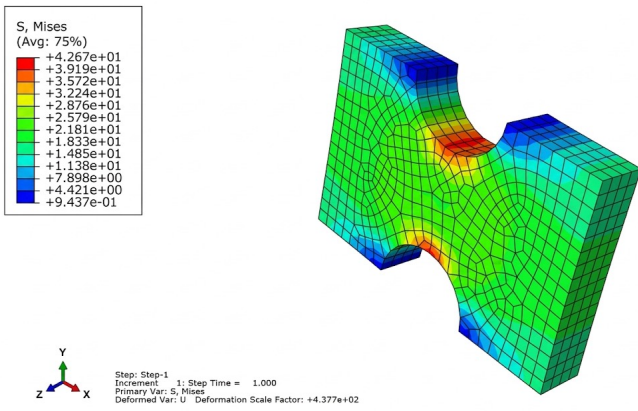
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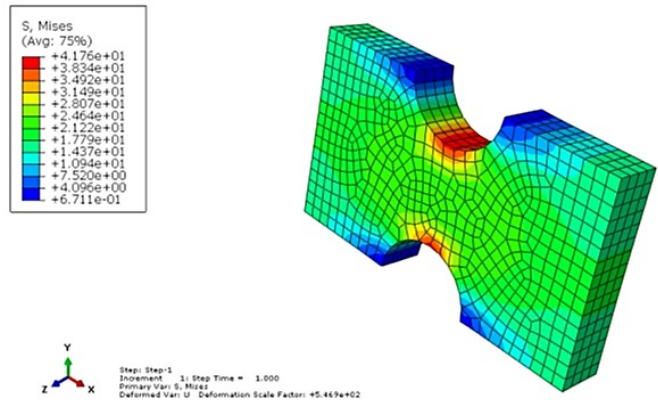
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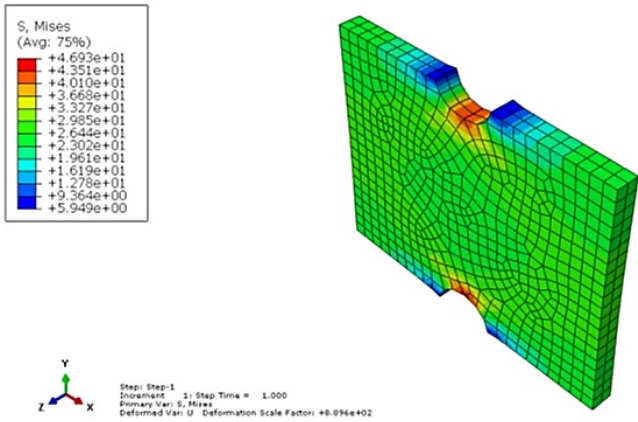
(f)



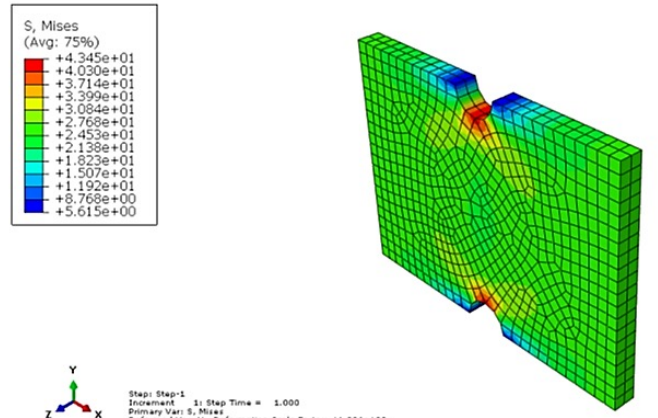
(g)



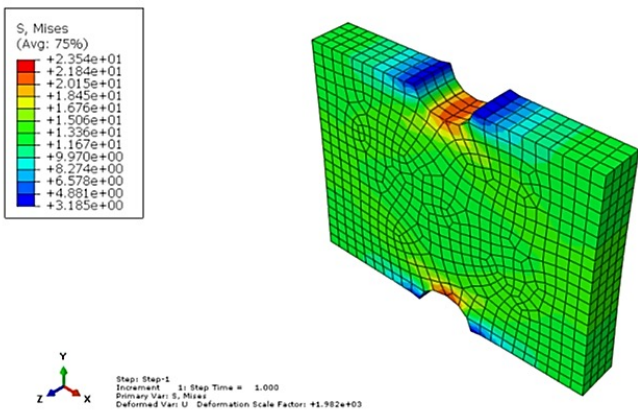
(h)



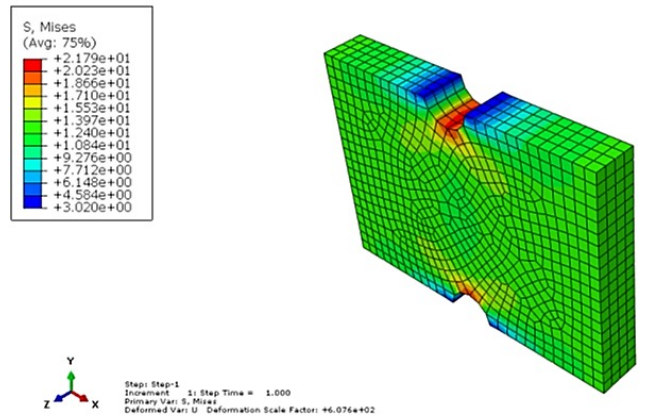
(i)



(j)



(k)



(l)

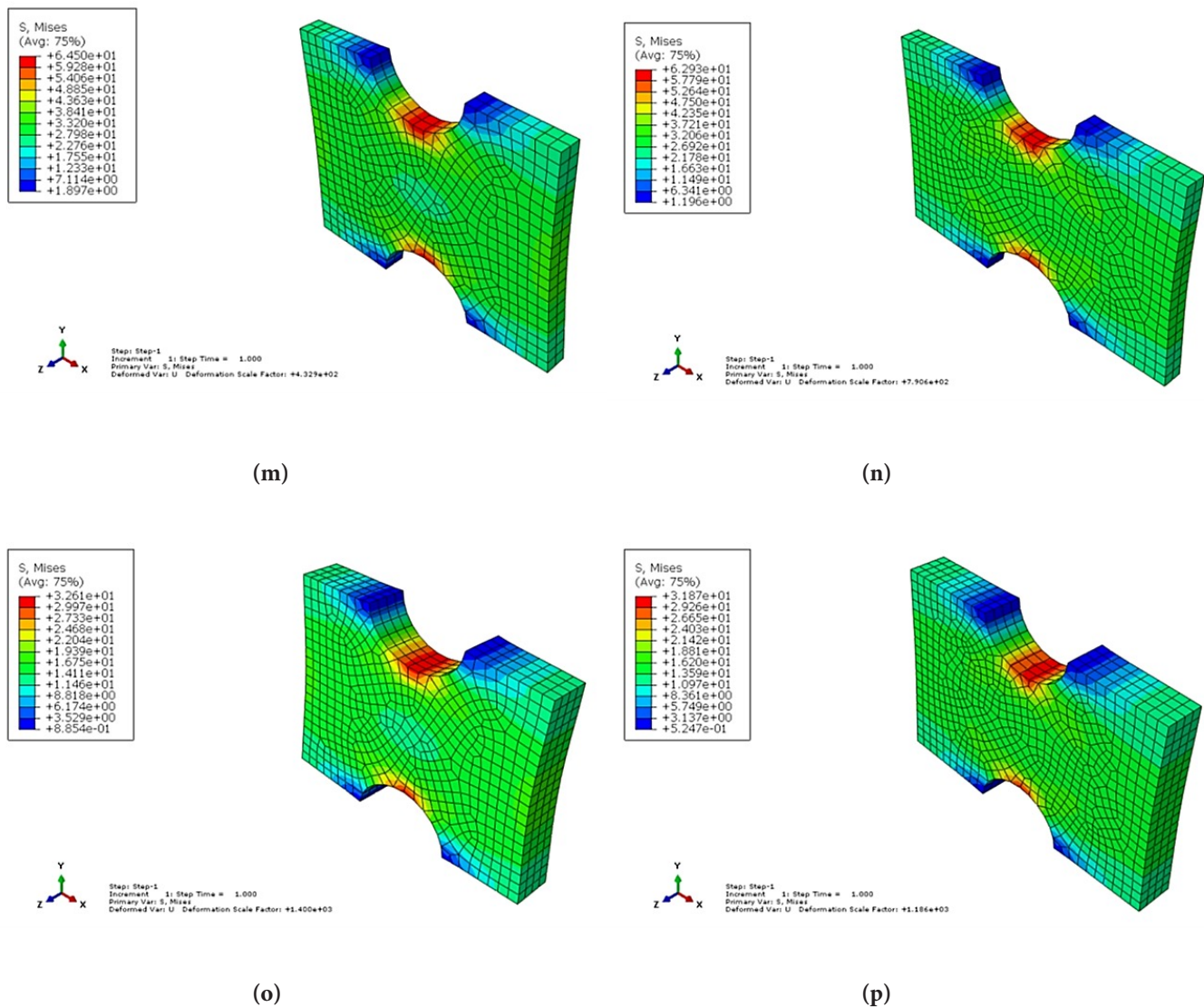


Figure 4. (a) – (p) ABAQUS-generated stress contour plots for all 16 DOE configurations showing stress concentration behaviour near the notches.

3.2. Numerical Results Summary

The numerical data of all sixteen ABAQUS simulations are summarized in Table 2 that provides the maximum von-Mises stress (σ_{\max}), nominal stress (σ_{nom}), and the calculated stress concentration factor (K_t) of each DOE configuration. The findings have clearly shown that the stress concentration factor is highly dependent on geometric parameters, particularly thickness and notch radius. The lowest value of K_t of 1.726 was achieved using the following configuration: $H = 16$ mm, $r = 2$ mm, $h = 2$ mm and $L = 28$ mm. The highest value of K_t was 2.731 at the following configuration: $H = 16$ mm, $r = 4$ mm, $h = 4$ mm and $L = 24$ mm. These results suggest that stress concentration depends on the combined action of geometric parameters

rather than solely on thickness. Particularly, larger notch radii have a strong effect on K_t , but the effect of thickness varies with the interaction with width and length of the specimen.

Table 2 shows that, other geometric parameters held constant, increasing thickness does not always reduce K_t . In some designs it can increase K_t slightly. As a result, the influence of thickness should be considered together with interaction effects, as shown in Figures 5 and 6. Increasing radius or width on the other hand increased K_t due to the larger effective stress concentration regions. The length parameter was not significant in all the runs. These numerical findings formed the basis for further statistical analyses and optimization research.

Table 2. Summary of ABAQUS simulation results showing maximum stress, nominal stress, and calculated stress concentration factors

DOE No.	Width (H) (mm)	Radius (r) (mm)	Thickness (h) (mm)	Length (L) (mm)	σ_{max} (MPa)	σ_{nom} (MPa)	$K_t = \sigma_{max}/\sigma_{nom}$
1	16	2	2	24	54.21	31.25	1.735
2	16	2	2	28	53.94	31.25	1.726
3	16	2	4	24	27.19	15.625	1.74
4	16	2	4	28	27.05	15.625	1.731
5	16	4	2	24	84.44	31.25	2.702
6	16	4	2	28	82.63	31.25	2.644
7	16	4	4	24	42.67	15.625	2.731
8	16	4	4	28	41.76	15.625	2.673
9	20	2	2	24	46.93	25	1.877
10	20	2	2	28	43.45	25	1.738
11	20	2	4	24	23.54	12.5	1.883
12	20	2	4	28	21.79	12.5	1.743
13	20	4	2	24	64.5	25	2.58
14	20	4	2	28	62.93	25	2.517
15	20	4	4	24	32.61	12.5	2.609
16	20	4	4	28	31.87	12.5	2.55

3.3. Main effects of geometric parameters

The main influence of the four control parameters (width (H), notch radius (r), thickness (h), and length (L)) on the stress concentration factor (K_t), was evaluated using MATLAB-generated main effect plots, as shown in Figure 5. The resultant plots indicate that thickness (h) has the strongest effect and is strongly negatively correlated with K_t . Increase in thickness improves load-bearing capacity, resulting in a more symmetric distribution of stress which further reduces stress concentration at notches. Conversely, the width (H) and notch radius (r) have positive gradients, which means that high values of these variables increase K_t . Reason behind increased K_t is increased stress concentration at the notch peripheries. The length of the specimen (L) has only a secondary effect. Length of specimen is responsible for overall structural stiffness rather than localized stress concentration. These observations indicate that maintaining smaller notch radii and carefully selecting component thickness are important measures for reducing stress concentrations in notched components. The observed parameters are sensitive in line with the classical theories of mechanical design (Peterson 1974).

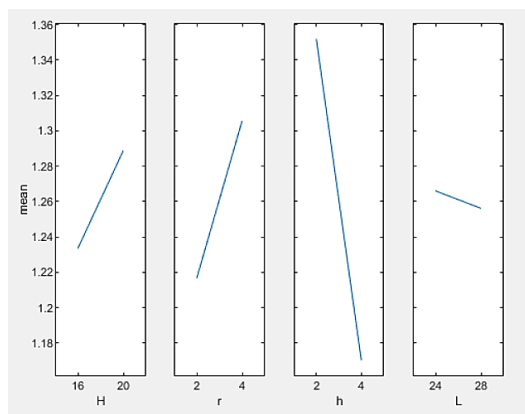


Figure 5. Main effect plots showing the individual influence of geometric parameters on the stress concentration factor

3.4. Interaction effects between parameters

The interaction effects between the geometric parameters were explored using interaction plots obtained with MATLAB, as shown in Figure 6. The plots suggest that certain combinations of parameters have a significant effect on the stress-concentration factor (K_t) which is greater than the effect of each parameter taken separately. The strongest interaction effects were observed between width and thickness, and between radius and thickness. In both cases, an inverse relationship was found that is as the thickness increases, the sensitivity of K_t to changes in radius decreases, whereas its sensitivity to changes in width increases. The same is indicated by the steeper slope of the K_t – width curve at $h = 4$ mm. Relationships between width-radius and length-thickness showed relatively small variation, indicating weak coupling. In general, the discussion highlights the importance of multi-parameter optimization in order to realize effective stress mitigation. Moreover, the fact that the thickness-related interactions are predominant supports its central role in the local stress concentration regulation (Peterson, 1974).

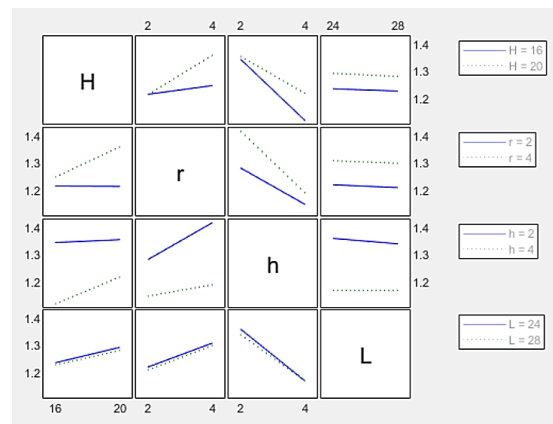


Figure 6. Interaction plots showing the combined influence of geometric parameters on the stress concentration factor

3.5. Optimization of the geometric configuration

Based on numerical and statistical analysis of all sixteen DOE configurations, the geometric combination with the lowest stress concentration factor (K_t) was $H = 16\text{mm}$, $r = 2\text{mm}$, $h = 2\text{mm}$, and $L = 28\text{mm}$. This geometric configuration leads to the lowest K_t , about 1.73. Reason being is a more favorable stress distribution and lower intensity at the notch edges. It enhances stress flow and reduces peak stress gradients with a reduced notch radius and increased specimen length. Reduced thickness results in reduced nominal stress whereas structural balance is achieved by a longer length. This is the best possible outcome, consistent with the negative effect of thickness and the positive effects of radius and width in the main-effect and interaction plots. Figure 4(b) shows the corresponding stress contour, which indicates low stress concentrations around the notches for this configuration.

4. Conclusion

This study explored the optimization of a tension strip with semi-circular notches along its edges using a hybrid approach combining Finite Element Analysis (ABAQUS) and a design of experiments (DOE) model automation using MATLAB.

The main conclusions of the analysis are as follows:

- Thickness was found to be the most decisive parameter, and it showed an inverse relationship with the stress concentration factor (K_t).
- Notch radius and width had positive relationships with K_t , i.e. increasing stress levels in the vicinity of the notch.
- Length did not significantly influence stress concentration across the parameter space under study.
- The best design topology was found to be $H = 16\text{ mm}$, $r = 2\text{ mm}$, $h = 2\text{ mm}$ and $L = 28\text{ mm}$ that gave the lowest K_t of 1.73.

Therefore, the combined MATLAB-ABAQUS-DOE approach was highly effective in both the structural optimization of reinforced components and the quantification of stress concentrations in notched geometries.

Declarations

Competing interests

There are no competing interests relevant to the content of this article.

Funding statement

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Consent to participate declaration

Not applicable. This study did not involve human participants.

Conflict of interest

No conflicts of interest are associated with this study.

Ethics declaration

This study did not involve human participants, animals, or sensitive personal data, so formal ethical approval was not required.

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