Research Article

Cetin Karakaya*

Numerical investigation on perforated sheet metals under tension loading

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Abstract: Perforated sheets are used in many areas due to their high specific load, economical production, aesthetic structure, and filtering ability. Their use in industrial machinery and the construction industry can be given as examples of these areas. In this study, the mechanical behaviour of perforated metal sheets under tensile loads has been investigated numerically. The influence of material type, hole geometry, and hole arrangement were examined with finite element analyses. Stainless steel and aluminium materials are used as sheet materials. The hole geometries are circle, ellipse, triangle, square, and hexagon. As a result of the simulations, the aluminium material gave the highest values in terms of carried load capacity and absorbed energy. The sheets with the staggered hole arrangement have higher load and energy values than the sheets with the linear arrangement. The elliptical perforated aluminium sheet provided the highest load value of 28,386 N in the staggered arrangement. In both hole arrangements, the elliptical perforated sheet gave the highest load value, while the triangle perforated sheet gave the lowest load value. The elliptical perforated sheet with linear hole arrangement provided the highest values in terms of specific load (435.57 N/g) and specific energy (0.27 J/g).

Keywords: perforated sheet metal, FE simulation, tension, hole geometry, hole arrangement

1 Introduction

Perforated sheets are sheets formed by drilling holes into flat sheets obtained from sheets by various methods. Holes drilled into flat sheets can be of different geometries and arrangements. The structures of perforated sheets are thin and light. Compared to flat sheets, they have a high strength/weight ratio. As with other parameters, hole sizes also have standards according to manufacturers. Perforated sheets have some advantages over flat sheets and have many uses, such as in screening, filtering, ventilation, and architecture. The holes in the sheet allow the passage of material, light, sound and fluid. Therefore, it is also used in industrial machinery [1]. In addition, since their strength is higher than their weight, they are used in the construction sector for both strengthening and balconies, stairs, fences, panels, etc. It is used in construction. Perforated metal sheets can be used in almost every field, from decorative use to industrial use.

Aluminium, steel, and chrome are generally used as the main material of perforated sheets [1–28]. Depending on the manufacturer’s choice, holes are made in different geometric shapes, sizes, and sequences using a hole punch press, laser cutting machine, or plasma cutting machine. Common hole geometries are circle, square, ellipse, triangle, and hexagon [1]. While there may be many different hole sequences, holes are drilled in sequences commonly called T, M, U, and Z. There are studies in which hole shape/size, hole arrangement loading conditions, and material change. It was mostly worked on circular perforated sheets. Apart from the circular hole, there are also studies on triangular and square perforated sheets [1,2]. The bending behaviour of perforated plates with a different numbers of sides has been investigated with finite element studies. The mid-point deflection and stress distribution were examined and it was understood that the circular hole shape was advantageous compared to the others [2]. The stress distribution and displacement were investigated for a circular plate perforated by 96 holes. An analysis of a nonperforated plate with the same dimensions and stiffness, similar loaded, was performed, determining the coefficient of stress concentration for a particular arrangement of holes [3].

Degtyarev and Degtyareva investigated the critical elastic buckling load of uniformly compressed isotropic plates perforated in equilateral triangular patterns using finite element method [4]. Baik et al. investigated the deformation behaviour of a perforated sheet during...
uniaxial tension using two-dimensional and three-dimensional finite element methods. They reported that as the thickness and the diameter of holes increase, the deformation behaviour at the yield point becomes closer to plane strain [5]. Jia et al. performed tensile tests on perforated aluminium plates to examine the effect of phase distribution in two-phase composite materials and reinforcement distribution in particle-reinforced composites [6,7]. In some studies, the vibration properties of perforated plates were examined and their natural frequencies were obtained [9–11]. Burian et al. investigated the protective properties of perforated bainitic steel plates experimentally and numerically. They reported that the designed hole patterns can reduce the weight of the armour by up to 40% compared to the monolithic plates of the same protection capability [13]. In most studies, the plastic behaviour of perforated sheets has been investigated both experimentally and numerically [14–17]. Studies examining the metal forming process of the perforated sheets are available in the literature [20–24]. Farsi et al. studied the influence of the area of the holes, die angles, die widths, and punch radius on the value of the spring-back and the bending forces in V-die bending are studied [20]. In a study in which shear stress analysis was performed under compression stress in circular perforated sheet metal plates with different arrays, the highest shear stress was obtained in the circular pattern [28]. There are also different works done on metals and other materials to investigate some properties [29–36].

In this study, the mechanical behaviour of linear and staggered arranged circle, triangle, square, hexagon, and ellipse perforated stainless steel and aluminium sheets under tensile loading was investigated by finite element analysis.

## 2 Simulation study

In this study, finite element analyses of perforated sheets with five different hole shapes were performed using stainless steel and aluminium alloy materials. Material properties of stainless steel and aluminium alloy are given in Table 1. Circle, triangle, square, hexagon, and ellipse geometries are used as the hole shapes. Linear and staggered hole arrangements were used in perforated sheet metals. The view of the finite element models of perforated sheets with both arrangement and hole geometry is given in Figure 1. The dimensions of sheet metals are $100 \times 200 \times 1.5$ in width, length, and thickness. Finite element analyses were carried out using the ANSYS programme. Nonlinear analyses were performed. It is fixed at one end of the sheet metal and a displacement of 1 mm is given from the other end. The schematic view of boundary conditions of the perforated sheet metal is given in Figure 2. Perforated sheet metal plates were modelled using a 3-D 20-node solid element (SOLID186). Three layers of solid elements are used through the thickness of the sheet metal.

### 3 Simulation results

#### 3.1 Effects of hole shapes and arrangements

##### 3.1.1 Stainless steel material

The force–displacement curves obtained as a result of the finite element analysis of stainless-steel metal sheets with linear and staggered arrangements with different hole geometries are given in Figure 3.

In Figure 3, the ellipse perforated sheet gave the highest load value with 22,424 N in the linear arranged stainless-steel sheet. The triangular perforated sheet showed the lowest load value with 12,513 N. While the load capacity increased with the change of hole geometry from the triangular to ellipse perforated sheet, the rigidity and energy-absorbing capacity of the sheets also increased.

In terms of hole arrangements, the load capacity of sheet metals belonging to the staggered arrangement was higher than that of the linear arrangement [1]. Ellipse perforated sheets gave the highest load value of 23,765 N in sheet metals with the staggered arrangement. Triangular perforated sheets gave the lowest load value of 18,610 N. The order of change of load according to geometry changes similarly to the linear order.

### Table 1: Elastic and plastic material properties of stainless steel and aluminium alloy

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Poisson’s ratio</th>
<th>Young’s modulus (GPa)</th>
<th>Yield strength (MPa)</th>
<th>Tangent modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>7,750</td>
<td>0.31</td>
<td>193</td>
<td>210</td>
<td>1,800</td>
</tr>
<tr>
<td>Aluminium alloy</td>
<td>2,770</td>
<td>0.33</td>
<td>71</td>
<td>280</td>
<td>500</td>
</tr>
</tbody>
</table>
Figure 1: Finite element models of perforated sheet metals (a) circle (linear), (b) circle (staggered), (c) square (linear), (d) square (staggered), (e) triangle (linear), (f) triangle (staggered), (g) hexagon (linear), (h) hexagon (staggered), (i) ellipse (linear), and (j) ellipse (staggered).
results of the stainless-steel perforated sheet metal (linear arrangement) obtained from finite element analyses are given in Table 2.

The specific load capacity (SLC) of the ellipse perforated sheet with 122.98 N/g, which has the highest load capacity, is also at the highest level compared to the others. At the same time, the energy absorption capacity is the highest in the ellipse perforated sheet with 19.6 J, and the specific energy absorption capacity is the highest among other perforated sheets with 0.11 J/g. Since the weights of the perforated sheets are approximately close to each other, the difference in the hole geometry is clearly evident when comparing the specific strength and energy absorption values. The triangular perforated sheet metal has the lowest specific load of 70.53 N/g and an energy absorption capacity of 0.06 J/g.

The simulation results of the staggered arranged perforated stainless-steel sheets are given in Table 3.

Perforated sheets with staggered arrangements have higher load capacity in all hole types compared to sheets with a linear arrangement. In terms of SLC, the highest value was obtained in an ellipse perforated sheet of 114.77 N/g, and the lowest value was obtained in a triangular perforated sheet of 90.87 N/g. In terms of specific energy absorption capacity, the ellipse perforated sheet has the highest value of 0.11 J/g. The specific load and

### Table 2: Simulation results of the stainless-steel perforated sheet metal (linear arrangement) obtained from finite element analyses

<table>
<thead>
<tr>
<th>Specimen core type</th>
<th>Force&lt;sub&gt;max&lt;/sub&gt; (N)</th>
<th>Weight (g)</th>
<th>Specific load capacity (SLC) (N/g)</th>
<th>Energy&lt;sup&gt;a&lt;/sup&gt; (J)</th>
<th>Specific absorbed energy (SAE) (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>17,270</td>
<td>176.29</td>
<td>97.96</td>
<td>14.84</td>
<td>0.08</td>
</tr>
<tr>
<td>Triangle</td>
<td>12,513</td>
<td>177.41</td>
<td>70.53</td>
<td>10.66</td>
<td>0.06</td>
</tr>
<tr>
<td>Square</td>
<td>18,601</td>
<td>182.8</td>
<td>101.76</td>
<td>16.17</td>
<td>0.09</td>
</tr>
<tr>
<td>Hexagon</td>
<td>15,334</td>
<td>169.23</td>
<td>90.61</td>
<td>13.09</td>
<td>0.08</td>
</tr>
<tr>
<td>Ellipse</td>
<td>22,424</td>
<td>182.34</td>
<td>122.98</td>
<td>19.6</td>
<td>0.11</td>
</tr>
</tbody>
</table>

<sup>a</sup>Energy values are calculated up to 1 mm displacement.
energy absorption capacities of the square perforated sheet metal are quite high and can be preferred after the ellipse.

### 3.1.2 Aluminium material

The force–displacement curves obtained as a result of the finite element analysis of aluminium metal sheets with linear and staggered arrangements with different hole geometries are given in Figure 4.

![Figure 4: The force–displacement curves of the aluminium sheet metal (a) linear arrangements and (b) staggered arrangements.](image)

In Figure 4, with the change of hole geometry in perforated aluminium sheets, while the maximum carried load increased, the energy absorption capacity also increased. In the aluminium plate where the holes are arranged linearly, the ellipse perforated sheet provided the highest load value of 28,836 N. Triangular perforated sheets showed the lowest load value of 14,584 N.

In terms of hole arrangement, the load capacity and energy absorption capacity of the sheets belonging to the staggered arrangement is higher than the linear arrangement. In the staggered arrangement, the ellipse perforated

### Table 3: Simulation results of the stainless-steel perforated sheet metal (staggered arrangement) obtained from finite element analyses

<table>
<thead>
<tr>
<th>Specimen core type</th>
<th>Force(_{\text{max}}) (N)</th>
<th>Weight (g)</th>
<th>Specific load capacity (SLC) (N/g)</th>
<th>Energy(^a) (J)</th>
<th>Specific absorbed energy (SAE) (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>20,392</td>
<td>204.23</td>
<td>99.85</td>
<td>17.50</td>
<td>0.09</td>
</tr>
<tr>
<td>Triangle</td>
<td>18,610</td>
<td>204.29</td>
<td>90.87</td>
<td>15.73</td>
<td>0.08</td>
</tr>
<tr>
<td>Square</td>
<td>20,941</td>
<td>207.51</td>
<td>100.92</td>
<td>17.94</td>
<td>0.09</td>
</tr>
<tr>
<td>Hexagon</td>
<td>19,331</td>
<td>200.68</td>
<td>96.33</td>
<td>16.55</td>
<td>0.08</td>
</tr>
<tr>
<td>Ellipse</td>
<td>23,795</td>
<td>207.32</td>
<td>114.77</td>
<td>20.56</td>
<td>0.10</td>
</tr>
</tbody>
</table>

\(^a\)Energy values are calculated up to 1 mm displacement.

### Table 4: Simulation results of the aluminium alloy perforated sheet metal (linear arrangement) obtained from finite element analyses

<table>
<thead>
<tr>
<th>Specimen core type</th>
<th>Force(_{\text{max}}) (N)</th>
<th>Weight (g)</th>
<th>Specific load capacity (SLC) (N/g)</th>
<th>Energy(^a) (J)</th>
<th>Specific absorbed energy (SAE) (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>20,910</td>
<td>63.01</td>
<td>331.85</td>
<td>13.58</td>
<td>0.22</td>
</tr>
<tr>
<td>Triangle</td>
<td>14,584</td>
<td>63.41</td>
<td>230.00</td>
<td>9.98</td>
<td>0.16</td>
</tr>
<tr>
<td>Square</td>
<td>23,278</td>
<td>65.34</td>
<td>356.26</td>
<td>14.70</td>
<td>0.22</td>
</tr>
<tr>
<td>Hexagon</td>
<td>18,134</td>
<td>60.49</td>
<td>299.79</td>
<td>12.04</td>
<td>0.20</td>
</tr>
<tr>
<td>Ellipse</td>
<td>28,386</td>
<td>65.17</td>
<td>435.57</td>
<td>17.67</td>
<td>0.27</td>
</tr>
</tbody>
</table>

\(^a\)Energy values are calculated up to 1 mm displacement.
Table 5: Simulation results of the aluminium alloy perforated sheet metal (staggered arrangement) obtained from finite element analyses

<table>
<thead>
<tr>
<th>Specimen core type</th>
<th>Force&lt;sub&gt;max&lt;/sub&gt; (N)</th>
<th>Weight (g)</th>
<th>Specific load capacity (SLC) (N/g)</th>
<th>Energy&lt;sup&gt;a&lt;/sup&gt; (J)</th>
<th>Specific absorbed energy (SAE) (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>24,729</td>
<td>72.99</td>
<td>338.80</td>
<td>15.91</td>
<td>0.22</td>
</tr>
<tr>
<td>Triangle</td>
<td>21,793</td>
<td>73.12</td>
<td>298.04</td>
<td>13.76</td>
<td>0.19</td>
</tr>
<tr>
<td>Square</td>
<td>25,044</td>
<td>74.17</td>
<td>337.66</td>
<td>16.60</td>
<td>0.22</td>
</tr>
<tr>
<td>Hexagon</td>
<td>23,368</td>
<td>71.72</td>
<td>325.82</td>
<td>14.77</td>
<td>0.21</td>
</tr>
<tr>
<td>Ellipse</td>
<td>29,167</td>
<td>74.1</td>
<td>393.62</td>
<td>18.92</td>
<td>0.26</td>
</tr>
</tbody>
</table>

<sup>a</sup>Energy values are calculated up to 1 mm displacement.

Figure 5: von Mises stress distribution of the perforated stainless-steel sheet.
sheet provided the highest load value of 29,167 N. The triangular perforated sheet showed the lowest load value of 21,793 N. The order of variation of the maximum load according to the geometry changes similarly to the linear order.

Simulation results of the aluminium perforated sheet metal (linear arrangement) obtained from finite element analyses are given in Table 4.

As seen in Table 4, the ellipse perforated sheet metal has the highest load capacity of 28,386 N. An SLC of 435.57 N/g is also at the highest level compared to the others. At the same time, the energy absorption capacity is the highest in ellipse perforated sheets with 17.67 J, and the specific absorbed energy is the highest among other perforated sheets with 0.27 J/g. The square hole sheet, on the other hand, is preferable after ellipse perforated sheets in terms of load capacity and energy absorption capacity. The simulation results of the staggered arranged perforated aluminium sheets are given in Table 5.

Perforated sheets with staggered arrangements have higher load capacity in all hole types compared to sheets with a linear arrangement. In terms of SLC, the highest value was obtained in an ellipse perforated sheet with 393.62 N/g, and the lowest value was obtained in a triangular perforated sheet with 298.04 N/g. In terms of specific energy absorption capacity, the ellipse perforated sheet has the highest value of 0.26 J/g.

3.2 Effect of ultimate stress pattern

3.2.1 Pattern of ultimate stress in the stainless-steel sheet

The views showing the von Mises stress distribution obtained from the simulations of the perforated stainless-steel sheet are given in Figure 5.

When the stress distributions are examined, the stress level of linearly arranged perforated sheets is lower than that of staggered [1]. When we look at the areas where the maximum stress occurs, we see that it occurs in different places for each hole type. Although the stress level in the sheet metal with the linear arrangement is lower than that in the other model, it is seen that the stress is concentrated at certain points. Stress in structures with edges such as hexagonal geometry is higher than that in more curved structures such as circles [2]. In the linearly arranged stainless-steel sheet, the highest stress was 302.24 MPa in the hexagon perforated sheet, and the lowest stress was in the ellipse perforated sheet with 248.32 MPa. The highest stress was 376.76 MPa in the hexagon perforated sheet, and the lowest stress was in the ellipse perforated sheet with 269.27 MPa in the staggered arranged stainless-steel sheet. The maximum stresses occurring in perforated sheets with the linear and staggered arrangement are more clearly shown in Figure 6.

A proportional increase was observed in all hole types in the staggered arrangement compared to the linear arrangement. In both orders, the highest stress occurred in the sheet metal with hexagon hole type.

3.2.2 Pattern of ultimate stress in the aluminium sheet

The views showing the von Mises stress distribution obtained from the simulations of the perforated aluminium sheet are given in Figure 7.

The stress level of linearly arranged perforated sheets is lower than that of staggered aluminium sheet metals. Stress in angular structures such as squares is higher than that in more curved structures such as circles [1,2]. In the linearly arranged aluminium sheet, the highest stress was 328.24 MPa in the square perforated sheet, and the lowest stress was in the ellipse perforated sheet with 300.62 MPa. The highest stress was 366.9 MPa in the ellipse perforated sheet, and the lowest stress was in the hexagon perforated sheet with 328.43 MPa in the
staggered arranged stainless-steel sheet. The maximum stresses occurring in perforated sheets with the linear and staggered arrangement are more clearly shown in Figure 8.

In Figure 8, the highest stress was observed in the square-holed sheet in the linearly arranged perforated sheet, while the elliptical-holed sheet in the staggered regular sheet was formed in the perforated sheet. It is clearly understood that the lowest stress occurs in the ellipse in the linear regular sheet, while it occurs in the hexagon perforated sheet in the staggered regular sheet. It has been observed that the maximum stresses occurring in two different hole arrangements in the aluminium perforated sheet are not proportional to each other. Only the stress level is different between the two-hole arrangements and the hole geometry in the stainless steel and there is a proportional variation (Figure 8).
The load and energy – The mechanical behaviour of a perforated sheet

Square

– The load capacity, energy absorption capacity of the

Triangular perforated sheets showed the lowest load – The ellipse perforated sheet showed the highest load

Perforated sheets with staggered arrangement have simulations are listed below:

– The load capacity, energy-absorbing capacity, and rigidity of perforated sheet metals changed with the hole geometry.

– Perforated sheets with staggered arrangement have higher load capacity in all hole types compared to sheets with the linear arrangement.

– The ellipse perforated sheet showed the highest load and absorbed energy value in the linear and staggered arranged stainless steel and aluminium sheet.

– Triangular perforated sheets showed the lowest load value in both types of materials and arrangements.

– Specific load and energy absorption capacity of the ellipse perforated aluminium sheet with linear arrangement gave the best results.

– Square-holed sheets, on the other hand, are preferable after the ellipse perforated sheets in terms of both load capacity and energy absorption capacity.

– The highest von Mises stress in the perforated sheet was observed in the staggered ellipse perforated sheet.

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**Data availability statement:** All data generated or analysed during this study are included in this published article.

### References


