Effect of location and orientation of two short dents on ultimate compressive strength of a thin square steel plate

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Abstract: Thin plates are subject to several imperfections (including dents) which reduce the ultimate strength of plates. In this work, nearness effect of two short dents of same size on the ultimate strength of a thin square steel plate is numerically investigated. Dents are modeled on the FE surface of the undented plate by varying the location and orientation of dents and the centre distance between dents. These dented plates are analysed using non-linear FE static buckling analysis. It is found that the influence of second dent is not as appreciable as that of the first one, irrespective of parameters considered.

Keywords: thin plates; buckling; dent; collapse load; nearness effect.


Biography notes:

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Balakrishnan Prabu received his Master of Engineering Degree in engineering design from Anna University, Chennai, India, in 1993 and his PhD in thin shell buckling from Pondicherry University, Puducherry, India in 2007. At present, he is working as an Associate Professor in the Department of Mechanical Engineering, Pondicherry Engineering College, Puducherry, India. His main research interest is in buckling behaviour of thin shell structures.

Natarajan Alagumurthi received both his Master of Technology Degree in Energy Technology and his PhD in heat generation and transfer in cylindrical grinding from Pondicherry University, Puducherry, India in 1996 and 2006, respectively. At present, he is working as a Professor in the Department of Mechanical Engineering, Pondicherry Engineering College, Puducherry, India. His main research interest is in modelling and simulation of manufacturing and thermal systems.

1 Introduction

Despite the fact that studies on the buckling of columns go back to the end of the nineteenth century, viable theoretical solutions for the plastic buckling of plates were proposed only in the late 1930s and 1940s. Most steel-plated structures such as ships, barges, offshore floating production units, deck structures of offshore platforms and other land-based structures (e.g., bins, bunkers) make extensive use of stiffened steel plate in their construction. Steel plates can normally suffer various types of damages while in service. Some types of damage, such as corrosion and fatigue cracking, are related to age, but others are more likely to be mechanical damage caused by accidental loading or impact. Structural damage can reduce the load carrying capacity of the structure and lead to catastrophic failure.

The analysis of a typical stiffened plate structure can be performed at grillage level, stiffened panel level between two adjacent transverses and bare plate element level between longitudinal and transverse stiffeners (Figure 1).
Local buckling and collapse of plating between stiffeners is a basic failure mode and is important for evaluating the exact strength for safe design. The bending rigidities of the boundary edges of plates in between transverse frames and between longitudinal stiffeners are quite high compared to that of the plate itself. The rotational restraints along the plate edges can be considered to be small for plates subjected to axial compression. Hence, the bare plate can be considered as simply supported along all the edges (Suneel Kumar et al., 2007). Under normal operational conditions, the plates between stiffeners experience significant compressive loading. Therefore, the compressive strength of steel plates is of primary concern to the designer.

A dent is one of the common geometrical imperfections (damage) present in thin plate structures and may be formed in the plate due to impact with sharp or foreign objects, etc. This type of dent imperfection reduces the ultimate load carrying capacity of the plates and the quantum of reduction depends on the number of dents, their size, location and their orientation. Hence, it is essential to predict the ultimate strength of the dented plates to determine the safe loads that can be applied on the structures.

2 Literature review

Though Euler produced the first paper on the buckling of columns in 1744, the first theoretical examination of plate buckling was by Bryan, who obtained a solution to the problem of a simply supported plate under uniform compression in 1891, as mentioned by Rhodes (2002). Since then, several researchers all over the world have investigated the buckling of plates with a wide variety of imperfections, under different loading and boundary conditions, using various methods of analysis that are broadly grouped into analytical methods, experimental tests, empirical approaches and non-linear finite element simulations. Numerous studies are available in the literature with regard to the ultimate strength of thin plates with imperfections like weld induced initial (distributed) imperfections, residual stresses, etc. (Guedes Soares and Kmiecik 1995; Hopperstad et al., 1997; Ikeda et al., 2007; Luong and Tuong, 2006; Paik and Seo, 2005; Paik et al., 2000, 2001; Sadovsky et al., 2005, 2006; Ueda and Yao, 1978, 1984, 1991; Ueda et al., 1977). However, to the best of the knowledge of the authors, only very limited literature is available that considers the effect of local imperfections on the ultimate strength of thin plates and a few of these studies are presented here.

Pal’chikov (1971) discussed the stress concentration around dents (spherical and elliptical shapes) and the mutual effect of dents on axially loaded thin plates and gave expression for stress variations due to the presence of dents, based on asymptotic analysis. Dow and Smith (1984) studied various forms of imperfections with particular reference to the influence of localised initial imperfections on stiffness and strength of rectangular plates, by assuming a sinusoidal form for initial imperfections, both in longitudinal and transverse directions. It was concluded that the effect of localised initial imperfections strongly depends on the amplitude and slightly depends on the shape and position of the imperfection along the length of the plate.

Paik et al. (2003) numerically studied the ultimate strength characteristics of dented plates under axial compressive loads, considering variations in shape, size and location of the dent. From the numerical analysis of the results obtained, an empirical formula was derived to determine the ultimate strength of the dented plates. It was concluded that the shape of the circular dent (with either spherical or conical depression) does not much affect the collapse strength of the plate. Paik (2005) numerically investigated the ultimate shear strength characteristics of dented plates and derived an empirical formula to predict the ultimate shear strength of dented plates. One of the important conclusions arrived at was that a centrally located dent affects the shear loading capacity more than dents located near edges, which is in contradiction to the findings of Paik et al. (2003) in the case of compressive loads. Luiz and Guedes Soares (2006) studied the effect of the level of localised imperfection and its spatial location on the ultimate collapse load of a plate assembly under compressive loads and it was concluded that the effect of position of the localised imperfections depends on the final shape of the imperfections, consisting of global and local imperfections. Lang and Kwon (2007) carried out numerical studies on the effect of impact velocity of forming the dent on the compressive failure load of aircraft fuselage panels (of aluminium alloy) with and without stiffeners. It was concluded that dents formed with low velocity impact gave lower buckling strength than virgin panels and as the impact velocity increases, the failure load of the dented panel increases, exceeding that of the virgin panel.

Witkowska and Guedes Soares (2008) numerically studied the collapse behaviour and ultimate strength of damaged (dented) stiffened panels and further investigated the influence of parameters like stiffener geometry, etc., on the ultimate strength of plates with and without local dents. Hai et al. (2010) studied the influence of multiple defects,
namely initial distortion, weld residual stresses, cracks and local dents on ultimate strength of the plate and also derived expressions for reliability index and sensitivity analysis of the plate. In their work, Hai et al. (2011) proposed a method to determine the global reliability index and sensitivity expression of the reliability index of a plate structure with a local dent based on ultimate strength reduction factor. Park et al. (2011) numerically investigated the influence of curvature, magnitude of initial deflection, slenderness ratio and aspect ratio on the characteristics of the buckling/ultimate strength and progressive collapse behaviour of unstiffened and stiffened curved plates under axial compression. In their previous work, Raviprakash et al. (2011) numerically studied the effect of transverse/longitudinal dents on the ultimate strength of a thin square plate under uniaxial compression and it was concluded that transverse dents affect the ultimate strength more drastically than longitudinal dents. Prabu et al. (2012) investigated in detail the neighbourhood effect of two circumferential short dents on the buckling behaviour of thin short stainless steel cylindrical shells for different centre distances between dents using non-linear FE static buckling analysis and their buckling behaviours are compared with that of a cylindrical shell with a short circumferential dent. It was concluded that the effect of two short dents and the nearness effect seems to be negligible compared with the effect of a single dent in reducing the buckling strength of a cylindrical shell.

From the above literature survey, it is clear that the effect of angle of orientation of the dent on the ultimate strength of thin plates is not considered in any of the studies, to the best of the knowledge of the authors. Further, there is not much in the available literature investigating the nearness effect of two dents on the ultimate strength of plates in particular. Hence, in the present work, efforts are made to numerically examine the influence of the presence of two short dents of the same size (dent length DL = 200 mm, dent width DW = 100 mm and dent depth DD = 24 mm) with different orientations (both transverse TT, both longitudinal LL and one transverse & one longitudinal TL) located centrally on the transverse/longitudinal axis of the plate on the ultimate strength of a thin plate of size 1000 mm × 1000 mm × 12 mm, under uniaxial compressive loading with simply supported boundary conditions. For this purpose, FE models of a perfect plate with two dents centrally located on the transverse axis of the plate at different orientations are generated and analysed using the non-linear static buckling analysis module of the general purpose FE software ANSYS V12.

3 Buckling analysis

Buckling analysis can be broadly classified into two types, namely,

1) eigen (linear) buckling analysis
2) non-linear (collapse) buckling analysis.

3.1 Linear buckling analysis

An eigen buckling analysis predicts the theoretical buckling strength of an ideal linear elastic structure. This analysis is used to predict the bifurcation point using a linearised model of elastic structure. It is a technique used to determine buckling loads – critical loads – at which a structure becomes unstable and buckled mode shapes – the characteristic shape associated with a structure’s buckled response. The other name for this eigen buckling analysis is ‘bifurcation analysis’. Bifurcation buckling refers to the unbounded growth of a new deformation pattern. This analysis involves calculating the points at which the primary load deflection path is bifurcated by a secondary load deflection path. The ANSYS finite element software package is used to determine the buckling strength of the perfect thin plate through an eigen buckling analysis. In the eigen buckling analysis, imperfections and non-linearities cannot be included. Sub-space iteration scheme can be used to extract the load factor or the eigen value. The basic form of the eigen buckling analysis is given by

$$[K][\phi_i] = \lambda_i [S][\phi_i]$$


3.2 Non-linear static buckling analysis

This is a more accurate approach, since this FE analysis has the capability to analyse actual structures (Devika and Arumaikkannu, 2011) with imperfections. This approach is highly recommended for design or evaluation of actual structures. This technique employs a non-linear structural analysis with gradually increasing loads to seek the load level at which the structure become unstable. Using this non-linear technique, features such as initial imperfections, plastic behaviour, etc., can be included in the model. In this analysis both geometrical and material non-linearities are utilised, because the thin shell structures are subjected to large deformations and further, at some of the imperfection location(s) on the structures, the stresses may exceed the elastic limit due to imperfections present in that location(s). Here, material non-linearity is defined with the kinematic hardening rule (Avner, 2001). A full incremental non-linear static stress analysis is used taking the initial displacement (imperfections) matrix into account and applying displacement loading incrementally. To find the maximum load carrying capacity of the structure accurately, a snap through approach of the non-linear analysis has been followed.

While using the Newton–Raphson iteration scheme to solve the system of equations in non-linear analysis near to the critical load of the structure, the tangential stiffness matrix may become singular and thereby, further load steps are not possible. To overcome this problem, the arc tangent iteration scheme is adopted (Forde and Stiemer, 1987). Both force and moment convergence criteria are selected with a
maximum and minimum convergence tolerance of 1 and 0.0001 respectively.

4 FE modelling

SHELL181 element of ANSYS is suitable for analysing thin to moderately-thin shell structures. This element can handle membrane, bending and transverse shear effects. It is a 4-node element with six degrees of freedom at each node. It is well-suited for linear, large rotation, or large strain non-linear applications. This element also has plasticity and stress stiffening capabilities.

4.1 Thin plate shell model

In the present work, a square structural steel (HT-32) plate is taken for the study. The dimensions and material properties of the plate (Paik, 2009) are as given below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length ( (L) )</td>
<td>1000 mm</td>
</tr>
<tr>
<td>Width ( (W) )</td>
<td>1000 mm</td>
</tr>
<tr>
<td>Thickness ( (t) )</td>
<td>12 mm</td>
</tr>
<tr>
<td>Young’s modulus ( (E) )</td>
<td>( 2.058 \times 10^5 ) N/mm²</td>
</tr>
<tr>
<td>Yield stress ( (\sigma_y) )</td>
<td>313.6 N/mm²</td>
</tr>
<tr>
<td>Poisson’s ratio ( (\gamma) )</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Zero strain hardening effect is assumed.

4.2 Boundary conditions

It is known that a square plate with all fixed boundary conditions is more stable than the same plate with all simply supported boundary conditions. Since the actual boundary conditions for a real plate may be somewhere between the all fixed and all simply supported extremes, the critical and conservative case of simply supported edges is selected in the present study (El-Sawy et al., 2004). Simply supported boundary conditions, as shown in Figure 2, are applied on all the edges of the thin plate and uniform displacement loading is applied on one side of the plate model, while the opposite side is restrained from moving along the load direction (Suneel Kumar et al., 2007).

4.3 Model validation

4.3.1 Linear analysis

The analytical solution of the perfect thin plate (Timoshenko and Gere, 1965) can be obtained using equation (3.1) given below.

\[
N_x = \frac{\pi^2 D}{W^2} \left( \frac{mW}{L} + \frac{n^2 L}{mW} \right)^2
\]

(3.1)

where

\[
D = \frac{Et^3}{12(1-\gamma^2)}
\]

\( m \) = number of longitudinal lobes and \( n \) = number of transverse lobes.

For the plate taken for the present study (1000 mm × 1000 mm × 12 mm), the analytical solution and the FE eigen buckling analysis result obtained are compared in Table 1, showing an error of 0.108%. The mode shape obtained from FE eigen buckling analysis is shown in Figure 3.

<table>
<thead>
<tr>
<th>( m )</th>
<th>( n )</th>
<th>Analytical solution (kN)</th>
<th>FEA result (kN)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1285.660</td>
<td>1284.271</td>
<td>(-) 0.108</td>
</tr>
</tbody>
</table>

4.3.2 Non-linear analysis

Validation of the non-linear analysis of the developed FE model is done with the published results of Paik et al. (2001) and Suneel Kumar et al. (2007). For this purpose,
Effect of location and orientation of two short dents

with von Mises stress distribution at limit load conditions is shown in Figure 5. A reasonably good agreement is observed between the numerical results (43.773 kN) obtained using the FE model developed (under static loading) and the published experimental results (41.174 kN) of Paik and Thayamballi (2003) with an error of 5.94%.

Figure 5 Load vs. edge displacement curve and von Mises stress distribution at limit load conditions for the model plate (500 × 500 × 1.6 mm) taken for comparison with the published experimental results of Paik and Thayamballi (2003) (see online version for colours)

To validate the FE model developed with published experimental results, the experimental results published by Paik and Thayamballi (2003) are taken for comparison. For this purpose, the same plate of size 500 × 500 × 1.6 mm (with material properties \(\sigma_y = 251.8\) MPa, \(E = 198.5\) GPa and \(\gamma = 0.3\)), used by Paik and Thayamballi (2003) for their experimentation studied under quasi-static axial compressive loading \(V_o = 0.05\) mm/s) and simply supported boundary conditions with side edge constraints (the same boundary conditions used in the present study), is considered. The load vs. edge displacement curve of the above plate model along with von Mises stress distribution is shown in Figure 5. A reasonably good agreement is observed between the published experimental results (41.174 kN) of Paik and Thayamballi (2003) with an error of 5.94%.

Figure 4 Load vs. edge displacement and out-of-plane displacement of the centre point of the undented plate under axial compression (see online version for colours)

(a) Load Vs edge displacement curve

(b) Comparison of load Vs out of plane displacement of the center point of FE model validated with Paik et al. (2001)

To validate the FE model developed with published experimental results, the experimental results published by Paik and Thayamballi (2003) are taken for comparison. For this purpose, the same plate of size 500 × 500 × 1.6 mm (with material properties \(\sigma_y = 251.8\) MPa, \(E = 198.5\) GPa and \(\gamma = 0.3\)), used by Paik and Thayamballi (2003) for their experimentation studied under quasi-static axial compressive loading \(V_o = 0.05\) mm/s) and simply supported boundary conditions with side edge constraints (the same boundary conditions used in the present study), is considered. The load vs. edge displacement curve of the above plate model along with von Mises stress distribution is shown in Figure 5. A reasonably good agreement is observed between the published experimental results (41.174 kN) of Paik and Thayamballi (2003) with an error of 5.94%.

4.3.3 Validation of dented plate

A validation study is performed on the dented HT 32 steel plate of size 1000 × 1000 × 12 mm (with dent size \(DL = 600\) mm and \(DW = 400\) mm) by decreasing the dent depth (DD) in steps. The Ultimate Compressive Strength

Using a 40 × 40 elements mesh, a non-linear FE analysis including both material and geometric non-linearities is carried out for the undented plate taken for the present study and its ultimate compressive strength is found to be 2882.834 kN.
2) At the place where there is change of curvature present in the shell structures, the change may cause local bending stress. Hence, it is essential to model the surrounding region carefully (Cook et al., 2002).

3) Size of the element in the dent region. According to Song et al. (2004), when the element size is reduced to half the previous element size, the variation in the numerical result obtained should be less than 1%.

In this work, all the above three points are taken into account carefully. A sample of the FE model of the dented plate (with two dents) generated is shown in Figure 7(a) and different dent orientations are shown in Figure 7(b).

5 Results and discussion

A non-linear static buckling analysis is used to determine the UCS (hereafter to be called ultimate strength) of the dented thin plates with two short dents located centrally at the transverse/longitudinal axis of the plate, having a distance between the centre of the dents (hereafter to be called centre distance) of 250 mm to 450 mm in steps of 50 mm, with different orientations (both transverse dents, both longitudinal dents and one transverse and one longitudinal dent). Throughout this study, dents of the same size (dent length $DL = 200$ mm, dent width $DW = 100$ mm and dent depth $DD = 24$ mm) are used. In this work, the angle of orientation of the dent ($\theta$) is measured (in an anti-clockwise direction) at the centre of the dent with reference to the line shown in Figure 7(b) with the longitudinal axis of the dent, (i.e.,) transverse and longitudinal dent orientation means $\theta = 0^\circ$ and $90^\circ$ respectively.

4.4 Modelling of dented plates

A dent has been modelled using the shape given in equation (4.1), which is similar to the equation used by Dow and Smith (1984) and Raviprakash et al. (2011) for modelling dents in plates and Wulsschleger and Peining Meyer (2002), Gavrilenko (2002) and Prabu et al. (2007, 2010) for modelling dents in cylindrical shells.

$$
\Delta = \frac{1}{4} \left[ 1 + \cos \frac{2\pi x(i)}{DL} \right] \left[ 1 + \cos \frac{2\pi y(i)}{DW} \right]
$$

where $\Delta$ = deformation due to dent geometry on perfect plate structure for the given $x(i)$ and $y(i)$ value, (taking the centre of the dent as origin)

While modelling localised geometrical imperfections such as dents, the following three points have to be considered carefully.

1) modelling the dent shape accurately (Janardhan Reddy et al., 2011) using FE data base of perfect plate.

<table>
<thead>
<tr>
<th>$DD$, mm</th>
<th>UCS, kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2882.834</td>
</tr>
<tr>
<td>0.05</td>
<td>2620.206</td>
</tr>
<tr>
<td>0.1</td>
<td>2518.638</td>
</tr>
<tr>
<td>1</td>
<td>2390.413</td>
</tr>
<tr>
<td>3</td>
<td>2295.197</td>
</tr>
<tr>
<td>5</td>
<td>2273.886</td>
</tr>
<tr>
<td>8</td>
<td>2241.989</td>
</tr>
<tr>
<td>16</td>
<td>2171.275</td>
</tr>
<tr>
<td>24</td>
<td>2111.641</td>
</tr>
<tr>
<td>36</td>
<td>2059.715</td>
</tr>
</tbody>
</table>

Figure 7 (a) FE model of the plate with two dents and (b) Front view of the plate with two dents (see online version for colours)

(UCS) of the dented plates is obtained and is shown in Table 2 and Figure 6. From Table 2 and Figure 6, it can be noted that as the dent depth decreases, the UCS progressively increases and converges to that of the undented plate.

Figure 6 Effect of variation of dent depth on the UCS of a HT 32 steel plate ($1000 \times 1000 \times 12$ mm) with a centrally located dent ($DL = 600$ mm & $DW = 400$ mm) (see online version for colours)
5.1 Variation of von Mises stress distribution at gradually applied loading conditions

Figure 8 shows the von Mises stress distribution of the dented plate having two transverse short dents of the same size located centrally along the transverse axis of the plate with a centre distance of 250 mm at different load sub-steps. As the compressive load applied on the dented plate is gradually increased to 1627.008 kN, the inner dent tips first reach the high stress conditions, as shown in Figure 8(a). As the load applied increased to 1976.289 kN, the stress concentration regions at the dent tips grow further and the two stress concentration regions near the inner tips merge together, as shown in Figure 8(d). On further loading, both the inner and outer dent tip stress concentration regions grow in size up to a load of 2173.496 kN. Thereafter, on further loading, up to limit load condition the outer dent tips stress concentrations spread to the entire surface of the plate, except the Dent Affected Regions (which is the low stress region created above and below the dent geometries, hereafter to be called DAR), as shown in Figure 8(h).

Figure 8  von Mises stress distribution of dented plate having two transverse short dents with a centre distance of 250 mm at different load substeps (see online version for colours)

Figure 9 shows load versus edge displacement curve (hereafter to be called stiffness curve). From this stiffness curve, it can be noted that before reaching the limit load conditions of zero stiffness, the curve shows two slopes with a kink. Up to the kink, the deformation along the depth direction of dents increases and at the kink, deformation along the depth direction reaches a limiting value and thereafter, the dent deforms along the transverse axis of the plate, as shown in Figure 10.

5.2 Ultimate strength of plate with two dents located along transverse axis of the plate with different orientations

The ultimate strength values obtained for a plate with two short dents (having varied centre distances) located centrally along the transverse axis of the plate with different orientations (two transverse dents \((TT)\), two longitudinal dents \((LL)\) and one transverse and one longitudinal dent \((TL)\)) are summarised in Table 3.
Table 3  Variation of ultimate strength of plate with two short dents (having varied centre distances) located centrally on the transverse axis of the plate with different orientations

<table>
<thead>
<tr>
<th>Centre distance, mm</th>
<th>Orientation of dents</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TT</td>
</tr>
<tr>
<td>250</td>
<td>2242.991</td>
</tr>
<tr>
<td>300</td>
<td>2220.586</td>
</tr>
<tr>
<td>350</td>
<td>2191.361</td>
</tr>
<tr>
<td>400</td>
<td>2158.393</td>
</tr>
<tr>
<td>450</td>
<td>2123.147</td>
</tr>
</tbody>
</table>

Figure 11  von Mises stress distribution of dented plate at limit load conditions with (a) one transverse dent and (b) to (f) two transverse dents with centre distances of 250, 300, 350, 400 and 450 mm respectively (see online version for colours)

5.2.1  Plate with two transverse dents

Figure 11 shows the von Mises stress distribution of a dented plate with one transverse dent and two transverse short dents of the same size located centrally along the transverse axis of the plate, having varied centre distances from 250 mm to 450 mm in steps of 50 mm at limit load conditions.

Compared to the ultimate strength of the undented plate (2882.834 kN), the reduction in the ultimate strength of the plate with one transverse dent (Figure 11(a)) is 19.77%, for the plate with two transverse dents having centre distances of 250 mm and 450 mm is 22.19% and 26.35%, respectively. From the above, it is clear that as the number of dents increases from one to two, the reduction in the ultimate strength is not doubled irrespective of the centre distance because of the fact that the load carrying region of the plate excluding DAR is reduced slightly due to the merging of DAR of two dents and this is evident from Figures 11(b) to (f).

Figure 12 shows the variation of ultimate strength of an undented plate, a plate with one transverse dent and a plate with two transverse dents having varied centre distances. From Figure 10, it can be noted that in the case of the plate with two transverse dents, as the centre distance between the dents increases from 250 mm to 450 mm, the reduction in the ultimate strength of the plate is 5.34%. This is due to the fact that as the centre distance increases, DAR increases while reducing the load carrying region of the plate other than DARs.

Figure 12  Variation of ultimate strength for an undented plate, a plate with one transverse dent and a plate with two transverse dents having varied centre distance (see online version for colours)

5.2.2  Plate with two longitudinal dents

Figure 13 shows the von Mises stress distribution of a dented plate with one longitudinal dent and two longitudinal short dents of the same size located centrally along the transverse axis of the plate, having varied centre distances from 250 mm to 450 mm in steps of 50 mm at their limit load conditions. Compared to the undented plate, the reduction in the ultimate strength of the plate with one longitudinal dent (Figure 13(a)) is 19.09% and for the plates with two longitudinal dents having centre distances of 250 mm and 450 mm, it is 19.61% and 22.17%, respectively. From the above, once again it is clear that as the number of dents increases from one to two, the reduction in the buckling strength is not doubled, irrespective of the centre distance and this is evident from Figures 13(b) to (f).

Figure 14 shows the variation of ultimate strength of an undented plate, a plate with a single longitudinal dent and a plate with two longitudinal dents having varied centre distances. It can be noted from Figure 14 that in the case of the plate with two longitudinal dents, as the centre distance between the dents increases from 250 mm to 450 mm, the reduction in the ultimate strength is only 3.18% (as against 5.34% for transverse dents). Further, it may also be noted that the ultimate strengths of the plate with single and two longitudinal dents are higher than those of the plates with transverse dent(s).
Effect of location and orientation of two short dents

5.2.3 Plate with one transverse and one longitudinal dent

Figure 15 shows the von Mises stress distribution of the plate with one transverse and one longitudinal dent with varying centre distances from 250 mm to 450 mm in steps of 50 mm at limit load conditions. Compared to the ultimate strength of the undented plate, the reduction in the ultimate strength of the plate with these two dents having centre distance of 250 mm and 450 mm is 20.86% and 24.15%, respectively.

Figure 16 shows the variation of ultimate strength of an undented plate, a plate with one transverse/longitudinal dent and a plate with one transverse and one longitudinal dent having varied centre distances. It can be noted from Figure 14 that in the case of the plate with one transverse and one longitudinal dent, as the centre distance between the dents increases from 250 mm to 450 mm, the reduction in the ultimate strength is only 4.16% (as against 5.34% and 3.18% for the plates with two transverse dents and two longitudinal dents, respectively).
Figure 18 shows the variation of the ultimate strength of an undented plate, a plate with one transverse dent and a plate with two transverse dents having varied centre distances. Compared to the ultimate strength of the undented plate, the reduction in the ultimate strength of the plate with two transverse dents having centre distances of 250 mm and 450 mm is 19.28% and 19.07%, respectively (with a marginal variation of 0.21%). It may be of interest to note that the ultimate strength of the plate with two transverse dents located along the longitudinal axis of the plate is more than that of one dent. The reason for this effect may be assigned to the fact that in the case of the plate with two dents, DARs decrease, causing increase in ultimate strength and this effect further increases marginally as the centre distance increases.

Comparing Tables 3 and 4 and Figures 12 and 18, it is clear that the plate with two transverse dents located along the longitudinal axis shows higher strength than that of the transverse axis, because the number of sub-regions of DARs or total area of DARs (Figures 11 and 17) is more in case of the two dents located along the transverse axis than in the other case, since DARs are formed only along the loading direction.

Table 4 Variation of ultimate strength of plate with two short dents (having varied centre distances) located centrally on the longitudinal axis of the plate with different orientations

<table>
<thead>
<tr>
<th>Center distance, mm</th>
<th>Orientation of dents</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TT</td>
</tr>
<tr>
<td>250</td>
<td>2327.040</td>
</tr>
<tr>
<td>300</td>
<td>2329.494</td>
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</tr>
<tr>
<td>400</td>
<td>2332.225</td>
</tr>
<tr>
<td>450</td>
<td>2332.990</td>
</tr>
</tbody>
</table>

5.3 Ultimate strength of plate with two dents located at longitudinal axis of the plate with different orientations

The ultimate strength values obtained for the plate with two short dents (having varied centre distances) located centrally on the longitudinal axis of the plate with different orientations (two transverse dents (TT), two longitudinal dents (LL) and one transverse and one longitudinal dent (TL)) are summarised in Table 4.

5.3.1 Plate with two transverse dents

Figure 17 shows the von Mises stress distribution of a dented plate having one and two short transverse dents of the same size located centrally along the longitudinal axis of the plate, with centre distances varying from 250 mm to 450 mm in steps of 50 mm at limit load conditions.

Figure 17 von Mises stress distribution of plate at limit load conditions with (a) one transverse dent and (b) to (f) two transverse dents with centre distances of 250, 300, 350, 400 and 450 mm respectively (see online version for colours)

5.3.2 Plate with two longitudinal dents

Figure 19 shows the von Mises stress distribution of a dented plate having one and two longitudinal short dents of the same size located centrally along the longitudinal axis of the plate, with centre distances varying from 250 mm to 450 mm in steps of 50 mm at limit load conditions.

Figure 20 shows the variation of ultimate strength of an undented plate, a plate with one longitudinal dent and a plate with two longitudinal dents having varied centre distances. Compared to the ultimate strength of the undented plate, the reduction in ultimate strength of the plate with two longitudinal dents having centre distances of 250 and 450 mm is 18.75% and 18.97%, respectively (with a marginal variation of 0.22%).
Effect of location and orientation of two short dents located on the longitudinal axis of the plate. Further, it can be noted that for all types of orientation of dents (TT, LL and TL), the ultimate strength of the plate with dents located along the longitudinal axis is higher compared to that of transverse axis.

5.3.3 Plate with one transverse and one longitudinal dent

Figure 21 shows the von Mises Stress distribution of the plate with one transverse and one longitudinal dent with varying centre distances from 250 mm to 450 mm in steps of 50 mm at limit load conditions.

Figure 22 shows the variation of ultimate strength of an undented plate, a plate with one transverse/longitudinal dent and a plate with one transverse and one longitudinal dent having varied centre distances. Compared to the ultimate strength of the undented plate, the reduction in the ultimate strength of the plate with these two dents having centre distances of 250 and 450 mm is 19.53% and 19.51%, respectively (with a marginal variation of 0.03%).

Comparing Tables 3 and 4, it can be concluded that the effect of centre distance variation on the ultimate strength of the plate is considerable in case of dents located along the transverse axis and insignificant in the case of dents located on the longitudinal axis of the plate.
6 Conclusions

The following conclusions are derived from the dented plates with short dent(s) considered in the present study.

- Load carrying capacity of the dented plates is directly proportional to the area of the plate region, excluding DAR(s).
- The ultimate strength of all plates with dent(s) is less than that of undented plates.
- In the case of a plate with one short dent (of size $DL = 200$ mm, $DW = 100$ mm and $DD = 24$ mm) located at the centre of the plate, though a reduction of about 20% in ultimate strength of the dented plate is noticed when compared to the undented plate, orientation of the dent does not seem to make much difference to the ultimate strength of the dented plate.
- Compared to the undented plate, the minimum and maximum reduction observed in the ultimate strength of dented plates with two short dents are 18.75% and 26.35%, respectively.
- In case of plates with transverse dent(s) located along the transverse axis of the plate, when the number of dents increases from one to two, the reduction in ultimate strength is not doubled, irrespective of centre distance and it is only in the range of 3.18 to 5.34%.
- The effect of centre distance variation on the ultimate strength of the plate is insignificant in the case of dents located on the longitudinal axis of the plate.
- The ultimate strength of the plate with two dents located along the longitudinal axis of the plate is more than that of one dent, whereas in case of two dents located along the transverse axis of the plate, the ultimate strength is less than that of one dent.
- For all types of orientation of dents, the ultimate strength of the plate with dents located along the longitudinal axis is higher compared to that of transverse axis, irrespective of the centre distance.

References


Effect of location and orientation of two short dents


