Springer

KSME

Journal of Mechanical Science and Technology 25 (9) (2011) 2377~2384
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-011-0527-4

Ultimate strength of a square plate with a longitudinal/transverse dent under axial compression†

A. V. Raviprakash*, B. Prabu and N. Alagumurthi

Department of Mechanical Engineering, Pondicherry Engineering College, Puducherry, 605 014, India

(Manuscript Received October 8, 2010; Revised April 18, 2011; Accepted April 28, 2011)

Abstract

Thin shell structures are efficient structures because of their high load-carrying capacity and small weight. Thin plates are one of the common structural elements. Their load-carrying capacity mainly depends on their buckling behavior, which is in turn affected by the imperfections present in them. Dent is one of the common geometrical imperfections in thin shell structures, which may be formed in the plate as an impact of sharp objects, among other reasons. Using ANSYS nonlinear FEA, the present work conducts a numerical study of the effect of various dent parameters on the ultimate strength of a thin plate, with a longitudinal or a transverse dent located centrally on the plate, under uniaxial compressive loading with simply supported boundary conditions.

Keywords: Thin plates; Buckling; Dent; Collapse load; Non-linear FEA

1. Introduction

Studies on the buckling of columns go back to the end of the 19th century; however, viable theoretical solutions for the plastic buckling of plates have only been proposed in the late 1930s and 1940s [1]. 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) use stiffened steel plates extensively in their construction. Steel plates normally suffer from various types of damage while in service. Some types of damage such as corrosion and fatigue cracking are related to age, but others are more likely classified as 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 typical stiffened plate structures can be performed at grillage level, stiffened panel level between two adjacent transverses, and bare plate element level between longitudinal and transverse stiffeners (Fig. 1). In the present work, local buckling and collapse of plating between stiffeners are considered because these are among the basic failure types. The bending resistance of the bounding edges of the bare plate in between longitudinal and transverse stiffeners is high compared with that of the plate itself. The rotational restraints along the plate edges can be considered small for plates subjected to axial compression; hence, the bare plate can be considered as simply supported along all edges [2]. Under normal operating conditions, the plates between stiffeners experience significant compressive loading; the ultimate collapse strength of steel plates is important in creating a safe design.

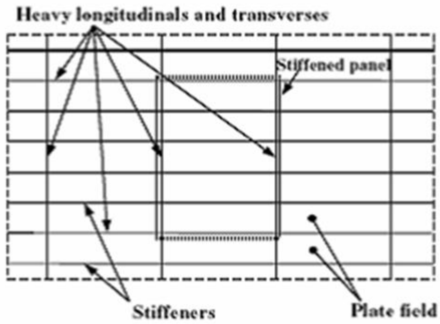


Fig. 1. Typical stiffened plate structure in a ship.

Dent is one of the common geometrical imperfections (damage) present in thin plate structures. They may be formed in the plate due to the impact of sharp or foreign objects, among other reasons. Hence, in the present work, the effect of dent parameters (length, width, and depth) on the ultimate compressive strength of a thin plate of size 1,000 mm x 1,000 mm x 12 mm with a longitudinal or a transverse dent located centrally on the plate is examined. This is done under uniaxial compressive loading with simply supported boundary conditions and using commercial FE software ANSYS V12.

† This paper was recommended for publication in revised form by Associate Editor Chongdu Cho

*Corresponding author. Tel.: +91 9487061455, Fax.: +91 4132655101
E-mail address: avrp@sify.com

2. Literature review

A number of studies are available in the literature on the ultimate compressive strength of thin plates with imperfections, such as weld-induced initial imperfections, residual stresses, and so on. (for e.g., Refs. [3-9]). However, available studies considering the effect of local imperfections on the ultimate strength of thin plates are limited, a few of which are discussed here.

Po'lchikov [10] discussed the stress concentration around dents (spherical and elliptical) and the mutual effect of dents on axially loaded thin plates; stress variation due to the presence of dents was reported based on asymptotic analysis. Dow and Smith [11] examined various forms of imperfections, with particular reference to the effect of localized initial imperfections on rectangular plate stiffness and strength. They assumed the sinusoidal form of initial imperfections both in longitudinal and transverse directions. Their study concluded that the effect of localized initial imperfections depends strongly on the amplitude and depends slightly on the shape and position of the imperfection along the length of the plate. Paik et al. [12] studied numerically the ultimate strength characteristics of dented plates under axial compressive loads, considering the variation 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. They concluded that the shape of the circular dent (whether spherical or conical) does not affect significantly the collapse strength of the plate. Paik [13] investigated numerically the ultimate shear strength characteristics of dented plates and derived an empirical formula to predict their ultimate shear strength. One important conclusion obtained is that centrally located dents affect the shear loading capacity more than the dents located near edges, which contradicted the findings in Ref. [12] in the case of compressive loads. Lang and Kwon [14] studied numerically the effect of the impact velocity that forms dents on the compressive failure load of aircraft fuselage panels (of aluminum alloy) with and without stiffeners. They concluded that dents formed by a low velocity impact give a lower buckling strength than virgin panels; as the impact velocity increases, the failure load of the dented panel increases, exceeding that of the virgin panel.

Witkowska and Guedes Soares [15] studied numerically the collapse behavior and ultimate strength of damaged (dented) stiffened panels, and further investigated the influence of parameters such as stiffener geometry on the ultimate strength of plates with and without local dents. Hai et al. [16] studied the influence of multiple defects, namely, initial distortion, weld residual stresses, cracks, and local dents, on the ultimate strength of the plate. They also derived expressions for the reliability index and sensitivity analyses of the plate. Hai et al. [17] proposed a method to determine a global reliability index and sensitivity expression of the reliability index of the plate structure with a local dent based on an ultimate strength reduction factor.

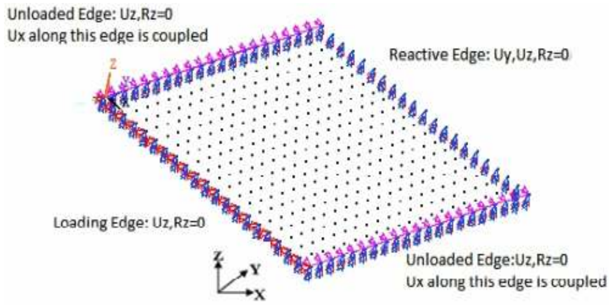


Fig. 2. Geometry, boundary conditions, and loading conditions used in the buckling analysis.

From the above literature survey, the effect of the angle of orientation of the dent on the ultimate strength of thin plates has not been considered. Hence, in the present work, efforts are made to examine numerically the effect of various dent parameters (length, width, and depth) on the ultimate strength of a thin plate taken for study with a longitudinal/transverse dent under uniaxial compression.

3. FE Modeling

A four-noded quadrilateral shell element, SHELL181 of ANSYS, is used for modeling the moderately thin and thin plates. The element has six degrees of freedom per node. This element can handle membrane, bending, and transverse shear effects for moderately thin plates. This element also has plasticity, stress stiffening, large deflection, and large strain capabilities.

3.1 Thin plate shell model

In the present work, a square structural steel plate is used. The dimensions and material properties of the plate [18] are given below.

Length (L)	= 1,000 mm
Width (W)	= 1,000 mm
Thickness (t)	= 12 mm
Young's modulus (E)	= 2.058x 10^5 N/mm^2
Yield stress (σ_y)	= 313.6 N/mm^2
Poisson's ratio (γ)	= 0.3
Mass density (ρ)	= 7800 kg/m^3

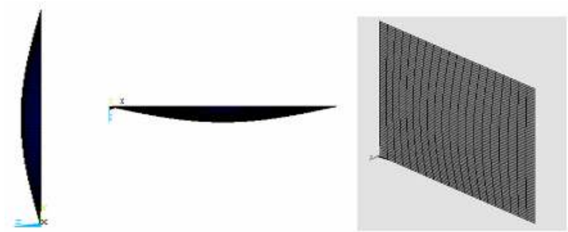
The zero strain hardening effect is assumed because the material used is HT-32 structural steel.

3.2 Boundary conditions

Simply supported boundary conditions, shown in Fig. 2, are applied on all the edges of the thin plate, and uniform displacement loading is applied on one side of the plate model. The corresponding opposite side is restrained from moving along the load direction. [2, 19].

Table 1. Comparison between the analytical solution with the FEA result.

m	n	Analytical solution (N)	FEA result (N)	% Error
1	1	1285660	1284271	(-) 0.108



(a) Front view (b) Side view (c) Isometric view

Fig. 3. Mode shape of the bare (undented) plate obtained from the FE Eigen buckling analysis.

3.3 Model validation

3.3.1 Linear analysis

The analytical solution of the perfect thin plate [20] can be obtained using Eq. (1) given below.

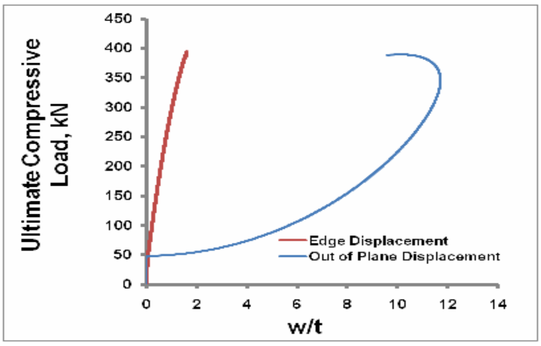
$$\text{Critical load per unit length} = Nx = \frac{\pi^2 D}{W^2}\left(\frac{mW}{L} + \frac{n^2 L}{mW}\right)^2 \tag{1}$$

where $D = \frac{Et^3}{12\left(1-\gamma^2\right)}$, m = number of longitudinal lobes, and n = number of transverse lobes.

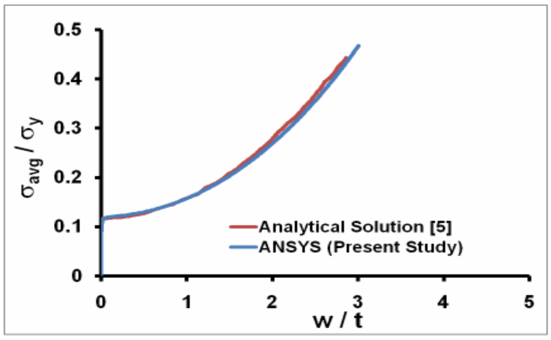
For the plate used in the present study (1,000 mm x 1,000 mm x 12 mm), the analytical solution and the FE Eigen buckling analysis result obtained are compared in Table 1, with an error of 0.108%. The mode shape obtained from the FE Eigen analysis is shown in Fig. 3.

3.3.2 Nonlinear analysis

To validate the nonlinear analysis, an unstiffened plate of size 500 mm x 500 mm x 3.2 mm given by Suneel Kumar et al. [2] and Paik et al. [5] is considered. The yield strength of plate σ_y is 264.6 N/mm^2 with a Young's modulus of elasticity (E) at 2.058 x 10^5 N/mm^2 and a Poisson's ratio (γ) of 0.3. From the mesh convergence study performed, a 40 x 40 element fine mesh gave an ultimate compressive strength of 393.87 kN. The load deflection curves are shown in Fig. 4(a). The obtained result is close to the published result of 392.93 kN by Suneel Kumar et al. [2]. A further comparison of the load Vs out-of-plane displacement of the center point of the plate for the developed model with the published result given in Ref. [5] is shown in Fig. 4(b); both results are in good agreement. Thus, both element selection and accuracy of nonlinear analysis are verified.



(a) Load Vs edge displacement and out-of-plane displacement of the center point of the undented plate in the FE model



(b) Comparison of load Vs out-of-plane displacement of the center point of the FE model validated with Ref. [5]

Fig. 4. Load Vs edge displacement and out-of-plane displacement of the center point of the undented plate under axial compression.

3.4 Modeling of Dented Plates

Eq. (2) represents the shape of the dent formed on the thin plate used in the present study, which is similar to the equation used in Ref. [11] for modeling dents in plates, and in Refs. [21-23] for modeling dents in cylindrical shells.

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

where Δ = deformation due to dent geometry on a perfect plate structure for the given x(i) and y(i) values (taking the center of the dent as the origin), ld = length of the dent, and wd = width of the dent.

While modeling localized geometrical imperfections such as dents, the following three points have to be considered carefully:

- The dent shape must be modeled accurately.
- In the area where there is a change in the curvature in shell structures, local bending stress may occur. Hence, the surrounding region must be modeled carefully [24].
- Size of the element in the dent region. According to Song et al. [25], when the element size is reduced to half its previous size, the variation in the numerical result obtained should be less than 1%.

In the present work, all the above three points have been taken into account carefully. A sample of the FE model of the dented plate generated is shown in Fig. 5.

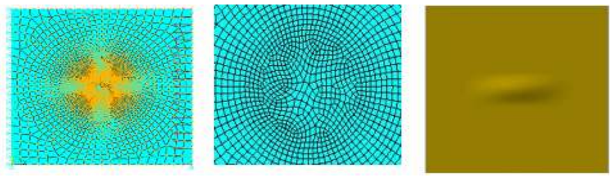
4. Results and discussion

Non-linear buckling analysis is used to determine the ultimate compressive strength (hereafter called ultimate strength) of the dented thin plate with a varying dent length (DL), dent width (DW), dent depth (DD), and angle of the orientation of the dent (θ). In the present work, θ is measured at the center of the dent with a reference line perpendicular to the load direction (i.e., orientation of 0^o and 90^o mean transverse and longitudinal dents, respectively).

4.1 Variation in von Mises stress distribution under gradually applied compressive loading conditions

4.1.1 Plate with a transverse dent

Fig. 6 shows the von Mises stress distribution of the plate



(a) FE model of the dented plate (b) Close-up view of the dented portion (c) Front view

Fig. 5. FE Model of the dented plate.

with a transverse dent (DL = 600 mm, DW = 200 mm, and DD = 24 mm), both on the dent side and swell side of the plate. As the load applied on the dented plate increased gradually to 1,215.792 kN (corresponding to an edge displacement of 0.6 mm at the loading edge), the dent tips first reach a high stress condition (minimum of 255 N/mm^2), as shown in Fig. 6(a). When the load is increased to 1,571.337 kN (corresponding to an edge displacement of 0.8 mm), the high-stress region (corresponding to a stress level of 250–313.6 N/mm^2) propagates to the complete dent geometry, evident in Fig. 6(b). After further loading to 1,836.648 kN (corresponding to an edge displacement of 1.0 mm), the high-stress region propagates as well to the other regions of the dented plate (Fig. 6(c)). The stress distribution at limit load condition (corresponding to a load of 2,105.303 kN and edge displacement of 1.36 mm) is shown in Fig. 6(d). The low-stress region above and below the dent geometry (called hereafter as dent affected region (DAR)) are noticed because the dent edge parallel to the longitudinal axis of the dent compresses freely, offering less resistance to the load applied. Fig. 6(d) clearly shows that the load-carrying capacity of the dented plate mainly depends on the area of the dented plate excluding the DARs.

4.1.2 Plate with a longitudinal dent

Fig. 7 shows the von Mises stress distribution of the plate with a longitudinal dent (DL = 600 mm, DW = 200 mm, and DD = 24 mm) on both the dent side and swell side of the dented plate. When the load applied on the dented plate is 1,636.178 kN (corresponding to an edge displacement of 0.8

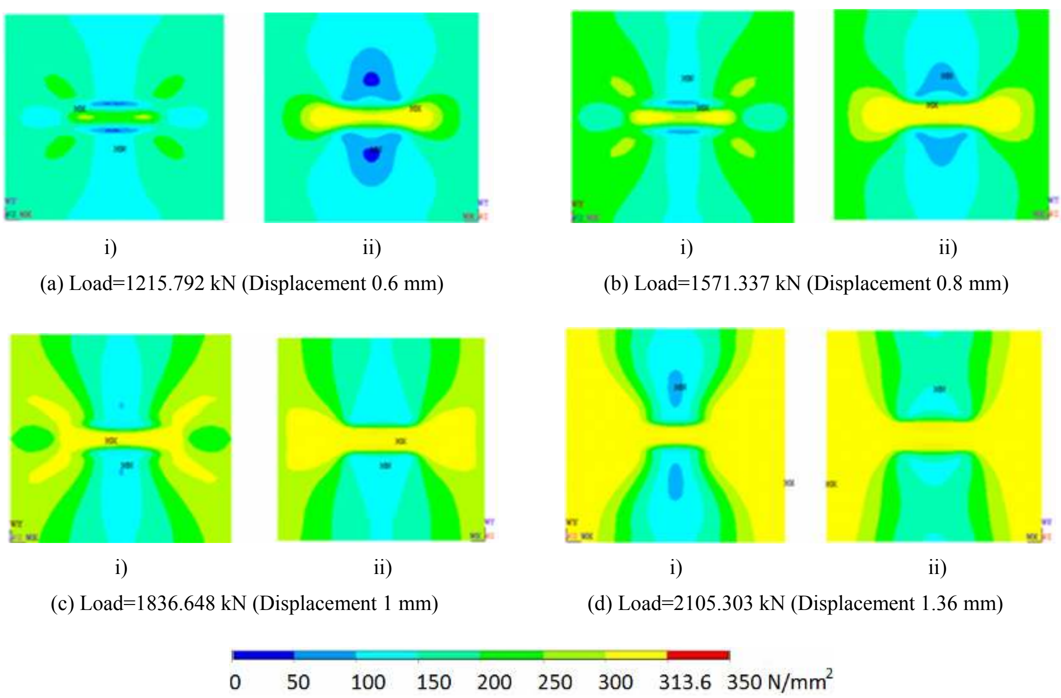


Fig. 6. Von Mises stress distribution of the plate with a transverse dent (DL = 600 mm, DW = 200 mm, and DD = 24 mm): i) Dent Side and ii) Swell Side.

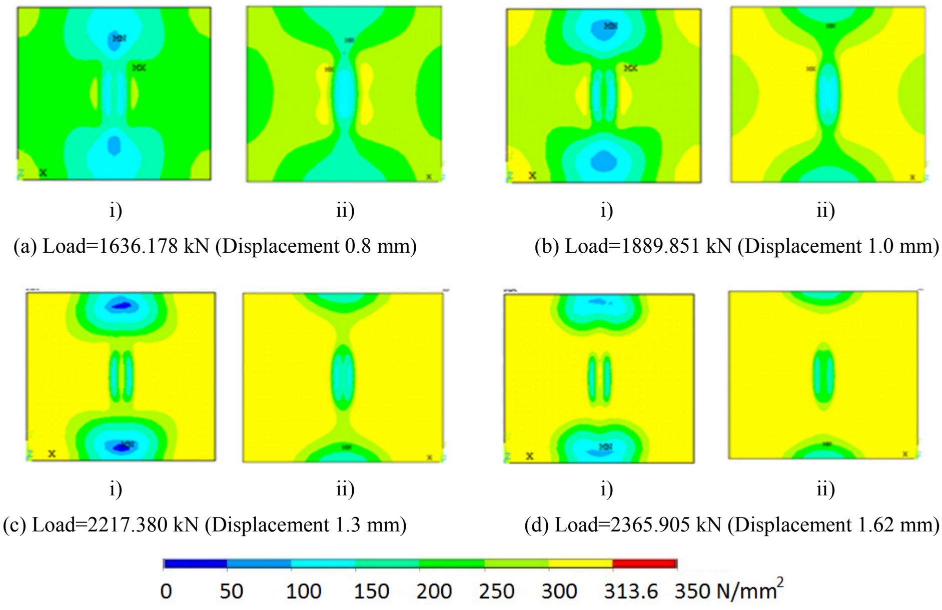


Fig. 7. Von Mises stress distribution of the plate with a longitudinal dent (DL = 600 mm, DW = 200 mm, and DD = 24 mm): i) Dent Side and ii) Swell Side.

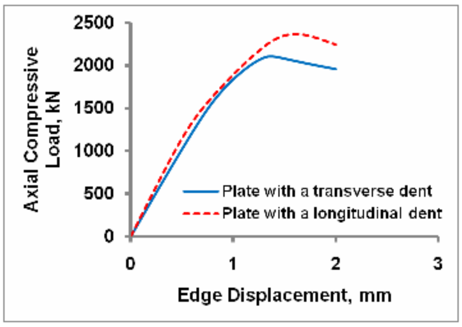


Fig. 8. Stiffness curves of transversely/longitudinally dented plates.

mm), a high stress condition (minimum of 252.5 N/mm^2) is noticed along both edges of the dent, parallel to the longitudinal axis of the dent (Fig. 7(a)). After further loading to 1,889.851 kN (corresponding to an edge displacement of 1.0 mm), this high-stress region (corresponding to a stress level of 250–313.6 N/mm^2) tends to propagate to the other regions of the plate, excluding the dent geometry and DARs (Fig. 7(b)). When the load applied on the dented plate is increased further to 2,217.380 kN (corresponding to an edge displacement of 1.3 mm), the high-stress region spreads to the DARs noticed in the previous loadstep, reducing the area of the DARs and further separating them from the dent geometry above and below the dent (Fig. 7(c)). Fig. 7(d) shows that upon reaching the limit load condition (corresponding to a load of 2,365.905 kN and edge displacement of 1.62 mm), the high-stress region separates fully the DARs from the dent geometry. Further, the central portion of the dent geometry bifurcating the stress contour of the dent geometry also takes part in sharing the load. The load-carrying capacity of the dented plate depends mainly on the area of the dented plate, excluding the DARs and low-stress regions of the dent geometry.

Fig. 8 shows the load versus edge displacement curves (hereafter called stiffness curves) of a transversely dented plate and a longitudinally dented plate of the same dent size (DL = 600 mm, DW = 200 mm, and DD = 24 mm). Initially, the slope of the stiffness curves are positive and constant; as the load is applied further, the slope of the stiffness curves decreases and reaches the ultimate load condition of zero stiffness. On further loading, the plate fails drastically because the slope of the stiffness curves becomes negative. A similar trend of collapse can be seen in Refs. [5, 11].

4.2 Effect of variation in dent length on the ultimate strength of the dented plate

The ultimate strength results obtained for the dented plate with varying dent length (keeping DW = 200 mm and DD = 24 mm constant) are shown in Table 2. Fig. 9 shows the effect of dent length variation on the Ultimate Strength Ratio (defined as the ratio between the ultimate strength of the plate and the yield stress of the material), hereafter referred as USR. As the length of the transverse dent increases from 200 to 800 mm, a drastic 16% reduction in ultimate strength of the plate is noticed. The reason for this may be that as the dent length increases, the high-stress region (corresponding to a stress level of 250–313.6 N/mm^2) decreases. In the case of a longitudinal dent, the ultimate strength of the dented plate is observed to have a slight increase (2.6%) when the length of the dent increases from 200 to 800 mm. The variation is not significant because the effective load sharing region (high-stress region corresponding to a stress level of 250–313.6 N/mm^2) is not affected due to the orientation of the dent along

Table 2. Variation in ultimate compressive strength of the plate with a transverse/longitudinal dent for different dent lengths (with DW = 200 mm and DD = 24 mm constant).

DW, mm	DD, mm	DL, mm	θ, deg.	Ultimate Load (P_u), kN	USR (σ_u/σ_y)
200	24	200	0	2317.445	0.6158
		400		2235.576	0.5941
		600		2104.946	0.5594
		800		1946.381	0.5172
		200	90	2317.445	0.6158
		400		2344.089	0.6229
		600		2365.675	0.6286
		800		2378.576	0.6321

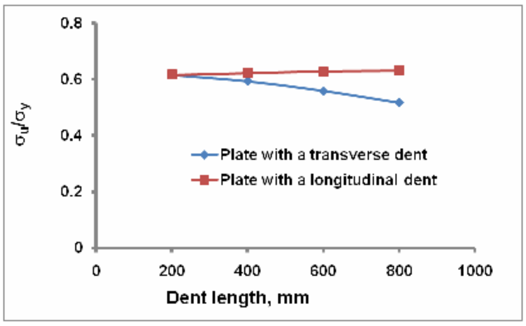


Fig. 9. Variation in USR of plate with a transverse/longitudinal dent for different dent lengths (with DW = 200 mm and DD = 24 mm constant).

the load direction. However, the slight increase in load-carrying capacity may be due to the increase in length of the central portion of the dent (bifurcating the stress distribution in the dent geometry along the loading direction) with the increase in dent length.

4.3 Effect of variation in dent width on the ultimate strength of the dented plate

Table 3 and Fig. 10 show the ultimate strength results obtained for the dented plate with varying dent width (DL = 800 mm and DD = 24 mm are constant). Fig. 10 clearly shows that the longitudinal dent has a marked effect on the ultimate strenth of the dented plate.

This may be due to the perpendicular orientation of the dent width to the load direction, which in turn decreases the load-sharing region. As the dent width increases from 200 to 800 mm, nearly 16.6% of the reduction in the ultimate strenth of the dented plate is noticed. For the plate with a transverse dent, the variation in dent width is practically insensitive, as expected.

4.4 Effect of variation in dent depth on the ultimate strength of the dented plate

The ultimate strength results obtained for the dented plate

Table 3. Variation in ultimate compressive strength of the plate with a transverse/longitudinal dent for different dent widths (with DL = 800 mm and DD = 24 mm constant).

DL, mm	DD, mm	DW, mm	θ, deg.	Ultimate Load (P_u), kN	USR (σ_u/σ_y)
800	24	200	0	1946.381	0.5172
		400		1954.494	0.5194
		600		1965.562	0.5223
		800		1983.643	0.5271
		200	90	2378.576	0.6321
		400		2317.835	0.6159
		600		2149.875	0.5713
		800		1983.643	0.5271

Table 4. Variation in ultimate compressive strength of the plate with a transverse dent or a longitudinal dent for different dent depths (with DL = 600 mm and DW = 400 mm constant).

DL, mm	DW, mm	DL, mm	θ, deg.	Ultimate Load (P_u), kN	USR (σ_u/σ_y)
600	400	8	0	2241.989	0.5958
		16		2171.275	0.5770
		24		2111.641	0.5611
		36		2059.715	0.5473
		8	90	2299.232	0.6110
		16		2284.957	0.6072
		24		2288.782	0.6082
		36		2311.811	0.6143

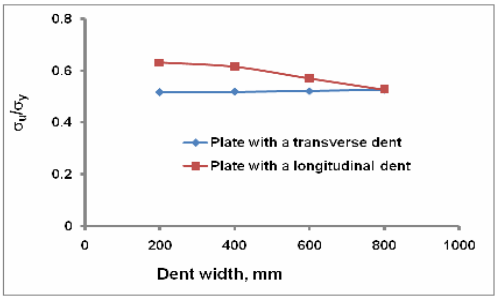


Fig. 10. Variation in USR of the plate with a transverse/longitudinal dent for different dent widths (keeping DL = 800 mm and DD = 24 mm constant).

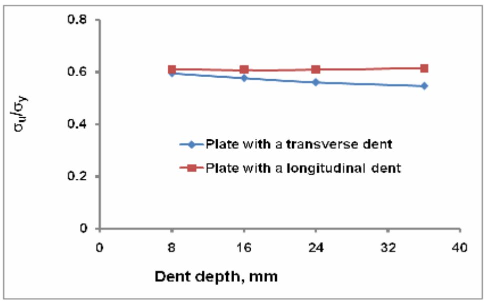


Fig. 11. Variation in the USR of the plate with a transverse/longitudinal dent for different dent depths (with DL = 600 mm and DW = 400 mm constant).

Table 5. Variation in USR of the plate with a small transverse/longitudinal dent of different sizes.

DL, mm	DW, mm	DD, mm	USR (σ_u/σ_y)	
			Transverse Dent (θ = 0°)	Longitudinal Dent (θ = 90°)
50	200	24	0.6178	0.6178
100			0.6173	0.6185
150			0.6157	0.6183
200			0.6158	0.6158
200	50	24	0.6152	0.6196
	100		0.6146	0.6198
	150		0.6149	0.6186
	200		0.6158	0.6158
200	100	8	0.6169	0.6180
		16	0.6154	0.6189
		24	0.6146	0.6198
		36	0.6146	0.6209

with varying dent depth (keeping DL = 600 mm and DW = 400 mm constant) are shown in Table 4 and Fig. 11. Fig. 11 shows that the longitudinal dents are not that sensitive toward dent depth variation. In the case of the plate with a transverse dent, an 8.1% reduction is observed in its ultimate strength when the dent depth is increased from 8 to 36 mm, that is, the dent depth accelerates the strength reduction tendency, as stated in Refs. [11, 12].

4.5 Effect of small dent on the USR of dented plates

The ultimate strength results obtained for the plates with a smaller dent (of various sizes, with a limiting value of 200 mm for both DL and DW, and 36 mm for DD) are given in Table 5. The minimum and maximum values obtained for USR are 0.6146 and 0.6209, respectively, for the plates with small dents of various sizes. A small overall variation of 1% is observed, which conforms to the conclusion of Paik et al. [12]: as long as the dent diameter is small, the effect of dent depth is insignificant.

5. Conclusions

The following conclusions are derived from the numerical results obtained for the dented plates considered in the present study:

(1) The minimum and maximum USR values of the dented plates considered for the present study are 0.5172 (P_u = 1,946.381 kN, corresponding to a transversely dented plate with DL = 800 mm, DW = 200 mm, and DD = 24 mm) and 0.6321 (P_u = 2,378.576 kN, corresponding to a longitudinally dented plate with DL = 800 mm, DW = 200 mm, and DD = 24 mm), respectively.

(2) In general, dented plates with a longitudinal dent have either equal or higher ultimate strength than those with a transverse dent of the same size.

(3) Longitudinal dents are sensitive only to dent width variation.

(4) Transverse dents are only sensitive to dent length and dent depth variations.

(5) In the case of small dents, variations in dent parameters have a negligible effect on the ultimate strength of the dented plate.

(6) At the ultimate load level, the stiffness of the dented plate becomes zero, and the plate fails suddenly.

(7) The load-carrying capacity of the dented plate largely depends on the area of the dented plate, excluding the area of DARs.

References

[1] J. Singer, J. Arbocz and T. Weller, *Buckling experiments, shells, built-up structures, composites and additional topics (buckling experiments)*, John Wiley & Sons (2002).

[2] M. Suneel Kumar, P. Alagusundaramoorthy and R. Sundaravadivelu, Ultimate strength of square plate with rectangular opening under axial compression, *Journal of Naval Architecture and Marine Engineering*, 4 (2007) 15-26.

[3] O. S. Hopperstad, M. Langseth and L. Hanssen, Ultimate compressive strength of plate elements in aluminium: Correlation of finite element analyses and tests, *Thin-Walled Structures*, 29 (1997) 31-46.

[4] J. K. Paik, A. K. Thayamballi, G. Wang and B. J. Kim, On advanced buckling and ultimate strength design of ship plating, *The Society of Naval Architects and Marine Engineers* (2000) 1-34.

[5] J. K. Paik, A. K. Thayamballi and B. J. Kim, Advanced ultimate strength formulations for ship plating under combined biaxial compression/tension, edge shear, and lateral pressure loads, *Marine Technology*, 38 (1) (2001) 9-25.

[6] J. K. Paik and J. K. Seo, Ultimate limit state assessment of ship structures, *Proc. of International Conference on Computational Methods in Marine Engineering*, Barcelona (2005).

[7] Z. Sadovsky, A. B. Teixeira and C. Guedes Soares, Degradation of the compressive strength of rectangular plates due to initial deflection, *Thin-Walled Structures*, 43 (2005) 65-82.

[8] Z. Sadovsky, A. B. Teixeira and C. Guedes Soares, Degradation of the compressive strength of square plates due to initial deflection, *Journal of Constructional Steel Research*, 62 (2006) 369-377.

[9] K. Ikeda, T. Kitada, M. Matsumura and Y. Yamakawa, Imperfection sensitivity of ultimate buckling strength of elastic-plastic square plates under compression, *International Journal of Non-Linear Mechanics*, 42 (2007) 529-541.

[10] O. I. Pal'chikov, *Asymptotic estimate of stress concentration near dents*, Translated from Problemy Prochnosti, No. 10, October (1971) 32-37.

[11] R. S. Dow and C. S. Smith, Effects of localized imperfections on compressive strength of long rectangular plates,

Journal of Constructional Steel Research, 4 (1984) 51-76.
[12] J. K. Paik, J. M. Lee and D. H. Lee, Ultimate strength of dented steel plates under axial compressive loads, *International Journal of Mechanical Sciences*, 45 (2003) 433-448.
[13] J. K. Paik, Ultimate strength of dented steel plates under edge shear loads, *Thin-Walled Structures*, 43 (2005) 1475-1492.
[14] N. C. Long and Y. W. Kwon, Investigation on effect of metallic fuselage dents on compressive failure loads, *Journal of Aircraft*, 44 (6) (2007) 2026-2031.
[15] M. Witkowska and C. Guedes Soares, Collapse strength of stiffened panels with local dent damage, *Proc. of the 27th ASME Intl. Conference on Offshore Mechanics and Arctic Engineering*, Estoril, Portugal (2008) 965-973.
[16] A. Hai, A. W. Gang and Z. W. Tao, Reliability analysis of ship structure system with multi-defects, *Sci China Phys Mech Astron*, 53 (11) (2010) 2113-2124.
[17] A. Hai, A. W. Guang and M. Liu, Reliability analysis for structure system with the local dented plate, *Advanced Materials Research*, 189-193 (2011) 4434-4437.
[18] J. K. Paik, Residual ultimate strength of steel plates with longitudinal cracks under axial compression-Nonlinear finite element method investigations, *Ocean Engineering*, 36 (2009) 266-276.
[19] M. Harada and M. Fujikubo, Estimation of buckling and ultimate strength of rectangular plate with cut-out, *Proc. of 12th Intl. Offshore and Polar Engineering Conference*, Kitakyushu, Japan (2002) 630-635.
[20] S. P. Timoshenko and J. M. Gere, *Theory of elastic stability*, McGraw-Hill, Second Edition, Singapore (1965).
[21] L. Wullscheger and H. R. Peining Meyer, Buckling of geometrically imperfect cylindrical shells-definition of a buckling load, *International Journal of Non-Linear Mechanics* (2002) 645-657.
[22] G. D. Gavrilenko, Stability of cylindrical shells with local imperfections, *International Applied Mechanics*, 38 (12) (2002) 1496-500.
[23] B. Prabu, A. V. Raviprakash and A. Venkatraman, Parametric study on buckling behavior of dented short carbon steel cylindrical shell subjected to uniform axial compression, *Thin-Walled Structures*, 48 (8) (2010) 639-649.
[24] R. Cook, D. Markus and M. Plesha, *Concept and applications of finite element analysis*, John Wiley (2002).
[25] C. Y. Song, J. G. Teng and J. M. Rotter, Imperfection sensitivity of thin elastic cylindrical shells subjected to partial axial compression, *International Journal of Solids and Structures* (2004) 7155-7180.

Alwardoss Velayutham Raviprakash received his ME (Prod. Eng.) from Annamalai University, India in 1983. He is currently pursuing Ph.D degree in Buckling Behaviour of Thin Shell Structures at Pondicherry University, India. At present, he is working as an Associate Professor in the Department of Mechanical Engineering, Pondicherry Engineering College, Puducherry, India.

Balakrishnan Prabu received his ME (Eng. Design) from Anna University, India in 1993, and his Ph.D in Thin Shell Buckling from Pondicherry University, India in 2007. At present, he is working as an Associate Professor in the Department of Mechanical Engineering, Pondicherry Engineering College.

Natarajan Alagumurthi received both his MTech (Energy Tech.) and Ph.D in Heat Generation and Transfer in Cylindrical Grinding from Pondicherry University, India in 1996 and 2006, respectively. At present, he is working as a Professor in the Department of Mechanical Engineering, Pondicherry Engineering College.