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Skewed Rhombic Plates Analysis for Bending and Deflection Using Simple Elastic Strip Method

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ABSTRACT

A simple technique, based on the recently developed elastic strip analysis (ESA)[1] of the bi-harmonic equation for moments and deflections of simply supported rectangular plates developed from finite series expression for suggested valid displacement function method, is applied to the analysis of skewed rhombic plates. The formulation uses a characterization of the load area contributed by the shorter diagonal strip and the longer diagonal strip to the skewed plates to obtain the load fractions in the four strips represented in the plate bi-harmonic equation. The maximum and minimum principal bending moments together with the deflection at the centre of the plate are obtained almost immediately with striking results. Skewed rhombic plates with any skew angles to the horizontal can be handled by this method. Numerical examples are presented and results compared with available ones in literature since 1959.

Keywords: Rhombic Plates; Elastic; Strip; Skewed angle; moments; deflections.

INTRODUCTION

Skewed plates are often used as component parts for large scale structures, such as bridge, building floor systems, aircraft industry and ship building. In recent decades there have been efforts to analytically investigate the behavior of skewed plates, in spite of the mathematical challenges involved using various methods, some of which have been cited by [2] who employed a double series which operate with two interdependent systems of infinite linear simultaneous equations. Morley [3],[4] presented the relationships between rectangular and oblique coordinate systems for load responses in skewed plates. The derived governing equation for isotropic skewed thin plates based on the Kirchhoff theory was analytically and numerically solved using a trigonometric series and the finite difference method respectively. The Kirchhoff theory is widely used in plate analysis for both analytical research [5] and in numerical research including the finite element method (FEM) [6] [7], [8] and [9] the finite strip method [10], [11] and [12] and the finite difference method [2] which has the problem of under-predicting deflections for thick plates because the effect of transverse shear deformation is neglected [13]. This led to the Mindlin theory which was developed by [14] and [15] together with theories by [16] which solved the problem. The Mindlin theory for static analysis of bending behavior have been used by [17,18], [19,20] [21] [22] [23] and [24] As described above, there are a number of numerical solutions. However, they are quite different to each other and thus it is difficult to judge which of them is valid. [25] in their paper reported such a solution which was expected to resolve the issue of variation in numerical solutions. The results from this method were validated using the commercial finite element analysis package ANSYS 11. This available results have led the author to test the recently developed simple strip method [1] its universality on skewed plates.

In doing this it was discovered that skewed plates can be divided into two i. skew plates with constant area of i.e constant length of the shorter span and longer span with varying skew angles and ii. skew plates with constant area of i.e. constant length of one span and varying length of the other span with varying skew angles. Skewed Rhombic plates fall in the second group and it is the interest of this paper. It is expected that the result from this simple method shall compare to established ones and shall be validated by the commercial FEM ANSYS II results.

It is assumed here that the strip moment ratio theory SMR [33, 34 35, 36 and 37] to rectangular plates for corners held down and allowed to lift as developed by the author and colleagues is understood, and the theory from [1] which forms the onions of this work is comprehended.

METHOD AND FORMULATION OF EQUATIONS

The governing equation for rectangular plate has the form.

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{q_0}{D} \quad \text{.......................(1)}$$

The equation 1 above is considered for the solution of the skewed rhombic plate below.

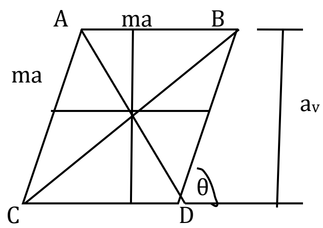


FIGURE 1: Skewed Rhombic Plate at angle θ

1. Theoretical Framework

The understanding of [1] is very key to a good follow-up of the present method. The equation 1 above has the following definition

q = load intensity

D = Flexural rigidity of plate

$$D = \frac{Eh^3}{12(1-\upsilon^2)} \text{ Dx=Dy} \quad (2)$$

$$Dxy = Dyx\frac{Eh^3}{24(1+\upsilon)} \quad (3)$$

E = Young's Modulus of Elasticity

h = Plate thickness

v = Poisson ratio

Equation (1) is broken down into Harmonic equations and using Valid displacement Function for the uniformly distributed load as given below as:

$$w = Amn\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b} \quad (4)$$

Where

m = number of half waves in the x direction and

n = number of half waves in the y direction

The finite series method [ESA] produced

The solution of equation 4 above yields the various strip displacement amplitude below

$$A_x = \frac{-16q_x a^4}{D_x\pi^6} \quad (5)$$

Similarly,

$$A_y = \frac{-16q_y b^4}{D_y\pi^6} \quad (6)$$

$$A_{xy} = \frac{-16q_{xy}a^2b^2}{D_{xy}\pi^6} \quad (7)$$

2. Geometry

The skewed Rhombic plates has

I. sides Lx=Ly=ma

II. Acute angle ABD=ACD=θ

III. Obtuse angle CAB=CDB=180- θ

IV. shorter diagonal Length AD(n_S)

$$\text{ns} = ma\frac{\text{Sin } \theta}{\text{Sin}(90-0.5\ \theta)} \quad (8)$$

V. Longer diagonal Length BC(n_L)

$$\text{nL} = ma\frac{\text{Sin}(180-\ \theta)}{\text{Sin}(0.5\ \theta)} \quad (9)$$

VI. Perpendicular length EF or GH of short diagonal nsp

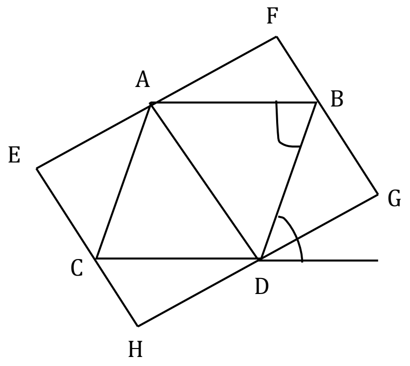


FIGURE 2: showing the shorter diagonal length AD(ns) and the perpendicular EF(HG) of a Skewed Rhombic Plate.

If here angle
DBA=**θ**,

then
ABC=0.5θ=FAB (10)

therefore
FAE=GDH=nsp
nsp = 2maCos (0.5 θ) (11)

nsp could also be obtained as

nsp=2mSin(90-0.5θ) (12)

nsp=nsTan(90-0.5θ) (13)

VII. Perpendicular length nLp of Longer diagonal

From similar derivation,
nlp = 2maSin(0.5 θ) (14)

nlp could also be obtained as

nlp=2maCos(90-0.5θ) (15)

nlp=nl/Tan(90-0.5θ) (16)

3. Effective Area of each strip in the rhombic plate

The effective area of the plate and each strip of the plate is the area covered by the rectangle of the plate and those of each strip respectively. It is the product of the strip length and the length of the perpendicular of the strip reaching or passing through all angle ends of the rhombic plate. For rhombic plate of side length ma, the areas are given as Ar, Arx, Ary, Arxy and Aryx for the overall plate area, area of the shorter strip, area of the rectangle of the longer strip, area of the rectangle of the shorter diagonal strip and area of the rectangle of the longer diagonal strip respectively, and are given as

Ar=ma.a_θ (17)

Arx=ma.a_θ (18)

Ary=ma.a_θ (19)

Arxy=ns.nsp.n (20)

Aryx=nl.nlp.n (21)

a_θ=maSinθ (22)

n=ma/ a_θ=1/Sinθ (23)

4. Load Sharing

$qAr = qArx + q_y Ary + q_{xy} Arxy + q_{yx} Aryx$ (24)

this can be reduced to

$$q = q_x + q_y + q_{xy}\frac{Axy}{A} + q_{yx}\frac{Ayx}{A} \qquad (25)$$

5. Compatibility

The compatibility criterion in this work shall be satisfied for the condition that the amplitudes A_x, A_y and A_{xy} must be same and equal as has been shown [1]

That is

$$A_x = A_y = A_{xy} \qquad (26)$$

Therefore for

$A_x = A_y$

$$A_x = \frac{-16q_x a^4}{D_x \pi^6} = A_y = \frac{-16q_y b^4}{D_y \pi^6} =$$

$$A_{xy} = \frac{-16q_{xy} a^2 b^2}{D_{xy}\pi^6}$$

From where [1] derived

$$q_x = \frac{n^4 q_y D_x}{D_y} \qquad (27)$$

$$q_x = \frac{n^2 q_{xy} D_x}{D_{xy}} \qquad (28)$$

$$q_y = \frac{q_x D_y}{n^4 D_x} \qquad (29)$$

$$q_{xy} = \frac{q_x D_{xy}}{n^2 D_x} \qquad (30)$$

Substituting equations 27, 28, 29 and 30 in equation 25 as applicable,
We shall have

$$\frac{q}{q_x} = 1 + \frac{D_y}{n^4 D_x} + \frac{(Arxy + Aryx)D_{xy}}{Arn^2 D_x} \qquad (31)$$

$$\frac{q}{q_y} = 1 + \frac{n^4 D_x}{D_y} + \frac{(Arxy + Aryx)n^2 D_{xy}}{ArD_x} \qquad (32)$$

The reciprocal of equations 31 and 32 are the fraction of the total loads carried by the shorter varying span a and longer fixed span ma respectively
Therefore let

$$\alpha = \frac{q_x}{q} \qquad (33)$$

and

$$\beta = \frac{q_y}{q} \qquad (34)$$

the equation 25 becomes

$$1 = \alpha + \beta + \gamma\frac{Arxy + Aryx}{Ar} \qquad (35)$$

From where

$$\gamma = \frac{Ar}{(Arxy + Aryx)}(1 - \alpha - \beta) \qquad (36)$$

6. Deflections

The deflections of Plates are determined by multiplying the beam deflection Δ of the x strip by the x-x strip load factor α

The plate deflection Δ_p is
$\Delta_p = \alpha\,\Delta$

For simply supported plates,
$\Delta_p = 5\alpha q a_\theta{}^4/384Dx$ (37)

7. Bending Moments

The bending moments in the plate is given as

$$M_x = D_x\frac{\partial^4 w}{\partial x^4} + \upsilon D_y\frac{\partial^4 w}{\partial y^4} \qquad (38)$$

$$M_y = \upsilon D_x\frac{\partial^4 w}{\partial x^4} + D_y\frac{\partial^4 w}{\partial y^4} \qquad (39)$$

Where

$$Dx = Dy = \frac{Eh^3}{12(1-\upsilon^2)}$$

$$Dxy = Dyx\frac{Eh^3}{24(1+\upsilon)}$$

The plate moments can now be written from equations 38 and 39 as

$M_x = \alpha M_x + \upsilon\ \beta M_y$ (40)

and

$M_x = \upsilon\,\alpha M_x + \beta M_y$ (41)

RESULTS OF APPLICATION

The following four step solution algorithm is convenient for use in any typical problem.
Step 1: Compute plate parameters a, b, L_{xy}, D_x, D_y, D_{xy}
Step 2: Compute quantities α, β, and ɣ,
Step 3: Compute plate deflection
Step 4: Compute plate moments

Problems of interest

Determine the moments and maximum deflection of a simply supported skewed rhombic plate for various skewed angle carrying a uniformly distributed load q.

Results

The solutions are given below

TABLE 1: showing the skew angles θ, length ratio of a fixed side m and calculated geometric length ratio n, $a_θ$, ns, nl, nsp, nlp and complimentary angle θc

n	m	θ	θc	$a_θ$	ns	nl	nsp	nlp
1	2	90	90	2	2.8284	2.8284	2.8284	2.8284
1.015	2	80	100	1.9696	2.5712	3.0642	3.0642	2.5712
1.035	2	75	105	1.9319	2.4350	3.1734	3.1734	2.4350
1.103	2	65	115	1.8126	2.1492	3.3736	3.3736	2.1492
1.155	2	60	120	1.7321	2.0000	3.4641	3.4641	2.0000
1.305	2	50	130	1.5321	1.6905	3.6252	3.6252	1.6905
1.414	2	45	135	1.4142	1.5307	3.6955	3.6955	1.5307
1.556	2	40	140	1.2856	1.3681	3.7588	3.7588	1.3681
2.000	2	30	150	1.0000	1.0353	3.8637	3.8637	1.0353
2.366	2	25	155	0.8452	0.8658	3.9052	3.9052	0.8658
3.864	2	15	165	0.5176	0.5221	3.9658	3.9658	0.5221
5.759	2	10	170	0.3473	0.3486	3.9848	3.9848	0.3486
11.474	2	5	175	0.1743	0.1745	3.9962	3.9962	0.1745

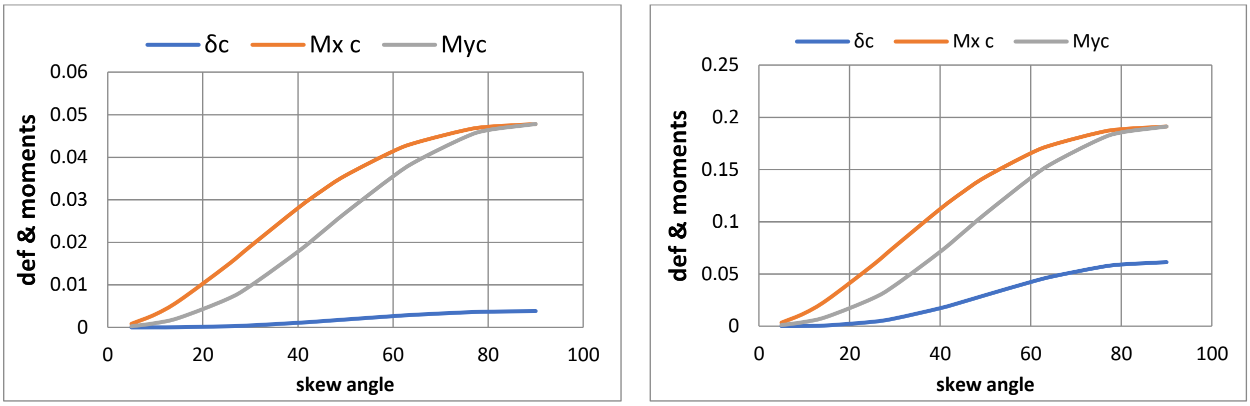
TABLE 2: showing load fractions for each strip. α, β and γ for various skew angles

θ	αc	βc	γc
90	0.2941	0.2941	0.1029
80	0.3013	0.2834	0.1023
75	0.3103	0.2701	0.1013
65	0.3397	0.2292	0.0977
60	0.3604	0.2027	0.0946
50	0.4138	0.1425	0.0850
45	0.4464	0.1116	0.0781
40	0.4829	0.0824	0.0698
30	0.5674	0.0355	0.0496
25	0.6159	0.0196	0.0385
15	0.7316	0.0033	0.0172
10	0.8038	0.0007	0.0085
5	0.8912	0.0001	0.0024

TABLE 3: showing deflections ($ΔD_X/qa^4$) and moments (Mxc / qa^2 and Mxc / qa^2) for various skew angles for m=2 and m=1

θ	$δcD_x/qa^4$	Mxc/qa^2	Myc/qa^2
90	0.061275	0.191176	0.191176
80	0.059036	0.188596	0.185513
75	0.056273	0.185268	0.17848
65	0.047752	0.173908	0.156463
60	0.042231	0.165544	0.141895
50	0.029684	0.142777	0.107664
45	0.023252	0.128351	0.089288
40	0.017176	0.112138	0.071154
30	0.007388	0.076241	0.039007
25	0.004093	0.057952	0.026325
15	0.000684	0.024997	0.008993
10	0.000152	0.012229	0.004001
5	1.07E-05	0.003393	0.001041

θ	$δcD_x/qa^4$	Mxc/qa^2	Myc/qa^2
90	0.00383	0.047794	0.047794
80	0.00369	0.047149	0.046378
75	0.003517	0.046317	0.04462
65	0.002985	0.043477	0.039116
60	0.002639	0.041386	0.035474
50	0.001855	0.035694	0.026916
45	0.001453	0.032088	0.022322
40	0.001074	0.028035	0.017789
30	0.000462	0.01906	0.009752
25	0.000256	0.014488	0.006581
15	4.27E-05	0.006249	0.002248
10	9.52E-06	0.003057	0.001
5	6.7E-07	0.000848	0.00026



(a) (b)

FIGURE 3: showing deflections and moments for various skew angles for m=1 (a) and m=2 (b)

DISCUSSION AND VALIDATION

The FEM analysis result obtained using a commercial package ANSYS 11 as used by [4] was used to validate this present analytical method. The table 4 below shows compared results.

TABLE 4: showing 100ΔDx/qa^4) and moments (10Mxc / qa^2 and 10Mxc / qa$^{2)}$ ^{for} various skew angles for m=2 by the present method compared to FEM ANSYS 11

Θ	Present Def	ANSYS 11 Def	Diff	Present Mmax	ANSYS 11 Mmax	Diff	Present Mmin	ANSYS 11 Mmin	Diff
75	5.6273	5.8662	-4.25	1.9150	1.9215	-0.34	1.78	1.71	4.34
60	4.2231	4.1455	1.84	1.7022	1.7051	-0.17	1.42	1.34	5.76
45	2.3252	2.1498	7.54	1.2926	1.2955	-0.22	0.89	0.88	1.17
30	0.7388	0.6721	9.02	0.7523	0.7656	-1.77	0.39	0.45	-14.90
15	0.0684	0.0650	4.96	0.2462	0.2580	-4.78	0.09	0.12	-32.77

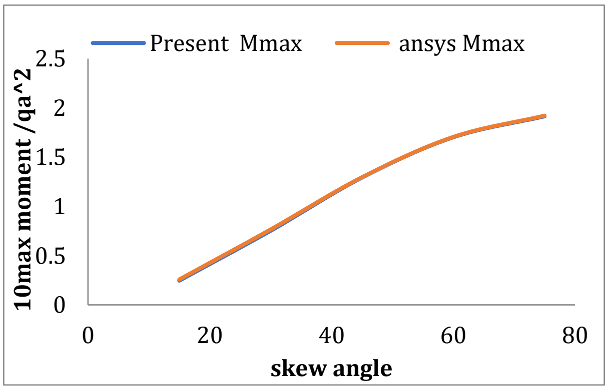


FIGURE 4: showing moments in varying span for (Mmax)

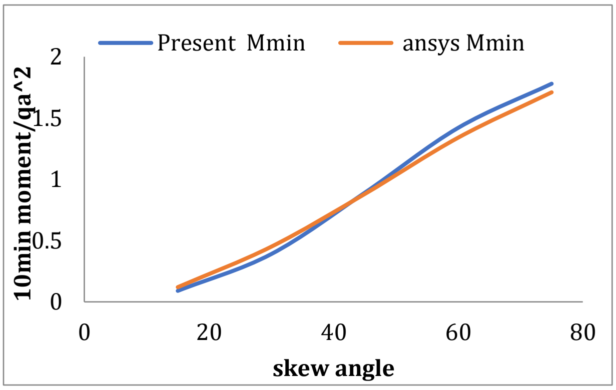


FIGURE 5: showing moments in fixed span span for (Mmin)

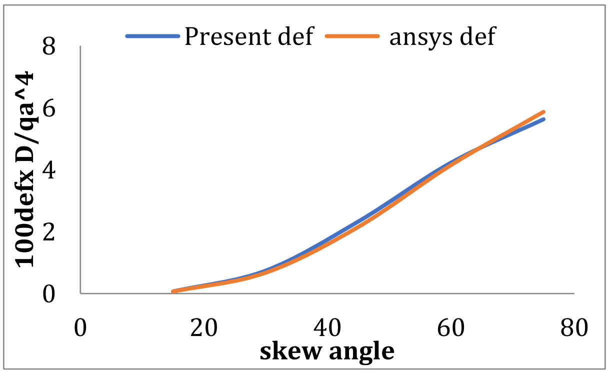


FIGURE 6: showing compared deflections

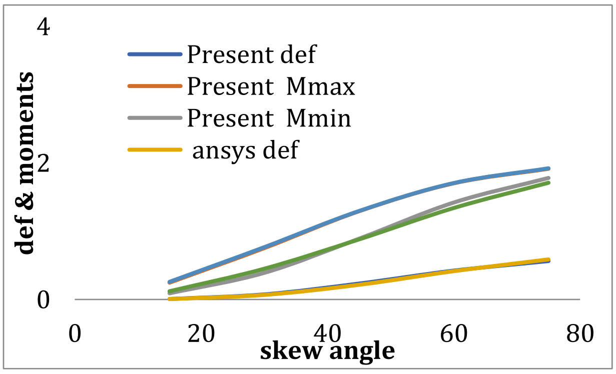


FIGURE 7: showing compared deflections and moments

To further validate the present method, several results established in literature for decades are compared and presented in tables 5 and 6 below.

TABLE 5: showing deflections and moments for various skew angles for m=2 by the present method compared to others in literature.

Skew angle θ		α 100ΔD/qa4	% diff	10Mmax /qa2	% diff	10Mmin /qa2	% diff
75^0	present	5.6273		1.8527		1.7848	
	Pang-jo Chun et al.	5.8513	-3.98	1.9318	-4.27	1.7191	3.68
	ANSYS	5.8662	-4.25	1.9215	-3.71	1.7074	4.34
	Butalia et al. (1990)	5.8013	-3.09	1.9207	-3.67	1.7082	4.29
	GangaRao and Chaudhary (1998)	5.824	-3.50	N/A	N/A	N/A	N/A
	Liew and Han (1997)	5.9257	-5.30	1.9512	-5.32	1.7261	3.29
	Sengupta (1991)	5.8468	-3.90	1.9241	-3.85	1.7097	4.21
	Sengupta (1995)	5.8172	-3.37	1.903	-2.72	1.6931	5.14
60°	present	4.2231		1.6554		1.4190	
	Pang-jo Chun et al.	4.1946	0.67	1.7227	-4.06	1.3614	4.06
	ANSYS	4.1455	1.84	1.7051	-3.00	1.3372	5.76
	Butalia et al. (1990)	3.9832	5.68	1.679	-1.42	1.298	8.52
	GangaRao and Chaudhary (1998)	4.096	3.01	N/A	N/A	N/A	N/A
	Liew and Han (1997)	4.1908	0.76	1.7349	-4.80	1.3561	4.43
	Morley (1963)	4.096	3.01	1.7	-2.69	1.332	6.13
	Muhammad and Singh (2004)	4.096	3.01	1.724	-4.14	1.372	3.31
	Sengupta (1991)	4.1123	2.62	1.7075	-3.14	1.3391	5.63
	Sengupta (1995)	4.1079	2.73	1.6909	-2.14	1.3267	6.50
45°	present	2.3252		1.2835		0.8929	
	Pang-jo Chun et al.	2.2105	4.93	1.3289	-3.54	0.9075	-1.64
	ANSYS	2.1498	7.54	1.2955	-0.93	0.8824	1.17
	Argyris (1965)	2.0787	10.60	1.2983	-1.15	0.857	4.02
	Butalia et al. (1990)	1.9125	17.75	1.2266	4.43	0.7803	12.61
	GangaRao and Chaudhary (1998)	2.112	9.17	N/A	N/A	N/A	N/A
	Liew and Han (1997)	2.1669	6.81	1.3194	-2.80	0.9032	-1.16
	Sengupta (1991)	2.133	8.27	1.2995	-1.25	0.8866	0.70
	Sengupta (1995)	2.1285	8.46	1.2892	-0.44	0.8787	1.59
30°	Present	0.7388		0.7624		0.3901	
	Pang-jo Chun et al.	0.6824	7.63	0.7888	-3.46	0.4678	-19.93
	ANSYS	0.6721	9.02	0.7656	-0.42	0.4482	-14.90
	Argyris (1965)	0.6158	16.65	0.7668	-0.58	0.4028	-3.26
	Butalia et al. (1990)	0.5194	29.69	0.6662	12.62	0.3166	18.84
	Carstensen et al. (2010)	0.6784	8.17	N/A	N/A	N/A	N/A
	GangaRao and Chaudhary (1998)	0.6496	12.07	N/A	N/A	N/A	N/A
	Jirousek (1987)	0.6526	11.66	0.7625	-0.01	0.4343	-11.34
	Liew and Han (1997)	0.6679	9.59	0.778	-2.04	0.4509	-15.59
	Morley (1963)	0.6528	11.64	0.764	-0.21	0.432	-10.75
	Muhammad and Singh (2004)	0.5658	23.41	0.68	10.81	0.3405	12.71
	Razaqpur et al. (2003)	0.6771	8.35	0.7568	0.74	0.4441	-13.85
	Sengupta (1991)	0.669	9.44	0.7734	-1.44	0.4481	-14.88
	Sengupta (1995)	0.6587	10.84	0.7628	-0.05	0.434	-11.26

Skew angle θ		α 100ΔD/qa4	% diff	10Mmax /qa2	% diff	10Mmin /qa2	% diff
15°	Present	0.0684		0.2500		0.0899	
	Pang-jo Chun et al.	0.0658	3.79	0.2637	-5.49	0.122	-35.66
	ANSYS	0.065	4.96	0.258	-3.21	0.1194	-32.77
	Butalia et al. (1990)	0.0422	38.30	0.1906	23.75	0.0639	28.94
	Liew and Han (1997)	0.0635	7.16	0.2566	-2.65	0.1149	-27.77
	Sengupta (1991)	0.0653	4.53	0.2586	-3.45	0.1226	-36.33
	Sengupta (1995)	0.0605	11.54	0.2461	1.55	0.103	-14.54

TABLE 6: showing deflections and moments for various skew angles
for m=2 by the present method compared to the average of all results presented in table 5 above.

Skew angle θ	α 100ΔD/qa4		% diff	10Mmax /qa2		% diff	10Mmin /qa2		% diff
	present	average		present	average		present	average	
75^0	5.6273	5.8200	-3.42	1.8527	1.9150	-3.36	1.78	1.7212	3.56
60^0	4.2231	4.1245	2.33	1.6554	1.7022	-2.82	1.42	1.3491	4.93
45^0	2.3252	2.1352	8.17	1.2835	1.2926	-0.71	0.89	0.8736	2.16
30^0	0.7388	0.6500	12.01	0.7624	0.7523	1.33	0.39	0.4174	-7.02
15^0	0.0684	0.0615	10.04	0.2500	0.2462	1.50	0.09	0.1051	-16.88

It is of great interest that a simple strip method can analytically solve hitherto complex rhombic plate problems with ease as shown in tables 1, 2, 3, 4, 5 and 6 together with graphs in figs 3, 4, 5, 6 and 7. Though the presented method is a hand method, it can be automated using Excel spread sheet in few lines. It is vast and so can give results for any skew angle as little as 0.1^0 to 90^0 as shown in the table 3 and figs 3. It can also handle rhombic plate with any side length ma as figs 3a and 3b show. To even get results for small skewed angles [25] the authors had to use for skewed angle α = 15°, 2 triangular elements at acute corners to avoid an extensively skewed element. Consequently, they had to use 1650 nodes and 1493 elements. The shear correction factor of 5/6 was used to obtain the results shown. In this present method no forcing function or factor was employed anywhere in the formation of the needed equations.

CONCLUSION AND RECOMMENDATIONS

Conclusion

A method of skewed rhombic plate analysis by extending the finite series method [1] has been developed in this paper. The compared results of this paper with that of commercial ANSYS 11 with other methods show that the hitherto mathematical manipulations needed for either analytical or numerical method for skewed rhombic plates can be avoided to obtain in a simple way striking results. This work has been extended to rhombic skewed plate with constant area. The details of this shall be published when the work is completed.

Recommendation

The method is recommended to be tested for skewed plates other than rhombic plates and for various boundary and loading conditions. It is expected that the results from classical analytical and numerical method packages will be obtained using this method in its original or modified state.

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