# Mesh less Analysis of Orthotropic Skew Plate under Sinusoidal Line Load

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**Abstract-**In this paper the analysis of orthotropic skew plate under sinusoidal line load is investigated. The analysis is done with polynomial radial basis function base mess free method using first order shear deformation theory (FSDT). A MATLAB code is developed to obtain the solutions. The governing differential equations of plate are obtained using Hamilton's principle. Effect of orthotropic ration, skew angle and span to thickness ratio is presented.

**Keywords**: Skew plate, Mesh free, FSDT, sinusoidal line load.

## I. INTRODUCTION

The analysis of skew plates as structural element gained the attention of researchers in the late 1940s. Rectangular, trapezoidal and skew plates are among the important members of the quadrilateral family that are used in aerospace, naval, automotive and other engineering structures. They are often used in modern structures in spite of the mathematical difficulties involved in their study.

In current date analysis of skew panels are much more in demand, as per analysis of skew plates already done by several researchers such as Using Boundary Element Method (BEM), a fundamental solution in oblique coordinates for the analysis of isotropic skew plates under transverse loading has been obtained by Rajamohan and Raamachandran [1].

Ferreira et al. [2] use the FSDT in the multiquadric radial basis function (MQRBF) procedure for predicting the free vibration behavior. The analysis of isotropic thick skew plates had been carried out by Muhammad and Singh, [3] Srinivasa et. al. [4] studies the buckling effect on skew plates using finite element. A review on the work done on the bending analysis of skew plates before 1989 has been carried out by Butalia et al. [5]. Sengupta [6] has studied the performance of a simple finite element for the analysis of skew rhombic plates.

## II. MATHEMATICAL FORMULATION

The plate geometry of is shown in Fig. 1. Thickness h is along z axis whose mid plane is coinciding with x-y plane of the coordinate system is considered.

The displacement field at any point in the plate is expressed as ignoring initial displacements in X and Y direction:

$$u = -z\phi_x \qquad v = -z\phi_y \qquad w = w_0 \tag{1}$$

The strain-displacement relations can be written as:

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} -z\dfrac{\partial\phi_x}{\partial x} \\ -z\dfrac{\partial\phi_y}{\partial y} \\ -z\dfrac{\partial\phi_x}{\partial y} - z\dfrac{\partial\phi_y}{\partial x} \end{Bmatrix} \tag{2}$$

$$\begin{Bmatrix} \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{Bmatrix} -\phi_y + \dfrac{\partial w_0}{\partial y} \\ -\phi_x + \dfrac{\partial w_0}{\partial x} \end{Bmatrix} \tag{3}$$

The constitutive stress strain relation can be written as:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{zx} \end{Bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & 0 & 0 & 0 \\ \bar{Q}_{12} & \bar{Q}_{22} & 0 & 0 & 0 \\ 0 & 0 & \bar{Q}_{66} & 0 & 0 \\ 0 & 0 & 0 & \bar{Q}_{44} & 0 \\ 0 & 0 & 0 & 0 & \bar{Q}_{55} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} \tag{4}$$

Where,

$$\bar{Q}_{11} = \bar{Q}_{22} = \frac{E}{\left(1-\nu^2\right)}, \quad \bar{Q}_{12} = \nu\bar{Q}_{11}, \; \bar{Q}_{44} = \bar{Q}_{55} = \bar{Q}_{66} = G \tag{5}$$

The governing differential equations of plate are obtained using Hamilton's principle and expressed as:

$$\frac{\partial M_{xx}}{\partial x} + \frac{\partial M_{xy}}{\partial y} - Q_x = 0$$
$$\frac{\partial M_{xy}}{\partial x} + \frac{\partial M_{yy}}{\partial y} - Q_y = 0$$
$$\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} - q_z = 0 \tag{6}$$

Where,

$$M_{xx} = D_{11}\frac{\partial\phi_x}{\partial x} + D_{12}\frac{\partial\phi_y}{\partial y}$$

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$$M_{yy} = D_{12}\frac{\partial \phi_x}{\partial x} + D_{22}\frac{\partial \phi_y}{\partial y}$$

$$M_{xy} = D_{16}\frac{\partial \phi_x}{\partial x} + D_{26}\frac{\partial \phi_y}{\partial y}$$

$$Q_x = kA_{55}\phi_x,\ Q_y = kA_{55}\phi_y$$

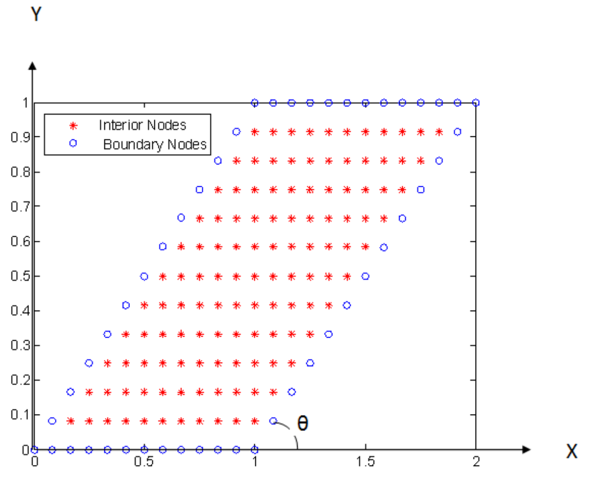


Fig.1 Geometry of discretized skew plate

The boundary conditions for an arbitrary edge with simply supported conditions are as follows:

$$\phi^s, w, M_{nn} = 0 \tag{7}$$

Where,

$$\phi^s = -n_y.\phi^x + n_x.\phi^y$$

$$M_{nn} = n_x^2 M_{xx} + 2n_x n_y M_{xy} + n_y^2 M_{yy}$$

$$n_x = \cos(\theta),\quad n_y = \sin(\theta)$$

## III. SOLUTION METHODOLOGY

The governing differential equations (5) are expressed in terms of displacement functions. Radial basis function based formulation works on the principle of interpolation of scattered data over entire domain. The variable $w_0, \phi_x$ *and* $\phi_y$ can be interpolated in form of radial distance between nodes. The solution of the linear governing differential equations is assumed in terms of polynomial radial basis function for nodes 1: N, as;

$$w_o, \phi_x, \phi_y = \sum_{j=1}^{N} (\alpha_j^w, \alpha_j^{\phi_x}, \alpha_j^{\phi_y})\ g\left(\left\|X - X_j\right\|, m\right) \tag{8}$$

Where, N is total numbers of nodes which is equal to summation of boundary nodes NB and domain interior nodes ND. $g\left(\left\|X - X_j\right\|, m\right)$ is polynomial radial basis function expressed as $g = r^m$ , $\delta = \alpha_j^w, \alpha_j^{\phi_x}, \alpha_j^{\phi_y}$ are unknown coefficients. $\left\|X - X_j\right\|$ is the radial distance between two nodes.

Where, $r = \left\|X - X_j\right\| = \sqrt{\left(x - x_j\right)^2 + \left(y - y_j\right)^2}$ and m is shape parameter. The value of 'm' taken here is 5. Polynomial radial basis function becomes singular, when r = 0 i.e. for zero distance. In order to eliminate the singularity, an infinitesimally small value is added into the $r^2$ or zero distance. Mathematically it is explained as; $r^2 = r^2 + \mu^2$ when r = 0 or i = j; $\mu^2$ is small numerical value of the order $10^{-10}$.
The discretized governing equations for linear flexural analysis can be written as:

$$\begin{bmatrix} [K]_L \\ [K]_B \end{bmatrix}_{3N\times 3N} \{\delta\}_{3N\times 1} = \begin{Bmatrix} [F]_L \\ 0 \end{Bmatrix}_{3N\times 1} \tag{9}$$

The unknown coefficients $\{\delta\}$ are calculated from equation (9).

## IV. NUMERICAL RESULTS AND DISCUSSIONS

In order to demonstrate the accuracy and applicability of present formulation, a RBF based mesh less code in MATLAB is developed following the analysis procedure as discussed above. Based on convergence study, a 13x13 node is used throughout the study.

The deflection and moments are normalized as:

$$\bar{w} = w_{c\max}.100.h^3/(qa^4) \qquad \bar{M} = M_{c\max}.40/(qa^2)$$

$$\bar{\sigma}_{xx} = \sigma_{xx\max}.(qa^4/h^2) \qquad \bar{\sigma}_{yy} = \sigma_{yy\max}.(qa^4/h^2)$$

$$\bar{\sigma}_{xy} = \sigma_{xy\max}.(qa^4/h^2) \qquad \bar{\sigma}_{xz} = \sigma_{xz\max}.(qa^4/h^2)$$

Unless until specified, the material properties are taken as: $E1 = 25, E2 = 1, \nu = 0.3, G1 = G2 = 0.5, G3 = 0.2$

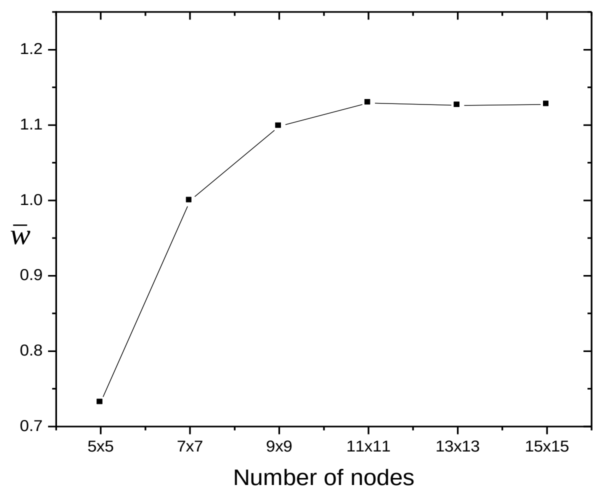


**Fig. 2** Convergence study for deflection $\bar{w}$ of skew plate (a/h = 10)

From Fig.2 it can be seen that a good convergence is achieved for thick plate. The convergence is within 2% for nodes more than 11x11.

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Other numerical examples have been also considered and the results obtained for different values of span to thickness ratio is shown in Table-1 to Table 9 and for different orthotropic ratio is shown in Table-10 to Table-16.

**Table-1** Effect of span to thickness ratio on $M_{xx}$ of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 7.4196 | 7.4099 | 6.6753 | 5.7322 | 4.1581 |
| **10** | 8.6617 | 8.0387 | 7.1615 | 5.9342 | 3.9634 |
| **20** | 8.4129 | 7.7343 | 7.2489 | 5.8902 | 3.8604 |
| **30** | 8.5174 | 8.0538 | 7.1508 | 5.7489 | 6.269 |
| **40** | 8.5999 | 8.0455 | 7.0057 | 5.5689 | 3.6202 |
| **50** | 8.639 | 8.011 | 6.8455 | 5.3754 | 3.5033 |
| **100** | 8.9621 | 7.7612 | 6.0869 | 4.6262 | 2.9583 |

**Table-2** Effect of span to thickness ratio on Myy of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| a/h | 90 | 75 | 60 | 45 | 30 |
| 5 | 1.6431 | 1.6117 | 1.5401 | 1.4312 | 1.2115 |
| 10 | 1.443 | 1.4182 | 1.3809 | 1.2786 | 1.2723 |
| 20 | 1.3582 | 1.3198 | 1.2631 | 1.1416 | 1.2543 |
| 30 | 1.3213 | 1.2854 | 1.2095 | 1.0686 | 1.2314 |
| 40 | 1.2963 | 1.2541 | 1.163 | 1.0114 | 1.0956 |
| 50 | 1.2784 | 1.2256 | 1.1183 | 0.9639 | 1.0166 |
| 100 | 1.2635 | 1.1027 | 0.9175 | 0.7337 | 0.7275 |

**Table-3** Effect of span to thickness ratio on Mxy of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| a/h | 90 | 75 | 60 | 45 | 30 |
| 5 | 0.5175 | 0.4499 | 0.524 | 0.5217 | 0.3586 |
| 10 | 0.3677 | 0.4665 | 0.5769 | 0.5786 | 0.5686 |
| 20 | 0.3567 | 0.467 | 0.6012 | 0.6121 | 0.4124 |
| 30 | 0.3211 | 0.4813 | 0.6014 | 0.6012 | 1.4833 |
| 40 | 0.3225 | 0.4854 | 0.589 | 0.5743 | 0.3736 |
| 50 | 0.332 | 0.4879 | 0.572 | 0.5422 | 0.3391 |
| 100 | 0.4054 | 0.4874 | 0.4781 | 0.3952 | 0.2329 |

**Table-4** Effect of span to thickness ratio on Mnn of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 1.9133 | 1.9005 | 1.9502 | 2.0337 | 2.6012 |
| **10** | 1.8543 | 1.8384 | 1.8731 | 1.9537 | 2.7147 |
| **20** | 1.8101 | 1.7712 | 1.7749 | 1.9866 | 2.7817 |
| **30** | 1.7244 | 1.6958 | 1.6876 | 1.9792 | 2.7757 |
| **40** | 1.6472 | 1.6183 | 1.5976 | 1.9597 | 2.5175 |
| **50** | 1.5783 | 1.5432 | 1.509 | 1.8745 | 2.3369 |
| **100** | 1.3594 | 1.2378 | 1.1406 | 1.3702 | 1.6067 |

**Table-5** Effect of span to thickness ratio on Mns of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 0.5175 | 1.4645 | 2.2515 | 2.1505 | 1.2729 |
| **10** | 0.3677 | 1.6956 | 2.5465 | 2.3287 | 1.2036 |
| **20** | 0.3567 | 1.6791 | 2.641 | 2.3766 | 1.2021 |
| **30** | 0.3211 | 1.7439 | 2.6229 | 2.3409 | 2.8749 |
| **40** | 0.3225 | 1.7524 | 2.5806 | 2.2807 | 1.1632 |
| **50** | 0.332 | 1.7537 | 2.5308 | 2.2107 | 1.138 |
| **100** | 0.4054 | 1.7395 | 2.2895 | 1.9463 | 0.9992 |

**Table-6** Effect of span to thickness ratio on $\bar{\sigma}_{xx}$ of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 6.9284 | 4.3947 | 3.3578 | 2.9475 | 2.6402 |
| **10** | 6.7897 | 6.9555 | 8.7584 | 2.6969 | 2.6792 |
| **20** | 10.269 | 27.5235 | 3.3789 | 5.8641 | 2.1067 |
| **30** | 6.1342 | 4.6263 | 3.5337 | 4.4658 | 30.6925 |
| **40** | 6.9732 | 3.7994 | 3.6857 | 3.6798 | 3.1723 |
| **50** | 6.644 | 3.7799 | 3.8394 | 3.9044 | 3.5081 |
| **100** | 8.037 | 4.0205 | 4.3509 | 4.4023 | 4.5025 |

**Table-7** Effect of span to thickness ratio on $\bar{\sigma}_{yy}$ of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 1.9133 | 1.9005 | 1.9502 | 2.0337 | 2.6012 |
| **10** | 1.8543 | 1.8384 | 1.8731 | 1.9537 | 2.7147 |
| **20** | 1.8101 | 1.7712 | 1.7749 | 1.9866 | 2.7817 |
| **30** | 1.7244 | 1.6958 | 1.6876 | 1.9792 | 2.7757 |
| **40** | 1.6472 | 1.6183 | 1.5976 | 1.9597 | 2.5175 |
| **50** | 1.5783 | 1.5432 | 1.509 | 1.8745 | 2.3369 |
| **100** | 1.3594 | 1.2378 | 1.1406 | 1.3702 | 1.6067 |

**Table-8** Effect of span to thickness ratio on $\bar{\sigma}_{xy}$ of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 0.4078 | 0.3709 | 0.411 | 0.4063 | 0.3668 |
| **10** | 0.2998 | 0.3435 | 0.4456 | 0.4989 | 0.4155 |
| **20** | 0.3045 | 0.9876 | 0.4925 | 0.66 | 0.5781 |
| **30** | 0.3096 | 0.3332 | 0.5201 | 0.7457 | 0.8229 |
| **40** | 0.3044 | 0.3307 | 0.5255 | 0.7729 | 0.6618 |
| **50** | 0.303 | 0.3257 | 0.5175 | 0.7594 | 0.6508 |
| **100** | 0.325 | 0.2929 | 0.4333 | 0.5938 | 0.4986 |

**Table-9** Effect of span to thickness ratio on $\overline{\sigma}_{xz}$ of a square orthotropic skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 0.2426 | 0.2446 | 0.2321 | 0.2104 | 0.1658 |
| **10** | 0.2447 | 0.2357 | 0.2131 | 0.1767 | 0.116 |
| **20** | 0.3489 | 0.3161 | 0.2909 | 0.2201 | 0.1254 |
| **30** | 0.4953 | 0.4602 | 0.3894 | 0.2811 | 0.1565 |
| **40** | 0.656 | 0.5972 | 0.4861 | 0.3378 | 0.1826 |
| **50** | 0.8221 | 0.7355 | 0.5767 | 0.3921 | 0.2098 |
| **100** | 1.8177 | 1.4187 | 0.9308 | 0.6016 | 0.3108 |

**Table--10** Effect of orthotropic ratio on $M_{xy}$ of a skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 1.286 | 1.3901 | 1.1466 | 0.7916 | 0.3297 |
| **10** | 0.9613 | 1.1355 | 0.9476 | 0.689 | 0.3224 |
| **20** | 0.5286 | 0.6547 | 0.5954 | 0.4795 | 0.2671 |
| **30** | 0.4549 | 0.5557 | 0.5262 | 0.4308 | 0.2481 |
| **40** | 0.4054 | 0.4874 | 0.4781 | 0.3952 | 0.2329 |
| **50** | 0.3692 | 0.4384 | 0.4409 | 0.3701 | 0.2203 |
| **100** | 0.3187 | 0.3742 | 0.3847 | 0.3357 | 0.2007 |

**Table-11** Effect of orthotropic ratio on $M_{nn}$ of a skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 2.7104 | 2.0914 | 1.7058 | 1.3578 | 0.8211 |
| **10** | 2.2674 | 1.9057 | 1.728 | 1.5518 | 1.0504 |
| **20** | 1.5031 | 1.5982 | 1.9407 | 2.1694 | 1.78 |
| **30** | 1.3607 | 1.5422 | 2.0359 | 2.3856 | 2.0365 |
| **40** | 1.2635 | 1.5055 | 2.1215 | 2.5718 | 2.2592 |
| **50** | 1.1909 | 1.4797 | 2.1985 | 2.737 | 2.4538 |
| **100** | 1.0859 | 1.4461 | 2.3218 | 3.0232 | 2.7861 |

**Table-12** Effect of orthotropic ratio on $M_{ns}$ of a skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 1.286 | 1.0692 | 0.6449 | 0.7634 | 0.7213 |
| **10** | 0.9613 | 0.9013 | 0.8859 | 0.7024 | 0.6528 |
| **20** | 0.5286 | 1.4313 | 1.7671 | 1.452 | 0.6721 |
| **30** | 0.4549 | 1.602 | 2.0529 | 1.7212 | 0.8503 |
| **40** | 0.4054 | 1.7395 | 2.2895 | 1.9463 | 0.9992 |
| **50** | 0.3692 | 1.8558 | 2.4916 | 2.142 | 1.1278 |
| **100** | 0.3187 | 2.0478 | 2.786 | 2.4742 | 1.3441 |

**Table-13** Effect of orthotropic ratio on $\overline{\sigma}_{xx}$ of a skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 1.9133 | 1.9005 | 1.9502 | 2.0337 | 2.6012 |
| **10** | 1.8543 | 1.8384 | 1.8731 | 1.9537 | 2.7147 |
| **20** | 1.8101 | 1.7712 | 1.7749 | 1.9866 | 2.7817 |
| **30** | 1.7244 | 1.6958 | 1.6876 | 1.9792 | 2.7757 |
| **40** | 1.6472 | 1.6183 | 1.5976 | 1.9597 | 2.5175 |
| **50** | 1.5783 | 1.5432 | 1.509 | 1.8745 | 2.3369 |
| **100** | 1.3594 | 1.2378 | 1.1406 | 1.3702 | 1.6067 |

**Table-14** Effect of orthotropic ratio on $\overline{\sigma}_{yy}$ of a skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 0.4078 | 0.3709 | 0.411 | 0.4063 | 0.3668 |
| **10** | 0.2998 | 0.3435 | 0.4456 | 0.4989 | 0.4155 |
| **20** | 0.3045 | 0.9876 | 0.4925 | 0.66 | 0.5781 |
| **30** | 0.3096 | 0.3332 | 0.5201 | 0.7457 | 0.8229 |
| **40** | 0.3044 | 0.3307 | 0.5255 | 0.7729 | 0.6618 |
| **50** | 0.303 | 0.3257 | 0.5175 | 0.7594 | 0.6508 |
| **100** | 0.325 | 0.2929 | 0.4333 | 0.5938 | 0.4986 |

**Table-15** Effect of orthotropic ratio on $\overline{\sigma}_{xy}$ of a skew plate

| | Skew angle | | | | |
|---|---|---|---|---|---|
| **a/h** | **90** | **75** | **60** | **45** | **30** |
| **5** | 0.2426 | 0.2446 | 0.2321 | 0.2104 | 0.1658 |
| **10** | 0.2447 | 0.2357 | 0.2131 | 0.1767 | 0.116 |
| **20** | 0.3489 | 0.3161 | 0.2909 | 0.2201 | 0.1254 |
| **30** | 0.4953 | 0.4602 | 0.3894 | 0.2811 | 0.1565 |
| **40** | 0.656 | 0.5972 | 0.4861 | 0.3378 | 0.1826 |
| **50** | 0.8221 | 0.7355 | 0.5767 | 0.3921 | 0.2098 |
| **100** | 1.8177 | 1.4187 | 0.9308 | 0.6016 | 0.3108 |

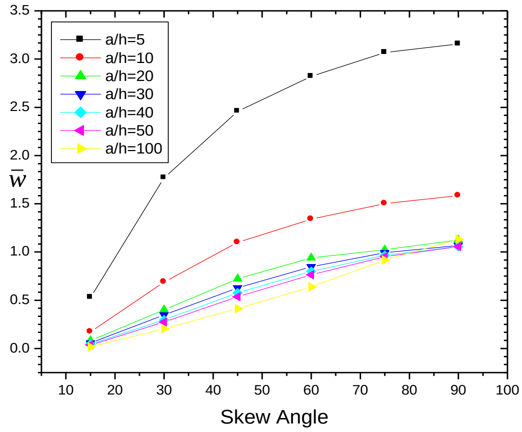


**Fig.3** Effect of skew angle along span to thickness ratio on deflection $\overline{w}$ of skew plate

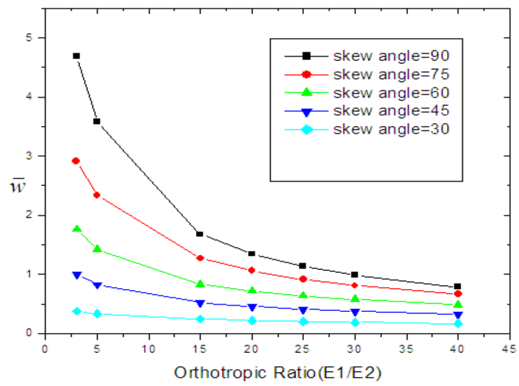


**Fig.4** Effect of orthotropic ratio on deflection $\overline{w}$ of a skew plate (a/h=1/100)

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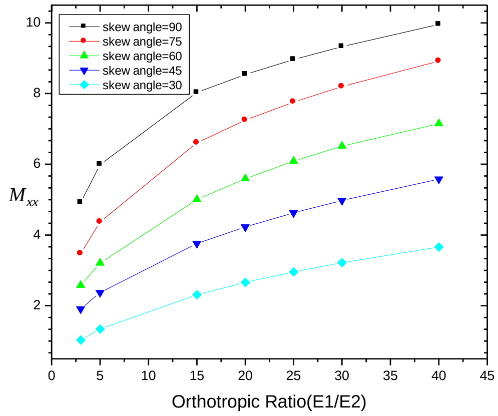


Fig.5 Effect of orthotropic ratio on moment Mxx of a skew plate (a/h=1/100)

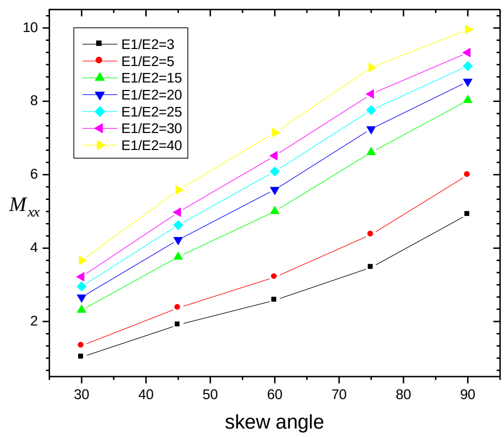


Fig.6 Effect of skew angle with variation of orthotropic ratio on $M_{xx}$ of a skew plate (a/h=1/100)

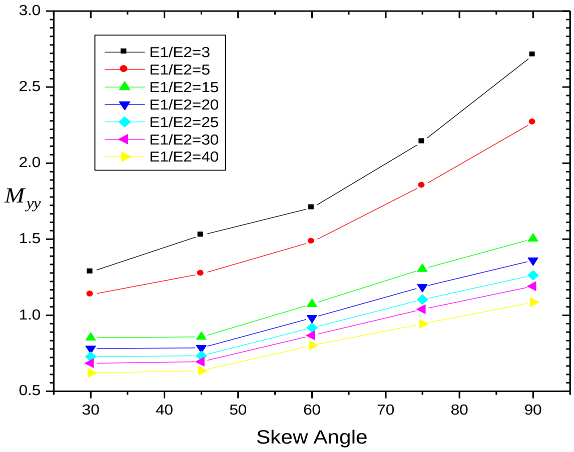


Fig.7 Effect of skew angle with variation of orthotropic ratio on $M_{yy}$ of a skew plate (a/h=1/100)

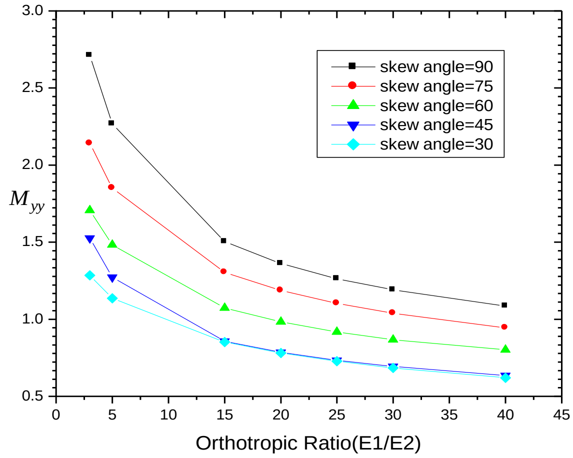


Fig.8 Effect of orthotropic ratio on moment Myy of a skew plate (a/h=1/100)

Fig. 3 to Fig.8 shows the effect of skew angle on deflection and moment. It is observed that the effect of span to thickness ratio seems to be negligible after a/h=40. The effect of orthotropy ratio seems to be negligible after E1/E2=30.

## 5. CONCLUSION

The present study shows that the proposed RBFs are capable to accurately predict the flexure behavior of skew plates. Effect of skewness on deflection, moments and stresses is obtained. It is found that all the parameters decrease as skewness increases. Effect is more prominent for thick plates as compared to thick plate. The study further can be extended for orthotropic, laminated and FGM plates.

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