ERRORS DUE TO MISALIGNMENT OF ROSETTES

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This paper presents an investigation of errors that are likely to creep in the evaluation of principal stresses when misaligned rosettes are used. It has been found that if the gauges forming the rosette are having orientation errors of the order of $+2°$, the error in the evaluation of principal stresses by using normal rosette equations will be about 1 to 3 percent.

GENERAL ROSETTE EQUATIONS

In any plane stress problem where a biaxial stress field exists with the directions of principal stresses unknown, three strain measurements are necessary to evaluate the principal stresses. It can easily be shown[1] that strain measured in any direction ϕ referred to a chosen x-axis is

$$\epsilon_\phi = \left(\frac{\epsilon_x + \epsilon_y}{2}\right) + \left(\frac{\epsilon_x - \epsilon_y}{2}\right)\cos 2\phi + \frac{\gamma_{xy}}{2}\sin 2\phi \tag{1}$$

where ϵ_ϕ = strain measured in any direction ϕ (See Fig. 1)

ϵ_x, ϵ_y = normal strains in the x, y directions respectively, and

γ_{xy} = shearing strain in the xy plane.

The presence of three unknowns *viz.* ϵ_x, ϵ_y and γ_{xy} necessitates three strain measurements. Normally these measurements are taken using Strain Gauge Rosettes.

Strain gauge rosettes are available commercially in discrete patterns like the Rectangular rosette, Delta rosette and the Tee-Delta rosette (see Fig. 2–4).

When the reference axis *viz.* x-axis is chosen along gauge 1, these patterns can then be defined by the orientations of the gauges with respect to the x-axis. These definitions are given in Table 1.

Any one of the rosettes may be used in the m asurement of strain. We will then have strain values in three directions ϵ_{ϕ_1}, ϵ_{ϕ^2} & ϵ_{ϕ_3} which, when successively substituted in (1) and solved, will give ϵ_x, ϵ_y and γ_{xy}. Then the principal strains are obtained from the relations[1]

$$\epsilon_{max} = \frac{\epsilon_x + \epsilon_y}{2} + \frac{1}{2}\sqrt{(\epsilon_x - \epsilon_y)^2 + \gamma_{xy}^2} \tag{2}$$

$$\epsilon_{min} = \frac{\epsilon_x + \epsilon_y}{2} - \frac{1}{2}\sqrt{(\epsilon_x - \epsilon_y)^2 + \gamma_{xy}^2} \tag{3}$$

$$\gamma_{max} = \sqrt{(\epsilon_x - \epsilon_y)^2 + \gamma_{xy}^2} \tag{4}$$

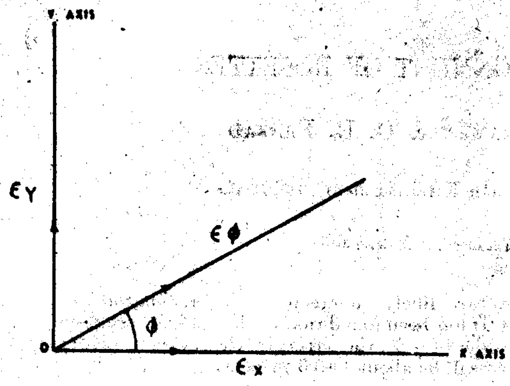


Fig. 1—Rosette Configuration with three gauges —general pattern.

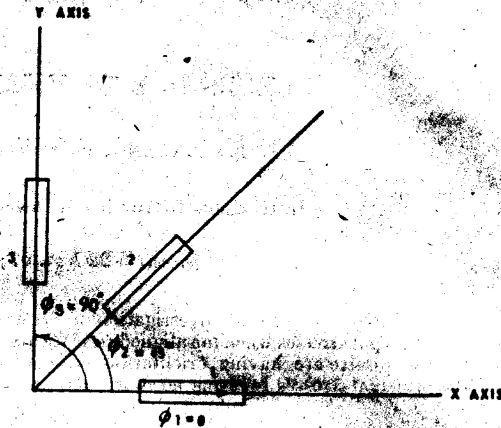


Fig. 2—Rectangular Rosette

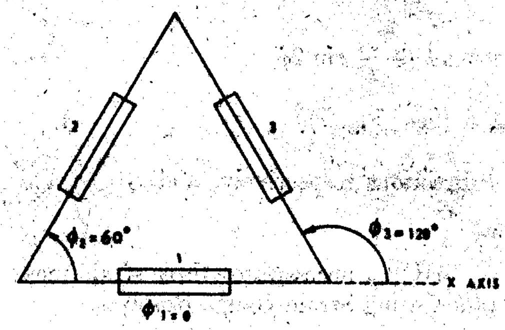


Fig. 3—Delta rosette.

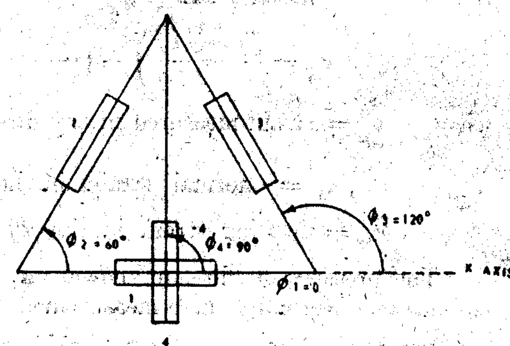


Fig. 4—Tee-Delta rosette.

TABLE 1

Type of rosette	Orientations			
	ϕ_1	ϕ_2	ϕ_3	ϕ_4
Rectangular	0°	45°	90°	—
Delta	0°	60°	120°	—
Tee-Delta	0°	60°	120°	90°

The principal stresses are then obtained using the relations[1].

$$\sigma_{max} = \frac{E}{1-\mu^2} (\epsilon_{max} + \mu \epsilon_{min}) \quad (5)$$

$$\sigma_{min} = \frac{E}{1-\mu^2} (\epsilon_{min} + \mu \epsilon_{max}) \quad (6)$$

$$\tau_{max} = \frac{E}{2 (1+ \mu)} \gamma_{max} \quad (7)$$

where E = Young's modulus of the material,

μ = Poisson's ratio of the material.

The direction of principal stresses is given by

$$\phi = \frac{1}{2} \tan^{-1} \frac{\gamma_{xy}}{\epsilon_x - \epsilon_y} \quad (8)$$

The principal stress equations for rectangular and delta rosette are given in the Table 2.

MODIFIED EQUATIONS WHEN THERE ARE ERRORS IN THE ALIGNMENT OF THE ROSETTES

Let us assume that there are errors in the alignment of the gauges forming the rosettes and modify the rosette equations listed in the Table 2 incorporating these errors.

CASE 1—*Rectangular Rosette*

Since we normally choose the axis of gauge 1 as the reference or the x-axis, the error in the alignment of gauge 1 can be taken as zero. Let α_2 and α_3 be the errors in the alignments of gauges 2 and 3 respectively (see Fig. 5). Introducing these angles in the general equation (1) successively we get

$$\epsilon_{\phi_1} = \epsilon_1 = \frac{\epsilon_x + \epsilon_y}{2} + \frac{\epsilon_x - \epsilon_y}{2} \cos 2\phi_1 + \frac{\gamma_{xy}}{2} \sin 2\phi_1 \quad (9)$$

$$\epsilon (\phi_2 + \alpha_2) = \epsilon_2 = \frac{\epsilon_x + \epsilon_y}{2} + \frac{\epsilon_x - \epsilon_y}{2} . \cos 2 (\phi_2+\alpha_2)+ \frac{\gamma_{xy}}{2} \sin 2(\phi_2+\alpha_2) \quad (10)$$

$$\epsilon (\phi_3 + \alpha_3) = \epsilon_3 = \frac{\epsilon_x + \epsilon_y}{2} + \frac{\epsilon_x - \epsilon_y}{2} . \cos 2(\phi_3 + \alpha_3) + \frac{\gamma_{xy}}{2} \sin 2 (\phi_3 + \alpha_3) \quad (11)$$

for a rectangular rosette $\phi_1 = 0°$, $\phi_2 = 45°$ and $\phi_3 = 90°$. Therefore (9), (10) and (11) reduce to

$$\epsilon_1 = \epsilon_x \quad (12)$$

$$\epsilon_2 = \frac{\epsilon_x + \epsilon_y}{2} - \frac{\epsilon_x - \epsilon_y}{2} \sin 2\alpha_2 + \frac{\gamma_{xy}}{2} \cos 2\alpha_2 \quad (13)$$

$$\epsilon_3 = \frac{\epsilon_x + \epsilon_y}{2} - \frac{\epsilon_x - \epsilon_y}{2} \cos 2\alpha_3 - \frac{\gamma_{xy}}{2} \sin 2\alpha_3 \quad (14)$$

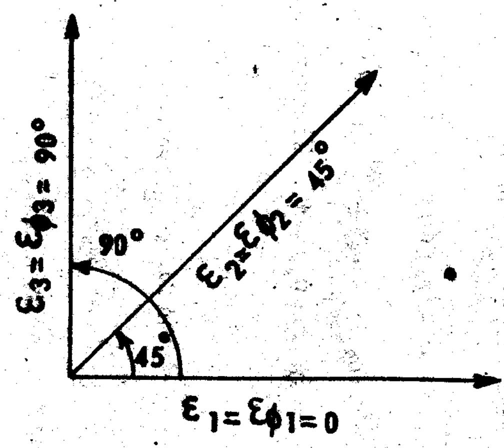
Solving (12), (13) and (14) for ϵ_x, ϵ_y and γ_{xy}, we get

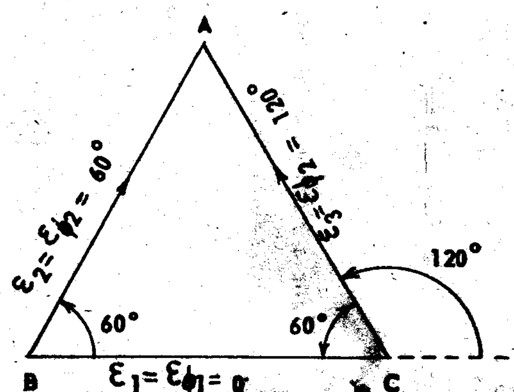
$$\epsilon_x = \epsilon_1 \quad (15)$$

$$\epsilon_y = \frac{2\beta - \epsilon_1 A}{?} \quad (16)$$

TABLE 2

Type of rosette	σ_{max}	σ_{min}	τ_{max}	ϕ_p
Rectangular:	$\frac{E}{2}\left[\frac{\epsilon_1+\epsilon_3}{1-\mu}+\frac{1}{1+\mu}\sqrt{(\epsilon_1-\epsilon_3)^2+(2\epsilon_2-\overline{\epsilon_1+\epsilon_3})^2}\right]$	$\frac{E}{2}\left[\frac{\epsilon_1+\epsilon_3}{1-\mu}-\frac{1}{1+\mu}\cdot\sqrt{(\epsilon_1-\epsilon_3)^2+(2\epsilon_2-\overline{\epsilon_1+\epsilon_3})^2}\right]$	$\frac{E}{2(1+\mu)}\cdot\sqrt{(\epsilon_1-\epsilon_3)^2+(2\epsilon_2-\overline{\epsilon_1+\epsilon_3})^2}$	$\frac{1}{2}\tan^{-1}\frac{(2\epsilon_2-\epsilon_1-\epsilon_3)}{(\epsilon_1-\epsilon_3)}$
Delta:	$E\left[\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3(1-\mu)}+\frac{1}{(1+\mu)}\cdot\left\{\left(\epsilon_1-\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3}\right)^2+\left(\frac{\epsilon_2-\epsilon_3}{\sqrt{3}}\right)^2\right\}^{\frac{1}{2}}\right]$	$E\left[\frac{\epsilon_1+\epsilon_2+\epsilon_4}{3(1-\mu)}-\frac{1}{(1+\mu)}\cdot\left\{\left(\epsilon_1-\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3}\right)^2+\left(\frac{\epsilon_2-\epsilon_3}{\sqrt{3}}\right)^2\right\}^{\frac{1}{2}}\right]$	$\frac{E}{2(1+\mu)}\left\{\left(\epsilon_1-\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3}\right)^2+\left(\frac{\epsilon_2-\epsilon_3}{\sqrt{3}}\right)^2\right\}^{\frac{1}{2}}$	$\frac{1}{2}\tan^{-1}\left(\frac{\frac{\epsilon_2-\epsilon_3}{\sqrt{3}}}{\epsilon_1-\frac{\epsilon_1+\epsilon_2+\epsilon_3}{3}}\right)$





$$\gamma_{xy} = \frac{\left[2\epsilon_2 - \left\{\frac{\epsilon_1 (B - A) + 2\beta}{B}\right\} + \left\{\frac{\epsilon_1 (B + A) - 2\beta}{B}\right\} \sin 2\alpha_2\right]}{\cos 2\alpha_2} \tag{17}$$

Where

$$\beta = \epsilon_2 \sin 2\alpha_3 + \epsilon_3 \cos 2\alpha_2$$

$$A = \sin 2\alpha_3 + \cos 2\alpha_2 - \cos 2 (\alpha_2 - \alpha_3)$$

$$B = \sin 2\alpha_3 + \cos 2\alpha_2 + \cos 2 (\alpha_2 - \alpha_3)$$

With expressions for ϵ_x, ϵ_y and γ_{xy} as given by equations (15), (16) and (17) we obtain the principal strains using the relationships vide equations (2) and (3). The principal stresses are then calculated using expressions given by equations (5), (6) and (7). The direction of principal stress is given by equation (8) used in conjunction with equations (15), (16) and (17).

CASE 2—*Delta Rosette*

For a Delta rosette $\phi_1 = 0°$, $\phi_2 = 60°$ and $\phi_3 = 120°$ choose again the x-axis along the axis of gauge 1. (see Fig. 6). Let us assume α_2 and α_3 as the errors in the alignment of gauges 2 and 3 respectively ($\alpha_2 = 0$ as before). Proceeding in the same manner as was done for rectangular rosette but substituting $\phi_1 = 0°$, $\phi_2 = 60°$ and $\phi_3 = 120°$ we get the expressions for ϵ_x, ϵ_y and γ_{xy} as:

$$\epsilon_x = \epsilon_1 \tag{18}$$

$$\epsilon_y = \frac{2\beta - \epsilon_1 A}{B} \tag{19}$$

$$\gamma_{xy} = \frac{4}{\delta'} \left[\frac{\epsilon_1}{2} \left\{ \left(1 + \frac{A}{B}\right) - \frac{1}{2} \delta \left(1 + \frac{A}{B}\right) \right\} + \frac{\beta}{B} \left(1 + \frac{\delta}{2}\right) - \epsilon_3 \right] \tag{20}$$

where

$$\beta = \epsilon_2 [\sqrt{3} \cos 2\alpha_3 + \sin 2\alpha_3] + \epsilon_3 [\sqrt{3} \cos 2\alpha_2 - \sin 2\alpha_2]$$

$$A = \sqrt{3} [\cos 2\alpha_3 + \cos 2\alpha_2 - \cos 2 (\alpha_2 - \alpha_3)] + [\sin 2\alpha_3 - \sin 2\alpha_2 - \sin 2 (\alpha_2 - \alpha_3)]$$

$$B = \sqrt{3} [\cos 2\alpha_3 + \cos 2\alpha_2 + \cos 2 (\alpha_2 - \alpha_3)] + [\sin 2\alpha_3 - \sin 2\alpha_2 + \sin 2 (\alpha_2 - \alpha_3)]$$

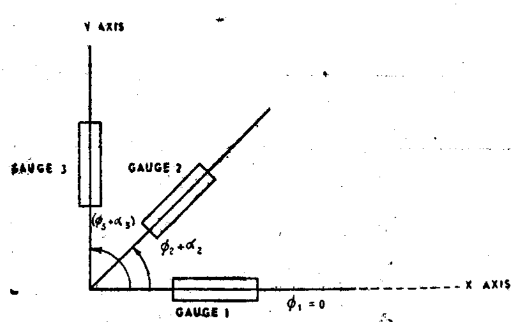


Fig. 5—Rectangular rosette with orientation errors.

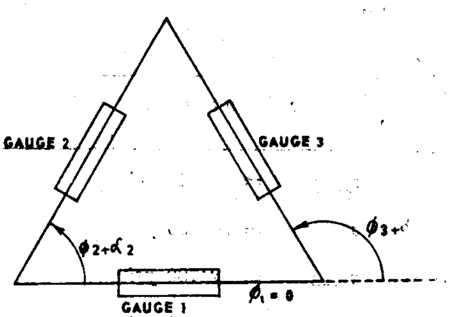


Fig. 6—Delta rosette with orientation errors.

$$\delta = (\cos 2a_3 - \sqrt{3} \sin 2a_3)$$

and $$\delta' = (\sqrt{3} \cos 2a_3 + \sin 2a_3)$$

Using the expressions for ϵ_x, ϵ_y and γ_{xy} as given by equations (18), (19) and (20) the principal strains and stresses are calculated using equations (2), (3) and (5), (6), (7) respectively. The direction of the principal stress is given by equation (8) used in conjunction with equations (18), (19) and (20).

EXAMPLES

CASE 1—*Rectangular Rosette*

(*a*) Let us assume that a rectangular rosette had been used with alignment errors of $+2°$ in gauges 2 and 3. Let the three measured strains be

$$\epsilon_1 = 2000 \times 10^{-6}$$
$$\epsilon_2 = 500 \times 10^{-6}$$
$$\epsilon_3 = 1000 \times 10^{-6}$$
$$a_2 = a_3 = + 2°$$

To start with let us calculate β, A & B. For $a_2 = a_3 = + 2°$ and for the given strain values in this example

$$\beta = 1032{\cdot}5 \times 10^{-6}$$
$$A = 0{\cdot}0674$$
$$B = 2{\cdot}0674$$

Then following previous mentioned procedure we get :

$$\sigma_{max} = 87645 \; psi$$
$$\sigma_{min} = 38085 \; psi$$
$$\tau_{max} = 24780 \; psi.$$

and

$$\phi_p = - 30° \; 07'$$

These values can be compared against the values that would have been obtained if the normal rosette equations, as shown in Table 2 were used. Table 3 shows this comparision.

TABLE 3

From modified equations			From normal rosette equations		
σ_{max}	=	87645 *psi*	σ_{max}	=	90090 *psi*
σ_{min}	=	38085 *psi*	σ_{min}	=	38490 *psi*
τ_{max}	=	24780 *psi*	τ_{max}	=	25800 *psi*
ϕ_p	=	—30° 07′	ϕ_p	=	—31° 43′

(*b*) We assume an error of —2 in the alignment of guages 2 and 3. As before let the measured strains be $\epsilon_1 = 2000 \times 10^{-6}$ in, per in. $\epsilon_2 = 500. \times 10^{-6}$ in. per in. and $\epsilon_3 = 1000 \times 10^{-6}$ in. per in.

The final result in this case along with the results obtained from the normal rosette equations, is given in Table 4.

(*c*) Let us take the case where the error in the alignment of guage 2 is —2° and the error in the orientation of gauge 3 is + 2° *i.e.* $\alpha_2 = -2°$ and $\alpha_3 = +2°$. Assuming the same values for the strains as before we get the results as shown in Table 5.

(*d*) Let us now assume that the error in the alignment of guage 2 is +2° and the error in the orientation of gauge 3 is —2° *i.e.* $\alpha_2 = +2°$ and $\alpha_3 = -2°$. The results are shown in Table 6.

(*e*) For the case where there is no error in the alignment of the gauge 2 but there is an error of +2° in gauge 3 the results are given in Table 7.

(*f*) Let $\alpha_2 = 0°$ and $\alpha_3 = -2°$. Results are shown in the Table 8.

(*g*) Let $\alpha_2 = +2°$ and $\alpha_3 = 0°$. Results are shown in Table 9.

(*h*) Let $\alpha_2 = -2°$ and $\alpha_3 = 0$. Results are shown in Table 10.

TABLE 4

From modified equations		From normal rosette equations	
σ_{max}	= 92820 *psi*	σ_{max}	= 90090 *psi*
σ_{min}	= 38910 *psi*	σ_{min}	= 38490 *psi*
τ_{max}	= 26940 *psi*	τ_{max}	= 25800 *psi*
ϕ_p	= —33° 19′	ϕ_p	= —31° 43′

TABLE 5

From modified equations		From normal rosette equations	
σ_{max}	= 89018 *psi*	σ_{max}	= 90090 *psi*
σ_{min}	= 36495 *psi*	σ_{min}	= 38490 *psi*
τ_{max}	= 26265 *psi*	τ_{max}	= 25800 *psi*
ϕ_p	= —30° 58′	ϕ_p	= —31° 43′

TABLE 6

From modified equations			From normal rosette equations		
σ_{max}	=	91313 *psi*	σ_{max}	=	90090 *psi*
σ_{min}	=	40214 *psi*	σ_{min}	=	38490 *psi*
τ_{max}	=	25551 *psi*	τ_{max}	=	25800 *psi*
ϕ_p	=	—33° 34′	ϕ_p	=	—31° 43′

TABLE 7

From modified equations			From normal rosette equations		
σ_{max}	=	88290 *psi*	σ_{max}	=	90090 *psi*
σ_{min}	=	37350 *psi*	σ_{min}	=	38490 *psi*
τ_{max}	=	25470 *psi*	τ_{max}	=	25800 *psi*
ϕ_p	=	30° 32′	ϕ_p	=	—31° 43′

TABLE 8

From modified equations			From normal rosette equations		
σ_{max}	=	91155 *psi*	σ_{max}	=	90090 *psi*
σ_{min}	=	39765 *psi*	σ_{min}	=	38490 *psi*
τ_{max}	=	26070 *psi*	τ_{max}	=	25800 *psi*
ϕ_p	=	—32° 56′	ϕ_p	=	—31° 43′

TABLE 9

From modified equations			From normal rosette equations		
σ_{max}	=	89400 *psi*	σ_{max}	=	90090 *psi*
σ_{min}	=	39150 *psi*	σ_{min}	=	38490 *psi*
τ_{max}	=	25125 *psi*	τ_{max}	=	25800 *psi*
ϕ_p	=	—31° 20′	ϕ_p	=	—31° 43′

TABLE 10

From modified equations			From normal rosette equations		
σ_{max}	=	90804 *psi*	σ_{max}	=	90090 *psi*
σ_{min}	=	37710 *psi*	σ_{min}	=	38490 *psi*
σ_{max}	=	26565 *psi*	τ_{max}	=	25800 *psi*
ϕ_p	=	—32° 08′	ϕ_p	=	—31° 43′

CASE 2—*Delta Rosette*

(*a*) Assuming now that a Delta rosette is used with errors $\alpha_2 = \alpha_3 = +2°$ and assuming that we obtain the three strain readings as

$$\epsilon_1 = 2000 \times 10^{-6}$$

$$\epsilon_2 = 500 \times 10^{-6}$$

and

$$\epsilon_3 = 1000 \times 10^{-6}$$

and then following the procedure mentioned before, we get

$$\sigma_{max} = 69828 \; psi$$

$$\sigma_{min} = 29622 \; psi$$

$$\tau_{max} = 20088 \; psi$$

$$\phi_p = -7° \; 40'$$

These values can be compared against the values that would have been obtained with the use of normal Delta rosette equations. Table 11 shows this comparision.

(*b*) Assuming the same strain readings as in (*a*) but with the errors $\alpha_2 = \alpha_3 = -2°$, we obtain the results as shown in Table 12.

(*c*) Case where $\alpha_2 = -2°$; $\alpha_3 = +2°$. Results are shown in Table 13.

(*d*) Case where $\alpha_2 = +2°$; $\alpha_3 = -2°$. Results are shown in Table 14.

(*e*) Case where $\alpha_3 = +2°$; $\alpha_2 = 0°$. Results are shown in Table 15.

(*f*) Case where $\alpha_3 = -2°$; $\alpha_2 = 0°$. Results are shown in Table 16.

(*g*) Case where $\alpha_3 = 0°$; $\alpha_2 = +2°$. Results are shown in Table 17.

(*h*) Case where $\alpha_3 = 0°$; $\alpha_2 = -2°$. Results are shown in Table 18.

TABLE 11

From modified equations			From normal rosette equations		
σ_{max}	=	69828 *psi*	σ_{max}	=	70350 *psi*
σ_{min}	=	29622 *psi*	σ_{min}	=	29670 *psi*
τ_{max}	=	20088 *psi*	τ_{max}	=	20340 *psi*
ϕ_p	=	—7° 40′	ϕ_p	=	—9° 34′

TABLE 12

From modified equations			From normal rosette equations		
σ_{max}	=	71025 *psi*	σ_{max}	=	70350 *psi*
σ_{min}	=	29595 *psi*	σ_{min}	=	29670 *psi*
τ_{max}	=	20715 *psi*	τ_{max}	=	20340 *psi*
ϕ_p	=	—11° 25′	ϕ_p	=	—9° 34′

TABLE 13

From modified equations			From normal rosette equations		
σ_{max}	=	69527 *psi*	σ_{max}	=	70350 *psi*
σ_{min}	=	27413 *psi*	σ_{min}	=	29670 *psi*
τ_{max}	=	21057 *psi*	τ_{max}	=	20340 *psi*
ϕ_p	=	—8° 53′	ϕ_p	=	—9° 34′

TABLE 14

From modified equations			From normal rosette equations		
σ_{max}	=	71130 *psi*	σ_{max}	=	70350 *psi*
σ_{min}	=	31590 *psi*	σ_{min}	=	29670 *psi*
τ_{max}	=	19770 *psi*	τ_{max}	=	20340 *psi*
ϕ_p	=	—10° 19′	ϕ_p	=	—9° 34′

TABLE 15

From modified equations			From normal rosette equations		
σ_{max}	=	69660 *psi*	σ_{max}	=	70350 *psi*
σ_{min}	=	28590 *psi*	σ_{min}	=	29670 *psi*
τ_{max}	=	20535 *psi*	τ_{max}	=	20340 *psi*
ϕ_p	=	—8° 20′	ϕ_p	=	—9° 34′

TABLE 16

From modified equations			From normal rosette equations		
σ_{max}	=	71070 *psi*	σ_{max}	=	70350 *psi*
σ_{min}	=	30660 *psi*	σ_{min}	=	29670 *psi*
τ_{max}	=	20205 *psi*	τ_{max}	=	20340 *psi*
ϕ_p	=	—10° 51′	ϕ_p	=	—9° 34′

TABLE 17

From modified equations			From normal rosette equations		
σ_{max}	=	70470 *psi*	σ_{max}	=	70350 *psi*
σ_{min}	=	30630 *psi*	σ_{min}	=	29670 *psi*
τ_{max}	=	19920 *psi*	τ_{max}	=	20340 *psi*
ϕ_p	=	—8° 59′	ϕ_p	=	—9° 34′

TABLE 18

From modified equations			From normal rosette equations		
σ_{max}	=	70425 *psi*	σ_{max}	=	70350 *psi*
σ_{min}	=	31125 *psi*	σ_{min}	=	29670 *psi*
τ_{max}	=	19650 *psi*	τ_{max}	=	20340 *psi*
ϕ_p	=	—8° 21′	ϕ_p	=	—9° 34′

CONCLUSIONS

It is noted that in case of Rectangular rosette, for orientation errors of $\pm 2^\circ$ in gauges 2 and 3, the errors in the evaluation of principal stresses using normal rosette equations vary between about 1% to 3% for different possible combinations of errors. In case of Delta rosette, for the same orientation errors, the errors in the evaluation of principal stresses using the normal equations vary between 0·1% to 1·3%. This suggests that the case of Delta rosette bears a distinct advantage over the Rectangular rosette. Actually this should be expected as Delta rosette gives the maximum possible angle between gauge axes and thus minimises the error in the computation of the principal strains. As for the direction of the principal strains, the error is close to the orientation error itself in most of the cases. In some of these cases this error is quite less and in any case the error in the direction of principal strains is not greater than the orientation error.

A study of the examples discussed in this paper also suggests that in certain cases the resultant errors in the principal stresses lie on the conservative side, and in some other cases on the non-conservative side. Taking the case of Rectangular rosette for the example discussed here, the maximum stress actually exists where misaligned rosette with error of $+2^\circ$ in gauges 2 & 3 is less than the values that are to be obtained from normal rosette equations. However, when the error is -2°, the actual maximum stress is greater than the one that is obtained from normal equations. It is quite clear that in the former case the error is conservative and as such is not detrimental as far as the design is concerned but this will result in the wastage of material. However, in the latter case where the error in not conservative it may lead to a design failure.

By studying cases (*e*) and (*f*) in comparison with cases (*g*) and (*h*) under Rectangular rosette, it can be seen that the orientation error in gauge 3 is more dominant than the error in gauge 2, so far as the errors in the principal stresses are concerned. These points hold equally good for Delta rosette. This suggests that proper care should be exercised in checking the error in gauges which are remote from the chosen reference gauge *viz* the gauge that is chosen to be along the x-axis.

In cases where 2% error in the principal stresses can be tolerated the normal rosette equations can be used directly. However, where accuracy is essential the modified equations may be used when errors in the alignment of the rosette gauges are known.

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