Errors Due to Transverse Sensitivity in Strain Gages

Transverse Sensitivity

Transverse sensitivity in a strain gage refers to the behavior of the gage in responding to strains which are perpendicular to the primary sensing axis of the gage. Ideally, it would be preferable if strain gages were completely insensitive to transverse strains. In practice, most gages exhibit some degree of transverse sensitivity; but the effect is ordinarily quite small, and of the order of several percent of the axial sensitivity.

In plane wire strain gages, transmission of strain into the wire from a direction perpendicular to the wire axis is nearly negligible. As a result, the transverse sensitivity of these gages is due almost entirely to the fact that a portion of the wire in the end loop lies in the transverse direction. Because of this, the sign of the transverse sensitivity for a plane wire gage will always be positive, and the magnitude of the effect can be calculated quite closely from the geometry of the grid. This statement does not apply to the small "wrap-around" gages having the wire wound on a flattened core. Such gages often exhibit negative transverse sensitivities.

In foil strain gages, on the other hand, the transverse sensitivity arises from much more complex phenomena, and it is affected by almost every aspect of grid design and gage construction. In addition to end loop effects, the foil gridlines, having a large ratio of width to thickness, are strained significantly by transverse strains. The magnitude of transverse strain transmission into the gridlines is determined by the relative thicknesses and elastic moduli of the backing and foil, by the width-to-thickness ratio of the foil gridlines, and, to a lesser degree, by several other parameters, including the presence or lack of an encapsulating layer over the grid.

Depending upon the foil material and its metallurgical condition, the contribution to transverse sensitivity from the transmission of transverse strain into the gridlines can be either positive or negative. Because of this, the overall transverse sensitivity of a foil strain gage can also be either positive or negative. While the transverse sensitivity of a foil gage is thus subject to a greater degree of control in the design of the gage, the compromises necessary to optimize all aspects of gage performance generally limit the attainable reduction in transverse sensitivity.

Errors Due to Transverse Sensitivity

Errors in strain indication due to transverse sensitivity are generally quite small since the transverse sensitivity itself is small. However, in biaxial strain fields characterized by extreme ratios between principal strains, the percentage error in the smaller strain can be very great if not corrected for transverse sensitivity. On the other hand, in the particular case of uniaxial stress in a material with a Poisson's ratio of 0.285, the error is zero because the gage factor given by the manufacturer was measured in such a uniaxial stress field and already includes the effect of the Poisson strain. It is important to note that when a strain gage is used under any conditions other than those employed in the gage-factor calibration, there is always some degree of error due to transverse sensitivity. In other words, any gage which is: (a) installed on a material with a different Poisson's ratio; or (b) installed on steel, but subjected to other than a uniaxial stress state; or (c) even installed on steel with a uniaxial stress state, but aligned with other than the maximum principal stress, exhibits a transverse-sensitivity error which may require correction.

The historical practice of quoting gage factors which, in effect, mask the presence of transverse sensitivity, and which are correct in themselves for only a specific stress field in a specific material, is an unfortunate one. This approach has generally complicated the use of strain gages, while leading to errors and confusion. Although the uniaxial stress field is very common, it is not highly significant to the general field of experimental stress analysis. There is no particular merit, therefore, in combining the axial and transverse sensitivities for this case.

In general, then, a strain gage actually has two gage factors, F_a and F_t, which refer to the gage factors as determined in a uniaxial strain field (not uniaxial stress) with, respectively, the gage axes aligned parallel to and perpendicular to the strain field. For any strain field, the output of the strain gage can be expressed as:

$$\frac{\Delta R}{R} = F_a \varepsilon_a + F_t \varepsilon_t \qquad (1)$$

where: ε_a, ε_t = strains parallel to and perpendicular to the gage axis, or the gridlines in the gage.
F_a = axial gage factor.
F_t = transverse gage factor.

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Or,

$$\frac{\Delta R}{R} = F_a\left(\varepsilon_a + K_t \varepsilon_t\right) \quad (2)$$

where: $K_t = \frac{F_t}{F_a}$ = transverse sensitivity coefficient, referred to from here on as the "transverse sensitivity".

When the gage is calibrated for gage factor in a uniaxial stress field on a material with Poisson's ratio, ν_0,

$$\varepsilon_t = -\nu_0 \varepsilon_a$$

Therefore,

$$\frac{\Delta R}{R} = F_a\left(\varepsilon_a - K_t \nu_0 \varepsilon_a\right)$$

or,

$$\frac{\Delta R}{R} = F_a\left(1 - \nu_0 K_t\right)\varepsilon_a \quad (3)$$

The strain gage manufacturers commonly write this as:

$$\frac{\Delta R}{R} = F\varepsilon \quad (3a)$$

where: F = manufacturer's gage factor, which is deceptively simple in appearance, since, in reality:

$$F = F_a\left(1 - \nu_0 K_t\right) \quad (4)$$

Furthermore, ε is actually ε_a, the strain along the gage axis (and only one of two strains sensed by the gage during calibration) when the gage is aligned with the maximum principal stress axis in a uniaxial stress (not uniaxial strain) field, on a material with ν_0 = 0.285. Errors and confusion occur through failure to fully comprehend and always account for the real meanings of *F* and ε as used by the manufacturers.

It is imperative to realize that for any strain field except that corresponding to a uniaxial stress field (and even in the latter case, with the gage mounted along any direction except the maximum principal stress axis, or on any material with Poisson's ratio other than 0.285), there is always an error in strain indication if the transverse sensitivity of the strain gage is other than zero. In some instances, this error is small enough to be neglected. In others, it is not. The error due to transverse sensitivity for a strain gage oriented at any angle, in any strain field, on any material, can be expressed as:

$$n_\varepsilon = \frac{K_t\left(\frac{\varepsilon_t}{\varepsilon_a} + \nu_0\right)}{1 - \nu_0 K_t} \times 100 \quad (5)$$

where: n_ε = the error as a percentage of the actual strain along the gage axis.

ν_0 = the Poisson's ratio of the material on which the manufacturer's gage factor, *F*, was measured (usually 0.285).

ε_a, ε_t = respectively, the actual strains parallel and perpendicular to the primary sensing axis of the gage.*

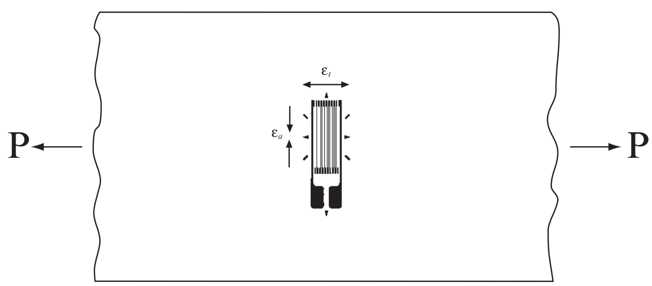
From the above equation, it is evident that the percentage error due to transverse sensitivity increases with the absolute values of K_t and $\varepsilon_t/\varepsilon_a$, whether these parameters are positive or negative. Equation (5) has been plotted in Figure 1 for convenience in judging whether the magnitude of the error may be significant for a particular strain field. Figure 1 also yields an approximate rule-of-thumb for quickly estimating the error due to transverse sensitivity – that is,

$$n_\varepsilon \approx K_t \frac{\varepsilon_t}{\varepsilon_a} \text{ x } 100 \quad \text{(percent)}$$

As Equation (5) shows, this approximation holds quite well as long as the absolute value $\varepsilon_t/\varepsilon_a$ is not close to ν_0. For an example, assume the task of measuring Poisson (transverse) strain in a uniaxial stress field. In this case, the Poisson strain is represented by ε_a, the strain along the gage axis, and the longitudinal strain in the test member by ε_t, since the latter is transverse to the gage axis (see sketch and footnote below).

$$\varepsilon_a = -\nu\varepsilon_t$$

$$\varepsilon_t/\varepsilon_a = -\frac{1}{\nu}$$



*Subscripts (*a*) and (*t*) always refer to the axial and transverse directions with respect to the gage (without regard to directions on the test surface), while subscripts (*x*) and (*y*) refer to an arbitrary set of orthogonal axes on the test surface, and subscripts (*p*) and (*q*) to the principal axes.

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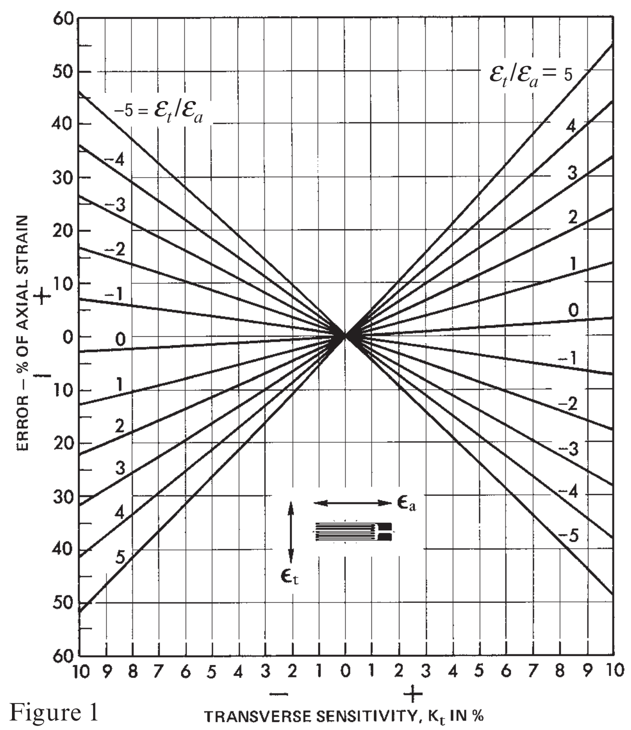

Figure 1

If the test specimen is an aluminum alloy, with $\nu = 0.32$, then $\varepsilon_t/\varepsilon_a = -1/\nu = -3.1$. Assuming that the transverse sensitivity of the strain gage is –3% (i.e., $K_t = -0.03$*), the rule of thumb gives an approximate error of +9.3%. The actual error, calculated from Equation (5), is +8.5%.

Correcting for Transverse Sensitivity

The effects of transverse sensitivity should always be considered in the experimental stress analysis of a biaxial stress field with strain gages. Either it should be demonstrated that the effect of transverse sensitivity is negligible and can be ignored, or, if not negligible, the proper correction should be made. Since a two- or three-gage rosette will ordinarily be used in such cases, simple correction methods are given here for the two-gage 90-degree rosette, the three-gage rectangular rosette, and the delta rosette. Unless otherwise noted, these corrections apply to rosettes in which the transverse sensitivities of the individual gage elements in the rosettes are equal to one another, or approximately so. Generalized correction equations for any combination of transverse sensitivities are given in the Appendix.

Consider first the two-gage 90-degree rosette, with the gage axes aligned with two orthogonal axes, x and y, on the test surface. When using this type of rosette, the x and y axes would ordinarily be the principal axes, but this need not necessarily be so. The correct strains along any two perpendicular axes can always be calculated from the following equations in terms of the indicated strains along those axes:

$$\varepsilon_x = \frac{(1-\nu_0 K_t)(\hat{\varepsilon}_x - K_t\hat{\varepsilon}_y)}{1-K_t^2} \qquad (6)$$

$$\varepsilon_y = \frac{(1-\nu_0 K_t)(\hat{\varepsilon}_y - K_t\hat{\varepsilon}_x)}{1-K_t^2} \qquad (7)$$

where:

$\hat{\varepsilon}_x = \hat{\varepsilon}_{a_1}$ = the indicated (uncorrected) strain from gage no. 1.
$\hat{\varepsilon}_y = \hat{\varepsilon}_{a_2}$ = the indicated (uncorrected) strain from gage no. 2.
$\varepsilon_x, \varepsilon_y$ = corrected strains along the x and y axes, respectively.

The $(1-K_t^2)$ term in the denominators of Equations (6) and (7) is generally in excess of 0.995, and can be taken as unity:

$$\varepsilon_x = (1-\nu_0 K_t)(\hat{\varepsilon}_x - K_t\hat{\varepsilon}_y) \qquad (6a)$$

$$\varepsilon_y = (1-\nu_0 K_t)(\hat{\varepsilon}_y - K_t\hat{\varepsilon}_x) \qquad (7a)$$

Data reduction can be further simplified by setting the gage factor control on the strain-indicating instrumentation at F_a instead of F, the manufacturer's gage factor. Since,

$$F_a = \frac{F}{1-\nu_0 K_1}$$

Equations (6a) and (7a) can be rewritten:

$$\varepsilon_x = \hat{\hat{\varepsilon}}_x - K_t\hat{\hat{\varepsilon}}_y \qquad (6b)$$

$$\varepsilon_y = \hat{\hat{\varepsilon}}_y - K_t\hat{\hat{\varepsilon}}_x \qquad (7b)$$

where:

$\hat{\hat{\varepsilon}}_x, \hat{\hat{\varepsilon}}_y$ = strains as indicated by instrumentation with gage factor control set at

* For substitution into any equation in this Tech Note, K_t must always be expressed decimally. Thus, the value of K_t (in percent) from the gage package data sheet must be divided by 100 for conversion to its decimal equivalent.

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$$\frac{F}{1-\nu_0 K_t}$$

As an alternative to the preceding methods, a quick graphical correction for the transverse sensitivity can be made through the use of Figure 2. To use the graph, the first step is to calculate:

$$\left(\frac{\hat{\varepsilon}_t}{\hat{\varepsilon}_a}\right)_1 = \frac{\hat{\varepsilon}_2}{\hat{\varepsilon}_1} = \frac{\hat{\varepsilon}_y}{\hat{\varepsilon}_x} \qquad \text{(Gage No. 1)}$$

$$\left(\frac{\hat{\varepsilon}_t}{\hat{\varepsilon}_a}\right)_2 = \frac{\hat{\varepsilon}_1}{\hat{\varepsilon}_2} = \frac{\hat{\varepsilon}_x}{\hat{\varepsilon}_y} \qquad \text{(Gage No. 2)}$$

Having done this, it is only necessary to enter the graph at the approximate value of K_t, move upward to the line (or interpolated line) representing the observed (indicated) strain ratio, $(\hat{\varepsilon}_t / \hat{\varepsilon}_a)$ for that particular rosette element, and horizontally to the vertical scale on the left to read the correction factor.

Then, $\varepsilon_x = \varepsilon_1 = C_1\hat{\varepsilon}_1$

Similarly, $\varepsilon_y = \varepsilon_2 = C_2\hat{\varepsilon}_2$

Following is a numerical example utilizing first Equations (6a) and (7a), and then Figure 2.
Assume that the indicated strains for rosette elements (1) and (2) along the *x* and *y* axes are, respectively:

$$\hat{\varepsilon}_1 = +1530\mu\varepsilon$$
$$\hat{\varepsilon}_2 = +920\mu\varepsilon$$

Assume also that K_t = –0.06. Substituting into Equations (6a) and (7a), with ν_0 = 0.285,

$$\varepsilon_x = (1 + 0.285 \text{ x } 0.06)\ (1530 + 0.06 \text{ x } 920) = 1612\mu\varepsilon$$
$$\varepsilon_y = (1 + 0.285 \text{ x } 0.06)\ (920 + 0.06 \text{ x } 1530) = 1029\mu\varepsilon$$

For use with the correction graph, Figure 2,

$$\left(\frac{\hat{\varepsilon}_t}{\hat{\varepsilon}_a}\right)_1 = \frac{920}{1530} = 0.601 \approx 0.6$$

$$\left(\frac{\hat{\varepsilon}_t}{\hat{\varepsilon}_a}\right)_2 = \frac{1530}{920} = 1.663 \approx 1.65$$

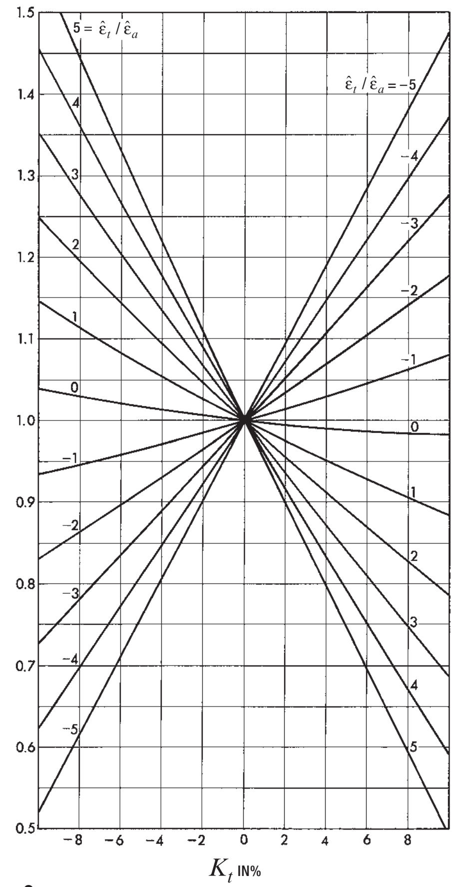

Figure 2

Following the line for K_t = – 0.06 upward, interpolating the location of $(\hat{\varepsilon}_t / \hat{\varepsilon}_a)_1$ = 0.6, and $(\hat{\varepsilon}_t / \hat{\varepsilon}_a)_2$ = 1.65, and reading the respective values of the correction factor,

$$C_1 = 1.06;\ C_2 = 1.12$$

From which,

$$\varepsilon_x = C_1\hat{\varepsilon}_x = 1.06 \text{ x } 1530 = 1620\mu\varepsilon$$
$$\varepsilon_y = C_2\hat{\varepsilon}_y = 1.12 \text{ x } 920 = 1030\mu\varepsilon$$

Correction For Shear Strain

A two-gage, 90-degree rosette, or "T"-rosette, is sometimes used for the direct indication of shear strain. It can be shown that the shear strain along the bisector of the gage axes, is, in this case, numerically equal to the difference in normal strains on these axes. Thus, when the two gage elements of the rosette are connected in adjacent arms of a Wheatstone bridge, the indicated strain is equal to the indicated shear strain along the bisector, requiring at

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most correction for the error due to transverse sensitivity. The latter error can be corrected for very easily if both gages have the same transverse sensitivity, since the error is independent of the state of strain. The correction factor for this case is:

$$C_\gamma = \frac{1-\nu_0 K_t}{1-K_t} \tag{8}$$

The actual shear strain is obtained by multiplying the indicated shear strain by the correction factor. Thus,

$$\gamma = C_\gamma \hat{\gamma} = C_\gamma \left(\hat{\varepsilon}_x - \hat{\varepsilon}_y\right) = \frac{1-\nu_0 K_t}{1-K_t}\left(\hat{\varepsilon}_x - \hat{\varepsilon}_y\right)$$

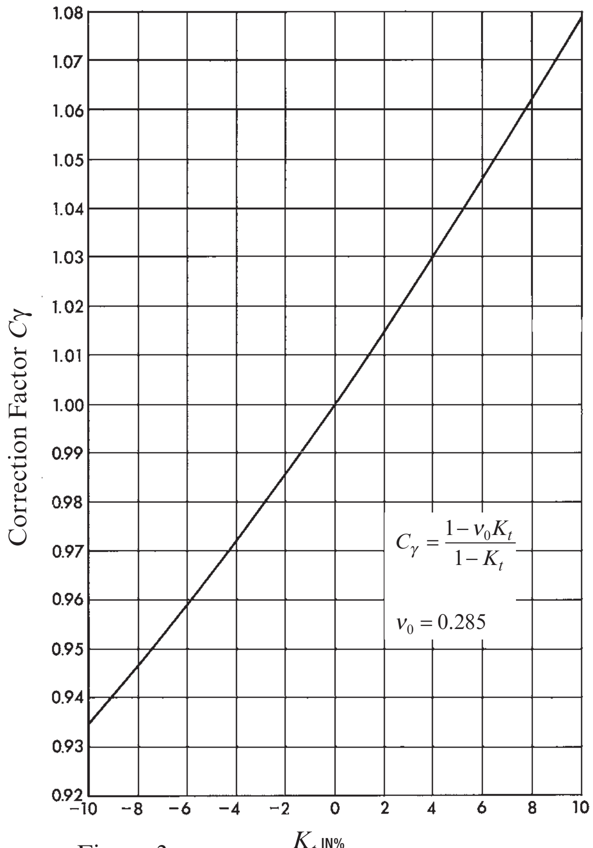

Figure 3

For convenience, the shear strain correction factor is plotted in Figure 3 against K_t, with $\nu_0 = 0.285$. Since this correction factor is independent of the state of strain, it can again be incorporated in the gage factor setting on the strain-indicating instrumentation if desired. This can be done by setting the gage factor control at:

$$F_\gamma = F\,\frac{1-K_t}{1-\nu_0 K_t} \tag{9}$$

With this change, the strain indicator will indicate the actual shear strain along the bisector of the gage axis, already corrected for transverse sensitivity in the strain gages.

Three-Gage Rectangular (45°) Rosette

When the directions of the principal axes are unknown, three independent strain measurements are required to completely determine the state of strain. For this purpose, a three-gage rosette should be used, and the rectangular rosette is generally the most convenient form.

If the transverse sensitivity of the gage elements in the rosette is other than zero, the individual strain readings will be in error, and the principal strains and stresses calculated from these data will also be incorrect.

Correction for the effects of transverse sensitivity can be made either on the individual strain readings or on the principal strains or principal stresses calculated from these. Numbering the gage elements consecutively, elements (1) and (3) correspond directly to the two-gage, 90-degree rosette, and correction can be made with Equations (6) and (7), or (6a) and (7a), or (by properly setting the gage factor control on the strain indicator) with Equations (6b) and (7b). The center gage of the rosette requires a special correction relationship since there is no direct measurement of the strain perpendicular to the grid. The correction equations for all three gages are listed here for convenience:

$$\varepsilon_1 = \frac{1-\nu_0 K_t}{1-K_t^2}\left(\hat{\varepsilon}_1 - K_t \hat{\varepsilon}_3\right) \tag{10}$$

$$\varepsilon_2 = \frac{1-\nu_0 K_t}{1-K_t^2}\left[\hat{\varepsilon}_2 - K_t\left(\hat{\varepsilon}_1 + \hat{\varepsilon}_3 - \hat{\varepsilon}_2\right)\right] \tag{11}$$

$$\varepsilon_3 = \frac{1-\nu_0 K_t}{1-K_t^2}\left[\hat{\varepsilon}_3 - K_t \hat{\varepsilon}_1\right] \tag{12}$$

where:
$\hat{\varepsilon}_1, \hat{\varepsilon}_2, \hat{\varepsilon}_3$ = indicated strains from the respective gage elements.
$\varepsilon_1, \varepsilon_2, \varepsilon_3$ = corrected strains along the gage axes.

It should be noted that Equations (10), (11), and (12) are based upon the assumption that the transverse sensitivity is the same, or effectively so in all gage elements, as it is in stacked rosettes. This may not be true for planar foil

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rosettes, since the individual gage elements do not all have the same orientation with respect to the direction in which the foil was rolled. It is common practice, however, to etch the rosette in a position of symmetry about the foil rolling direction, and therefore the transverse sensitivities of gage elements (1) and (3) will be nominally the same, while that of element (2) may differ. Correction equations for rosettes with nonuniform transverse sensitivities among the gage elements are given in the Appendix.

Delta Rosettes

A delta strain gage rosette consists of three gage elements in the form of an equilateral triangle or a "Y" with equally spaced branches. The delta rosette offers a very slight potential advantage over the three-gage rectangular rosette in that the lowest possible sum of the strain readings obtainable in a particular strain field is somewhat higher than for a three-gage rectangular rosette. This is because the three gage elements in the delta rosette are at the greatest possible angle from one another. However, the data reduction for obtaining the principal strains or correcting for transverse sensitivity is also more involved and lengthy than for rectangular rosettes.

As in the case of rectangular rosettes, plane foil delta rosettes are manufactured symmetrically with respect to the rolling direction of the foil. Thus, two of the gage elements will ordinarily have the same nominal transverse sensitivity, and third may differ. Correction equations for this condition are given in the Appendix. In the stacked delta rosette, all three gages have the same nominal sensitivity.

The individual strain readings from a delta rosette can be corrected for transverse sensitivity with the following relationships when a single value of K_t can be used for the transverse sensitivity:

$$\varepsilon_1 = \frac{1-\nu_0 K_t}{1-K_t^2}\left[\left(1+\frac{K_t}{3}\right)\hat{\varepsilon}_1 - \frac{2}{3}K_t\left(\hat{\varepsilon}_2+\hat{\varepsilon}_3\right)\right] \quad (13)$$

$$\varepsilon_2 = \frac{1-\nu_0 K_t}{1-K_t^2}\left[\left(1+\frac{K_t}{3}\right)\hat{\varepsilon}_2 - \frac{2}{3}K_t\left(\hat{\varepsilon}_3+\hat{\varepsilon}_1\right)\right] \quad (14)$$

$$\varepsilon_3 = \frac{1-\nu_0 K_t}{1-K_t^2}\left[\left(1+\frac{K_t}{3}\right)\hat{\varepsilon}_3 - \frac{2}{3}K_t\left(\hat{\varepsilon}_1+\hat{\varepsilon}_2\right)\right] \quad (15)$$

As before, simplification can be achieved by treating $(1 - K_t^2)$ as unity, and by incorporating the quantity $(1 - \nu_0 K_t)$ into the gage factor setting for the strain instrumentation. When doing this, the gage-factor control is set at:

$$F_a = \frac{F}{1-\nu_0 K_t}$$

Correction of Principal Strains

With any rosette, rectangular, delta, or otherwise, it is always possible (and often most convenient) to calculate the indicated principal strains directly from the completely uncorrected gage readings, and then apply corrections to the principal strains. This is true because of the fact that the errors in principal strains due to transverse sensitivity are independent of the kind of rosette employed, as long as all gage elements in the rosette have the same nominal transverse sensitivity. Since Equations (6) and (7) apply to any two indicated orthogonal strains, they must also apply to the indicated principal strains. Thus, if the indicated principal strains have been calculated from strain readings uncorrected for transverse sensitivity, the actual principal strains can readily be calculated from the following:

$$\varepsilon_p = \frac{1-\nu_0 K_t}{1-K_t^2}\left(\hat{\varepsilon}_p - K_t\hat{\varepsilon}_q\right) \quad (16)$$

$$\varepsilon_q = \frac{1-\nu_0 K_t}{1-K_t^2}\left(\hat{\varepsilon}_q - K_t\hat{\varepsilon}_p\right) \quad (17)$$

Furthermore, Equations (16) and (17) can be rewritten to express the actual principal strain in terms of the indicated principal strain and a correction factor. Thus,

$$\varepsilon_p = \hat{\varepsilon}_p\left[\left(\frac{1-\nu_0 K_t}{1-K_t^2}\right)\left(1-K_t\frac{\hat{\varepsilon}_q}{\hat{\varepsilon}_p}\right)\right] \quad (18)$$

$$\varepsilon_q = \hat{\varepsilon}_q\left[\left(\frac{1-\nu_0 K_t}{1-K_t^2}\right)\left(1-K_t\frac{\hat{\varepsilon}_p}{\hat{\varepsilon}_q}\right)\right] \quad (19)$$

Since Equations (18) and (19) are the same relationship used to plot the correction graph of Figure 2, this graph can be used directly to correct indicated principal strains by the procedure described earlier, merely noting that:

$$\frac{\hat{\varepsilon}_t}{\hat{\varepsilon}_a} = \frac{\hat{\varepsilon}_q}{\hat{\varepsilon}_p} \quad \text{when correcting } \hat{\varepsilon}_p$$

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and

$$\frac{\hat{\varepsilon}_t}{\hat{\varepsilon}_a} = \frac{\hat{\varepsilon}_p}{\hat{\varepsilon}_q} \quad \text{when correcting } \hat{\varepsilon}_q$$

In fact, the indicated strains from three gages with any relative angular orientation define an "indicated" Mohr's circle of strain. When employing a data-reduction scheme that produces the distance to the center of Mohr's circle of strain, and the radius of the circle, still another simple correction method is applicable. To correct the indicated Mohr's circle to the actual Mohr's circle, the distance to the center of the indicated circle should be multiplied by $(1 - \nu_0 K_t)/(1 + K_t)$, and the radius of the circle by $(1 - \nu_0 K_t)/(1 - K_t)$. The maximum and minimum principal strains are the sum and difference, respectively, of the distance to the center and the radius of Mohr's circle of strain.

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APPENDIX

The following relationships can be used to correct for transverse sensitivity when the gage elements in a rosette do not all have the same value of K_t. In each case, ν_0 is the Poisson's ratio of the material on which the manufacturer's gage factor was measured (usually 0.285).

Two-Gage, 90-Degree rosette

$$\varepsilon_1 = \frac{\hat{\varepsilon}_1\left(1-\nu_0 K_{t_1}\right) - K_{t_1}\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right)}{1-K_{t_1}K_{t_2}} \tag{20}$$

$$\varepsilon_2 = \frac{\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right) - K_{t_2}\hat{\varepsilon}_1\left(1-\nu_0 K_{t_1}\right)}{1-K_{t_1}K_{t_2}} \tag{21}$$

where:

$\hat{\varepsilon}_1, \hat{\varepsilon}_2$ = indicated strains from gages (1) and (2), uncorrected for transverse sensitivity.
K_{t_1}, K_{t_2} = transverse sensitivities of gages (1) and (2).
$\varepsilon_1, \varepsilon_2$ = actual strains along gage axes (1) and (2).

Three-Gage Rectangular (45-Degree) Rosette

$$\varepsilon_1 = \frac{\hat{\varepsilon}_1\left(1-\nu_0 K_{t_1}\right) - K_{t_1}\hat{\varepsilon}_3\left(1-\nu_0 K_{t_3}\right)}{1-K_{t_1}K_{t_3}} \tag{22}$$

$$\varepsilon_2 = \frac{\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right)}{1-K_{t_2}} - \frac{K_{t_2}\left[\hat{\varepsilon}_1\left(1-\nu_0 K_{t_1}\right)\left(1-K_{t_3}\right) + \hat{\varepsilon}_3\left(1-\nu_0 K_{t_3}\right)\left(1-K_{t_1}\right)\right]}{\left(1-K_{t_1}K_{t_3}\right)\left(1-K_{t_2}\right)} \tag{23}$$

$$\varepsilon_3 = \frac{\hat{\varepsilon}_3\left(1-\nu_0 K_{t_3}\right) - K_{t_3}\hat{\varepsilon}_1\left(1-\nu_0 K_{t_1}\right)}{1-K_{t_1}K_{t_3}} \tag{24}$$

When the transverse sensitivities of the orthogonal gages (1) and (3) are nominally the same, let

$$K_{t_1} = K_{t_3} = K_{t13}$$

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Then:

$$\varepsilon_1 = \frac{1-\nu_0 K_{t13}}{1-K_{t13}^2}\left(\hat{\varepsilon}_1 - K_{t13}\hat{\varepsilon}_3\right) \tag{25}$$

$$\varepsilon_2 = \frac{\left(1-\nu_0 K_{t_2}\right)\left(1+K_{t13}\right)\hat{\varepsilon}_2 - K_{t_2}\left(1-\nu_0 K_{t13}\right)\left(\hat{\varepsilon}_1+\hat{\varepsilon}_3\right)}{\left(1+K_{t_{13}}\right)\left(1-K_{t_2}\right)} \tag{26}$$

$$\varepsilon_3 = \frac{1-\nu_0 K_{t13}}{1-K_{t13}^2}\left(\hat{\varepsilon}_3 - K_{t13}\hat{\varepsilon}_1\right) \tag{27}$$

where:

$\hat{\varepsilon}_1, \hat{\varepsilon}_2, \hat{\varepsilon}_3$ = indicated strains from gages (1), (2), and (3), uncorrected for transverse sensitivity.
$K_{t_1}, K_{t_2}, K_{t_3}$ = transverse sensitivities of gages (1), (2), and (3).
$K_{t_{13}}$ = transverse sensitivity of orthogonal gages (1) and (3).
$\varepsilon_1, \varepsilon_2, \varepsilon_3$ = actual strains along gage axes (1), (2), and (3).

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$$\varepsilon_1 = \frac{\hat{\varepsilon}_1\left(1-\nu_0 K_{t_1}\right)\left(3-K_{t_2}-K_{t_3}-K_{t_2}K_{t_3}\right)-2K_{t_1}\left[\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right)\left(1-K_{t_3}\right)+\hat{\varepsilon}_3\left(1-\nu_0 K_{t_3}\right)\left(1-K_{t_2}\right)\right]}{3K_{t_1}K_{t_2}K_{t_3}-K_{t_1}K_{t_2}-K_{t_2}K_{t_3}-K_{t_1}K_{t_3}-K_{t_1}-K_{t_2}-K_{t_3}+3} \tag{28}$$

$$\varepsilon_2 = \frac{\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right)\left(3-K_{t_3}-K_{t_1}-K_{t_3}K_{t_1}\right)-2K_{t_2}\left[\hat{\varepsilon}_3\left(1-\nu_0 K_{t_3}\right)\left(1-K_{t_1}\right)+\hat{\varepsilon}_1\left(1-\nu_0 K_{t_1}\right)\left(1-K_{t_3}\right)\right]}{3K_{t_1}K_{t_2}K_{t_3}-K_{t_1}K_{t_2}-K_{t_2}K_{t_3}-K_{t_1}K_{t_3}-K_{t_1}-K_{t_2}-K_{t_3}+3} \tag{29}$$

$$\varepsilon_3 = \frac{\hat{\varepsilon}_3\left(1-\nu_0 K_{t_3}\right)\left(3-K_{t_1}-K_{t_2}-K_{t_1}K_{t_2}\right)-2K_{t_3}\left[\hat{\varepsilon}_1\left(1-\nu_0 K_{t_1}\right)\left(1-K_{t_2}\right)+\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right)\left(1-K_{t_1}\right)\right]}{3K_{t_1}K_{t_2}K_{t_3}-K_{t_1}K_{t_2}-K_{t_2}K_{t_3}-K_{t_1}K_{t_3}-K_{t_1}-K_{t_2}-K_{t_3}+3} \tag{30}$$

When two of the gages, for example, (1) and (3), have the same nominal transverse sensitivity,

$$\varepsilon_1 = \frac{\hat{\varepsilon}_1\left(1-\nu_0 K_{t13}\right)\left(3-K_{t_2}-K_{t13}-K_{t13}K_{t_2}\right)-2K_{t13}\left[\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right)\left(1-K_{t13}\right)+\hat{\varepsilon}_3\left(1-\nu_0 K_{t13}\right)\left(1-K_{t_2}\right)\right]}{3K_{t_{13}}^2 K_{t_2}-K_{t_{13}}^2-2K_{t13}K_{t_2}-2K_{t13}-K_{t_2}+3} \tag{31}$$

$$\varepsilon_2 = \frac{\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right)\left(3+K_{t13}\right)-2K_{t_2}\left[\left(\hat{\varepsilon}_1+\hat{\varepsilon}_3\right)\left(1-\nu_0 K_{t13}\right)\right]}{K_{t13}-3K_{t13}K_{t_2}-K_{t_2}+3} \tag{32}$$

$$\varepsilon_3 = \frac{\hat{\varepsilon}_3\left(1-\nu_0 K_{t13}\right)\left(3-K_{t_2}-K_{t13}-K_{t13}K_{t_2}\right)-2K_{t13}\left[\hat{\varepsilon}_1\left(1-\nu_0 K_{t13}\right)\left(1-K_{t_2}\right)+\hat{\varepsilon}_2\left(1-\nu_0 K_{t_2}\right)\left(1-K_{t13}\right)\right]}{3K_{t_{13}}^2 K_{t_2}-K_{t_{13}}^2-2K_{t13}K_{t_2}-2K_{t13}-K_{t_2}+3} \tag{33}$$

The subscripts in Equations (28) through (33) have the same significance as in Equations (22) through (27), except that the two gages with common transverse sensitivity, $K_{t_{13}}$, are not orthogonal.