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PROBABILISTIC EVALUATION OF TEST RESULTS

by

Teoman Pekoz* and W. Brent Hall**

ABSTRACT

A rational probabilistic approach for evaluating test results is presented. The procedure formulated can readily be put into a test specification format. It is closely related to the calibration procedures used to develop the proposed Load and Resistance Factor Design (LRFD) specifications, and is compatible with the LRFD design format. The approach can also be made compatible with the present AISI cold-formed steel specification through the use of factors of safety.

The proposed evaluation approach provides a rational basis for deciding upon the factors of safety or resistance factors to be applied to test results. The number of test results influences these values in a way that avoids the common but somewhat arbitrary use of confidence limits and tolerance factors.

The evaluation procedure is applied to an example involving connection tests on specimens with multiple thicknesses. The approach is general, however, and can be applied to all kinds of members as well as to tests on specimens having the same thickness. Although similar procedures can be formulated for deflection criteria, the presesentation is limited to the procedures relevant to strength calculations.

INTRODUCTION

Until recently, the development of probability based design codes such as Load and Resistance Factor Design (LRFD) has primarily concentrated upon design by calculation. Testing based design has received little attention by comparison. However, testing is an important part of much structural design and there is a growing need for test evaluation procedures that are consistent with the forthcoming LRFD codes. In cold-formed steel design, if and when LRFD criteria are adopted, testing standards will have to be revised to reflect the new approach. This paper describes an approach to test evaluation that may prove helpful during and after the period of transition between these design approaches. It offers compatibility with both the older safety-factor based design code formats and the newer LRFD formats.

The problem of test evaluation has received some attention in Europe, and the general approach used there is probability based. However, as will be discussed below, the European approach based on characteristic values is not compatible with the LRFD approach based on nominal values being considered in the U.S. Nevertheless, it is instructive to look at the European approach

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first. The approach contained in some of the E.C.C.S. Recommendations such as "European Recommendations for the Testing of Connections in Profiled Sheeting and other Light Gauge Steel Components" ECCS-XVII-3E,21, as well as some European Specifications such as the Swedish Government Specifications 1975:4 - Designing by Tests, differ significantly from the current AISI Specification approach. The approach in the first document can be summarized as follows:

- For a series of tests involving different thicknesses an empirical (experimental) curve is fit through a plot of test results versus thickness. This curve is fitted by minimizing the error between the load carrying capacity observed and the load carrying capacity predicted by the empirical curve. This curve gives the predicted capacity P_p as a function of thickness t.

- The mean, P_m, and the coefficient of variation, V_P, of the ratios of the observed load to the predicted load are calculated for all the tests.

- The characteristic load, P_k, for a given thickness is determined as follows:

$$P_k = P_p \ (1 - c \ V_P) \qquad (1)$$

where c is a statistical number that depends on the number of tests conducted, the probability distribution of the test results, and the confidence level desired. A characteristic value obtained in this manner is compared with the factored design load. In this way the European approach is different from that of the Load and Resistance Factor Design approach proposed in the US, which uses nominal values.

If other sources of uncertainty in strength exist other than those accounted for by the tests (i.e., in V_P), then V_P in Eq. 1 can be replaced by V_R, the total coefficient of variation of resistance, of which V_P is a component. The report by Bijlaard et al (1987) contains a good description of the current European approach to test evaluation, and several promising extensions of the basic method.

The evaluation approach proposed by the writers differs in the last step above. The approach involves using the parameters P_m and V_P to obtain a resistance factor that will result in the reliability index targeted by the proposed AISI LRFD Specification for cold-formed steel design. As a by-product, the safety factor implied in this calculation can be found and used in allowable stress design, if desired. The approach is illustrated using an example involving connection testing.

RELATIONSHIPS FROM LRFD CALIBRATION

The proposed test evaluation procedure is essentially a calibration procedure applied to test results. Therefore, a brief description of the most relevant LRFD relationships is presented here. For the purposes of this paper a good overview of the theory behind LRFD approaches can be obtained from several references on the specifications being considered for hot-rolled and cold-formed steel structures in this country. These include the papers by

Galambos (1972), Ravindra and Galambos (1978), and several papers and research reports written by Yu, Galambos and others on research in cold-formed steel design at the University of Missouri - Rolla. Of these, the Ninth Progress Report on Calibration of the AISI Design Provisions, by Hsiao, Yu and Galambos (1987), is the document most relevant.

Briefly, as the name indicates, the LRFD approach involves the comparison of factored load effects with factored resistances. The load factors, which are determined from statistics on the variability of loading, are not of concern here. The resistance factors are of prime concern, however. They are applied to nominal values of strength estimates and are calculated from reliability indices β. The target reliability indices β_o used in this process have been derived from the current practice by a procedure called calibration. The calibration is based on a model of resistance R which divides strength uncertainty into three components, as follows:

$$R = R_n \; M \; F \; P \qquad (2)$$

R_n is the nominal (calculated) strength, and M, F and P are random variables accounting for uncertainty from, loosely speaking, Material, Fabrication, and Professional factors, respectively. The last of these components includes the accuracy of engineering strength predictions, and during code calibration its influence is estimated from a comparison of calculated (predicted) resistance values with test results. The proposed test evaluation procedure is essentially a modification of this evaluation procedure for the professional factor P.

The calibration process and the selection of a target reliability index β_o are sensitive to the ratio of dead load to live load. In calibration of the AISI Specification for Cold-Formed Steel Design the dead to live load ratio was assumed to be 1/5. Also, different types of failure modes require different reliability indices and hence different resistance factors, ϕ. For connections, using the above dead to live load ratio and the other parameter values given below, the resistance factor was found to be (Hsiao, Yu and Galambos, 1987),

$$\phi = 1.521 \; (R_m/R_n) \; \exp \; (-\beta_o \sqrt{V_R^2 + V_Q^2}) \qquad (3)$$

in which

$$R_m/R_n = M_m \; F_m \; P_m \qquad (4)$$

and the coefficient of variation of resistance R is

$$V_R = \sqrt{V_M^2 + V_F^2 + V_P^2} \; . \qquad (5)$$

The subscript n indicates a nominal value while the subscript m indicates a mean value.

The expression for ϕ is obtained from first-order reliability theory based on lognormal distributions for the random variables, which is consistent with the product form assumed for the mathematical model of R. The above equations include approximations that apply when the coefficients of variation are small (less than about 0.3). The reader is referred to the above references for further details.

It is assumed that

$$\beta_o = 4.0, \; M_m = 1.1, \; F_m = 1.0, \; V_M = 0.1, \; V_F = 0.1, \; V_Q = 0.21 \quad (6)$$

which are the values used in the calibration of connections. The target reliability index $\beta_o = 4$ is chosen to give a reliability implicit in the present AISI Specification. The value of V_Q has been determined for a dead to live load ratio of 1/5. For other types of behavior and members, although the general procedure would be the same, a different set of values for some or all of the above parameters would need to be selected.

FACTORS OF SAFETY

It is of interest to consider the factor of safety implied by the LRFD approach outlined above. To do this it is necessary to consider the load factors. In LRFD a typical load combination case is

$$1.2\ D_n + 1.6\ L_n \quad (7)$$

where D_n and L_n are the nominal dead and live loads. The factor of safety implied can then be written as

$$FS = \frac{1.2 \frac{D_n}{L_n} + 1.6}{\phi \left[\frac{D_n}{L_n} + 1\right]} \quad (8)$$

Thus, once the resistance factor has been determined, it is a simple matter to find the corresponding safety factor for allowable stress design.

The above can be contrasted with the factor of safety implied by the European approach. A typical load factor combination used in Europe is

$$1.3\ D_k + 1.5\ L_k \quad (9)$$

where D_k and L_k are characteristic dead and live loads fixed at specified fractiles of the estimated load distributions. The characteristic strength is given by Equation 1, or rewriting,

$$P_k = K_v\ P_p \quad (10)$$

in which

$$K_v = 1 - c\ V_R \quad (11)$$

Here, K_v plays a role similar to the resistance factor ϕ. The factor of safety implied by the European approach can then be written as

$$FS = \frac{1.3 \frac{D_k}{L_k} + 1.5}{K_v \left[\frac{D_k}{L_k} + 1\right]} \quad (12)$$

The LRFD approach involves the use of nominal loads with load factors whereas the European approach uses characteristic loads. Also the loads are, in general, reached in a rather empirical fashion and may differ from country to country. Therefore, a comparison between the two safety factors defined in Equations 8 and 12 is not straightforward.

SUMMARY OF THE PROPOSED TEST EVALUATION METHOD -- BASIC PROCEDURE

The following steps summarize the proposed test evaluation procedure as applied to connection tests. A large number of test results is assumed to be available.

- For a series of tests involving different thicknesses, an empirical (experimental) curve is fit through a plot of test results versus thickness. This curve is fitted by minimizing the error in the load carrying capacity observed and the load carrying capacity predicted by the empirical curve. This curve gives the predicted capacity P_p as a function of thickness t.

- If the tests involve a single thickness then the preceding step is not necessary. The mean of the test results is the predicted capacity for the thickness tested.

- The mean, P_m, and the coefficient of variation, V_P, of the ratios of the observed to the predicted loads are calculated for all the tests. P_m and V_P are well known because of the large sample size.

- In the context of the proposed LRFD Specification format a ϕ factor is calculated according to Equation 3 and the factored nominal resistance is compared with the factored load effect. The variation of ϕ with V_P is shown in Figure 1 for P_m=1 and the other parameter values given in Equations 5 and 6.

- In the context of the present AISI Specification format the design load is the predicted load P_p divided by a factor of safety calculated according to Equation 8. This is illustrated in Figure 2 for the same conditions as Figure 1. Note that for less test scatter (lower V_P) the required safety factor is lower, which is perfectly reasonable.

In general, the values of some of the parameters used in reaching the resistance factor ϕ and the factor of safety will need to be determined by the committee deliberating upon the subject. In cases where the tests are closely related to an existing LRFD calibration result, it may be reasonable to assume the parameter values used in calibration.

MODIFIED PROCEDURE FOR A SMALL NUMBER OF TESTS

The procedure given above does not apply to a limited number of test results because the true values of P_m and V_P will not be well known for a small sample size. This statistical uncertainty in the values of P_m and V_P is accounted for in the European approach by the use of the factor c in Equation 1, which depends upon the sample size. There are drawbacks to this approach, however. Both the desired fractile for a characteristic strength and a statistical confidence level must be chosen. For the same test results but different confidence levels different safety factors will result, even though the basic state of uncertainty is unchanged. The proposed LRFD approach in the U.S. does not use the notion of statistical confidence, nor even characteristic values. Therefore, a method is needed to account for sample uncertainty that does not have these difficulties associated with it.

One approach to eliminate these difficulties is to model the uncertainty from the sample size by a random variable in the resistance equation, representing statistical noise. Equation 2 becomes

$$R = R_n \, M \, F \, P' N \qquad (13)$$

where the professional factor P has been replaced by its estimator P' from the test results, and N represents the statistical uncertainty in P' caused by a small sample size n. Assuming that the mean value of N is 1, the only change in the procedure is in the calculation of the coefficient of variation of resistance, Equation 5, which becomes

$$V_R = \sqrt{V_M^2 + V_F^2 + V_{P'}^2 + V_N^2} \;. \qquad (14)$$

Appropriate values for V_N can be determined in a number of ways. Space permits only one to be presented here: The value of V_N is chosen that has the same effect as assuming a probability distribution for ln P that is Student t in shape (rather than normal) with degree of freedom m = n-1, a mean equal to to the sample value ln P_m', and a standard deviation approximately as follows:

$$\sigma_{\ln P} \approx V_P \approx \sqrt{m/(m-2)} \cdot V_{P'} \qquad (15)$$

The factor under the square root is the variance of the standardized Student t distribution with mean zero and degree of freedom m. It acts as a correction factor on the value of $V_{P'}$ for small sample sizes. The classic use of the Student t distribution is in small sample statistics, and it is in fact the basis of the evaluation methods using confidence limits and tolerance factors. Equation 15 has been found assuming that the errors in the estimate P_m' (which is reasonably well known for a sample size of about 9 or 10 test results) are small in comparison to the errors in $V_{P'}$. It can be regarded as a first-order approximation for sample uncertainty in the same spirit as the first-order reliability theory used throughout LRFD and other probability-based design codes.

In terms of V_N, Equation 15 implies

$$V_N^2 = \left(\frac{m}{m-2} - 1\right) V_{P'}^2 = \left(\frac{2}{n-3}\right) V_{P'}^2 \qquad (16)$$

where the degree of freedom m has been taken as n-1. However, it is more convenient to use Equation 15, then Equation 5, and then to follow the basic procedure as before using Equation 3 for the resistance factor or Equation 8 for the safety factor.

The effects of sample size on the resistance factor are shown in Figure 3, and on the safety factor in Figure 4, for $P_m' = 1.0$ and $V_P' = 0.1$. These effects diminish as the number of tests increases. For example, Equation 16 approaches zero as n becomes large. This is as it should be, since the estimates of P_m and V_P become accurate for a large number of tests.

EXAMPLE -- CONNECTION TESTING

The proposed procedure is illustrated below for multiple tests of connections on several thicknesses of sheet steel. The procedure is equally applicable when only one thickness of member or connecting parts of a connection is investigated. This would be a special case for the procedure. The example is based on one found in the E.C.C.S document referenced earlier. Though the example deals with connections, the proposed procedure is general and applies to connections and members of any kind with minor modifications.

The following general requirements for tests of members or connections appear reasonable for cases when the behavior for a variety of thicknesses is investigated:

- A consistent mode of failure should be observed in all tests.
- When multiple thicknesses are involved and special interpolation formulas cannot be obtained analytically, at least three thicknesses must be tested.
- At least three sets of observations must be made for each thickness. Further provisions in accordance with the current AISI requirements may be specified.
- The design expressions must be applied with care when extrapolations are required.

Test results

The results of 9 tests on straps connected with 1/4 inch diameter self tapping screws are given in Table 1. One of the connected plates was 1/8 inch thick. The thickness of the other plate was varied as seen in the table. Plates of different thickness had different ultimate strengths.

Experimental Load Capacity Versus Thickness Expression

It will be assumed that the strength P_u of the connection is directly proportional to the ultimate strength F_u of the connected plates. For the example considered, this assumption appears reasonable since the ultimate strength of the plates of various thicknesses do not vary significantly. One can either adjust the test results in proportion to the strengths or one can write the equations for the parameter P_u/F_u. The second alternative was followed.

Plots of the data in the form P_u/F_u versus t are given in Figure 5 (disregard the regression line for now). Curves through the test points can be fitted either graphically or analytically. For the purposes of minimizing the error, it is more convenient to use an analytical procedure as follows.

Two types of expressions were tried. These are a linear expression:

$$P_u/F_u = k_1 + k_2\ t \tag{17}$$

and a nonlinear expression:

$$P_u/F_u = k_3\ t^{k_4} \tag{18}$$

Intuitively, the second expression is expected to be better because of the distribution of the test results in Figure 5, and because of the fact that only this equation gives zero P_u for t equal to zero. Thus, extrapolation to thicknesses less than those tested would be more accurate if Equation 18 is used.

The coefficients k_1 to k_4 can be determined easily by a least squares approach. For ease of use of equations given in statistics books, Equations 17 and 18 can be re-expressed as, respectively,

$$y = a + b\ x \tag{19}$$

and

$$y = k\ x^b \tag{20}$$

where $y = P_u/F_u$ and $x = t$.

For Equation 19 the coefficients a and b can be calculated as

$$b = \frac{[n\ (XY)] + (X)(Y)}{[n\ (X2)] - (X)^2} \tag{21}$$

and

$$a = \frac{[n\ (XY)] - [(X)(Y)]}{n} \tag{22}$$

where

$$X = \sum_{i=1}^{n} X_i \tag{23}$$

$$Y = \sum_{i=1}^{n} Y_i \tag{24}$$

$$XY = \sum_{i=1}^{n} (X_i)(Y_i) \tag{25}$$

and

$$X2 = \sum_{i=1}^{n} (X_i)^2. \quad (26)$$

X_i and Y_i are the values of t and P_u/F_u, respectively, observed in test number i. Test number i varies from 1 to n. The above are standard linear regression equations, and many scientific calculators have functions to obtain the coefficients a and b easily.

The coefficients k and b in Equation 20 can be obtained by re-expressing the equation as

$$\ln (y) = \ln (k) + b \ln (x) \quad (27)$$

where ln designates the natural logarithm. Equation 27 can be treated as a linear regression equation just like Equation 19 if one takes ln (y) as y, ln (x) as x, and ln (k) equal to a. The coefficients k and b can then be determined by Equations 21 and 22 observing that

$$k = \exp (a). \quad (28)$$

For the test results given, k_1 and k_2 in Equation 17 are found to be -0.00566 and .9847, respectively, and k_3 and k_4 in Equation 18 are found to be 1.3400 and 1.1515. (All numbers are given to four places even though the test data does not warrant such accuracy.)

Thus, the experimental load prediction equations are

$$P_p = (-0.00566 + .9847\ t)\ F_u \quad (29)$$

and

$$P_p = 1.3400\ F_u\ t^{1.1515} \quad (30)$$

where the predicted ultimate load is designated P_p. Plots of the test results and the above equations are presented in Figures 5 and 6. The results are also tabulated in Tables 2 and 3.

Mean and Coefficient of Variation

The ratio of the observed ultimate load to the predicted load for test number i is designated R_i:

$$R_i = \frac{P_{ui}}{P_{pi}} \quad (31)$$

where P_{ui} and P_{pi} are the observed and predicted failure loads for the test number i. The mean and the standard deviation can be calculated as follows:

$$P'_m = \frac{\sum_{i=1}^{n} R_i}{n} \quad (32)$$

and

$$S'_P = \sqrt{\frac{R1 - \frac{R2}{n}}{n - 1}} \simeq V'_P \qquad (33)$$

where the prime (') is a reminder that these values have been obtained from a small sample. In the above,

$$R1 = \sum_{i=1}^{n} R_i^{\,2} \qquad (34)$$

and

$$R2 = (\sum_{i=1}^{n} R_i)^2. \qquad (35)$$

Again, these are standard statistical equations for the sample mean and standard deviation, and many calculators have these functions built in. The coefficient of variation is

$$V_{P'} = \frac{S_{P'}}{P'_m} \qquad (36)$$

which is approximately equal to Equation 33, since P_m' will be very close to unity.

P_m' and V_P' for Equation 29 are 1.0569 and 0.0910, respectively. For Equation 30, P_m' and V_P' are 1.0019 and 0.0705, respectively. As was stated before on an intuitive basis, Equation 30 is a better expression for the situation at hand. This is reflected in the lower value of V_P (scatter) and in the value of P_m closer to unity (mean correction). Equation 30 will be used for design.

Correction for Small Sample Size

For 9 tests the value of V_P' is modified using Equation 15. For the superior prediction Equation 30:

$$V_P = \sqrt{\frac{m}{m-2}}\ V'_P = \sqrt{\frac{9-1}{9-3}}\ (0.0705) = 0.0814. \qquad (37)$$

For strengths predicted by Equation 29 the result is $V_P = 0.1051$.

Resistance Factor and Safety Factor

Using the above results for P_m and V_P, and Equations 3 to 6, the LRFD resistance factor for Equation 30 at a safety index of 4.0 is $\phi = 0.5859$ and the corresponding safety factor for use with current design provisions is, from Equation 8, FS = 2.617.

The above implied factor of safety of about 2.6 is somewhat higher than the factor of 2.5 specified in Section 6.2 of the present AISI Specification. Primarily, the reason is the target reliability factor β_o of 4 used in the calculations. A parametric study of the relationship between β_o, V_P and the implied factor of safety was carried out. The results have been included in Figures 1 and 2. It is seen that by a calibration of β_o one can obtain any desired value of the factor of safety (if appropriate). The advantage of the procedure is that it results in a rational approach to the evaluation of the effects of various parameters such as the scatter of test data and the number of tests.

It is also seen in Figures 1 and 2 that an improvement in the scatter of test data as indicated by the coefficient of variation V_P results in a smaller implied factor of safety, which is perfectly reasonable.

European Approach

Using a characteristic value of resistance at the 5% fractile, with 50% confidence and a sample size of n = 9 tests, the appropriate value for c in Equation 11 is 1.86. However, in the E.C.C.S. example referenced earlier a value of c = 1.74 is obtained for this case, by treating the 9 tests on 18 pairs of fasteners as if n = 18. This is questionable, since there are in fact only 9 test results. Using the value c = 1.74 anyway, for the sake of comparison, with $D_n/L_n = 1/5$ and $V_R = V_P$, Equations 11 and 12 give $K_v = 0.8773$ and FS = 1.6718 for prediction Equation 30. (A value of c = 1.86 yields K_v = 0.8689 and FS = 1.6718). However, as explained before, these values cannot be compared directly with the LRFD values of ϕ and FS.

CONCLUSIONS

A probabilistic approach has been developed for the evaluation of test results that is compatible with both the forthcoming load and resistance factor design (LRFD) and the current safety factor design specification formats. The procedure is flexible and computationally straightforward. It appears to have a good potential for practical evaluation methods.

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APPENDIX -- NOTATION

a,b	=	regression coefficients
c	=	statistical number used to determine tolerance factors
D	=	dead load
F	=	random variable representing fabrication uncertainty
FS	=	factor of safety
K_v	=	statistical tolerance factor
L	=	live load
M	=	random variable representing material uncertainty
m	=	student t degree of freedom (n-1)
N	=	random variable representing sample uncertainty
n	=	no. of test results
P	=	random variable representing prediction uncertainty
P_k	=	characteristic load capacity
P_p	=	predicted load capacity
P_u	=	observed load capacity
R	=	resistance or strength
R_i	=	ratio of observed to predicted load for test no. i
V	=	coefficient of variation
X,x	=	regression variables
Y,y	=	regression variables
ϕ	=	resistance factor
σ	=	standard deviation

Subscripts

n	=	nominal value
k	=	characteristic value
m	=	mean value
p	=	predicted value

Superscripts

′	=	small-sample value

TABLE 1 -- TEST RESULTS

Test No.	t (inches)	F_u (ksi)	P_u (k/screw)
1	.0610	48.1159	2.6652
2	.0610	48.1159	2.6404
3	.0610	48.1159	2.6090
4	.0299	45.6522	1.0494
5	.0299	45.6522	.9775
6	.0299	45.6522	.9685
7	.0209	45.5072	.7820
8	.0209	45.5072	.7708
9	.0209	45.5072	.6854

TABLE 2 -- TEST RESULTS VS. PREDICTION EQUATION 29

Test No.	P_u/F_u	P_p	P_u/P_p
1	.0554	2.5122	1.0609
2	.0549	2.5122	1.0510
3	.0542	2.5122	1.0385
4	.0230	1.0366	1.0124
5	.0214	1.0366	.9430
6	.0212	1.0366	.9343
7	.0172	.6447	1.2129
8	.0169	.6447	1.1955
9	.0151	.6447	1.0631

For P_u/P_p: Mean =1.0569, Standard Deviation = .0962

TABLE 3 -- TEST RESULTS VS. PREDICTION EQUATION 30

Test No.	$\ln(P_u/F_u)$	P_p	P_p/P_u
1	.0554	.9652	.8456
2	.0549	.9742	.8535
3	.0542	.9860	.8638
4	.0230	1.0250	.8980
5	.0214	1.1004	.9641
6	.0212	1.1106	.9731
7	.0172	.9060	.7938
8	.0169	.9192	.8054
9	.0151	1.0338	.9057

For P_u/P_p: Mean =1.0019, Standard Deviation = .0705

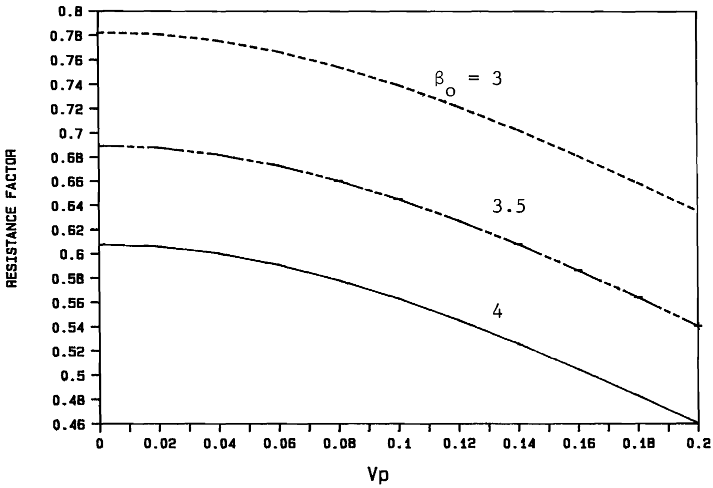

Fig. 1 - Resistance Factor versus the Coefficient of Variation of Test Results

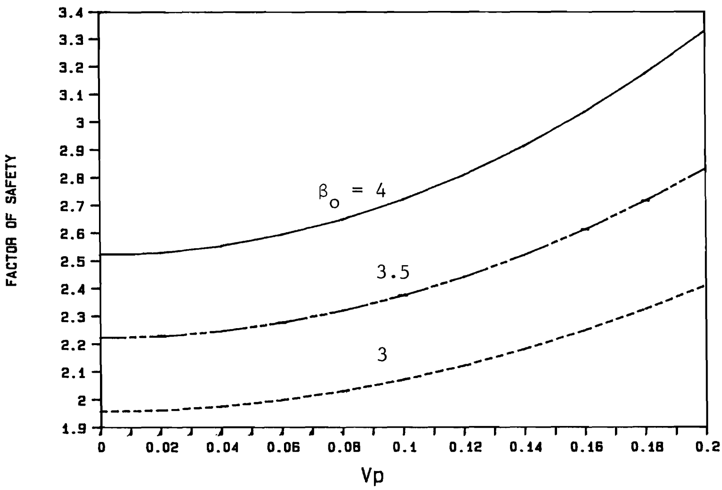

Fig. 2 - Factor of Safety versus the Coefficient of Variation of Test Results

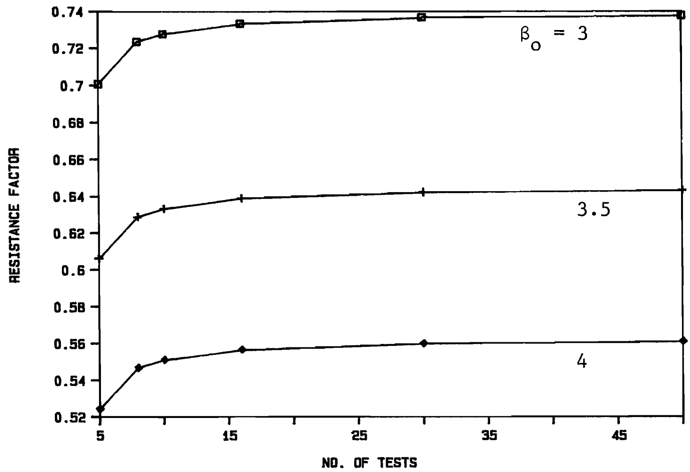

Fig. 3 - Resistance Factor versus the No. of Tests
(Pm=1.0 , Vp=0.1)

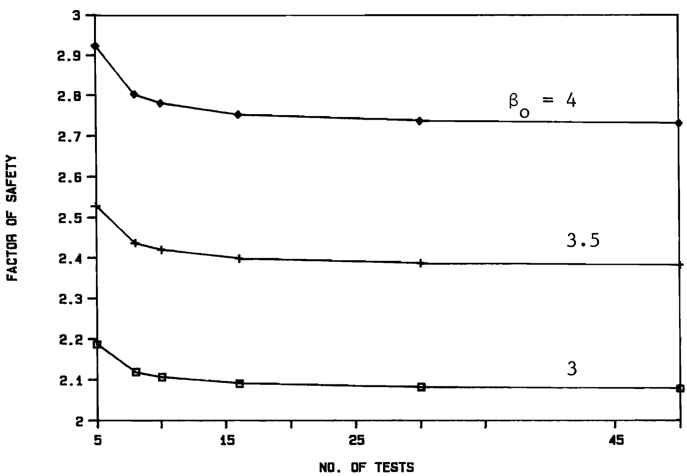

Fig. 4 - Factor of Safety versus the No. of Tests
(Pm=1.0 , Vp=0.1)

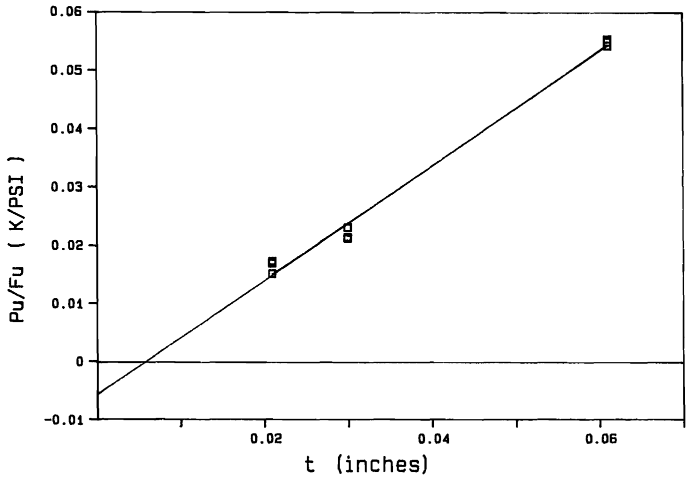

Fig. 5 - Observed and Predicted Test Results
Prediction by Equation 29

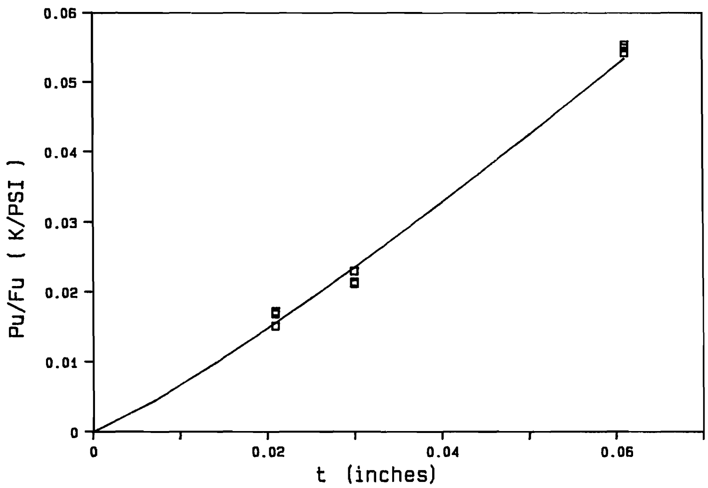

Fig. 6 - Observed and Predicted Test Results
Prediction by Equation 30