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Tension-Bearing Couples (TBC), Part III[*]: Developing Fastener Maximum Load Correction Factors Charts

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Abstract: A study was conducted to determine the effect of fasteners/fitting modulus of elasticity ratio on the fastener maximum load correction factors obtained from realistic FEM models and the proposed enhanced analysis approach. This study entails 392 FEM and analytical model runs. Statistical analyses demonstrate that the fastener maximum load correction factors curves reach constant plateaus at a fasteners/fitting modulus of elasticity ratio of approximately 1.00. The angle factor curve, on the other hand, is increasing with increasing values of the fasteners/fitting modulus of elasticity ratio. The proposed enhanced analysis approach, together with the fastener maximum load correction factors curves of this study, can yield results that are comparable with those obtained from realistic FEM models.

Keywords: Tension-Bearing Couple, Tensile-Loaded Fasteners, Bolted Joints, Fastener Joints, Finite Element Method, Finite Element Analysis, Finite Element Modeling

1. Introduction

A new analysis approach to compute fastener tensile loads in tension-bearing couples (TBC) loaded with out-of-plane bending moments was introduced in Reference 1. Finite Element validation of this analysis approach[1], using idealized FEM models that preclude flexural and shear deformations in the fitting, is introduced in Reference 2. Validation of the proposed enhanced analysis approach[2], using realistic FEM models that permit flexural and shear deformations in the fitting, is introduced in Reference 3. Results of the realistic FEM models exhibit significant differences from the results of proposed enhanced analysis approach[3].

This article discusses the study that was conducted to develop fastener maximum load correction factors charts to be used in conjunction with the proposed enhanced analysis approach[2,3]. Together, they yield fastener maximum loads that are conservative and equal to, or higher than, the fastener maximum loads predicted by the realistic FEM models. This study entails 56 realistic FEM models based on the seven (7) joints used in Reference 3. Each of these joints has eight (8) different material combinations for the fasteners and fitting. Each model and material combination was run for seven (7) values of the applied out-of-plane bending moment angle with respect to the local x-axis. These angle values entail: 0°, 15°, 30°, 45°, 60°, 75°, and 90°. Details of the realistic FEM models and their material combinations are depicted in Table 1 . The total processing time of these 392 (56x7) realistic FEM model runs is approximately 506 hours plus 196 hours for data collection and model setting.

[*] Refer to the other two parts in this volume

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2. Finite Element Modeling

Autodesk™ Algor™ Simulation 2010 was used to construct the realistic FEM models under investigation. All components of these models (fitting, fasteners, and substrate/base) are meshed using isotropic 8-node brick elements with compatibility enforced. An approximate absolute mesh size of 0.065" is used for all components. Surface contact pairs are established between the upper fastener heads and the upper surface/plane of the fitting, the lower surface/plane of the fitting and the upper surface/plane of the substrate/base, and the lower surface/plane of the substrate/base and the lower fastener heads. The details of these realistic finite element models are described and depicted in Reference 3. Specifications of the fitting and fastener materials used are detailed in Table 2.

Table 1: Fasteners/Fitting Material Combinations and Number of Model Runs

		Fitting			
		Fictitious	Aluminum	Titanium	Steel
Fasteners	Aluminum			49 (7x7)*	49 (7x7)*
	Titanium	49 (7x7)*	49 (7x7)*	49 (7x7)*	49 (7x7)*
	Steel		49 (7x7)*	49 (7x7)*	

* 7 joints and 7 applied out-of-plane bending moment angles

Table 2: Specifications of the Materials Used for the Fitting and Fasteners

Component	Material	Material Specification	Modulus of Elasticity [psi]
Fitting & Substrate/Base	Fictitious	Fictitious material based on AISI 4130 low-alloy Steel per AMS 6350	29.0E+12
Fitting	Aluminum	7050-T74 Aluminum Die Forging per AMS 4107, MIL-A-22771	10.2E+06 10.7E+06
	Titanium	Ti-6Al-4V Titanium Annealed Plate per MIL-T-9046 AB-1, and AMS 4911	16.0E+06
	Steel	4140 125-145 Forging Steel per MIL-S-5626, AMS 6382	29.0E+06
Fasteners	Aluminum	2024-T4 Aluminum Bar per AMS 4120 and AMS-QQ-A-225/6	10.5E+06
	Titanium	Ti-6Al-4V Solution Treated and Aged Titanium Bar per MIL-T-9047, AMS 4965, AMS-T-9047, and AMS 6930	16.9E+06
	Steel	4140 125-145 Steel Bar per MIL-S-5626, AMS 6382	29.0E+06

The fasteners/fitting modulus of elasticity ratios are computed using the modulus of elasticity values listed in Table 2. The fictitious material was used also for the substrate/base of all realistic FEM models. Table 3 summarizes all the fasteners/fitting modulus of elasticity ratios investigated in this study. These ratios represent every possible material combination from a structural engineering perspective. Fastener maximum load correction factors for other ratios can be interpolated or extrapolated using the results of current ratios.

Table 3: Fasteners/Fitting Modulus of Elasticity Ratios

		Fitting			
		Fictitious	Aluminum	Titanium	Steel
Fasteners	Aluminum			0.656250	0.362069
	Titanium	0.000001	1.495327*	1.056250	0.582759
	Steel		2.843138	1.812500	

* Based on moduli of elasticity of 16.0E+06 and 10.7E+06 for Titanium fasteners and Aluminum fitting, respectively.

3. Results and Discussions

The fastener maximum load correction factors plots are depicted in Figure 1 through Figure 8. A fastener maximum load correction factor is the ratio between the prediction of a realistic FEM model for a fastener maximum load and the prediction of the proposed enhanced analysis approach for it. Each of these plots, with the exception of that for titanium fasteners and fictitious material fitting, has an upper bound for the fastener maximum load correction factors. The upper bound can be computed for any fasteners/fitting material combination and value of the applied out-of-plane bending moment angle with respect to the local x-axis using the following expression. The formula depicted on each of these figures is a simplified version.

$$\mathrm{FMLCF}(p,\alpha) = \mathrm{FMLCF}(p) - \mathrm{AngFac} \cdot \sin(2 \cdot \alpha) \tag{1}$$

where:

FMLCF(p,α)	Fastener maximum load correction factor as function of the angle of applied out-of-plane bending moment with respect to the local x-axis and selected confidence level
FMLCF(p)	Fastener maximum load correction factor as of function of selected confidence level
AngFac	Factor to account for the angle of the applied out-of-plane bending moment vector with respect to the local x-axis
α	Angle of applied out-of-plane bending moment with respect to the local x-axis

StatSoft®'s STATISTICA 9.0.231.9 was utilized to create normal probability plots for the fastener maximum load correction factors. Each of these plots entails correction factors for all joints and applied out-of-plane bending moment angles for a given fasteners/fitting material combination. Resulting probability plots are depicted in Figure 9 through Figure 16. The abscissa of each of these plots represents observed values of fastener maximum load correction factors and the ordinate represents expected normal values, expressed in terms of a normal distribution's standard deviation multiplier. Observed values of fastener maximum load correction factors were obtained from the realistic FEM models and proposed enhanced analysis approach runs.

STATISTICA was also used to fit a standard normal distribution to the observed fastener maximum load correction factors data of each of the fasteners/fitting material combinations. This statistical analysis entails correction factors for all joints and applied out-of-plane bending moment angles for a given fasteners/fitting material combination. An additional outcome of this analysis is the observed and expected probability and cumulative probability for the fastener maximum load correction factors.

As part of the above statistical analysis, STATISTICA performed a chi-square test[4] to evaluate the goodness of fit of the fastener maximum load correction factors to a standard normal distribution. Based on the p-values obtained, none of the null hypotheses can be rejected. This simply means that the difference between expected and observed values is due to mere chance or random error. These results are illustrated in Table 4 and Table 5 below.

Table 4: Results of the χ^2 Analyses

Material Combination	Modulus of Elasticity Ratio	Mean	Variance	χ^2	DOF	p Value	Can Reject Null Hypothesis?
TF	0.0000	0.978373	0.002699	1.559180	3	0.66868	NO
AS	0.3621	1.950424	0.361029	0.484700	3	0.92224	NO
TS	0.5828	2.004325	0.392798	0.55204	3	0.90732	NO
AT	0.6563	2.016000	0.400324	0.803530	3	0.84862	NO
TT	1.0563	2.041159	0.422400	1.505400	3	0.68102	NO
TA	1.4953	2.065630	0.414040	1.048170	3	0.78960	NO
ST	1.8125	2.055205	0.432974	1.185240	3	0.75655	NO
SA	2.8431	2.041898	0.426272	2.133870	3	0.54509	NO

where:

TF Titanium fasteners and fictitious material fitting
AS Aluminum fasteners and steel fitting
TS Titanium fasteners and steel fitting
AT Aluminum fasteners and titanium fitting
TT Titanium fasteners and titanium fitting
TA Titanium fasteners and aluminum fitting
ST Steel fasteners and titanium fitting
SA Steel fasteners and aluminum fitting

Expected probability and cumulative probability for the fastener maximum load correction factors, resulting from fitting a standard normal distribution to the fastener maximum load correction factors data of each of the fasteners/fitting material combinations, were used to construct expected probability and cumulative probability plots for this material combination. These plots, together with observed probability and cumulative probability, are depicted in Figure 17 through Figure 24.

Figure 25 is the summary of all data generated by this study. All fastener maximum load correction factors curves reach constant plateaus at a fasteners/fitting modulus of elasticity ratio of approximately 1.00. To compute fastener maximum load correction factor for a given fasteners/fitting material combination use the following steps: 1) compute the modulus of elasticity ratio of the fasteners/fitting material combination; 2) locate this value on the abscissa of Figure 25 and construct a vertical line at it; 3) choose a confidence level and find the point of intersection of the vertical line with the fastener maximum load correction factors curve corresponding to chosen confidence level, interpolate between curves for other levels of confidence not included in Figure 25; 4) draw a horizontal line at this point of intersection and find its point of intersection with the left ordinate; 5) read the FMLCF(p) value from the left ordinate; 6) find the point of intersection of this vertical line with the angle factor curve; 7) draw a horizontal line at this point and find its point of intersection with the right ordinate; 8) read the AngFac value from the right ordinate; 9) compute FMLCF(p,α) using equation 1; 10) apply this factor to the fastener tensile loads, computed with the proposed enhanced analysis approach, at the joint's periphery only.

Table 5: Results of Fitting Normal Probability Plots to Fastener Maximum Load Correction Factors

Material Combination	Max. Observed	Max. Expected	Histogram Categories	Lower Limit	Upper Limit	Angle Factor	Coefficient of Variation
TF	1.086109	1.119990	17	0.82	1.12	0.00	5.31%
AS	3.069767	3.400000	10	0.60	3.40	0.20	30.81%
TS	3.229002	3.600000	10	0.60	3.60	0.35	31.27%
AT	3.262869	3.600000	10	0.60	3.60	0.40	31.38%
TT	3.375743	3.800000	11	0.60	3.80	0.55	31.84%
TA	3.446003	3.800000	11	0.60	3.80	0.70	31.15%
ST	3.456797	3.800000	11	0.60	3.80	0.75	32.02%
SA	3.461427	3.800000	10	0.60	3.80	0.80	31.97%

4. Conclusions

Based on the statistical analyses performed on the fastener maximum load correction factors we can make the following conclusions. These conclusions, however, are valid only for joints with aspect ratios ranging from 0.538 to 9.75:

a. The upper bound of the fastener maximum load correction factors for a given fasteners/fitting material combination can be represented by a mathematical expression composed of: 1) fastener maximum load correction factor for a given fasteners/fitting modulus of elasticity ratio and 100% confidence level; 2) angle factor that accounts for the angle of applied out-of-plane bending moment; and 3) the angle of applied out-of-plane bending moment with respect to local x-axis.

b. The fastener maximum load correction factors curves achieve constant plateaus at a fasteners/fitting modulus of elasticity ratio of approximately 1.0 for all confidence levels.

c. The Angle Factor increases with increasing fasteners/fitting modulus of elasticity ratio.

d. The proposed enhanced analysis approach, together with the curves of Figure 25, can yield fastener maximum loads that are comparable to those obtained from realistic FEM models.

5. Acknowledgement

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6. References

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[3] Daken, Hatem H. and Shoukry, M. Kamal, “Tension-Bearing Couples (TBC), Part II: Adding Realism to the FEM Validation of Proposed Analysis Approach,” 14th International Conference on Aerospace Sciences & Aviation Technology, ASAT- 14, May 24 – 24, 2011

[4] Maben, Anne F., “CHI-SQUARE TEST - Adapted by from "Statistics for the Social Sciences" by Vicki Sharp,” http://www.enviroliteracy.org/pdf/materials/1210.pdf

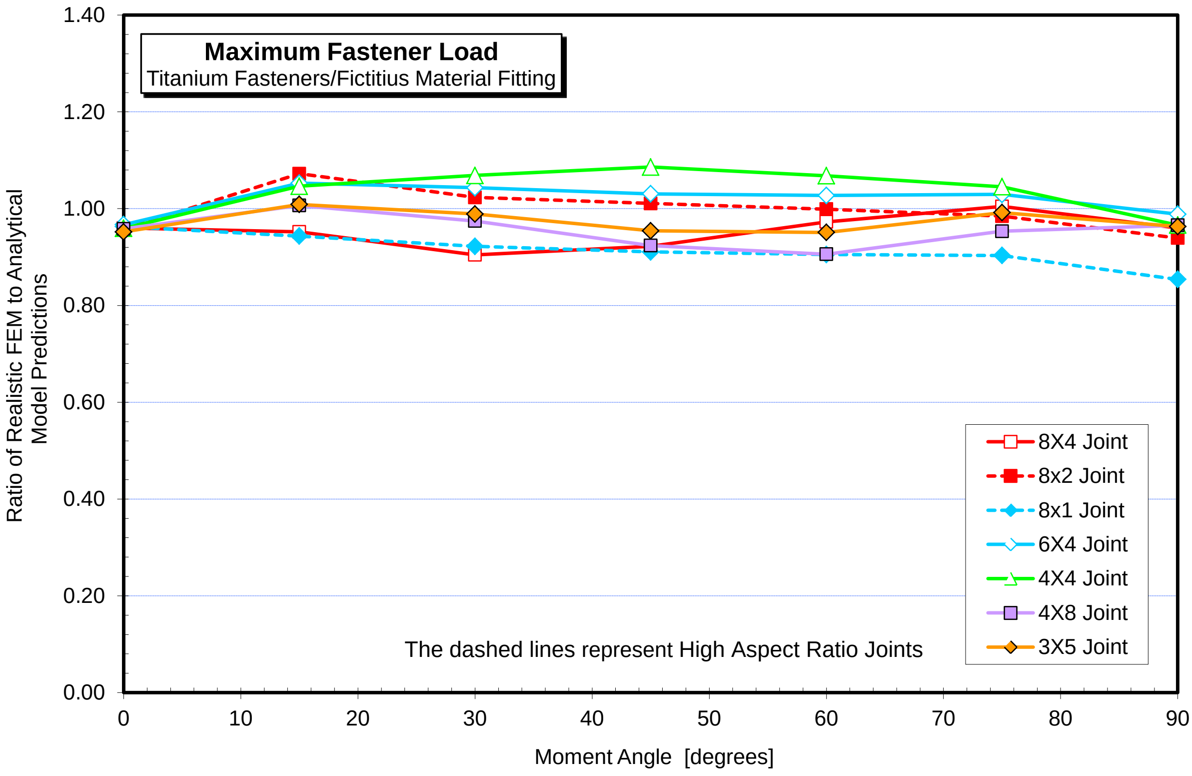

Figure 1: Fastener Maximum Load Correction Factor Plots for Titanium Fasteners and Fictitious Material Fitting

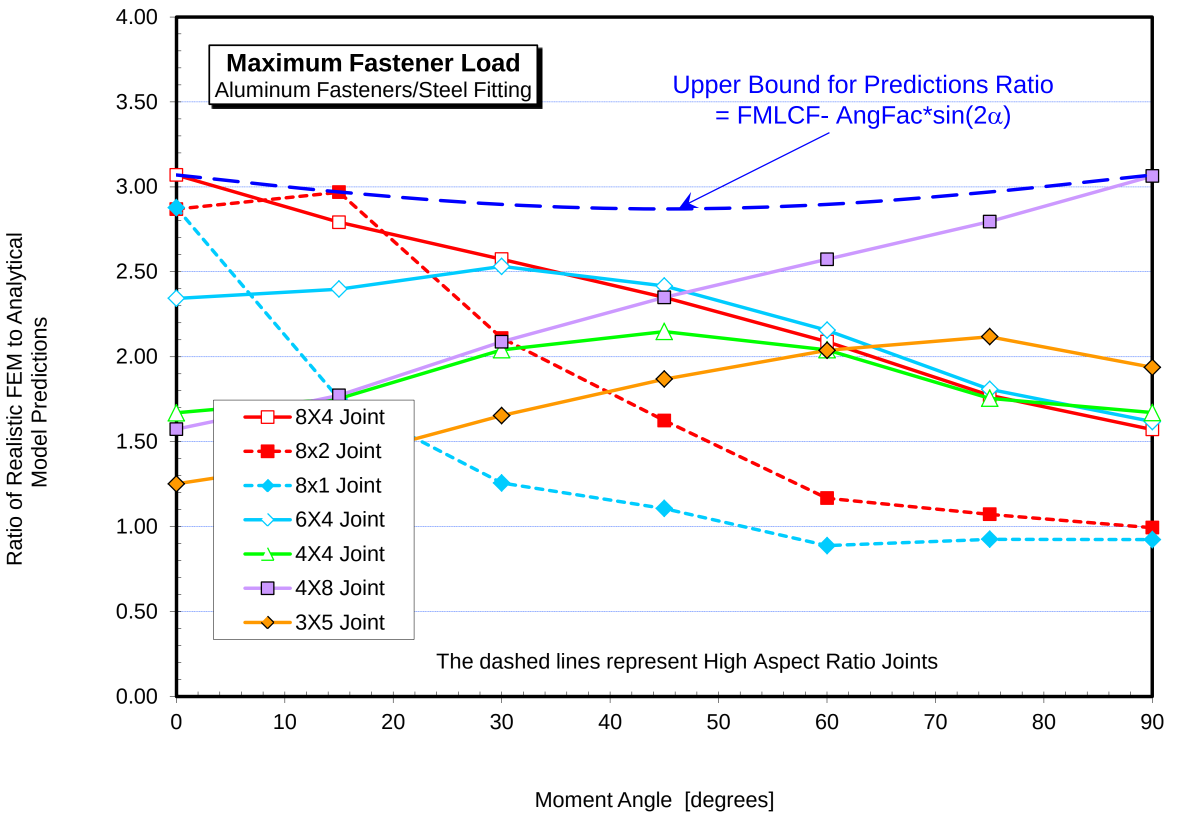

Figure 2: Fastener Maximum Load Correction Factor Plots for Aluminum Fasteners and Steel Fitting

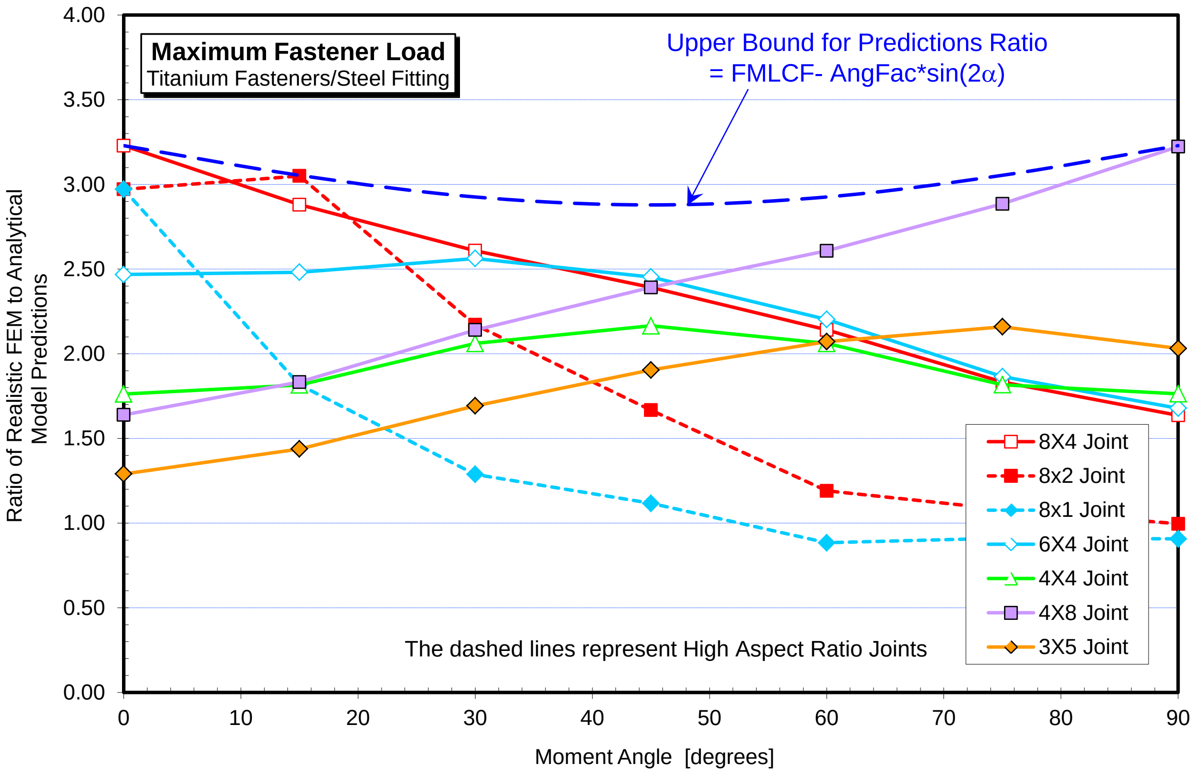

Figure 3: Fastener Maximum Load Correction Factor Plots for Titanium Fasteners and Steel Fitting

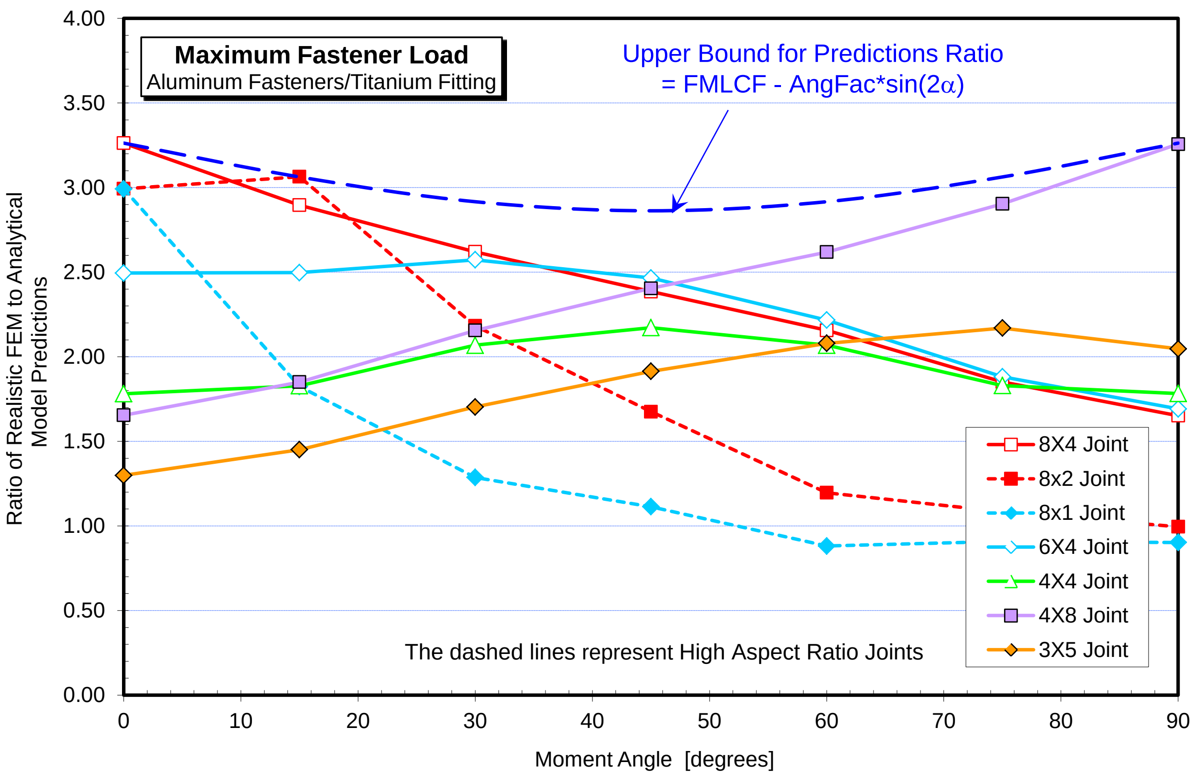

Figure 4: Fastener Maximum Load Correction Factor Plots for Aluminum Fasteners and Titanium Fitting

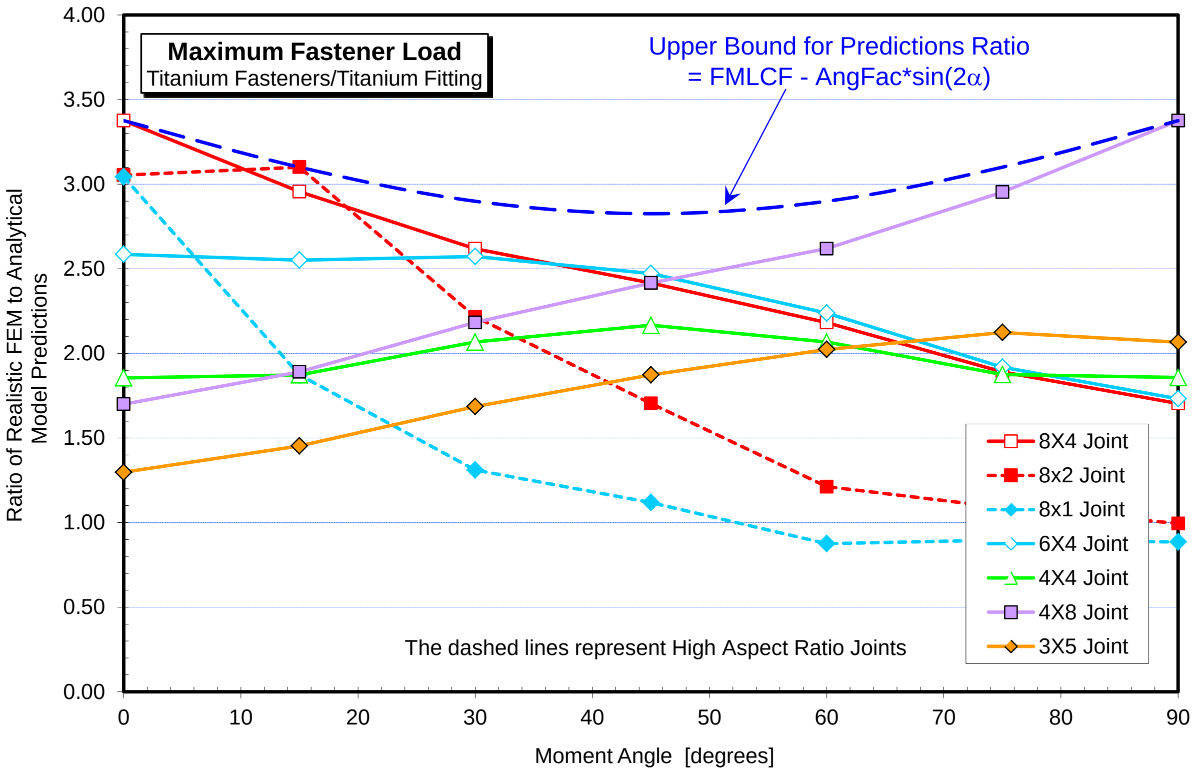

Figure 5: Fastener Maximum Load Correction Factor Plots for Titanium Fasteners and Titanium Fitting

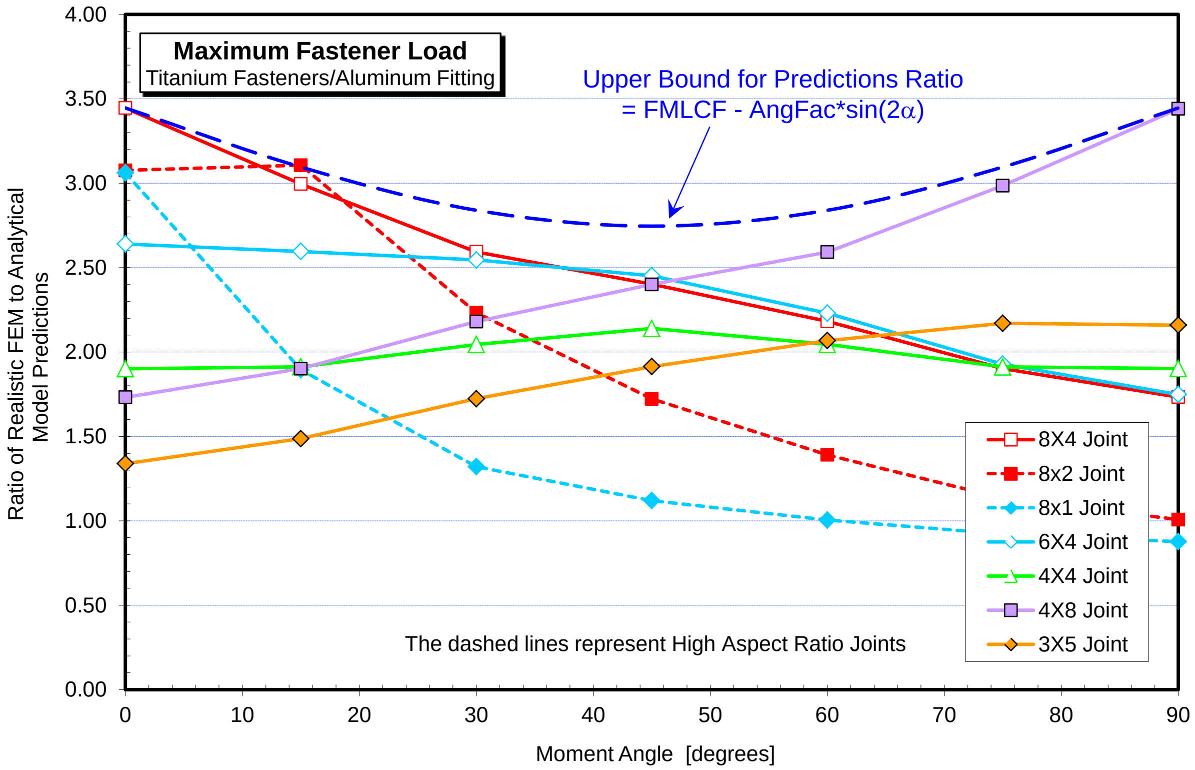

Figure 6: Fastener Maximum Load Correction Factor Plots for Titanium Fasteners and Aluminum Fitting

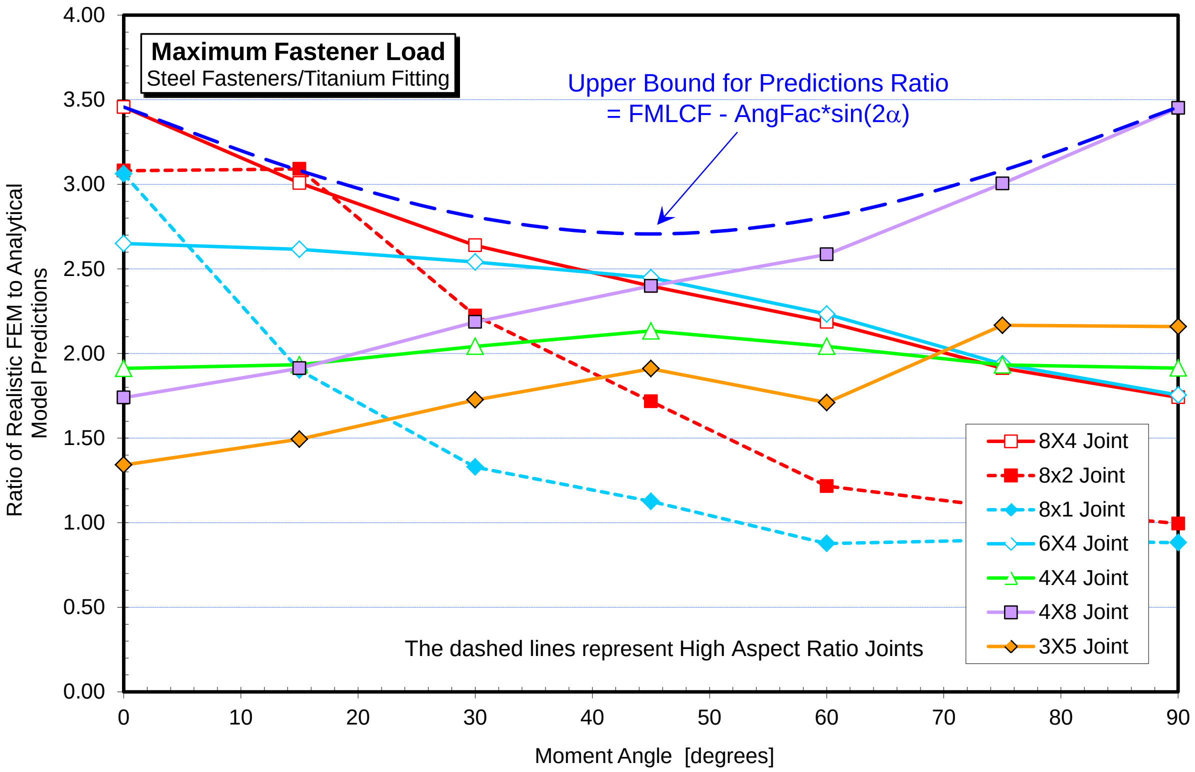

Figure 7: Fastener Maximum Load Correction Factor Plots for Steel Fasteners and Titanium Fitting

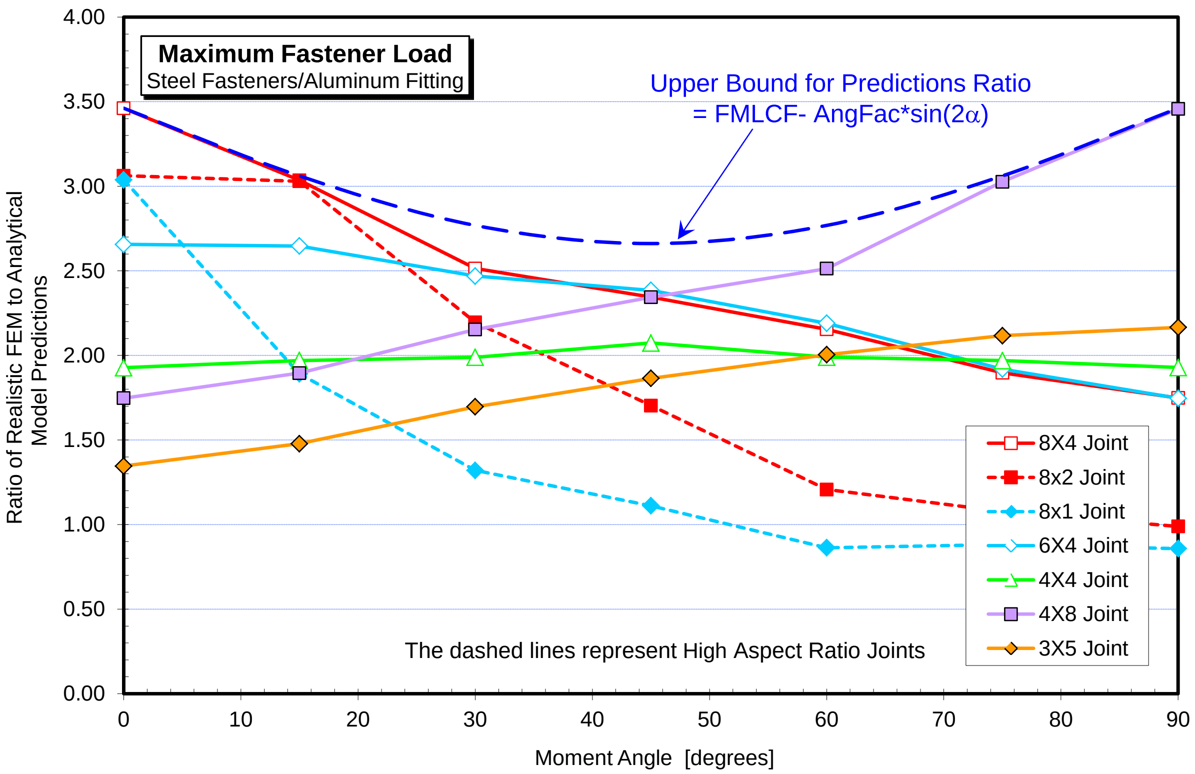

Figure 8: Fastener Maximum Load Correction Factor Plots for Steel Fasteners and Aluminum Fitting

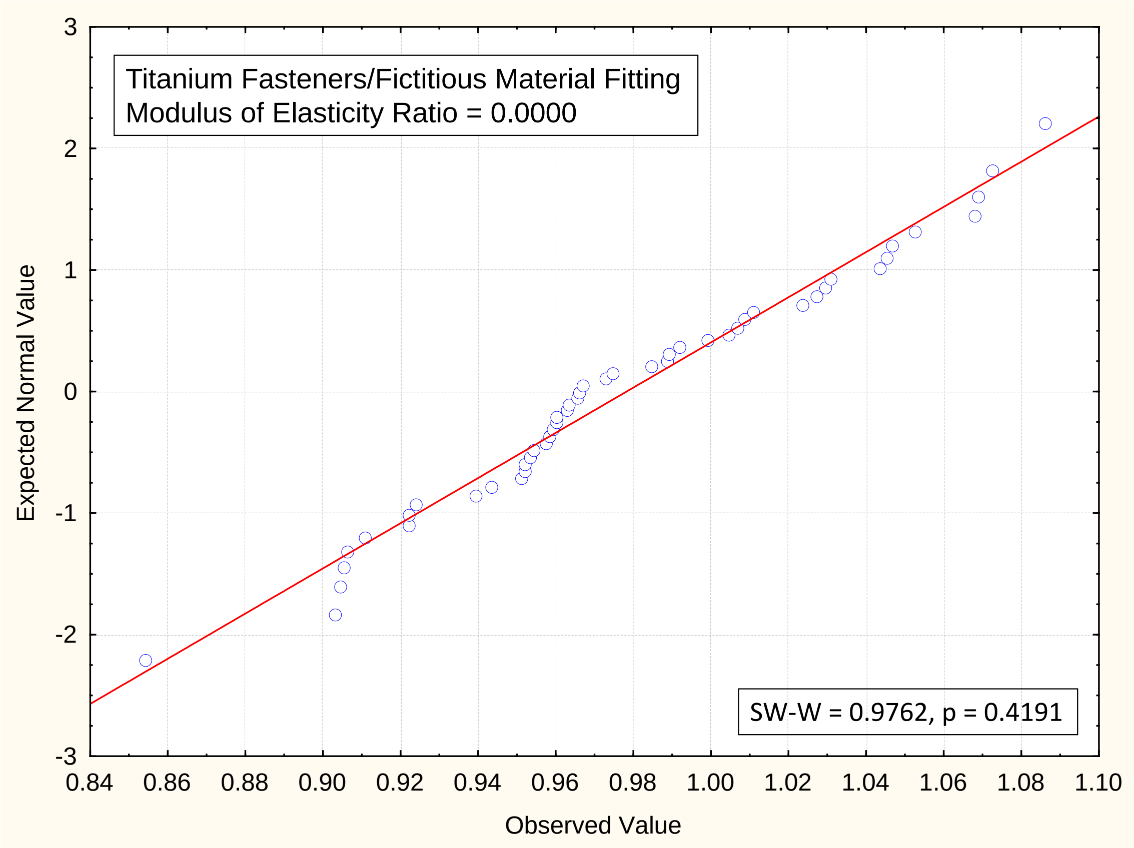

Figure 9: Normal Probability Plot of Fastener Maximum Load Correction Factors for Titanium Fasteners and Fictitious Material Fitting

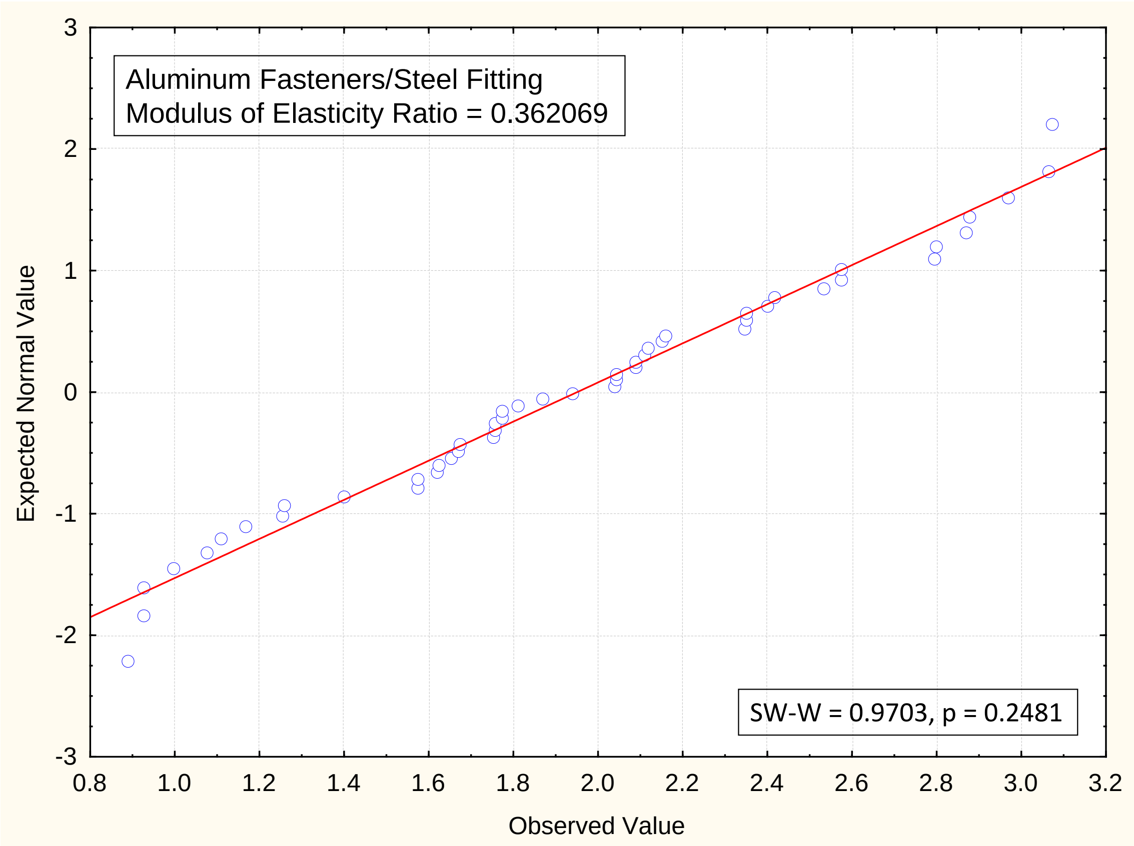

Figure 10: Normal Probability Plot of Fastener Maximum Load Correction Factors for Aluminum Fasteners and Steel Fitting

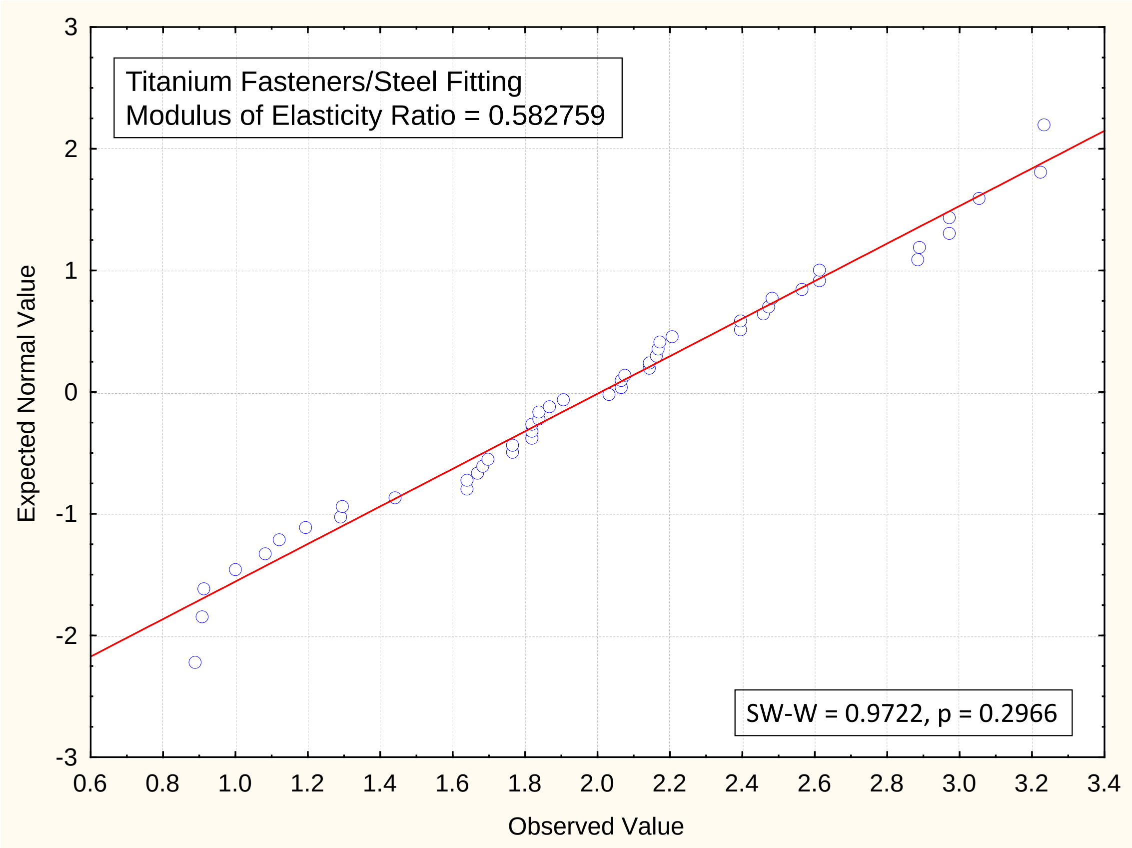

Figure 11: Normal Probability Plot of Fastener Maximum Load Correction Factors for Titanium Fasteners and Steel Fitting

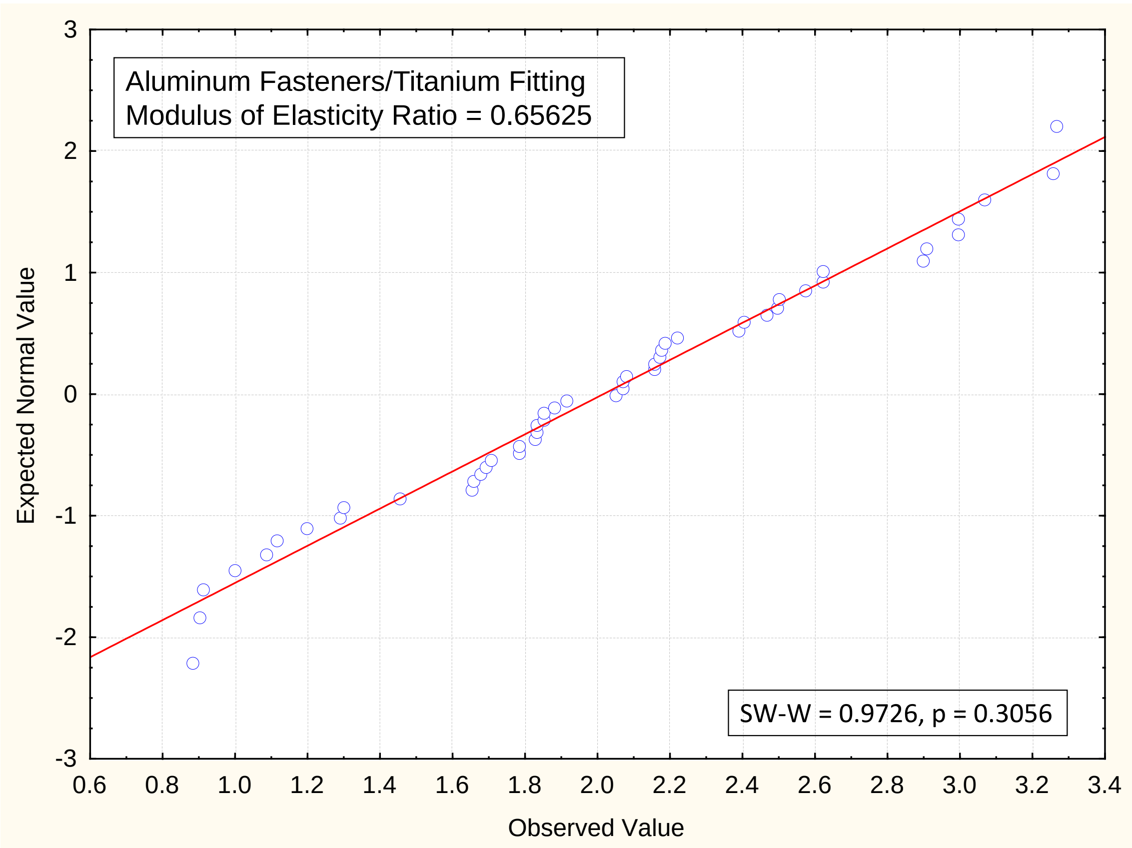

Figure 12: Normal Probability Plot of Fastener Maximum Load Correction Factors for Aluminum Fasteners and Titanium Fitting

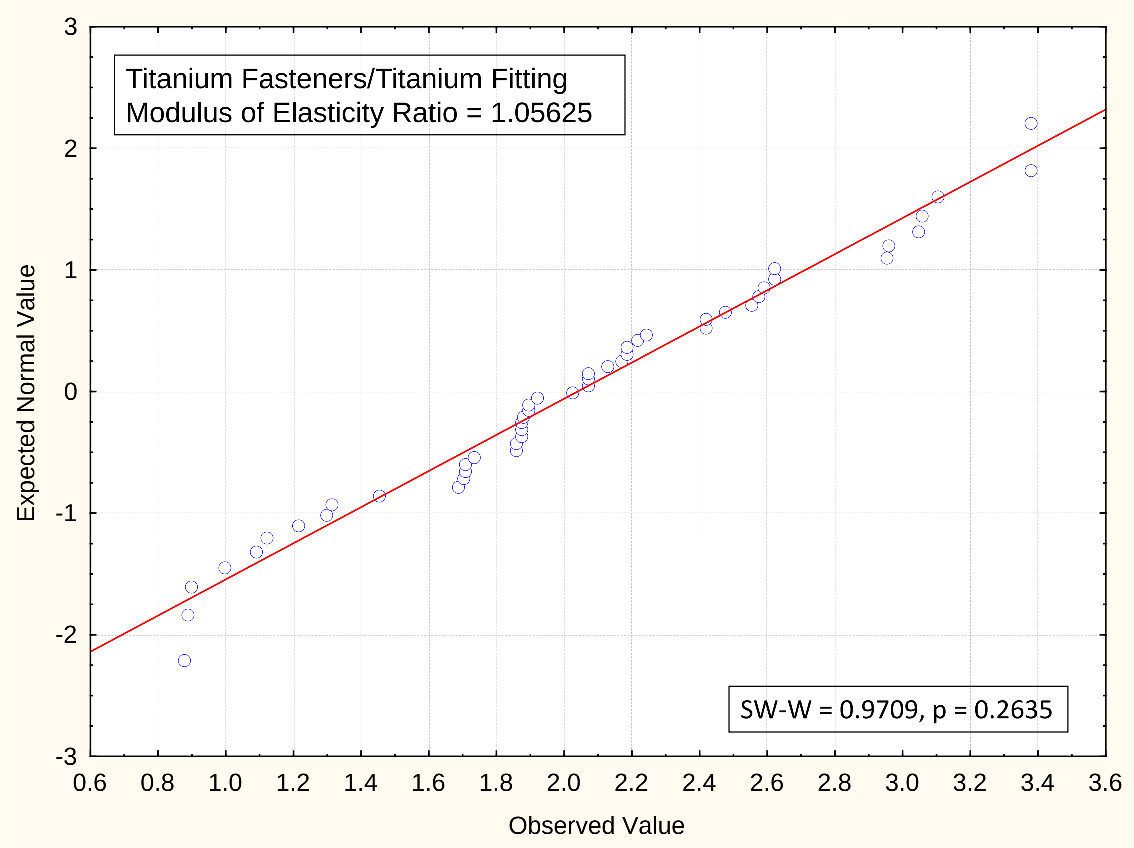

Figure 13: Normal Probability Plot of Fastener Maximum Load Correction Factors for Titanium Fasteners and Titanium Fitting

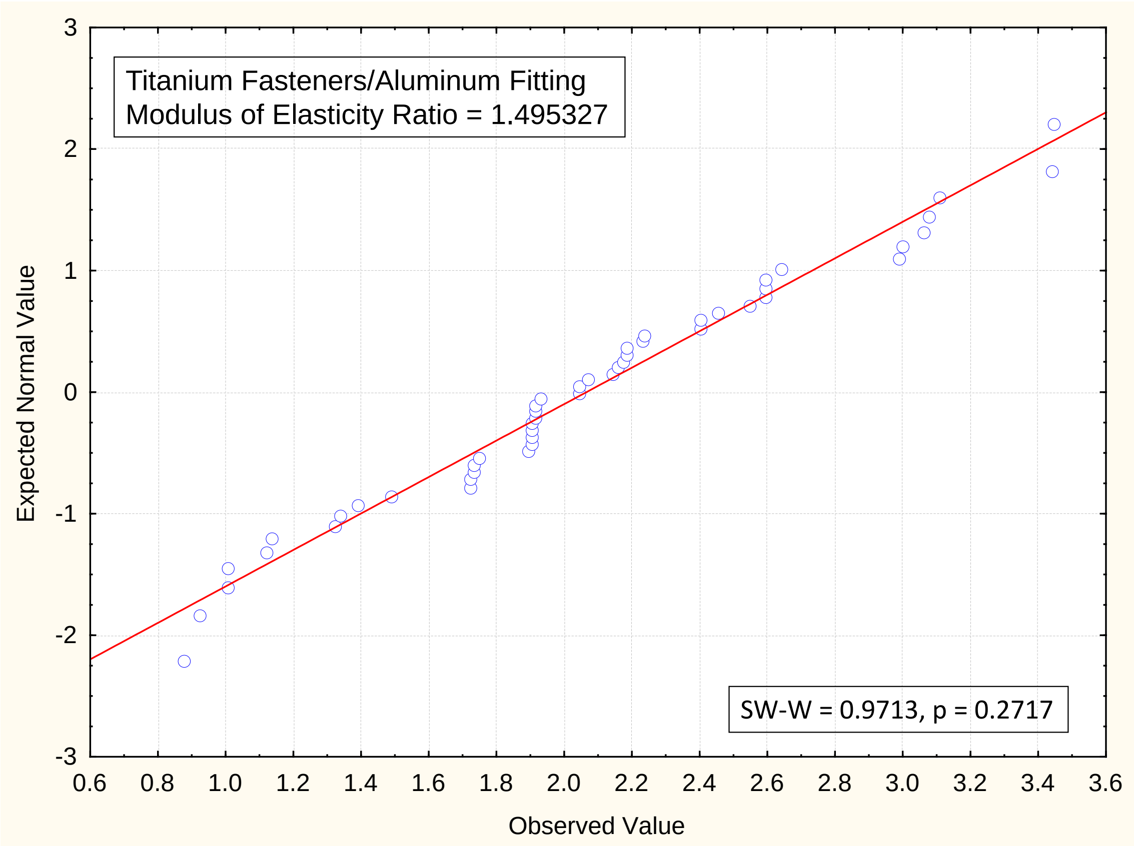

Figure 14: Normal Probability Plot of Fastener Maximum Load Correction Factors for Titanium Fasteners and Aluminum Fitting

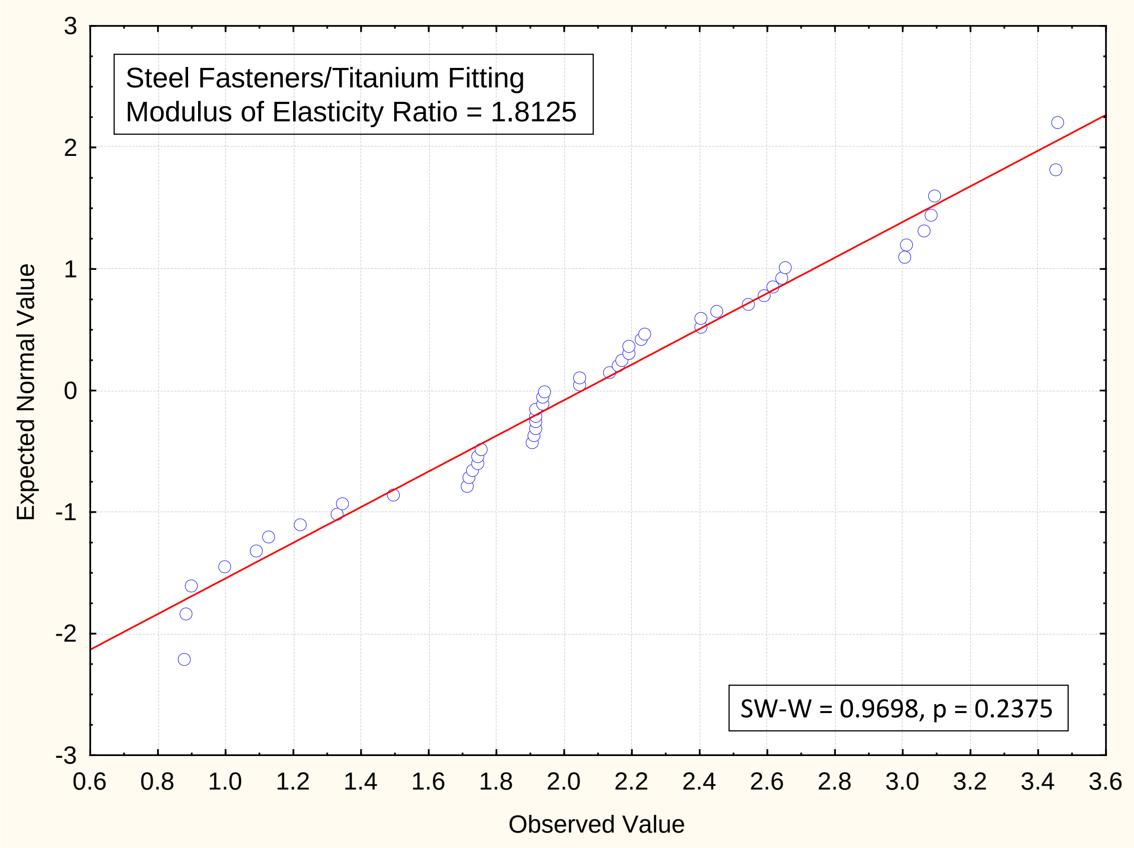

Figure 15: Normal Probability Plot of Fastener Maximum Load Correction Factors for Steel Fasteners and Titanium Fitting

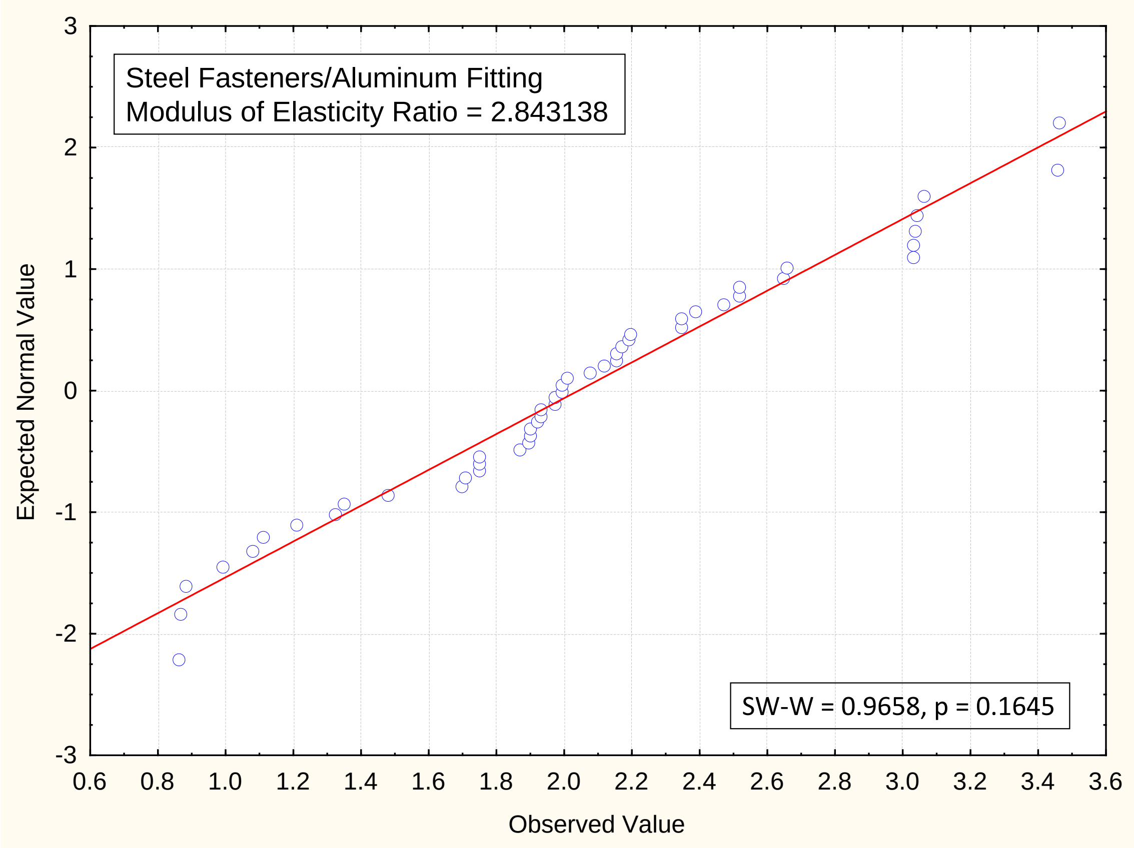

Figure 16: Normal Probability Plot of Fastener Maximum Load Correction Factors for Steel Fasteners and Aluminum Fitting

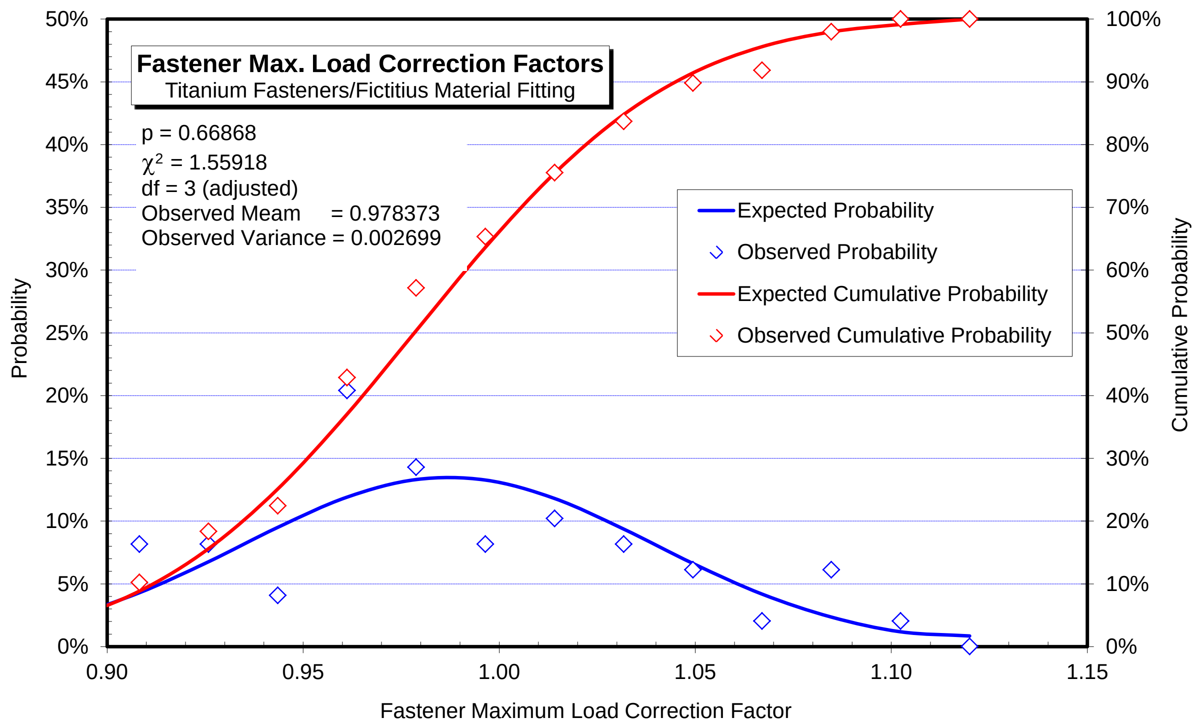

Figure 17: Normal Probability and Cumulative Probability Plots for the Fastener Maximum Load Correction Factors of Titanium Fasteners and Fictitious Material Fitting

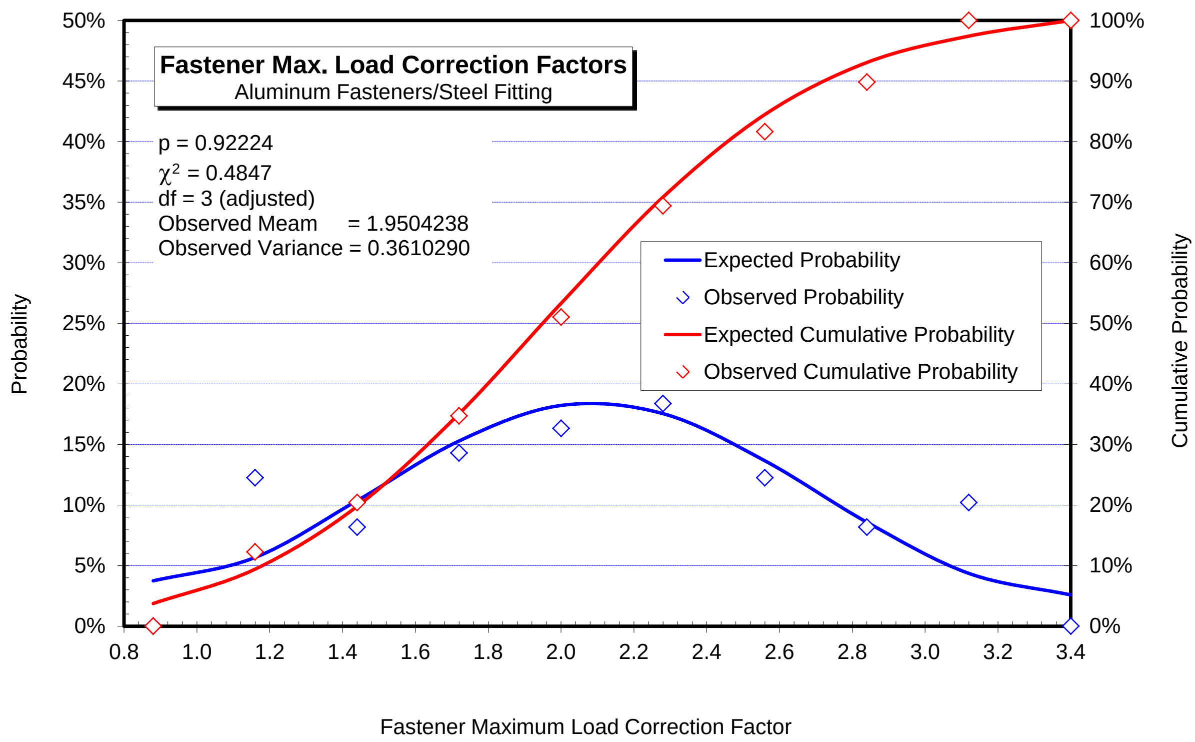

Figure 18: Normal Probability and Cumulative Probability Plots for the Fastener Maximum Load Correction Factors of Aluminum Fasteners and Steel Fitting

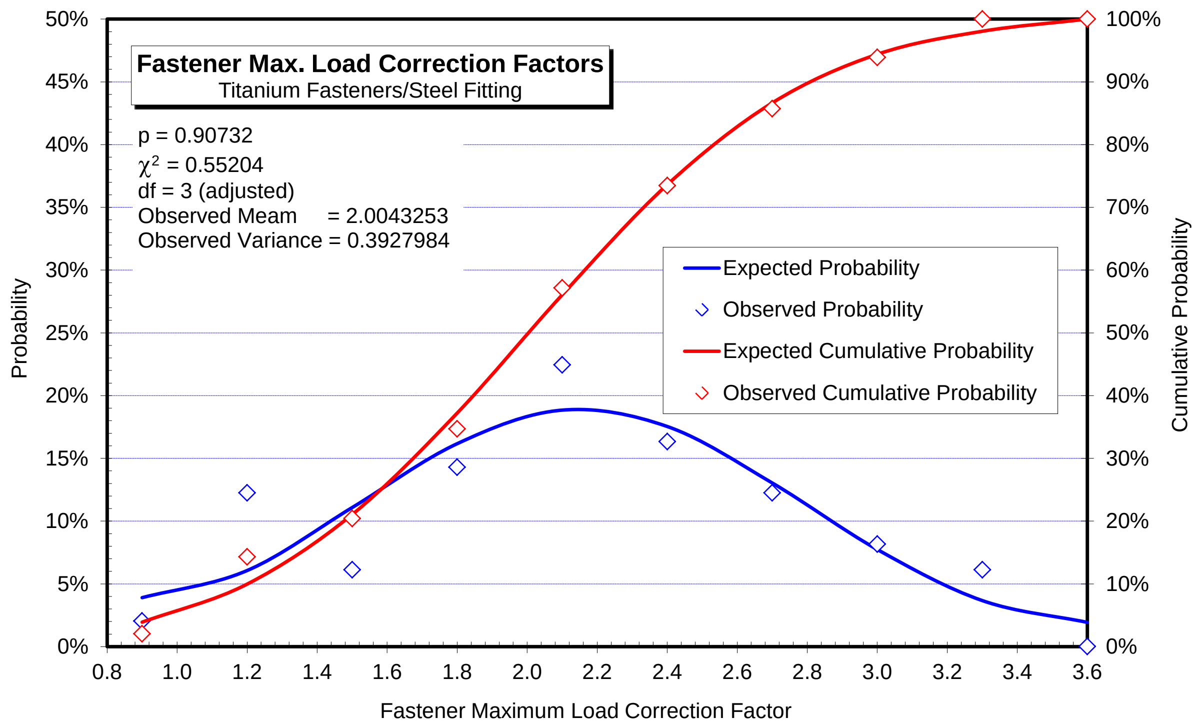

Figure 19: Normal Probability and Cumulative Probability Plots for the Fastener Maximum Load Correction Factors of Titanium Fasteners and Steel Fitting

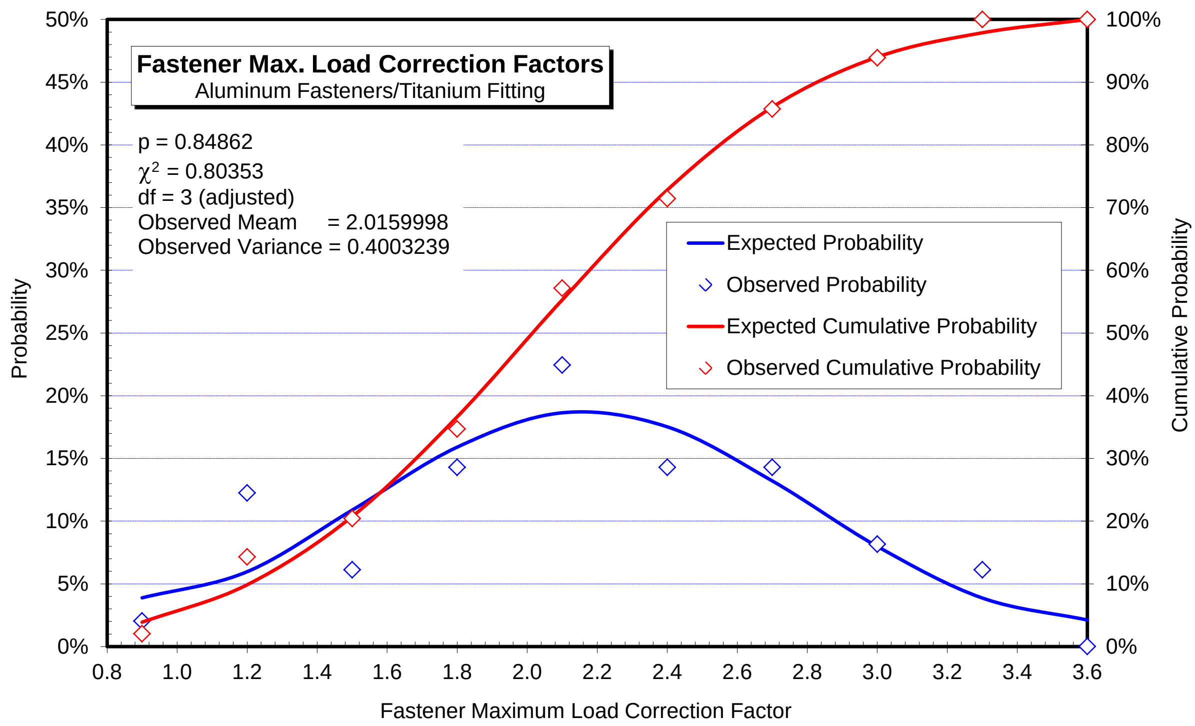

Figure 20: Normal Probability and Cumulative Probability Plots for the Fastener Maximum Load Correction Factors of Aluminum Fasteners and Titanium Fitting

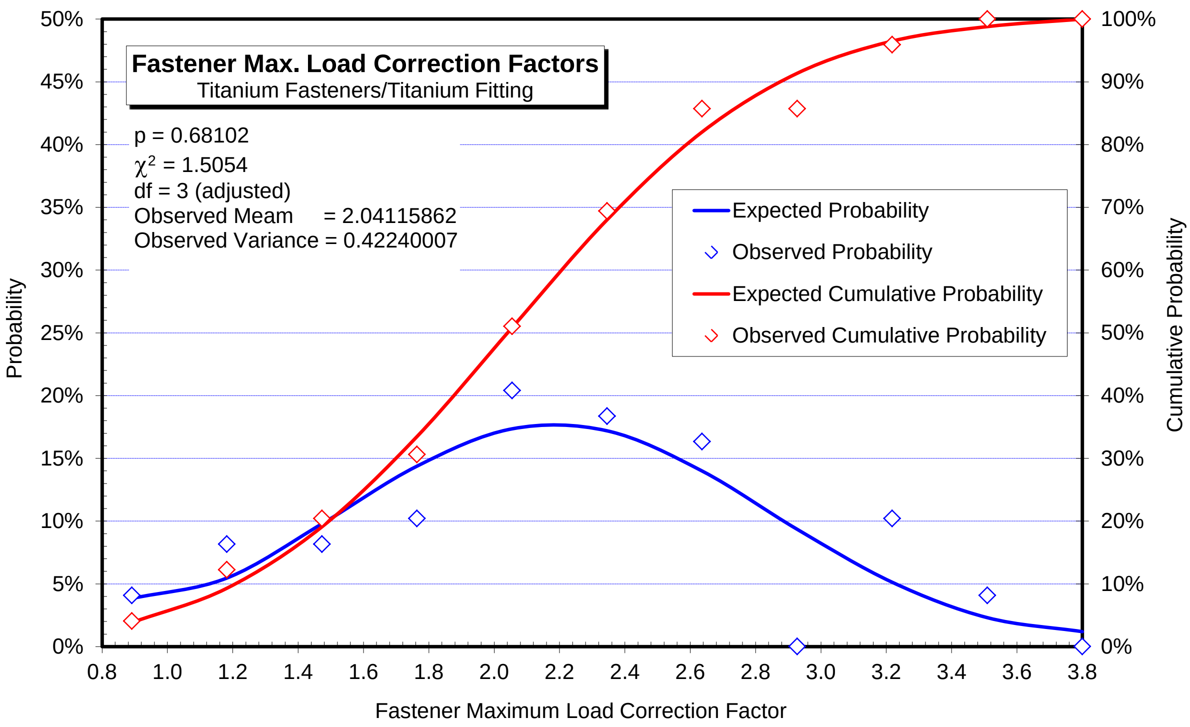

Figure 21: Normal Probability and Cumulative Probability Plots for the Fastener Maximum Load Correction Factors of Titanium Fasteners and Titanium Fitting

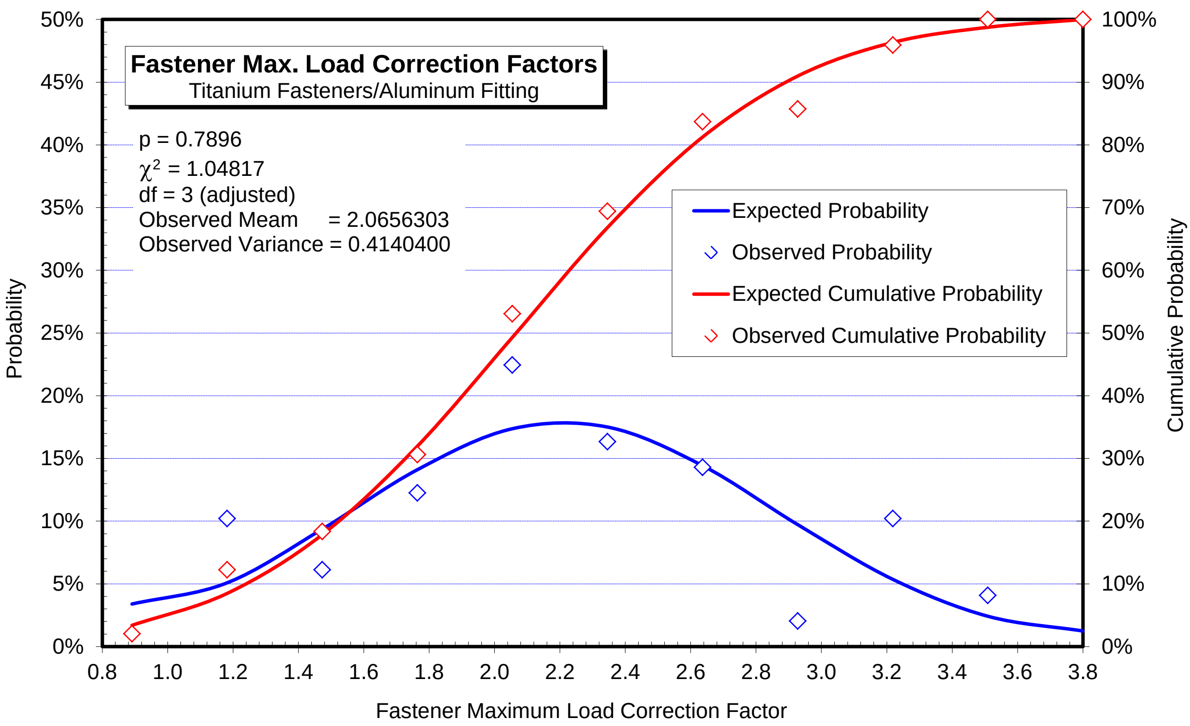

Figure 22: Normal Probability and Cumulative Probability Plots for the Fastener Maximum Load Correction Factors of Titanium Fasteners and Aluminum Fitting

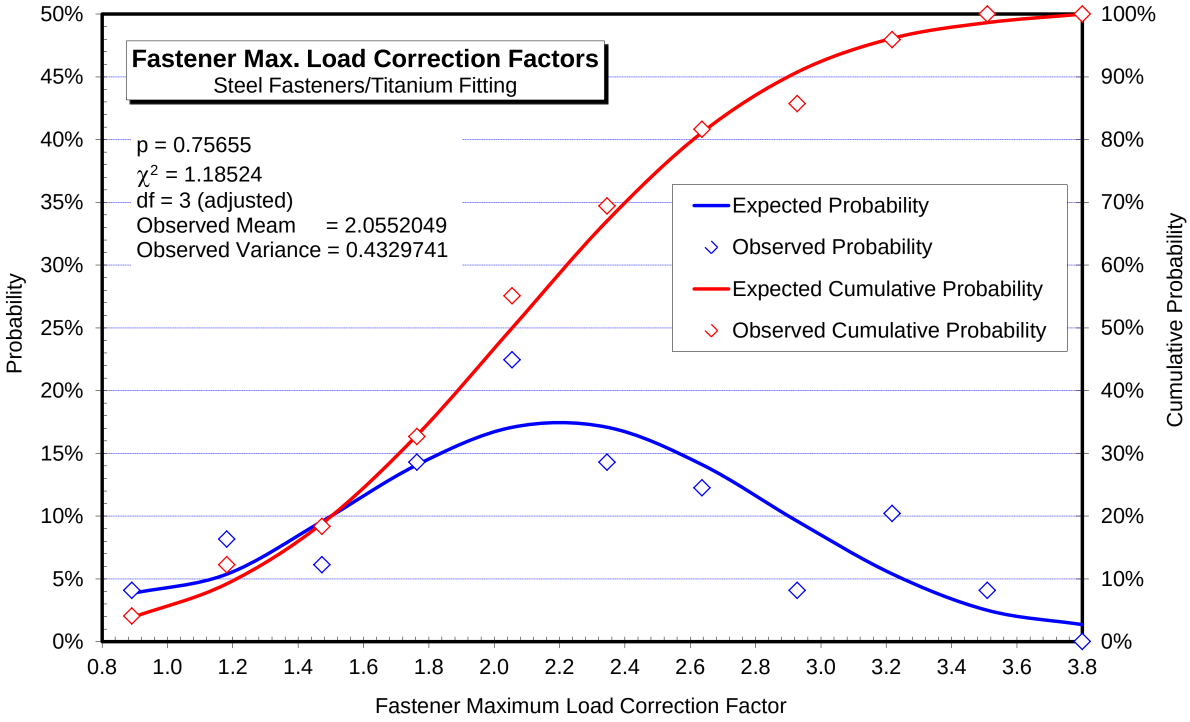

Figure 23: Normal Probability and Cumulative Probability Plots for the Fastener Maximum Load Correction Factors of Steel Fasteners and Titanium Fitting

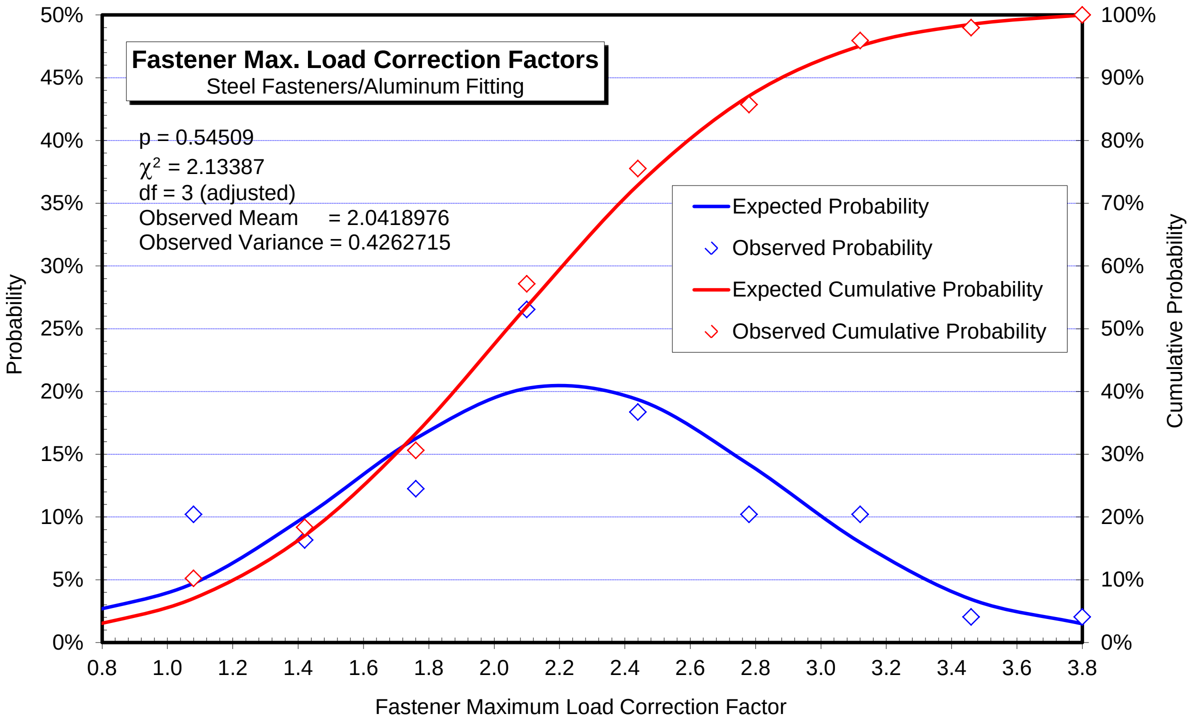

Figure 24: Normal Probability and Cumulative Probability Plots for the Fastener Maximum Load Correction Factors of Aluminum Fasteners and Steel Fitting

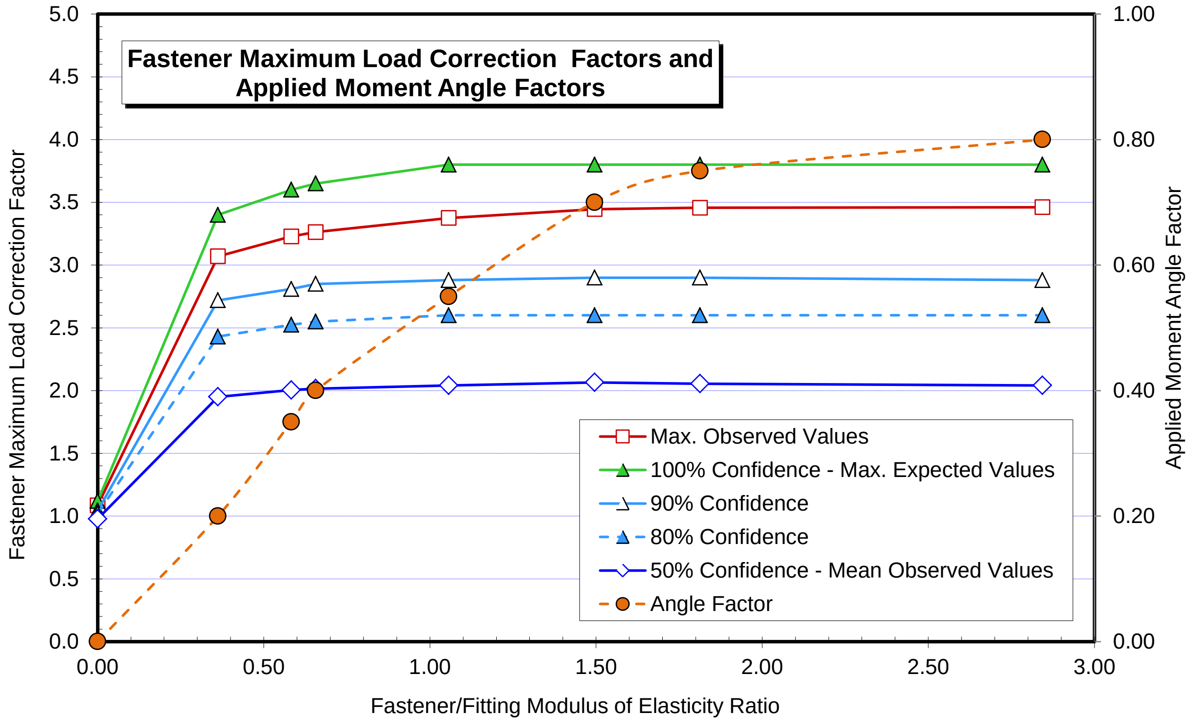

Figure 25: Fastener Maximum Load Correction Factors and Angle Factors versus the Fasteners/Fitting Modulus of Elasticity Ration