12-1998

Reliability Analysis of FRP Composite Columns

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University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Jeremy McNutt entitled "Reliability Analysis of FRP Composite Columns." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Richard Bennett, Major Professor

We have read this thesis and recommend its acceptance:

Karen Chou, Martha Mauldon

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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and recommend its acceptance:

Karen C. Chou

Matthew Mench

Accepted for the Council:

Anne Mayhew

Associate Vice Chancellor and
Dean of The Graduate School

Reliability Analysis of FRP Composite Columns

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Jeremy Allen McNutt

December 1998

Acknowledgment

I would like to thank Dr. Richard Bennett for his help, guidance, and patience in the completion of this thesis. Dr. Bennett has been an excellent friend and mentor during my graduate career. I would also like to thank Dr. Chou and Dr. Mauldon for reviewing this thesis and for sitting on my defense committee.

I would like to thank my father, Ron McNutt, who has provided constant financial and emotional support throughout my life. I would also like to thank my sister Jaime, who has always put up with me. I feel very lucky to have a father and a family of such high caliber.

Most of all I would like to thank my wife, Dana, without her love and support I would not be the person I am today.

Abstract

Many companies are producing fiber reinforced polymeric structural shapes. At this time there has not been enough research performed to establish a load and resistance factor design approach. This thesis utilizes the work of Dr. Abdul-Hamid Zureick and his graduate students on concentrically loaded doubly symmetric fiber reinforced polymeric columns to develop the factors needed to implement a load and resistance factor design based design approach. This includes the selection of the target reliability index, the determination of the statistical properties of the material, the model error, and the development of the resistance factors used in design.

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Chapter 1

Introduction

1.1 FRP Composites

A composite is defined as a matrix of polymeric material, such as resin, reinforced most of the time by fibers. Composites have many distinct advantages over other materials when used in structural engineering applications. Some of these advantages are durability, long life-cycles, high strength to weight ratios, corrosion resistance, neutral buoyancy, and non-conductivity. Composites are beginning to move from the defense market into the infrastructure market.

Many companies around the world are producing fiber reinforced polymeric (FRP) structural shapes. One of the main manufacturing processes used to produce these shapes is the pultrusion process. The pultrusion process is used to mold parts with constant cross sections such as most common structural profiles. The first step in the pultrusion process is the pulling of a continuous roving or strand through a resin bath. The strand is then pulled through a heated die which controls the shape and resin to reinforcement ratio. Finally the strand is pulled through an oven to cure the resin and then cut to length.

Composites are currently successfully being used in offshore oil rigs where their neutral buoyancy and corrosion resistance give them a distinct advantage over other common structural materials. They are also being used to build light weight strong bridge decks which have reduced transportation and erection costs considerably. Another successful application has been in the repair and retrofit of existing structures. In the

above applications, as well as many others, the high initial cost of composite materials is outweighed by the many other advantages and long term savings.

1.2 Design Code

Currently there is no universally recognized design code for composite design. An outline for the code has been developed (Chambers, 1997) but more research is required before the code can be completed. The code will be written in the Load and Resistance Factor Design (LRFD) format.

LRFD was developed to estimate the loads applied to the structure as well as the capacity of the structure. LRFD defines the limit state as the point where the structure no longer performs adequately under the design requirements. In LRFD design the probability of exceeding the limit state is equal to or less than a certain predetermined amount.

To develop the code, information is needed on the design loads. Resistance factors, elastic properties, and reference resistances are also needed (Chambers, 1997). The reference resistance is the nominal resistance used in design. The reference resistance is usually less than the mean value. ASCE 7-95 can be used for the design loads. There is still a need for research on the resistance factors, elastic properties, and the reference resistance.

1.3 Objective

The objective of this paper is to develop the factors needed to implement an LRFD based design approach. The study is limited to concentrically loaded doubly symmetric

columns. This includes the selection of a target reliability index, the determination of the statistical properties of the material (stiffness and strength), the model error, and the development of the resistance factors used in design.

1.4 Collaboration

The reliability analyses, which form the basis of this thesis, utilize the work of Dr. Abdul-Hamid Zureick, currently at the Georgia Institute of Technology. Dr. Zureick and his graduate students performed all tests and assembled the data which this thesis was based on. Dr. Zureick also performed the engineering mechanics analysis to develop the design equations. This thesis covers the statistical and reliability analysis necessary to develop a resistance factor for design. Together with Dr. Zureick's work the basis for an LRFD code is developed.

1.5 Description

This paper is divided into three main sections. These sections are material properties, reliability analysis, and conclusions. The material property section deals with the test specimen width and location, and the data distribution. The reliability analysis section describes the selection of the target reliability index and describes in detail the calculation of the resistance factors. The conclusion presents the results obtained from the analysis.

Chapter 2

Material Properties

Material properties are required to perform a reliability analysis. The material properties are affected by many factors. One of the main factors affecting material properties is the specimen width (Zureick and Wang, 1994). Another factor affecting the material properties is the specimen location (Zureick and Wang, 1994). A consistent basis needs to be established for obtaining the material properties of FRP composite members. The study of the material properties consists of an examination of three elements. These elements are specimen width, specimen location, and data distribution. This chapter describes in detail the work done on each of these elements.

2.1 Specimen Width

The size of the specimen is very important. A large specimen size would cause testing difficulty. A small specimen size would not be representative of the member. The FRP member is only homogenous on a macroscopic scale. The determination of specimen width was carried out using three methods. First ASTM specifications were consulted so that comparisons could be made with the testing methods of other materials. The next two methods involved analytical studies. The first of these studies was an analysis of the bounds on mean strength for deterministic distribution with random sampling. The second analysis was performed using a Poisson process model.

ASTM specifications for wood, steel, plastic, fabrics, concrete, and glass were consulted in an attempt to find similar tests to use as a comparison. The most interesting and meaningful comparison was with the fabric tests. The specification for testing wool fibers (ASTM, D1294-94) and textile fabrics (ASTM, D5035-90) both specified a 1 inch width. This comparison is the most meaningful because FRP pultruded shapes are essentially fabrics encased in resin. It was also thought that a comparison with wood testing, specifically the requirements relating to growth rings, would be meaningful. Unfortunately no data on this subject could be found. The specification for testing concrete states that the diameter of the test cylinder should be at least three times the nominal maximum size of the coarse aggregate (ASTM, C39-93a). Concrete is also similar to FRP shapes because a comparison can be made between the aggregate in the concrete and the fibers in the FRP shapes. This implies that the width of a FRP test specimen should be three times the size of the fiber bundles.

An analytical study to determine the bounds on the mean strength for deterministic distribution of fiber reinforcement widths with random sampling was also performed. To do this analysis it was assumed that the pattern repetition width in the FRP beam was defined as having a length L. The pattern repetition width is the width over which the fiber reinforcement pattern repeats itself. This pattern is assumed to be constant throughout the cross section. This length was divided into two sections each with a length of L/2. The sections will be defined as sections A and B. It is assumed that one section, section A, will contain a significantly larger number of fibers than the other, section B.

These sections are illustrated in Figure 1. The mean strength of section A can be defined as some factor (greater than one) multiplied by the mean strength of B. A plot can be made which illustrates the effect of specimen width, in terms of L, on the upper and lower bounds of mean strength. As the width increases the distance between the upper and lower bound of the strength is reduced. This effect is illustrated in Figures 2 and 3. Figure 2 assumes that the mean strength of A is twice the mean strength of B. Figure 3 assumes that the mean strength of A is four times the mean strength of B. Figure 2 illustrates that if the width is at least three L, then the maximum error in the measured mean strength is approximately 8%. Figure 3 illustrates that if the width is at least three L, then the maximum error in the measured mean strength is approximately 10%.

The data were also analyzed using a Poisson process model as described in Ang and Tang (1975). This model assumes that the occurrence of fiber reinforcement bundles is random, following a Poisson process. Specimen width values were used in place of the typical time values in the model. The mean rate of fiber occurrences is defined as ν. The width of the specimen is defined as L. The mean number of fiber occurrences in the spacing is νL. For the Poisson process, the standard deviation is the square root of the mean.

$$s = \sqrt{\nu L}\ .$$

The coefficient of variation, COV, is the standard deviation divided by the mean. For the Poisson process the coefficient of variation is

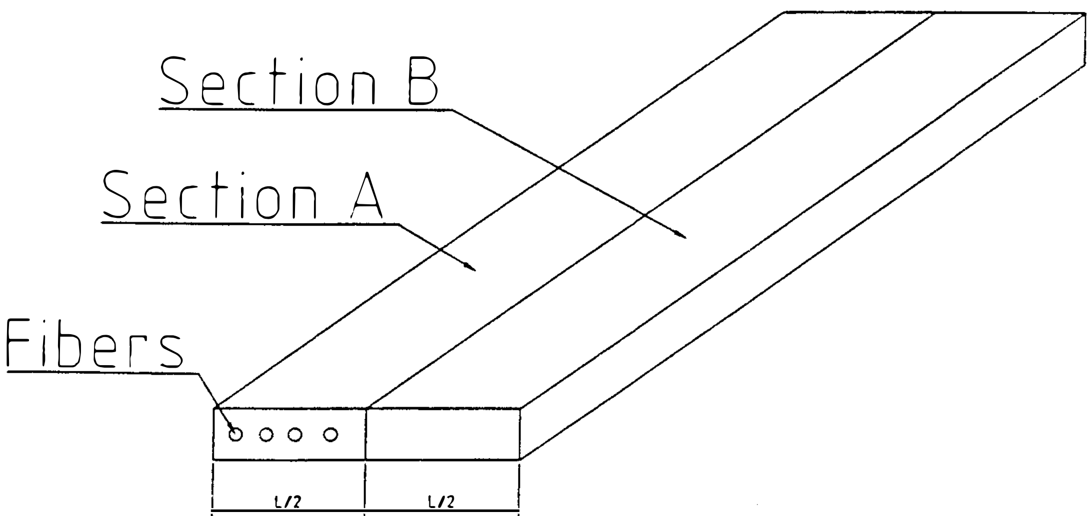

Figure 1
FRP with two sections, one containing a significantly higher number of fibers than the other

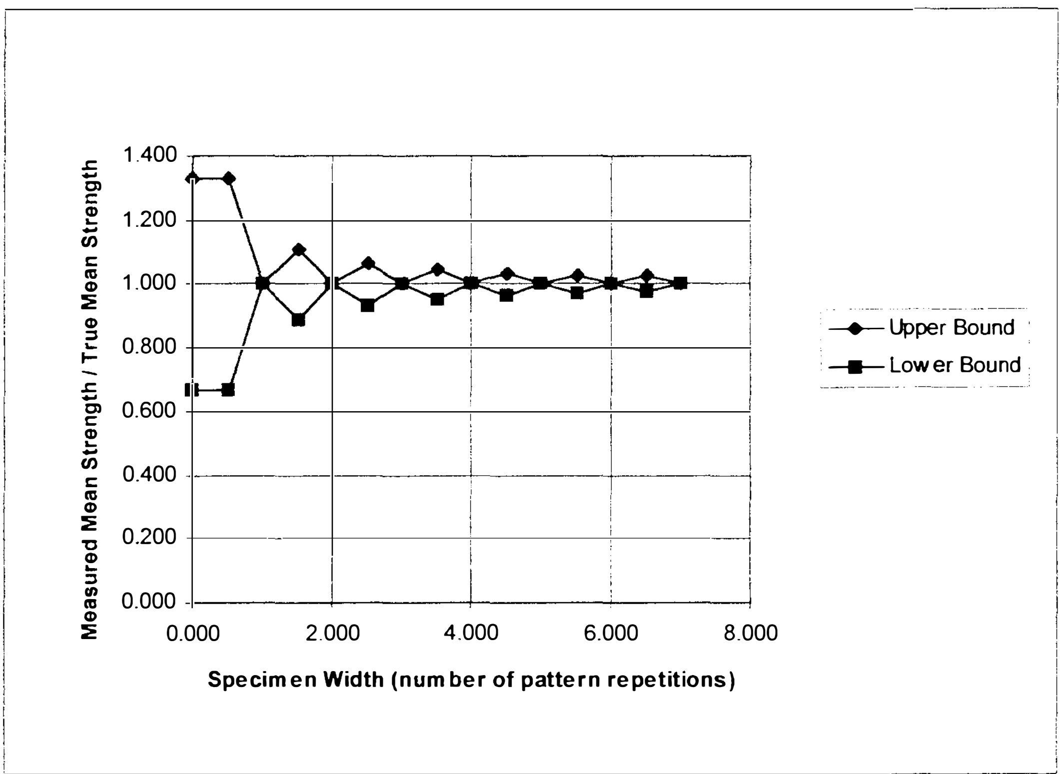

Figure 2
Bounds on mean strength with section A having twice the mean strength of section B

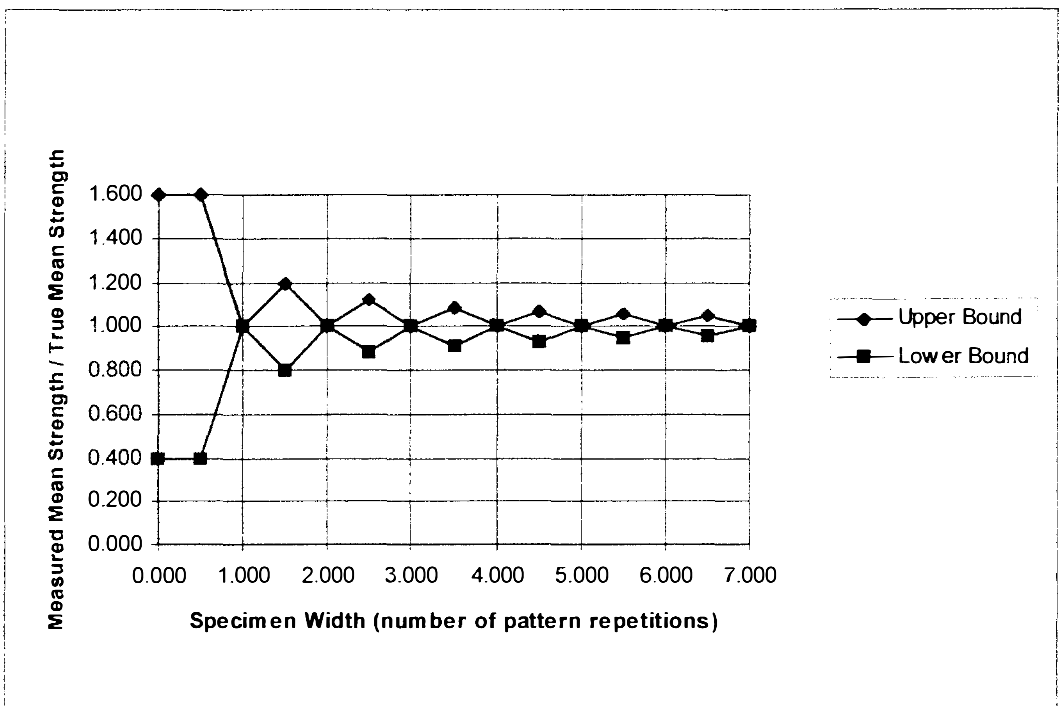

Figure 3
Bounds on mean strength with section A having four times the mean strength of section B

$$COV = \frac{1}{\sqrt{\nu L}}.$$

Using this method a plot can be made of the coefficient of variation of the number of occurrences versus the mean rate times the width. This plot shows that as the mean rate times the width is increased the coefficient of variation decreases. The plot is included as Figure 4. This plot shows that with νL equal to three, the coefficient of variation is approximately 0.6. This value is fairly large but the reduction in the coefficient of variation with increasing width beyond $\nu L = 3$ is rather slow.

As the width of the specimen increases, the variation in the results decreases. This makes sense intuitively and is confirmed by the above calculations. When considering established tests of similar materials as well as the above analysis results, a specimen width of 1 inch seems to be appropriate and is recommended. If a width of 1 inch does not contain at least three fiber bundles then a larger width which includes three bundles should be used. This recommendation is supported by the Poisson model, the bounds on mean strength analyses, and the comparison to other materials.

2.2 Specimen Location

Zureick (1998) presented the following conclusions on specimen location:

1. The average strength of all flanges are not significantly different.

2. The average strength of the flanges along the length of the member are not significantly different.

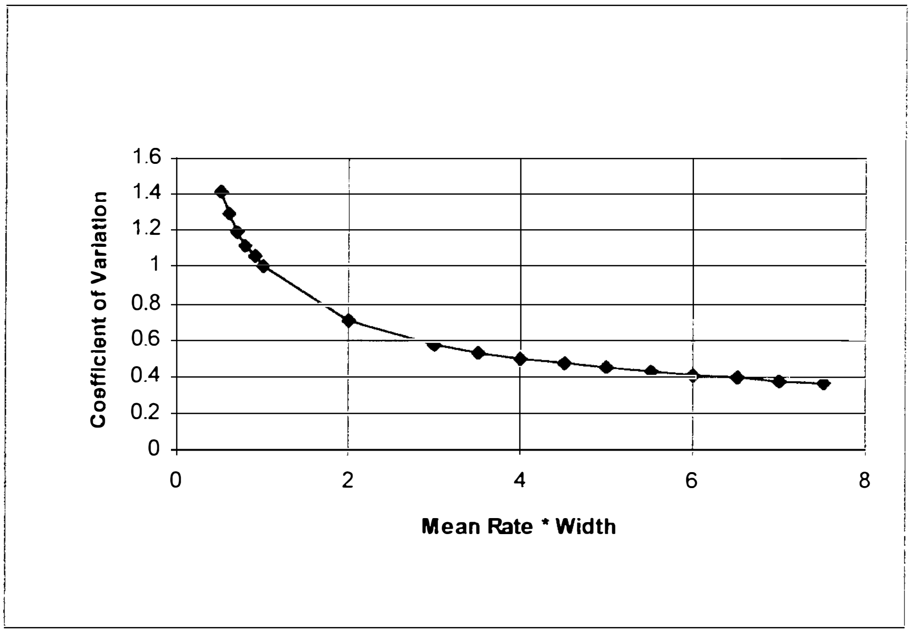

Figure 4
Coefficient of variation of number of occurrences of fiber bundles using the Poisson process model

3. The coupon strength within a flange varies from the tip to the flange web junction, with the strength increased from tip to web junction.

4. The strength between the top and bottom half of the web is not significantly different.

5. The average strength of the web is not significantly different along the length of the member.

6. The strength across the web from centroid to flange junction differs significantly, with the web strongest at the center.

7. The average strength between the flange and the web is not significantly different.

Zureick concluded that an arbitrary coupon cut from the beam will not necessarily give an accurate representation of the beam's behavior.

Two approaches were taken in the determination of specimen location. First, comparisons were made with other materials using the ASTM specifications. A correlation coefficient was also developed between locations.

Very little data on specimen location could be found in the ASTM standards. The fabric (ASTM, D4964-94), steel (ASTM, A370-92), and concrete (ASTM, C39-93A) specifications all had references to specimen orientation. These stated that the specimen should be either parallel or perpendicular to the long direction, depending on the specific test. Some comparisons can be made to the concrete specification which states that the specimens can contain no cracked, spalled, undercut, or otherwise damaged concrete. The specification also states that the sample can contain no reinforcing steel. The steel code also states that the specimens should not be taken from the edge of the member.

Galambos and Ravindra (1978) stated that in structural steel "mill test samples are taken from the webs of rolled shapes, and the yield stresses of the thicker flange is usually smaller". From these requirements it can be concluded that a specimen from a FRP composite beam should not be taken from the edge and the resin should be undamaged. No more specific recommendation on this subject can be made based solely on a comparison with other materials.

A correlation coefficient matrix was developed which compared different locations in the flange and web. The data used consisted of strength values from Zureick (1998). Coupon locations are illustrated in Figure 5. There were 24 values each for coupons 1, 2, and 3. There were 12 values each for coupons 4, 5, and 6. The first matrix compares values from coupons 1, 2, and 3 which are from each side of the top and bottom flanges. The second matrix compares values taken from coupons 4, 5, and 6 which are from different parts of the web.

The first step in developing the matrices was to calculate the mean, unbiased variance, and unbiased standard deviation of the data for each coupon. The equations used are the same as those listed below when describing the process of fitting the data. The correlation coefficient, $\hat{\rho}$, was then found using these values. The correlation coefficient was found using the following equation in which n is the number of samples and an overbar indicates the mean.

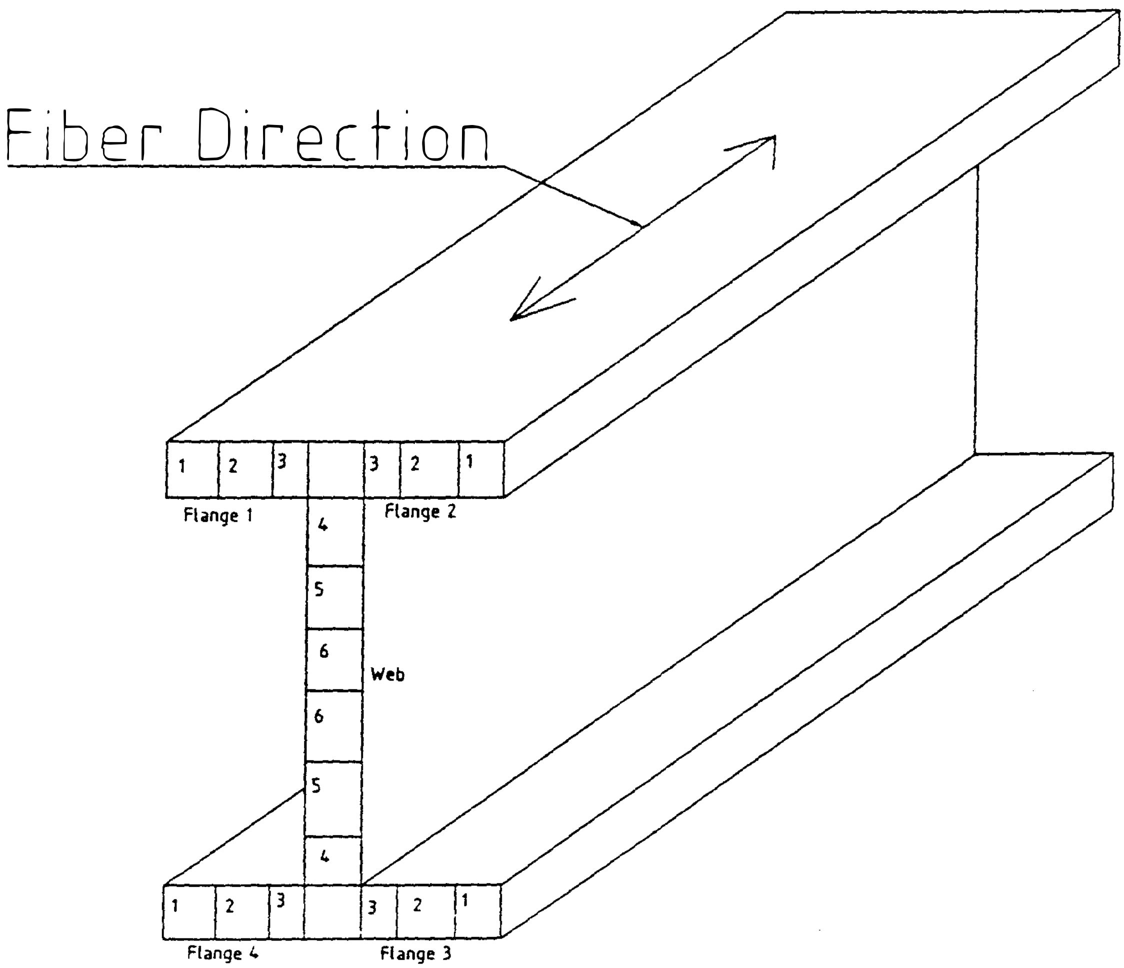

Figure 5
Coupon locations

$$\hat{\rho} = \left(\frac{1}{n-1}\right)\left(\frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{s_x s_y}\right)$$

Values of correlation coefficients are tabulated in Table 1. As illustrated in Figure 5, each location in the flange had four values while each location in the web had only two values. Therefore no correlation coefficients were calculated between the flange and web values. Excluding the value between 5 and 6, all the values are small indicating very little linear dependence. Thus sampling from one location, such as the web or flange, does not give information on other locations.

Therefore samples are needed from locations throughout the cross-section of the member to determine representative material properties.

2.3 Distribution of Data

The probabilistic distribution of the data was needed for the reliability analysis. To determine the distribution of the data the methods outlined in the military handbook (DOD, 1997) were used. This analysis was done using a Microsoft Excel Spreadsheet. The initial setup and the test for each distribution type is described below. Also, correlation coefficients were developed between the strength and modulus values. The data consisted of strength and modulus values, as well as the following properties: Etl - modulus in tension, Ftl - strength in tension, Ecl - modulus in compression, Fcl - strength in compression, GLT - shear modulus, and Fv - shear strength. Data was taken from Zureick and Scott (1997) and Zureick (1998).

Table 1
Correlation coefficients between strength values of coupons

	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6
Location 1	1.000	-0.218	-0.257			
Location 2	-0.218	1.000	-0.173			
Location 3	-0.257	-0.173	1.000			
Location 4				1.000	0.103	-0.088
Location 5				0.103	1.000	-0.571
Location 6				-0.088	-0.571	1.000

First the values were input and sorted in ascending order. Then the mean was found using the equation

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

where x_i = ith value and n = number of values being tested. Next the unbiased variance was found using the equation

$$s^2 = \left(\frac{1}{n-1}\right)\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 .$$

The unbiased standard deviation s was found by taking the square root of the unbiased variance. The coefficient of variation in percent was found by using the following equation.

$$COV = \left(\frac{s}{\bar{x}}\right)(100)$$

After the above values were found the data were tested for outliers. This was done by finding the maximum normal residual, MNR, which is defined as

$$MNR = \max\left(x_i - \bar{x}\right).$$

The MNR was compared to the MNR critical value for the given number of data points which was tabulated in the military handbook. If the MNR was less than the critical value then no outliers were detected. If the MNR was greater than the critical value then the corresponding data value was removed and the test was repeated until no outliers were found. The above values for each data set are tabulated in Table 2.

Table 2
Summary of general statistical values

					Unbiased	Unbiased				
Cross Section	Spec. #	Property	N	Mean	Variance	Std. Dev.	COV	MNR	Critical Value	Outlier?
Wide Flange 102x6.4 mm	VG1-6	Etl (GPa)	30	21.0	2.03	1.43	6.78	1.95	2.908	No
		Ftl (MPa)	30	285	442	21.0	7.37	2.65	2.908	No
		Ecl (GPa)	30	21.0	1.30	1.14	5.43	1.96	2.908	No
		Fcl (MPa)	30	326	572	23.9	7.35	2.61	2.908	No
Wide Flange 152x9.6 mm	VG7-12	Etl (GPa)	30	17.1	2.69	1.64	9.57	2.65	2.908	No
		Ftl (MPa)	30	182	565	23.8	13.0	1.80	2.908	No
		Ecl (GPa)	30	17.8	2.41	1.55	8.71	2.02	2.908	No
		Fcl (MPa)	30	315	856	29.3	9.30	2.16	2.908	No
Box 76x6.4 mm	VG13-18	Etl (GPa)	24	29.0	11.3	3.37	11.6	1.65	2.802	No
		Ftl (MPa)	24	460	2210	47.0	10.2	1.82	2.802	No
		Ecl (GPa)	24	27.7	13.5	3.67	13.3	1.689	2.802	No
		Fcl (MPa)	24	343	1530	39.1	11.4	1.94	2.802	No
Box 102x6.4 mm	VG19-24	Etl (GPa)	24	27.2	1.60	1.27	4.65	1.80	2.802	No
		Ftl (MPa)	24	331	653	25.6	7.72	2.54	2.802	No
		Ecl (GPa)	23	26.5	1.13	1.06	4.02	2.23	2.780	Yes
		Fcl (MPa)	24	371	1570	39.6	10.7	2.05	2.802	No
		GLT (GPa)	24	4.37	0.244	0.494	11.3	2.33	2.802	No
		Fv (MPa)	24	73.8	28.0	5.29	7.17	2.54	2.802	No
Strength Values (MPa)			108	293.48	1652.7	40.654	13.85	3.030	3.410	No
Modulus Values (GPa)			96	17.286	6.617	2.572	14.88	3.052	3.370	No

The data were taken from Zureick and Scott (1997) and Zureick (1998), all of the data were combined (flange and web values). Data used for Table 1 is also used in the following statistical analyses. The procedure followed is directly from the Military Handbook (DOD, 1997). The Military Handbook required that the first test performed on the data was the test for the Weibull distribution. The first step in this test was to find the shape parameter, $\hat{\beta}$, and the scale parameter, $\hat{\alpha}$. The following equation was used to solve for the shape parameter using trial and error.

$$\left(\frac{n}{\hat{\beta}}\right) + \sum_{i=1}^{n} \ln(x_i) - \left(\frac{n}{\sum_{i=1}^{n} x_i^{\hat{\beta}}}\right)\left(\sum_{i=1}^{n} x_i^{\hat{\beta}} \ln x_i\right) = 0$$

After the shape parameter was determined the scale parameter was determined using the following equation.

$$\hat{\alpha} = \left(\frac{\sum_{i=1}^{n} x_i^{\hat{\beta}}}{n}\right)^{\frac{1}{\hat{\beta}}}$$

The Anderson Darling test statistic (DOD, 1997), AD, was then computed using the following equation.

$$AD = \sum_{i=1}^{n} \frac{1-2i}{n} \left\{\ln\left[1-\exp(-z_i)\right] - z_{(n+1-i)}\right\} - n$$

where

$$z_i = \left(\frac{x_i}{\hat{\alpha}}\right)^{\hat{\beta}}$$

Next the observed significance level was calculated using the following equation.

$$OSL = \frac{1}{\left\{1 + \exp\left[-.10 + 1.24\ln\left(AD^*\right) + 4.548AD^*\right]\right\}}$$

where

$$AD^* = \left(1 + \frac{.2}{\sqrt{n}}\right)AD$$

If the observed significance level was greater than 0.05, the data fit the Weibull distribution. The above values are tabulated in Table 3.

If the observed significance level was less than 0.05, the data did not fit the Weibull distribution and were tested for the normal distribution. The Anderson Darling test statistic was calculated using the following equation

$$AD = \sum_{i=1}^{n} \frac{1-2i}{n}\left\{\ln\left[F_o(z_i)\right] + \ln\left[1 - F_o(z_{n+1-i})\right]\right\} - n$$

where

$$z_i = \frac{x_i - \bar{x}}{s}$$

and F_o represents the standard normal cumulative distribution function.

The observed significance level was then calculated using the following equation.

$$OSL = \frac{1}{\left\{1 + \exp\left[-.48 + .78\ln\left(AD^*\right) + 4.548AD^*\right]\right\}}$$

Table 3
Summary of values from Weibull test

Cross Section	Spec. #	Property	Shape Parameter	Scale Parameter	AD	AD*	OSL	Weibul?
Wide Flange 102x6.4 mm	VG1-6	Etl (GPa)	16.070	21.677	0.511	0.530	0.179	Yes
		Ftl (MPa)	13.062	295.347	1.004	1.041	0.009	No
		Ecl (GPa)	20.065	21.507	0.537	0.557	0.154	Yes
		Fcl (MPa)	12.795	337.225	1.379	1.429	0.001	No
Wide Flange 152x9.6 mm	VG7-12	Etl (GPa)	15.466	17.802	0.859	0.890	0.022	No
		Ftl (MPa)	8.815	192.649	0.419	0.434	0.302	Yes
		Ecl (GPa)	15.460	18.491	0.714	0.740	0.053	Yes
		Fcl (MPa)	11.509	328.026	0.482	0.499	0.213	Yes
Box 76x6.4 mm	VG13-18	Etl (GPa)	10.195	30.523	0.978	1.018	0.010	No
		Ftl (MPa)	11.111	481.325	0.555	0.578	0.136	Yes
		Ecl (GPa)	8.578	29.309	0.985	1.025	0.010	No
		Fcl (MPa)	9.648	360.696	0.627	0.652	0.088	Yes
Box 102x6.4 mm	VG19-24	Etl (GPa)	23.120	27.830	0.511	0.532	0.177	Yes
		Ftl (MPa)	12.462	343.195	1.014	1.055	0.008	No
		Ecl (GPa)	31.350	26.948	0.418	0.436	0.299	Yes
		Fcl (MPa)	10.305	388.337	0.329	0.342	0.469	Yes
		GLT (GPa)	9.165	4.590	0.676	0.704	0.065	Yes
		Fv (MPa)	18.265	76.012	0.306	0.319	0.517	Yes
Strength Values (MPa)			8.313	310.615	0.252	0.257	0.649	Yes
Modulus Values (GPa)			7.758	18.366	41.006	41.843	0.000	No

where

$$AD^* = \left[1 + \frac{4}{n} - \frac{25}{n^2}\right] AD$$

If the observed significance level was greater than 0.05, the data fit the normal distribution. The above values are tabulated in Table 4.

If the observed significance level was less than 0.05, the data did not fit the normal distribution and were tested for the lognormal distribution. The Anderson Darling test statistic was calculated using the following equation.

$$AD = \sum_{i=1}^{n} \frac{1-2i}{n} \left\{ \ln\left[F_0(z_i)\right] + \ln\left[1 - F_o(z_{n+1-i})\right] \right\} - n$$

where

$$z_i = \frac{\ln(x_i) - \bar{x}_L}{s_L}$$

and F_o represents the standard normal cumulative distribution function.

The observed significance level was then calculated using the following equation.

$$OSL = \frac{1}{\left\{1 + \exp\left[-.48 + .78\ln(AD^*) + 4.58AD^*\right]\right\}}$$

where

$$AD^* = \left[1 + \frac{4}{n} - \frac{25}{n^2}\right] AD$$

Table 4
Summary of values from normal test

Cross Section	Spec. #	Property	AD	AD*	OSL	Normal?
Wide Flange 102x6.4 mm	VG1-6	Etl (GPa)				
		Ftl (MPa)	23.419	27.192	0.000	No
		Ecl (GPa)				
		Fcl (MPa)	23.680	27.495	0.000	No
Wide Flange 152x9.6 mm	VG7-12	Etl (GPa)	24.386	28.315	0.000	No
		Ftl (MPa)				
		Ecl (GPa)				
		Fcl (MPa)				
Box 76x6.4 mm	VG13-18	Etl (GPa)	19.997	24.198	0.000	No
		Ftl (MPa)				
		Ecl (GPa)	19.900	24.080	0.000	No
		Fcl (MPa)				
Box 102x6.4 mm	VG19-24	Etl (GPa)				
		Ftl (MPa)	18.830	22.786	0.000	No
		Ecl (GPa)				
		Fcl (MPa)				
		GLT (GPa)				
		Fv (MPa)				
Strength Values (MPa)						
Modulus Values (GPa)			0.334	0.348	0.427	Yes

If the observed significance level was greater than 0.05, the data fit the lognormal distribution. If the observed significance level was less than 0.05, the data did not fit the lognormal distribution and no further tests were performed. The data were then classified as fitting no distributions. The above values are tabulated in Table 5.

The statistical analyses showed that most of the data fit the Weibull distribution. Seven out of ten strength values fit the Weibull distribution. Six out of ten stiffness values fit the Weibull distribution.

A set of strength and modulus values were also taken from Zureick (1998). A correlation coefficient was calculated between these two sets of data. The correlation coefficient between the strength and modulus values was calculated to be 0.91 and is tabulated in Table 6 along with the other statistical properties of the data.

Correlation coefficients were also calculated between the following properties for each section: Etl, Ftl, Ecl, Fcl, GLT, and Fv. These properties were defined earlier. The values are tabulated in Tables 7 and 8.

There was a high correlation between Etl and Ftl and between Ecl and Fcl. This means that there is a high correlation between strength and stiffness in a given direction. The correlation was also high between Etl and Ecl which means that there is a high correlation between stiffness in tension and compression. The correlation was not near as high between Ftl and Fcl which means that that there is not a high correlation between strength in tension and compression.

Table 5
Summary of values from lognormal test

Cross Section	Spec. #	Property	AD	AD*	OSL	Lognormal?
Wide Flange 102x6.4 mm	VG1-6	Etl (GPa)				
		Ftl (MPa)	0.475	0.551	0.171	Yes
		Ecl (GPa)				
		Fcl (MPa)	0.518	0.601	0.133	Yes
Wide Flange 152x9.6 mm	VG7-12	Etl (GPa)	1.756	2.039	0.000	No
		Ftl (MPa)				
		Ecl (GPa)				
		Fcl (MPa)				
Box 76x6.4 mm	VG13-18	Etl (GPa)	0.947	1.146	0.008	No
		Ftl (MPa)				
		Ecl (GPa)	0.900	1.090	0.010	No
		Fcl (MPa)				
Box 102x6.4 mm	VG19-24	Etl (GPa)				
		Ftl (MPa)	0.413	0.500	0.220	Yes
		Ecl (GPa)				
		Fcl (MPa)				
		GLT (GPa)				
		Fv (MPa)				
Strength Values (MPa)						
Modulus Values (GPa)						

Table 6
Correlation coefficient between strength and modulus values

	n	mean	unbiased variance	unbiased standard deviation	correlation coefficient
Strength (ksi)	96	42.450	36.117	6.010	
Modulus (ksi)	96	2507.05	139191	373.08	
					0.91

Table 7
Correlation coefficients between properties

Spec #	EtL vs. FtL	EtL vs. EcL	EtL vs. FcL	Etl vs. GLT	EtL vs. Fv	FtL vs. EcL	FtL vs. FcL	FtL vs. GLT
VG1-6	0.68	0.38	0.36	N. A.	N. A.	0.10	0.21	N. A.
VG7-12	0.77	0.88	0.59	N. A.	N. A.	0.71	-0.19	N. A.
VG13-18	0.73	0.84	0.67	N. A.	N. A.	0.72	0.69	N. A.
VG19-24	0.08	0.56	-0.14	0.17	0.02	0.03	0.29	-0.10

Table 8
Correlation coefficients between properties (continued)

Spec #	FtL vs. Fv	EcL vs. FcL	EcL vs. GLT	EcL vs. Fv	FcL vs. GLT	FcL vs. Fv	GLT vs. Fv
VG1-6	N. A.	0.40	N. A.	N. A.	N. A.	N. A.	N. A.
VG7-12	N. A.	0.73	N. A.	N. A.	N. A.	N. A.	N. A.
VG13-18	N. A.	0.75	N. A.	N. A.	N. A.	N. A.	N. A.
VG19-24	-0.03	0.29	0.08	-0.18	-0.24	-0.06	0.37

Chapter 3

Reliability Calculations

This chapter describes the four main parts of the reliability calculations. First a target reliability index was chosen. Then the reliability index was computed. Next a code format and resistance factor were determined. Finally the results are reported and discussed. Two failure modes are considered for the concentrically loaded columns, buckling and material failure.

3.1 Target Reliability Index

The first step in the reliability calculations was to choose a target reliability index. For the failure mode of buckling, a target reliability index of 3.0 was chosen. Load deformation curves show ductility, or a plateau in the load deformation response (Zureick and Scott, 1997). For a failure mode consisting of material failure a target reliability index of 3.25 was chosen.

Support for these choices comes from many sources. The wood standard (ASTM, D5457-93) uses a reliability index of 2.4 for flexure. It should be noted that the consequences of column failure are generally greater than beam failure, so columns should have a higher reliability index. In a recent paper on the reliability of reinforced concrete columns (Ruiz and Aguilar, 1994) it was shown that in pure compression the reliability index varied between 3.0 and 3.9 depending on the live load to dead load ratio. For pure bending the reliability index ranged from 2.4 to 2.8. Another paper (Israel et al, 1987) showed that the reliability index for reinforced concrete columns was approximately 3.23.

The reliability index for reinforced concrete members was reported to be 3.2 for flexure, 3.0 for shear, and 2.8 for torsion (Ruiz , 1993). In the same paper it was reported that the reliability index approached 4.0 for pure compression, which is really a material failure. Centrally loaded steel columns were reported to have reliability index values of 2.6 to 3.2 for buckling and slenderness ratio greater than 1.5 (NBS, 1980). Centrally loaded steel columns in material failure were reported to have a reliability index of 3.1 to 3.3 for material failure and slenderness ratios less than .5 (NBS, 1980). Also, concrete columns were reported to have reliability indexes of 3.04 for long columns and 3.0 for short columns (NBS, 1980).

After considering the above research 3.0 seems consistent with steel and concrete columns with large eccentricities. A value of 3.25 seems consistent with short column material failure for concrete and steel.

3.2 Computing Reliability Index

In reliability analysis, loads and resistances are assumed to be statistical variables. A mathematical model can be defined using the equation

$$g(X_1, X_2, \dots X_n) = 0$$

where X_i = resistance and load variables such that failure occurs when $g < 0$ for the specific limit state. This model is called the performance function. The reliability index can be visualized by reformulating the above equation in terms of independent normally distributed variables that have zero means and unit standard deviations. In this reduced

coordinate system the reliability index, β, is the shortest distance from the origin to the failure surface (Galambos et al, 1982).

A computer program written by Dr. Richard Bennett was used to calculate the reliability index (Bennett and Koh, 1986). The performance function used for the analysis is the performance function for the axial compressive limit state for doubly symmetric unidirectionally reinforced polymeric members in which the global buckling limit state controls (Zureick and Scott, 1997).

$$g_1 = X_1' \frac{\pi^2 E_L}{\left(\frac{L_{eff}}{r}\right)^2} \frac{1}{1+\left[\frac{n_s \pi^2}{\left(\frac{L_{eff}}{r}\right)^2}\right]\left[\frac{E_L}{G_{LT}}\right]} A_g - D - L$$

in which, X_1' is the model error, E_L is the modulus of elasticity, G_{LT} is the shear modulus, A_g is the gross cross sectional area, $\left(\frac{L_{eff}}{r}\right)$ is the governing effective slenderness ratio about one of the member principal axes, n_s is the shear coefficient, D is the dead load, and L is the live load. It should be noted that the resistance is Euler's buckling load times a shear deformation parameter.

The dead load was assumed to be normally distributed with a ratio of mean to nominal of 1.05 and a coefficient of variation of 0.10 (Ellingwood et al, 1982). The live load was considered to be an extreme type 1 distribution with a mean to nominal ratio of 1.0 and a coefficient of variation of 0.25 (Ellingwood et al, 1982). The value of n_s is

approximately 2 for wide flange shapes and is exactly 2 for box sections. Therefore n_s was taken as 2. The slenderness ratio, $\left(\frac{L_{eff}}{r}\right)$ was taken as deterministic. Statistics for the model error are from tests by Zureick and Scott (1997). For the case of buckling the data from 22 tests were analyzed and a normal distribution with a mean of 0.94 and a standard deviation of 0.039 was determined for the model error (Zureick and Scott 1997).

Results from tests on FRP panels are listed in Table 9 (Tingley et al, 1997). After examining these results along with Zureick's data (Zureick and Scott, 1997) a Weibull distribution with a coefficient of variation of 0.15 was used in the reliability calculations for values of E_L and G_{LT}. These values were used because they appeared to be a reasonable choice for a base value.

All variables are statistically independent except for E_L and G_{LT} for which the correlation coefficient was 0.08. This value is also shown in Table 8. This correlation coefficient was small and assumed to be zero.

The performance function for material failure is

$$g_2 = X_2 F_L^c A_g - D - L$$

where A_g, D, and L are the same as for g_1, X_2 is the model error for material failure, and F_L^c is the compressive strength. For the compression case the model error was assumed to be a normal distribution with a mean of 1.00 and a standard deviation of 0.05.

3.3 Code Format and Determining Resistance Factor

The standard case for design under dead and live loads is suggested to be

Table 9
Values of COV from Tingley et al, 1997

Test	Material	n	Modulus	Strain	Strength
Tension	Aramid	17	0.050	0.131	0.053
	Aramid	131	0.068	0.170	0.056
	Aramid	15	0.129	0.273	0.040
	Carbon-aramid	94	0.080	0.175	0.078
	Carbon-aramid	80	0.120	0.275	0.070
	Carbon-aramid	88	0.126	0.272	0.067
	Fiberglass-aramid	5	0.030	0.055	0.031
Compression	Carbon-aramid	33	0.260	0.378	0.160
	Carbon-aramid	28	0.538	0.689	0.094
	Carbon-aramid	29	0.362	0.603	0.157
Shear	Aramid	6			0.272
	Aramid	46			0.167
	Aramid	5			0.114
	Carbon-aramid	34			0.215
	Carbon-aramid	28			0.177

$$1.2D_n + 1.6L_n \prec j_i R_n \phi .$$

in which D_n = nominal dead load, L_n = nominal live load, and j_i = distribution adjustment factor. The distribution adjustment factor is somewhat analogous to the reliability adjustment factor in the wood code (ASTM, D5457-93). It accounts for different probability distributions and different coefficients of variation of resistance.

The nominal resistance can be based on the B-basis value which can be calculated according to the method outlined in the military handbook (DOD, 1997). The B-basis value is the tenth percentile value.

In the military handbook procedure the first step is to classify the distribution type. If the Weibull distribution can not be rejected then it is assumed for resistance. If it is rejected then the data are tested for the normal distribution. If the normal distribution is rejected then the data are tested for the lognormal distribution.

The B-basis value is defined as the value at which at least 90% of the population is expected to fall with 95% confidence. The B-basis value for the two parameter Weibull distribution is defined as

$$B = \hat{q} \exp\left(\frac{-V}{\hat{\beta}\sqrt{n}} \right)$$

where

$$\hat{q} = \hat{\alpha}(.10536)^{\frac{1}{\hat{\beta}}}$$

and V is the value tabulated in Table 8.5.8 of the Military Handbook corresponding to a sample size n.

The B-basis value for the normal distribution is defined as

$$B = \bar{x} - k_B s$$

where k_B is the appropriate one-sided tolerance-limit factor from table 8.5.10 in the Military Handbook.

The B-basis value for the lognormal distribution is calculated using the equations for the normal distribution. The calculations are performed using the logarithms of the data rather than the original observations. The computed B-basis value must then be transformed back to the original units by applying the inverse of the log transformation which was used. The handbook procedure accounts for inherent variability as well as statistical uncertainty.

The reliability index computer program by Dr. Bennett was used to iteratively solve for the resistance values that would give the desired safety level (Bennett and Koh, 1986). When the mean value of resistance was known, the nominal resistance value was found. For a normal distribution the equation used was

$$\frac{Nominal}{Mean} = 1 - 1.281(COV).$$

For a lognormal distribution the equation used was

$$\frac{Nominal}{Mean} = \exp^{-(.5\xi^2 + 1.281\xi)}$$

where

$$\xi = \sqrt{\ln(1 + (COV)^2}.$$

For a Weibull distribution the equation used was

$$\frac{Nominal}{Mean} = \frac{\left(-\ln(.90)\right)^{\frac{1}{\beta}}}{\Gamma\left(1+\frac{1}{\beta}\right)}$$

where

$$COV = \sqrt{\frac{\Gamma\left(1+\frac{2}{\beta}\right)}{\Gamma^{2}\left(1+\frac{1}{\beta}\right)} - 1}\,.$$

Values used in calculations from the above equations are summarized in Table 10.

There are five random variables in the buckling case. The resistance factor was determined with Ln / Dn = 1.0, and a Weibull distribution and COV of 0.15 for both E_L and G_{LT}. The value of n_s was assumed to be 2 and a slenderness ratio of 40 was used. The slenderness ratio of 40 was chosen since the lower the slenderness ratio, the more effect of the shear modification factor. Forty was considered a lower limit for most practical members. A resistance factor of 0.794 was calculated. Next the value of η_s was assumed to be deterministic and a resistance factor of 0.770 was calculated. Considering the small difference in the above values it was decided that a deterministic value of η_s could be used in the reliability analyses. It should also be noted that the difference in resistance values would decrease with increasing slenderness ratios.

Table 10
Summary of values from resistance calculations

Distribution	COV	Nominal to Mean Ratio	Beta	Zeta
Normal	0.10	1.197		
	0.15	1.328		
	0.20	1.490		
	0.25	1.699		
	0.30	1.974		
	0.40	2.924		
Weibull	0.10	1.224	12.150	
	0.15	1.370	7.910	
	0.20	1.545	5.800	
	0.25	1.756	4.540	
	0.30	2.010	3.710	
	0.40	2.676	2.696	
Lognormal	0.10	1.184		0.100
	0.15	1.292		0.149
	0.20	1.413		0.198
	0.25	1.545		0.246
	0.30	1.692		0.294
	0.40	2.030		0.385

3.4 Results

A plot of the resistance factor versus nominal live load to nominal dead load ratio for a reliability index of 3.0 is included as Figure 6. This corresponds to the buckling failure mode. A plot of resistance factor versus nominal live load to nominal dead load ratio for a reliability index of 3.25 is included as Figure 7. This corresponds to the material failure failure mode. A plot of resistance factor versus coefficient of variation for a reliability index of 3.0 is included as Figure 8, and for a reliability index of 3.25 as Figure 9. Tables 11 and 12 summarize the calculated resistance factors for different coefficient of variations and nominal live to nominal dead load ratios. Table 11 corresponds to a reliability index of 3.0. Table 12 corresponds to a reliability index of 3.25. The tables show that as the COV increases, the resistance factor decreases due to higher uncertainty. The resistance factor also remains reasonably uniform as the load ratio changes. As with other materials, one resistance factor value will be chosen which is not a function of the live to dead load ratio.

High Ln / Dn ratios are anticipated for composite structures. The proposed resistance factors were chosen to account for this. Resistance factors of 0.75 and 0.70 are proposed for buckling and compression failure modes. The distribution adjustment factor is the required resistance factor divided by 0.75 or 0.70, depending on failure mode. The distribution adjustment factors are summarized for reliability indexes of 3.0 and 3.25 in Tables 13 and 14. One combined preliminary table is proposed which takes into account

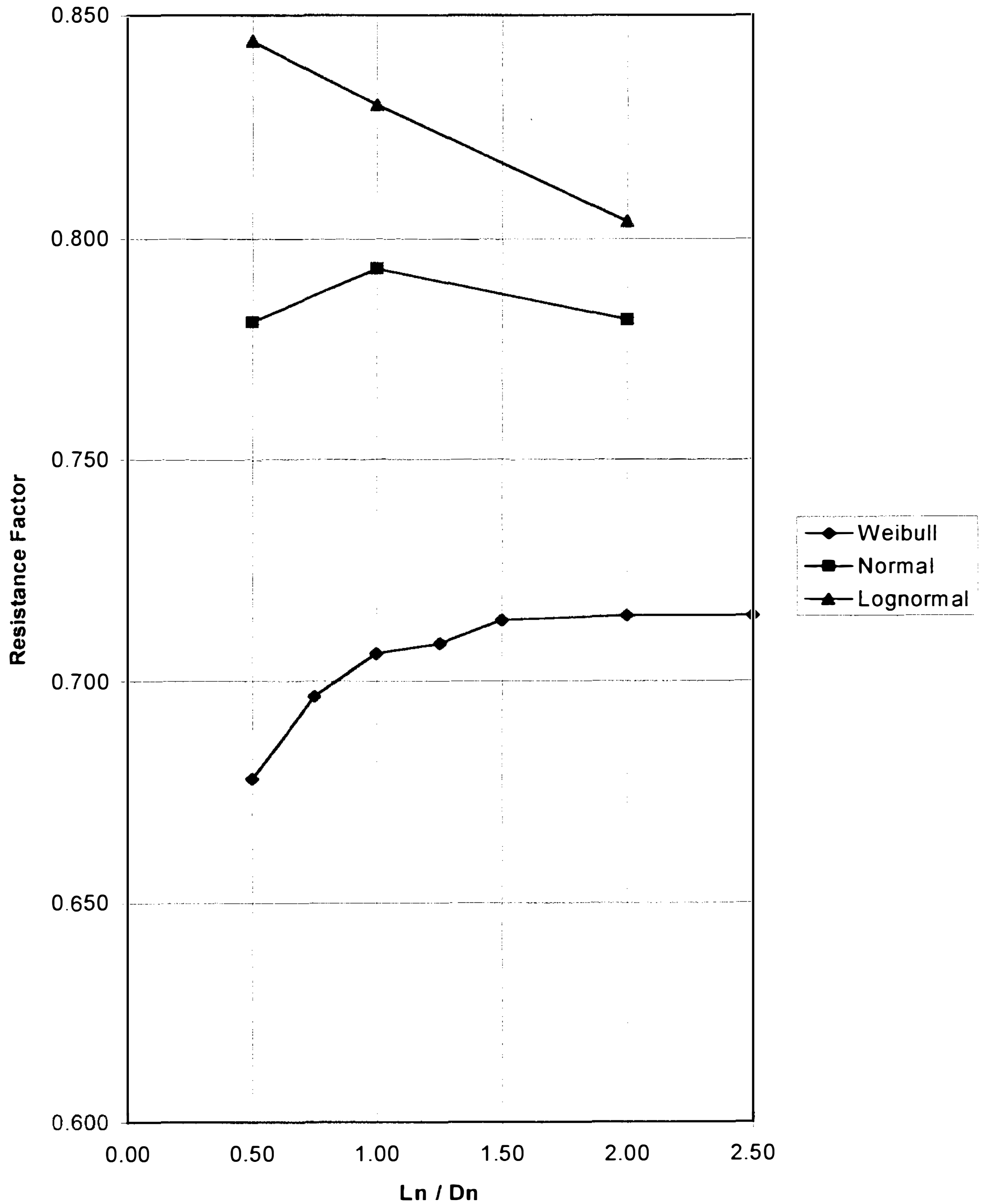

Figure 6
Resistance factor versus Ln / Dn for beta = 3.0
and COV of resistance = 0.15

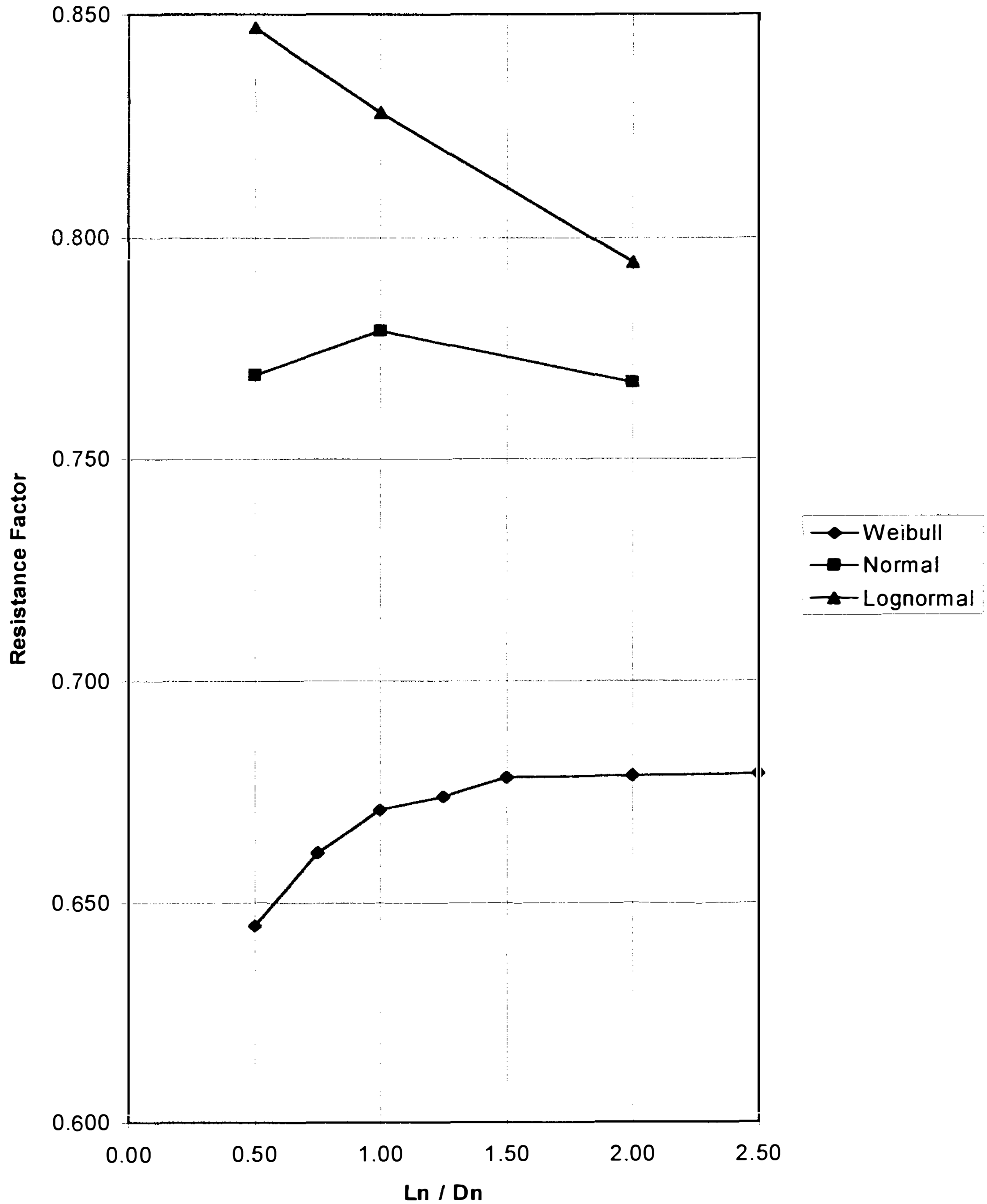

Figure 7
Resistance factor versus Ln / Dn for beta = 3.25 and COV of resistance = 0.15

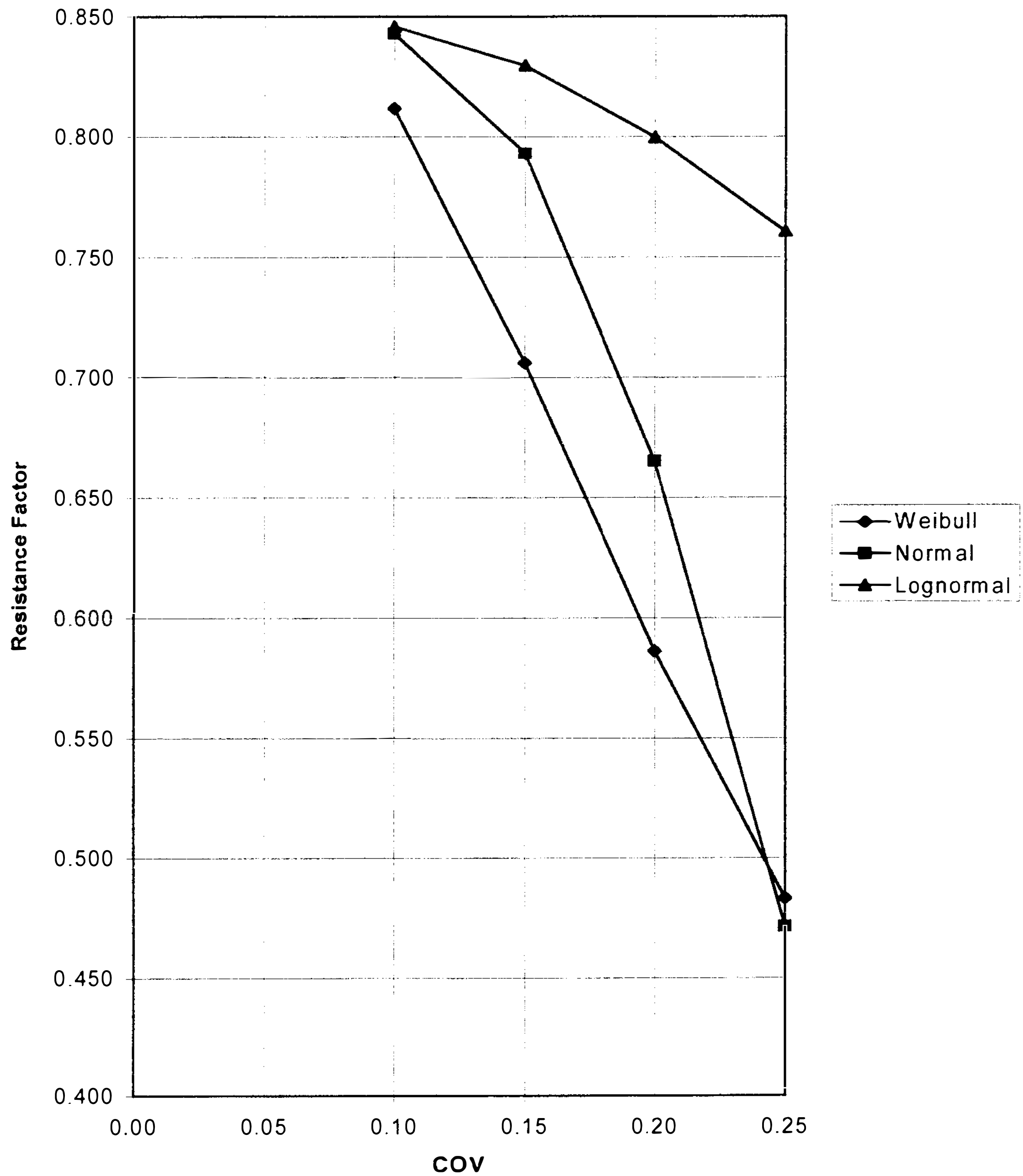

Figure 8
Resistance factor versus COV for beta = 3.0 and Ln / Dn = 1.0

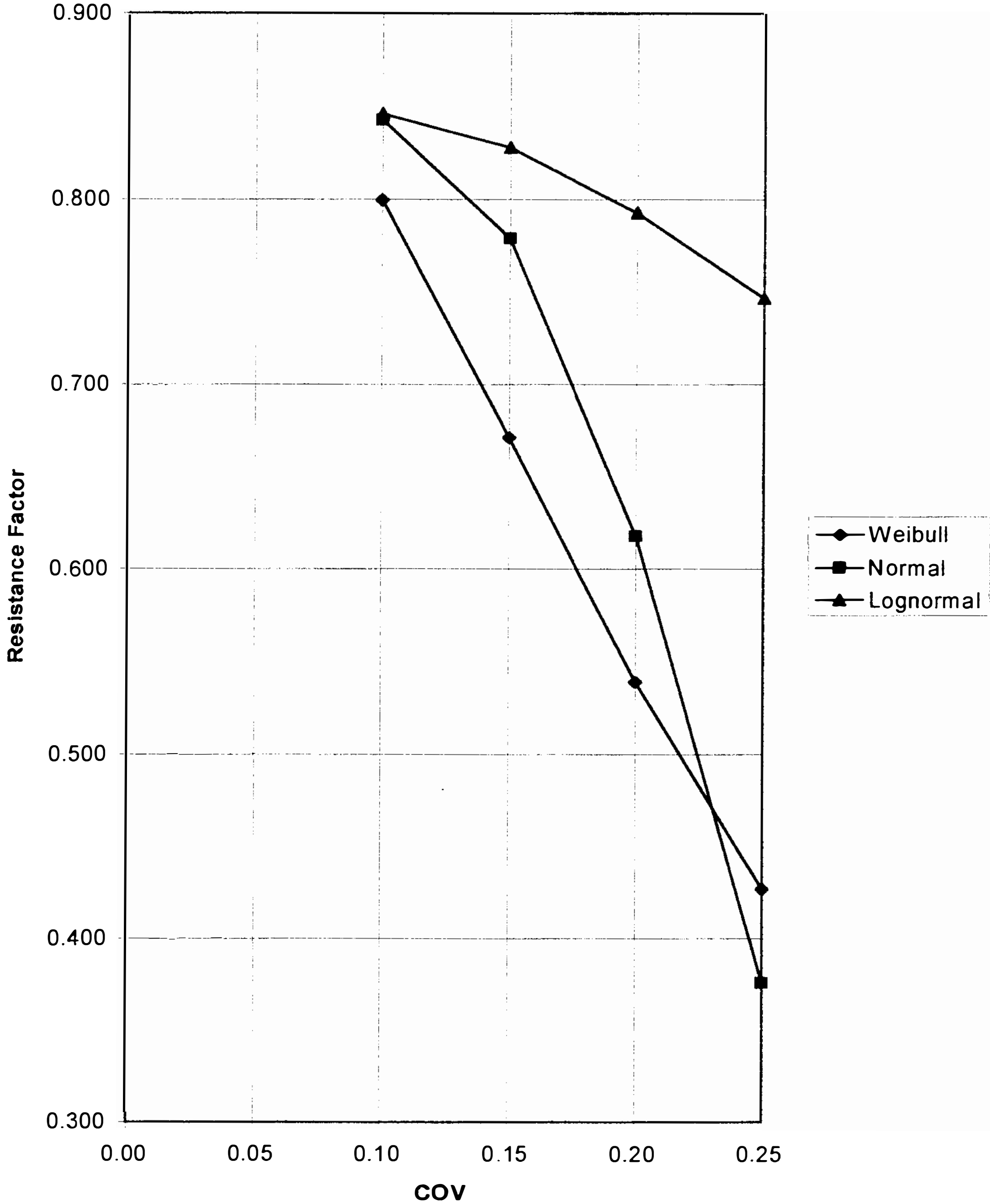

Figure 9
Resistance factor versus COV for beta = 3.25 and Ln / Dn = 1.0

Table 11
Resistance factors for different coefficient of variations and distributions
beta = 3.0

Resistance Distribution	COV	Ln/Dn	Resistance Factor
Weibull	0.15	1.00	0.706
Weibull	0.15	0.50	0.678
Weibull	0.15	0.75	0.697
Weibull	0.15	1.25	0.709
Weibull	0.15	1.50	0.714
Weibull	0.15	2.00	0.715
Weibull	0.15	2.50	0.715
Weibull	0.10	0.50	0.801
Weibull	0.10	1.00	0.812
Weibull	0.10	2.00	0.796
Weibull	0.20	0.50	0.559
Weibull	0.20	1.00	0.586
Weibull	0.20	2.00	0.604
Weibull	0.25	0.50	0.459
Weibull	0.25	1.00	0.483
Weibull	0.25	2.00	0.505
Normal	0.15	0.50	0.781
Normal	0.15	1.00	0.793
Normal	0.15	2.00	0.782
Normal	0.10	1.00	0.843
Normal	0.20	1.00	0.665
Normal	0.25	1.00	0.471
Lognormal	0.15	0.50	0.844
Lognormal	0.15	1.00	0.830
Lognormal	0.15	2.00	0.804
Lognormal	0.10	1.00	0.846
Lognormal	0.20	1.00	0.800
Lognormal	0.25	1.00	0.761

Table 12
Resistance factors for different coefficient of variations and distributions
beta = 3.25

Resistance Distribution	COV	Ln/Dn	Resistance Factor
Weibull	0.15	1.00	0.671
Weibull	0.15	0.50	0.645
Weibull	0.15	0.75	0.661
Weibull	0.15	1.25	0.674
Weibull	0.15	1.50	0.678
Weibull	0.15	2.00	0.679
Weibull	0.15	2.50	0.679
Weibull	0.10	0.50	0.790
Weibull	0.10	1.00	0.800
Weibull	0.10	2.00	0.784
Weibull	0.20	0.50	0.516
Weibull	0.20	1.00	0.539
Weibull	0.20	2.00	0.555
Weibull	0.25	0.50	0.407
Weibull	0.25	1.00	0.427
Weibull	0.25	2.00	0.441
Normal	0.15	0.50	0.769
Normal	0.15	1.00	0.779
Normal	0.15	2.00	0.767
Normal	0.10	1.00	0.843
Normal	0.20	1.00	0.618
Normal	0.25	1.00	0.376
Lognormal	0.15	0.50	0.847
Lognormal	0.15	1.00	0.828
Lognormal	0.15	2.00	0.794
Lognormal	0.10	1.00	0.846
Lognormal	0.20	1.00	0.793
Lognormal	0.25	1.00	0.746

Table 13
Distribution adjustment factor Ln / Dn = 1.0 and beta = 3.0

	COV	0.1	0.15	0.2	0.25
Distribution					
Weibull		1.08	0.94	0.78	0.64
Normal		1.12	1.06	0.89	0.63
Lognormal		1.13	1.11	1.07	1.01

Table 14
Distribution adjustment factor Ln / Dn = 1.0 and beta = 3.25

	COV	0.1	0.15	0.2	0.25
Distribution					
Weibull		1.14	0.96	0.77	0.61
Normal		1.20	1.11	0.88	0.54
Lognormal		1.21	1.18	1.13	1.07

both failure modes. This table is shown as Table 15 and is an approximate average of Tables 13 and 14 rounded to the nearest 0.05 for simplicity in design. This table should be modified as more data on different failure modes, such as bending and shear, becomes available.

Table 15
Proposed distribution adjustment factors

	COV	0.1	0.15	0.2	0.25
Distribution					
Weibull		1.10	1.00	0.80	0.65
Normal		1.15	1.10	0.90	0.60
Lognormal		1.15	1.15	1.10	1.05

Chapter 4

Conclusion

The purpose of this thesis was to develop the resistance factors needed to implement an LRFD based design approach for concentrically loaded FRP columns. A resistance factor of 0.75 for buckling and 0.70 for compression or material failure is proposed. If the distribution is not Weibull or the coefficient of variation is not 0.15 then a distribution adjustment factor should be used to modify the resistance value. Values for the distribution adjustment factor were listed in Table 15. The above values should be used along with the design equations developed by Zureick and Scott (1997) for the analysis of fiber reinforced pultruded composite members.

The mechanistic work was performed by Zureick and Scott (1997) and resulted in the following design equations.

$$P_r = P_n \phi_c$$

$$P_n = A_g F_{cr}$$

$$F_{cr} = \eta_s F_E \leq F_L^c$$

In the above equation $\eta_s F_E$ represents buckling failure and F_L^c represents material failure.

$$F_E = \frac{\pi^2 E_L}{\left(\frac{L_{eff}}{r}\right)^2}$$

$$\eta_s = \frac{1}{1+\left[\frac{n_s \pi^2}{\left(\frac{L_{eff}}{r}\right)^2}\right]\left(\frac{E_L}{G_{LT}}\right)}$$

In the above equations P_r is the factored axial compressive resistance, ϕ_c is the resistance factor which was determined in this thesis, P_n is the nominal compressive resistance, A_g is the gross sectional area, F_{cr} is the critical global buckling stress, F_E is the elastic buckling stress, η_s is the shear deformation parameter, $\left(\frac{L_{eff}}{r}\right)$ is the governing effective slenderness ratio, and n_s is a shear coefficient as defined in (Zureick and Scott, 1997).

The resistance to be used is the B-basis value as determined from the Military Handbook. The proposed resistance factor for buckling is

$$\phi_c = 0.75.$$

The proposed resistance factor for material failure is

$$\phi_c = 0.70.$$

The above resistance factors are based on the Weibull distribution with a coefficient of variation of 0.15.

If the resistance distribution is other than Weibull or if the coefficient of variation is other than 0.15 then the distribution adjustment factor j_t should be used. Values for the distribution adjustment factor are tabulated in Table 15.

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