Uncertainty in Marine Structural Strength with Application to Compressive Failure of Longitudinally Stiffened Panels

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(ABSTRACT)

It is important in structural analysis and design, whether deterministic or reliability-based, to know the level of uncertainty for the methods of strength prediction. The uncertainty associated with strength prediction is the result of ambiguity and vagueness in the system. This study addresses the ambiguity component of uncertainty; this includes uncertainty due to randomness in the basic strength parameters (random uncertainty) and systematic errors and scatter in the prediction of strength (modeling uncertainty). The vagueness component is briefly discussed.

A methodology for quantifying modeling and random uncertainty is presented for structural failure modes with a well defined limit state. A methodology is also presented for determining the relative importance of the basic strength parameters in terms of their importance to the total random uncertainty. These methodologies are applied to the compressive failure of longitudinally stiffened panels. The strength prediction model used in this analysis was developed in the UK and is widely used in analysis and design. Several experimental sample sets are used in the analysis. Mean values and coefficients of variation are reported for the random and modeling uncertainties.

A comparison with results from other studies with several strength prediction algorithms is undertaken for the modeling uncertainty. All of these studies involve longitudinally stiffened panels which fail in axially compressive collapse. Ranges for the mean and coefficient of variation of the modeling uncertainty are presented.

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1.0 INTRODUCTION

1.1 Definition of the Problem

Structural design may be characterized as the determination of a structural system that has a required level of performance. Ship structural design has historically been done through the use of codes based on deterministic formulations and experience. These codes have been developed with levels of safety determined through the use of conservative assumptions in the prediction algorithms and conservative values of the design variables (this includes the use of working stresses). The resulting structure meets the design criteria yet has a level of safety which is hard to quantify. The desire for lighter ship structures is causing the removal of excess material in designs, with a corresponding lowering of the traditional levels of safety. The margin between the actual and design strength needs to be assessed to quantify this safety factor.

Structural analysis is an evaluation of the performance of existing structures. An analysis is done with the best information available on the structure. This includes the loading, the structural geometry and material properties. When this information is fully available and input into the best available algorithm, a predicted strength results. This analytical strength may not equal the actual strength. The discrepancy may be quantified in the form of a bias, or ratio, between the two strengths. (This bias is a combination of the modeling and experimental biases to be discussed in section 2.1.1.)

With the bias between the predicted value, whether for design or analysis, and the actual strength, comes added uncertainty due to the statistical nature of the variables involved. Each dimension or material property has an inherent variability. When each variables' statistics are taken into account in an analysis, the strength can be shown to vary statistically as well. This uncertainty in the strength becomes extremely important in a structure which is designed with a small factor of safety.

Reliability-based methods of design are becoming more the norm in various engineering disciplines, with growing interest in the commercial and naval ship design industry. These methods require knowledge of the uncertainties inherent in the analytical models, structural geometry and material properties. The complexity of ship structures makes full probability analysis and design somewhat impractical. Load and resistance factor design (LRFD) is a simplification which makes use of reliability methods. LRFD allows the designer to artificially reduce the resistance and increase the load with multiple safety factors. The magnitudes of these factors are dependent upon the required level of safety and the uncertainty associated with the strength and loading prediction methods.

An understanding of the uncertainty in the prediction of structural strength is an important element in reliability-based design methods as well as more conventional design and analysis of ship structures.

1.2 Types of Uncertainty

Structural strength uncertainty may be due to vagueness and ambiguity in the definition of the system. These types may be attributed to cognitive and non-cognitive sources respectively. Cognitive uncertainty is the result of vagueness in various definitions (limit state, quality of material, experience levels of designers and builders), definition of complex systems, and other human factors. Non-cognitive uncertainty may be due to randomness in the basic parameters, limited experimental sampling, and modeling assumptions. The main focus in this study are uncertainties associated with ambiguity. Assessing uncertainty due to vagueness is discussed in Ayyub and Lai (92).

Random uncertainty is a result of the randomness in the basic strength parameters. This uncertainty may also be addressed as objective uncertainty (Ang and Tang 1975, Faulkner 1977). The basic strength parameters are the physically measurable parameters identified as the fundamental variables upon which the strength of a structure is dependent. Randomness in the plate thickness, Young's Modulus, yield strength, etc., leads to variability in the strength from the nominal value used in design. The randomness of the basic strength parameters may be quantified statistically from measurements of materials and actual structures. The information needed to get an accurate assessment of the variability is not always available. The form of the data is often difficult to use or the data doesn't exist. For example, yield strength data has been compiled for many shapes and types of material (Mansour 1984). This particular data set contains samples from the 1950's and earlier, which may not represent current material properties. The assessment of random uncertainty in the strength is highly dependent on the availability and quality of sample measurements.

Statistical uncertainty can result from the limited information being used to quantify the basic strength parameter characteristics. Sample sets may not typify the behavior of the overall population for a particular variable. A measure of this uncertainty is difficult to quantify and apply in a meaningful fashion, yet may be used to gain a qualitative understanding of the behavior of the population.

Modeling uncertainty has been defined as subjective in nature (Ang and Tang 1975, Faulkner 1977). It is primarily due to an incomplete understanding of the physical behavior of the structural system and its failure mechanisms. This can manifest itself in assumptions in areas such as the appropriate amount of effective plating to allow for shear lag effects, small deflection plate theory, simple beam theory for ship primary bending, and others.

1.3 Previous Work

Uncertainty in structural strength for the collapse failure of longitudinally stiffened panels, has been evaluated in previous studies by Faulkner (77), Bonello and Dowling (92), and Guedes Soares and Soreide (83). Prevention of this type of failure is important for both ships and box girder bridges. This has lead to efforts at collecting experimental data for this failure mode and at assessing the uncertainty associated with several prediction methods.

Modeling and random uncertainties are referred to by Faulkner as the subjective and objective uncertainties respectively. Faulkner estimated these uncertainties for his nominally identical series of panel tests. A discussion of these tests and his results can be found throughout Section 3.0. Bonello and Dowling (92) discuss the modeling uncertainty, and its associated statistics, based on a series of 85 experimental tests and on 63 numerical predictions using inelastic column analysis. These results are discussed in Section 3.4.2. Guedes Soares and Soreide (83) compare prediction methods from a number of sources by estimating the modeling bias mean and c.o.v. for each prediction algorithm as compared to multiple sets of experimental data. This includes data presented by Faulkner (77). The results from this paper are also discussed in Section 3.4.2.

1.4 Objectives

There are ongoing efforts in the commercial and military industry to develop a reliability based method for the structural design of ship structures. The main task in the development of a reliability-based design method is the determination of the load and resistance factors. In order to achieve this task it is necessary to have a quantitative measure of the various uncertainties in both the loads and the strength models. The objective of this thesis is to develop and demonstrate a method for quantifying the bias and uncertainty in structural strength prediction in order to further the overall goal. The failure mode used for demonstration is the compressive failure of a longitudinally stiffened panel.

1.5 Outline of Thesis

The outline of this thesis is as follows:

1. A methodology was developed for assessing the random and modeling uncertainties inherent in structural strength prediction for design and analysis.

2. A methodology was developed for determining the importance of the basic strength parameters in the random uncertainty of strength prediction.

3. The analytical strength models for compressive failure of longitudinally stiffened panels are discussed.

4. The available data found suitable for this study is reviewed, of experimental tests of longitudinally stiffened panels which failed under a compressive load.

5. The methodology is applied to the experimental data, for the assessment of the effects of random uncertainty on the strength prediction.

6. The relative importance is determined of the basic strength parameters on the bias and variability of the strength prediction.

7. The modeling uncertainty is estimated for the experimental data with the methodology and compared to the findings of previous studies.

8. The general and specific conclusions are discussed.

2.0 METHODOLOGY

2.1 Assessment of Uncertainty

One may quantify uncertainty by referring to it in the form of two components: the bias and its associated randomness. The bias represents the disparity between two values, or means of random variables, while the randomness addresses the statistical variability of this disparity.

2.1.1 Bias

The bias component of uncertainty between the actual strength and the nominal (design) strength can be divided into three parts which satisfy equation 2-1.

$$b_T = b_E b_M b_R \tag{2-1}$$

where:

b_T = total bias	(actual / design)
b_E = experimental bias	(actual / experimental)
b_M= modeling bias	(experimental / predicted)
b_R= random bias	(predicted / design)

The total bias can be expressed as

$$b_T = \frac{S_A}{S_D} \tag{2-2}$$

where S_A is the actual (real-life) value of the strength parameter and S_D is the design value of the strength parameter. The design strength, S_D, is calculated using nominal values of the dimensions and material properties. The experimental bias is given as

$$b_E = \frac{S_A}{S_E} \tag{2-3}$$

where S_E is the value of the strength parameter obtained using an experimental model of the actual structure. For the purposes of this study the experimental model is assumed to be equivalent to the actual structure, therefore $b_E = 1$. The modeling bias is given by

$$b_M = \frac{S_E}{S_P} \tag{2-4}$$

where S_P is the predicted value of the strength parameter. S_P is obtained by using the measured dimensions and material properties from the actual structure as inputs for the prediction algorithm. For this study the measured values are from the experimental model. The random bias is given by

$$b_R = \frac{S_P}{S_D} \tag{2-5}$$

2.1.2 Randomness

The statistical nature of the variables leads to randomness in the strength. A measure of the random component of the strength uncertainty can be found in the coefficient of variation (c.o.v.) of the strength. The definition of the c.o.v. is

$$\delta = \frac{\sigma}{\mu} \tag{2-6}$$

where σ and μ are the population standard deviation and mean of the random variable. In this study the sample standard deviation and mean will be used in place of the values for the whole population. The sample mean is given by

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2-7}$$

where n is the sample size and x_i is the i^{th} sample. The sample standard deviation is given by

$$\sigma_X = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \overline{X}\right)^2} \tag{2-8}$$

This leads to statistical uncertainty due to the limited sample size and the dependence on the sample. The uncertainty in the assessed mean can be given as

$$\delta_{\overline{X}} = \frac{1}{\sqrt{n}}\frac{\sigma_X}{\overline{X}} \tag{2-9}$$

if the sample mean is assumed to be an unbiased estimate of the population mean (page 231, Ang and Tang 1975). This c.o.v. is purely a measure of the statistical uncertainty. Other forms of uncertainty may result from uncertainty inherent in the sampling program.

The c.o.v. of the bias, δ_b, can be obtained from equations 2-6, 2-7, and 2-8, where b_i is the value of the bias of the i^{th} sample. The c.o.v. of the random bias can be derived using Monte Carlo simulation.

The predicted strength, S_P, is obtained from

$$S_P = S\left(X_1, X_2, \ldots, X_i, \ldots, X_n\right) \tag{2-10}$$

where X_i is the i^{th} basic random variable. The prediction method may be a closed form solution (as in this study) or may be the result of a complex, computer analysis. Monte Carlo simulation can be used to generate a set of samples of predicted strength values corresponding to random realizations of the basic random variables. The mean random bias, $\overline{b}_R$, can be obtained using equation 2-7 as

$$\overline{b}_R = \frac{1}{n}\sum_{i=1}^{n}\frac{S_{P_i}}{S_D} \tag{2-11}$$

for n predicted strength samples and a value of S_D for the design strength parameter. Similarly, the standard deviation, σ_{b_R}, can be found with equation 2-8 and the c.o.v. can be calculated using equation 2-6.

The c.o.v. of bias for m sources of uncertainty can be found by using the sum of squares, a first order approximation for small (less than ten to fifteen percent) values of c.o.v., where the bias of the sources is related in the form: $b = b_1 b_2 b_3 \ldots . b_n$. The relationship between the c.o.v.'s of these biases is:

$$\delta_b = \sqrt{\delta_{b_1}^2 + \delta_{b_2}^2 + \ldots + \delta_{b_m}^2} \tag{2-12}$$

Equation 2-12 may be used to combine the c.o.v. of the modeling bias and the random bias to obtain the c.o.v. of the total bias.

$$\delta_{b_T} = \sqrt{\delta_{b_M}^2 + \delta_{b_R}^2} \tag{2-13}$$

2.2 Relative Importance of the Basic Strength Parameters

The relative importance of the basic strength parameters needs to be assessed for the purpose of allocating resources in quantifying unknown uncertainties, quality control, development of design changes, and reliability improvements. Several methods can be used for this purpose such as parametric analysis, sensitivity factors, and weighted sensitivity factors.

2.2.1 Parametric Analysis

Parametric analysis may be considered a conventional method of sensitivity analysis. It is a parametric study of the effect of randomness in each variable on the strength, independent of the variability of others. Monte Carlo simulation is used to obtain the sample set of predicted strength values. The effect on the strength of each random variable is determined by allowing the variable under consideration to be random (active) while the other variables are fixed at their mean values. Values for the active variables are created using a random number generator.

The strength is predicted for every random value of the active variable and the means of the other variables. The c.o.v. of this predicted strength sample set , δ_{S_i} , is calculated using equations 2-6, 2-7, and 2-8. This c.o.v. is a measure of the uncertainty in the strength due to one variable and is recorded for each random variable, X_i. Parametric coefficients, P_i, are a normalization of δ_{S_i} according to the following equation:

$$P_i = \frac{\delta_{S_i}}{\sqrt{\sum_{i=1..n}\left(\delta_{S_i}\right)^2}} \tag{2-14}$$

This equation can be applied for n basic strength parameters. The basic strength parameters may then be ranked according to the magnitude of their respective parametric coefficients.

2.2.2 Sensitivity Coefficients

The sensitivity coefficients used in this study are normalized measures of the change in the strength prediction statistics due to perturbations of the moments of the basic strength parameters. Four types of sensitivity coefficients were developed. Monte Carlo simulation is used to obtain the predicted strength sample set. For each of the four methods the mean or c.o.v. of the basic random variable (strength parameter) is perturbed by some constant factor while the other variables behave randomly with their unperturbed statistical values and distributions. The sensitivity coefficient is a measure of the gradient of the strength prediction surface and may be viewed as a direction cosine. These coefficients are presented in the following sections

1. $C_{\mu\mu}$

The sensitivity coefficient for the change in the mean predicted strength due to a constant percentage change in the mean of the basic random variable. The standard deviation of the basic random variable remains constant.

$$C_{\mu\mu_i} = \frac{\dfrac{\overline{X}_i}{\overline{S}} \cdot \dfrac{\Delta\overline{S}_i}{\Delta\overline{X}_i}}{\sqrt{\sum\limits_{i=1..n}\left(\dfrac{\overline{X}_i}{\overline{S}} \cdot \dfrac{\Delta\overline{S}_i}{\Delta\overline{X}_i}\right)^2}} \tag{2-15}$$

where $\Delta\overline{X}_i$ is the change in the mean of the ith basic random variable, X_i, (10 percent for this study) and $\Delta\overline{S}_i$ is the resulting change in the mean predicted strength. $\overline{S}$ is the mean of the strength calculated from the unperturbed values of the basic random variables, and $\overline{X}_i$ is the mean of X_i. $\overline{S}$ and $\overline{X}_i$ are held constant at their initial values. Equation 2-15 can be simplified by canceling out constant terms to obtain:

$$C_{\mu\mu_i} = \frac{\Delta\overline{S}_i}{\sqrt{\sum\limits_{i=1..n}(\Delta\overline{S}_i)^2}} \tag{2-16}$$

2. $C_{\sigma\mu}$

The sensitivity coefficient for the change in the c.o.v. of the predicted strength sample set due to a constant percentage change in the mean of a basic random variable. The basic random variable standard deviation is held constant.

$$C_{\sigma\mu_i} = \frac{\dfrac{\overline{X}_i}{\delta_S} \cdot \dfrac{\Delta\delta_{S_i}}{\Delta\overline{X}_i}}{\sqrt{\sum_{i=1..n}\left(\dfrac{\overline{X}_i}{\delta_S} \cdot \dfrac{\Delta\delta_{S_i}}{\Delta\overline{X}_i}\right)^2}} \tag{2-17}$$

where $\Delta\delta_{S_i}$ is the change in the c.o.v. of the strength corresponding to the change (+10%) in the mean of the i^{th} basic random variable, $\Delta\overline{X}_i$. δ_S is the c.o.v. of the predicted strength calculated using the unperturbed values of the basic random variables and is constant. The simplified equation is

$$C_{\sigma\mu_i} = \frac{\Delta\delta_{S_i}}{\sqrt{\sum_{i=1..n}(\Delta\delta_{S_i})^2}} \tag{2-18}$$

3. $C\mu\sigma$

The sensitivity coefficient for the change in the mean of the predicted strength sample set due to a constant percentage change in the c.o.v. of the basic random variable, X. As the basic random variable mean is held constant, the actual change is applied to the standard deviation of X, resulting in the same change in δ_X. $C\mu\sigma$ is computed as

$$C_{\mu\sigma_i} = \frac{\dfrac{\delta_{Xi}}{\overline{S}} \cdot \dfrac{\Delta\overline{S}_i}{\Delta\delta_{Xi}}}{\sqrt{\sum_{i=1}^{n}\left(\dfrac{\delta_{Xi}}{\overline{S}} \cdot \dfrac{\Delta\overline{S}_i}{\Delta\delta_{Xi}}\right)^2}} \tag{2-19}$$

where $\Delta\overline{S}_i$ is the change in the predicted strength due to $\Delta\delta_{X_i}$, the change in the c.o.v. of the i^{th} basic random variable (+10%). The simplified form of 2-19 is

$$C_{\mu\sigma_i} = \frac{\Delta \bar{S}_i}{\sqrt{\sum_{i=1}^{n} \left(\Delta \bar{S}_i\right)^2}} \tag{2-20}$$

4. $C_{\sigma\sigma}$

The sensitivity coefficient for the change in the c.o.v. of the predicted strength sample set due to a constant percentage change in the c.o.v. of the basic random variable, X. As the basic random variable mean is held constant, the actual change is applied to the standard deviation of X, resulting in the same change in δ_X. $C\sigma\sigma$ is computed as

$$C_{\sigma\sigma i} = \frac{\frac{\delta_{Xi}}{\delta_S} \cdot \frac{\Delta\delta_{Si}}{\Delta\delta_{Xi}}}{\sqrt{\sum_{i=1}^{n} \left(\frac{\delta_{Xi}}{\delta_S} \cdot \frac{\Delta\delta_{Si}}{\Delta\delta_{Xi}} \right)^2}} \tag{2-21}$$

where $\Delta\delta_{S_i}$ is the change in the c.o.v. of the strength prediction due to $\Delta\delta_{X_i}$, the change in the c.o.v. of the i^{th} basic random variable. Simplifying equation 2-21 one obtains

$$C_{\sigma\sigma i} = \frac{\Delta\delta_{Si}}{\sqrt{\sum_{i=1}^{n} \left(\Delta\delta_{Si}\right)^2}} \tag{2-22}$$

2.2.3. Weighted Sensitivity Coefficients

The first two sensitivity coefficients dèscribed in the previous section, $C_{\mu\mu}$ and $C_{\sigma\mu}$, are normalized measures calculated using perturbed values of the basic strength parameters. This leads to different cumulative probabilities for the random variables according to their probabilistic characteristics. To achieve a constant cumulative probability for all the basic random variables, the perturbed values of their respective means may be based on a constant percent change in their standard deviations (c.o.v.). The sensitivity coefficients are weighted based on the characteristics of the basic random variables. This is not necessary for the second two cases of the previous section

The weighted sensitivity coefficients are normalized measures of the effect of changing the mean of each basic random variable by a constant percentage of its respective standard deviation, with all other random variables unperturbed and active.

1. $W_{\mu\mu}$

The sensitivity coefficient $W_{\mu\mu}$ represents the gradient of the mean predicted strength for a change in the mean of a basic random variable, where for each basic random variable, the mean is perturbed by a constant percentage of the standard deviation . $W_{\mu\mu}$ is computed as

$$W_{\mu\mu_i} = \frac{\dfrac{\overline{X}_i}{\overline{S}} \cdot \dfrac{\Delta\overline{S}_i}{\Delta\overline{X}_i}}{\sqrt{\displaystyle\sum_{i=1}^{n}\left(\dfrac{\overline{X}_i}{\overline{S}} \cdot \dfrac{\Delta\overline{S}_i}{\Delta\overline{X}_i}\right)^2}} \tag{2-23}$$

where $\Delta\overline{S}_i$ is the change in the mean of the i^{th} strength prediction sample set due to the change in the i^{th} basic random variable mean value. $\overline{S}$, the original mean strength, and $\overline{X}_i$, the mean of the i^{th} random variable, are constant. Simplification leads to

$$W_{\mu\mu_i} = \frac{\Delta\overline{S}_i/\delta_{x_i}}{\sqrt{\displaystyle\sum_{i=1}^{n}\left(\Delta\overline{S}_i/\delta_{x_i}\right)^2}} \tag{2-24}$$

2. $W_{\sigma\mu}$

The sensitivity coefficient $W_{\sigma\mu}$ represents change in the c.o.v. of the predicted strength sample set due to a change in the mean of a basic random variable, where for each basic random variable, the mean is perturbed by a constant percentage of the standard deviation. $W_{\sigma\mu}$ is computed as

$$W_{\sigma\mu_i} = \frac{\dfrac{\overline{X}_i}{\delta_S} \cdot \dfrac{\Delta\delta_{Si}}{\Delta\overline{X}_i}}{\sqrt{\sum_{i=1}^{n}\left(\dfrac{\overline{X}_i}{\delta_S} \cdot \dfrac{\Delta\delta_{Si}}{\Delta\overline{X}_i}\right)^2}} \tag{2-25}$$

where the $\Delta\delta_{S_i}$ is the change in the i^{th} strength prediction sample set c.o.v. due to a change in the mean of the i^{th} basic random variable. Simplification leads to

$$W_{\sigma\mu_i} = \frac{\Delta\delta_{Si} / \delta_{X_i}}{\sqrt{\sum_{i=1}^{n}\left(\Delta\delta_{Si} / \delta_{X_i}\right)^2}} \tag{2-26}$$

3.0 UNCERTAINTY IN STRENGTH MODELS FOR COMPRESSIVE COLLAPSE OF STIFFENED PANELS

Ship structures are highly complex structures with many possible failure modes. Stiffened panel collapse is one of the more serious failure modes. This mode was chosen for this study for the following reasons:

1. size and importance of the member.
2. the sudden nature of failure (buckling) as opposed to more progressive failure.
3. availability of test data suitable for statistical analysis.
4. general acceptance of definition of the limit state (i.e. as opposed to exceeding some specified value such as maximum deflection)

3.1 Strength Models

"Standard" Algorithm

A computational model for the strength of stiffened panels was developed in the UK under the guidance and sponsorship of the Merrison Committee, which led to the UK LRFD Code for steel box girder bridges, BS5400 (British Standards Institute, 1982). This computational model is directly applicable to ship panels and is presented for that application in Section 14.2 of Ship Structural Design (SSD, Hughes 1988). It has been adopted by Lloyds Register of Shipping and is implemented in the LR computer program for panel strength: LR Pass Program 20202. This algorithm was also implemented in the MAESTRO program. Because of its thorough validation and wide acceptance, it will herein be referred to as the "Standard" algorithm.

The Standard algorithm is presented in full on pages 466-477 of SSD. In this model each stiffener is regarded as an isolated beam-column, with the plating acting as one of the two flanges. If the stiffener is a tee section, then the beam-column is monosymmetric. Because of the relatively large width of the plate flange, the neutral axis of the beam-column is close to the plating; and hence the largest flexural stress occurs in the stiffener flange. Because of the asymmetry about the neutral axis, the two directions of primary bending (bending in the plane of the web) have quite different consequences. When the bending deflection is toward the plating, the flexural stress in the stiffener flange is compressive, and it combines with the applied axial compressive stress, so that the stiffener flange is the most highly stressed location in the cross section. Eventually it reaches the yield stress and the beam-column collapses. In this case we speak of the collapse as being "stiffener-induced". In the terminology of SSD, this is called a "Mode I" collapse. In contrast, when the bending deflection is toward the stiffener, the compressive flexural stress now occurs in the plating and it combines with the applied axial compressive stress. Eventually this combined compressive stress causes the plate to buckle and the beam-column, having lost its major flange, simultaneously collapses. In this case we speak of the collapse as being "plate-induced". In the terminology of SSD, this is called a "Mode II" collapse.

Other Algorithms

Prior to the publication of the Standard method, various researchers had developed five other methods: Faulkner (75), Murray (75), Carlsen (80), Dwight and Little (76) and Horne and Narayanan (77). Faulkner's method (75) is based on a Johnson-Ostenfeld approximation together with an effective width approach for plate behavior. This method was also presented in Faulkner et al (73). The methods of Murray (75), Carlsen (80), Dwight and Little (76), and Horne and Narayanan (77) are all based on a Perry-Robertson formulation, also with an effective width model for the plating. The main differences in these methods are the ways they account for the effects of residual stress, initial imperfections, and eccentricity due to loss of plate effectiveness.

A quite different algorithm is presented in Smith (75), which makes use of an extremely detailed model and large amounts of iteration. The computational resources needed to implement this algorithm makes it unsuitable for the purposes of this study.

3.2 Available Experimental Data

The main focus of this study is the uncertainty in the strength of longitudinally stiffened panels under axial compression. The data sets used in this study are the those which were readily obtainable, dealt with the compressive failure of longitudinally stiffened panels, and had sufficient data to further the objectives of this study. Other sources of data were either proprietary, of insufficient scope or lacking background information. There may well be other sources not found due to limited publication. In the end, sufficient data was found to be available only for single bay panels under purely axial compression. Even here there were only three test series which fulfilled the requirements – the nominally identical and parametric series reported in Faulkner (77) and the panels reported in Michelutti (77).

The tests reported in Smith (75) are for three-bay panels, and in general they were each different and they each involved a different mode of failure, including stiffener tripping and grillage buckling. The only exception was one pair of nominally identical panels. Unfortunately there are very few other three-bay panel tests, none of which sufficiently similar in loading and geometry to be grouped with Smith's tests.

Faulkner (77) reported on four test programs: the student series, the nominally identical series, the residual welding stress series, and the parametric series. The nominally identical and parametric series data are analyzed in this study. The student series was deemed inappropriate for use as a result of vagueness in the reporting. The residual stress series was conducted to investigate the effect of residual stress on the overall strength of a welded panel, and consists of two sets of panels. This series was not used herein because the first set was stress relieved by baking, and the second set is not fully documented. The second set was constructed similarly to the nominally identical series, but the welding methods were varied to create different amounts of residual stress. The dimensions and material properties are not reported for the panels, nor are their statistics, aside from the mean values.

The nominally identical tests were conducted to quantify the strength uncertainties resulting from normal shipyard construction methods. The panels were all constructed from the same design with variation resulting purely from fabrication and material randomness. The panels consisted of plating reinforced with five stiffeners, oriented longitudinally, approximating quarter scale deck panels of one bay length. Each panel was loaded axially to compressive failure. In order to make the panels more sensitive to variations in dimensions and residual stress, they were designed such that the stiffener slenderness parameter, λ_S, was of the order of 0.9, and the plate slenderness parameter, β, was of the order of 2.1. Faulkner(77) presented an analysis of the subjective and objective uncertainties associated with these tests. In Section 3.4.2 we compare our analysis with his and give reasons why we believe ours to be more accurate.

The parametric series tests were conducted to examine the effect on ultimate strength of varying slenderness ratios. The slenderness ranges were 1,2,3,4 for β and 0.375, 0.750, 1.125 for λ_S. They were of the same scale as the nominally identical series, constructed from plating with 5 longitudinal stiffeners, and of one bay length. The loading was purely axial and increased until ultimate failure. The construction methods were consistent for each panel. All but three of the panels had tee stiffeners.

The tests conducted by Michelutti (77) consisted of single bay models with combined axial and lateral pressure loads. Of the 15 models reported, three were axially loaded and two of these were used in this study.

3.2.1 Faulkner

Nominally Identical Series

The nominally identical series of panel tests in Faulkner (77) were conducted to examine strength uncertainties in longitudinally stiffened panels under axial compressive loading. The models were fabricated at a naval shipyard under normal conditions and tested to failure. Of the 13 models tested, 4 failed in stiffener-induced collapse (Mode I) and 9 failed in plate-induced collapse (Mode II). (For brevity we will use the "Mode" terminology; a description of the two modes was given in Section 3.1). The four panels that failed in Mode I initially had unusually large eccentricities, and they were straightened out after construction, and before testing, by means of an unspecified amount of heating. We did not include these four panels because of the artificial and completely unknown amount of bias that they contain.

Figure 1 depicts a panel in the nominally identical series. The panels were designed to represent a quarter scale deck panel and were stiffened by five stiffeners cut from 3"x1" Ministry of Defense (UK) Standard Tees. Simply supported boundary conditions were simulated by applying the load through knife edges at the elastic neutral axis. End caps were used to shed the load from the knife edge into the cross section. The stiffness added to the panels by these end caps shorten the simply supported length for analysis purposes to the reported effective length. The effective length formulation is treated in Faulkner (77).

As the panels were nominally identical, any differences in the panels were due to randomness in the variables. The statistics of the measured material properties and the dimensions of the panels are reported in Table 3.1, along with the nominal (design) values. The actual scantlings of each panel were not reported in Faulkner (77). All random variables in Table 3.1 were assumed to be normal. The effective length (a_e), stiffener spacing (b), and stiffener flange breadth (b_f) were all considered constant, as follows.

$$a_e = 790.0 \text{ mm},$$
$$b = 183.0 \text{ mm},$$
$$b_f = 25.4 \text{ mm}.$$

We used effective length in all calculations. For simplicity, in the rest of the section we will refer to effective length using the term "length" and denote it by "a". The plate free edges had a width of b/3 to approximate the same buckling stress as the supported plate.

Table 3.1: Nominal values and sample statistics of the panel dimensions and material properties of Faulkner's Nominally Identical series.

Random Variable	Nominal Value[1]	Mean	Standard Deviation	c.o.v. (%)
Plate Thickness (TPL)	3.0 mm	3.07 mm	0.027937 mm	0.91
Depth of stiffener (d)	32.5 mm	32.5 mm	0.26975 mm	0.83
Web thickness (TSW)	4.4 mm	4.90 mm	0.01519 mm	0.31
Flange thickness (TSF)	6.4 mm	5.84 mm	0.012848 mm	0.22
Plate yield stress (SigY(PL))	240 N/mm^2	238 N/mm^2	19.754 N/mm^2	8.3
Stiffener yield stress (SigY(STF))	240 N/mm^2	295 N/mm^2	16.52 N/mm^2	5.6
Eccentricity (e)	±0.5273[2]	±0.5273[2]	0.5273[3]	100.
Tension zone parameter, η, due to residual stresses[4]	2.772	2.7095	0.294	10.85
Young's modulus	208 kN/mm^2	201 kN/mm^2	3.015 kN/mm^2	1.5

Notes:

[1]Nominal dimensions from Ministry of Defense (UK) Standard Tee Bar catalog

[2]The mean and nominal values were estimated to be -a/1500 for Mode I and +a/1500 for Mode II.

[3]The standard deviation of the eccentricity was assumed to be equal to the length of the panel over 1500.

[4]Pages 393-394 of Hughes (88) address this parameter. The nominal and mean values of η are based on the assumption that $\sigma_r/\sigma_Y = 0.10$, where σ_r is the compressive residual stress and σ_Y is the yield stress of the plating.

The compressive residual stress, which was measured after fabrication, corresponds to a tension zone parameter (η) of 4.2. The strength prediction algorithm uses a fixed value for the residual stress equal to approximately ten percent of the yield stress of the plating. In this study we use a mean tension zone parameter, $\eta = 2.710$, which corresponds to a residual stress equal to ten percent of the yield stress.

The statistics of the panel eccentricity were not given and so values were assumed, based on the following statement from Section 2.2 of Faulkner (77): "the stiffener deformations were very small, usually much less than a/1000 and in no case greater than a/500...". We therefore assumed mean eccentricities of -a/1500 for Mode I and +a/1500 for Mode II, with a standard deviation of a/1500. To check if our assumption on the standard deviation of the panel eccentricity was reasonable, we estimated the standard deviation of the eccentricity of fourteen panels studied by Michelutti and Murray (77). The standard deviation was found to be a/1376, which indicated that our assumption was reasonable.

Finally, it is observed from Table 3.1 that the eccentricity, the yield stresses of the plate and stiffener and the residual stress have the largest coefficients of variation.

Parametric Series

The second set of panels used in this study is the set referred to as the parametric series in Faulkner (77). In this series 24 panels were tested to study the effect of varying slenderness ratios on the column strength. 19 of these panels failed in Mode II and were used in this study. Of the five not used, 2 experienced tripping failure and 3 had flat bar stiffeners instead of T-shaped stiffeners.

The panel dimensions and properties were reported for each panel and are given in Table 3.2. The panels had the same layout as the nominally identical series, with 5 stiffeners aligned longitudinally and b/3 free-edge plate width. The stiffeners were also cut from 3" x 1" Admiralty tees. Residual compressive stresses were measured and found to correspond to a range of η from 3 to 4.5. For the strength predictions η was defaulted to 2.710 as in the nominally identical series. The test procedure was identical with the exception of the load being applied at the midpoint of the distance between the initial (elastic) neutral axis and the predicted final neutral axis. The predicted final neutral axis location was based on an assumption of 40t of the plating being effective.

The panel mid span eccentricity was reported for each panel. For the nominal calculations the mean eccentricity was set to one standard deviation (a/1500). For Mode I the mean is negative, positive for Mode II.

Table 3.2: Panel dimensions and material properties of Faulkner's Parametric Series

Model	a (mm)	b (mm)	TPL (mm)	d (mm)	TSW (mm)	b_f (mm)	TSF (mm)	SigY (PL)	SigY (STF)
1	244.00	88.40	3.07	23.60	4.88	12.70	6.17	250.00	283.00
2	384.00	147.00	2.62	36.60	4.83	12.70	6.22	250.00	262.00
3	638.00	221.00	2.54	60.20	4.90	12.70	6.10	256.00	247.00
4	523.00	236.00	2.01	49.80	4.80	12.70	6.25	221.00	250.00
5	488.00	88.40	3.07	23.60	4.88	12.70	6.17	225.00	259.00
6	767.00	147.00	2.62	36.60	4.83	12.70	6.22	239.00	259.00
7	1275.00	221.00	2.54	60.20	4.90	12.70	6.10	270.00	246.00
8	1046.00	236.00	2.01	49.80	4.80	12.70	6.25	247.00	259.00
9	732.00	88.40	3.07	23.60	4.88	12.70	6.17	230.00	283.00
10	1151.00	147.00	2.62	36.60	4.83	12.70	6.22	239.00	258.00
11	1913.00	221.00	2.54	60.20	4.90	12.70	6.10	239.00	252.00
12	1570.00	236.00	2.01	49.80	4.80	12.70	6.25	249.00	266.00
13	262.00	88.40	3.10	26.40	3.10	0.00	0.00	253.00	261.00
14	244.00	177.00	3.05	23.60	4.85	12.70	6.15	242.00	269.00
15	422.00	265.00	3.07	40.10	4.95	12.70	6.20	227.00	267.00
16	384.00	295.00	2.57	36.60	4.90	12.70	6.12	244.00	273.00
17	523.00	88.40	3.10	26.40	3.10	0.00	0.00	229.00	256.00
18	488.00	177.00	3.05	23.60	4.85	12.70	6.15	229.00	246.00
19	843.00	265.00	3.07	40.10	4.95	12.70	6.20	253.00	266.00
20	767.00	295.00	2.57	36.60	4.90	12.70	6.12	261.00	247.00
21	785.00	88.40	3.10	26.40	3.10	0.00	0.00	258.00	262.00
22	732.00	177.00	3.05	23.60	4.85	12.70	6.15	242.00	262.00
23	1265.00	265.00	3.07	40.10	4.95	12.70	6.20	244.00	262.00
24	1151.00	295.00	2.57	36.60	4.90	12.70	6.12	239.00	267.00

Note: Yield stresses of stiffener and plate are expressed in N/mm^2

3.2.2 Michelutti

Fifteen panels were tested in a variety of loading conditions. Three of these panels were loaded in purely axial compression. Of these three, a panel called "panel J" failed in Mode I and the remaining two panels called "Panels A6 and H" failed in mode II. Panel J was predisposed to fail in Mode I by moving the point of load application closer to the free edge of the stiffeners from the centroid. The two other panels, A6 and H, were not arranged to favor either failure mode.

Panels A6 and H share similar dimensions and properties with the most significant difference being overall length. The panels are stiffened by five bulb stiffeners and are loaded at the elastic neutral axis. The panel properties are listed in Table 3.3.

Table 3.3: Panel dimensions and material properties from Michelutti (77)

Panel	a (mm)	b (mm)	t_p (mm)	d (mm)	t_w (mm)	b_f (mm)	t_f (mm)	SigY (PL)	SigY (Stf)
A6	4930	530	9.60	152.0	7.31	28.6	15.9	368	383
H	3450	530	9.47	152.0	7.08	28.6	15.9	378	389

Note: Yield stresses are expressed in N/mm^2

3.3 Results for Random Uncertainty

We estimated the uncertainty in the compressive strength of the stiffened panels described in Section 3.2 due to random uncertainties in geometry and material properties for two failure modes: stiffener initiated inelastic buckling (Mode I) and plate initiated inelastic buckling (Mode II). Section 3.3.1 presents the results. We also estimated the effect of each random uncertainty in geometry and material properties on the strength, and ranked these uncertainties in terms of importance. Those results are presented in Section 3.3.2.

3.3.1 Effect of random uncertainty on strength

Several combinations of axial and transverse in-plane loads and lateral pressure were studied to cover the range of realistic combinations of these loads. Specifically, the lateral pressure, p, ranged from -0.07 MPa to 0.07 MPa (positive pressure is from the plate to the stiffener). We considered four cases where transverse stress to axial stress ratio was 0, 1/16, 1/8 and 1/4.

The statistics of the strength were estimated using Monte-Carlo simulation. In each replication, we predicted the axial strength of a panel corresponding to a set of samples of the random variables using the Standard algorithm described in Section 3.1 and presented in Section 14.2 of SSD. The computer implementation of the algorithm was taken from the MAESTRO program.

The Standard algorithm assumes a fixed design value for residual stress, equal to ten percent of the yield stress. In contrast, Faulkner's algorithm (73) explicitly allows for variation in the residual stress. Therefore, in order to account for the uncertainty in residual stress, we used two separate Monte-Carlo simulations. In the first simulation we used Faulkner's algorithm (73) to estimate the c.o.v. of the strength due to variation in residual stress only, $\delta_{residual}$. All other variables were fixed at their mean values. In the second simulation, we used the Standard algorithm to estimate the c.o.v of the strength due to all the other random variables, δ_{other}. We obtained the total uncertainty in the strength, δ_T, using the following equation:

$$\delta_T = (\delta^2_{residual} + \delta^2_{other})^{1/2} \tag{3.3-1}$$

In this equation, δ_T is the c.o.v. of the strength due to all uncertainties. For Mode I, the residual stress does not significantly affect the strength. Therefore, we assumed that $\delta_T = \delta_{other}$ for Mode I.

Whether a panel fails under Mode I or Mode II is heavily dependent upon the direction of the eccentricity and lateral pressure. As a result, some of the samples generated in one simulation failed under Mode I and the others under Mode II. We separated the samples depending on the mode under which they failed and estimated the mean and c.o.v. of each mode separately.

The mean value of the strength for Mode I was found to be 247.5 MPa and the c.o.v. 10.20%. The corresponding values for Mode II were 156.5 MPa and 6.33%. The mean strength, the nominal strength and the mean strength plus and minus one and two standard deviations are plotted in Figures 2 to 9 as a function of the lateral pressure. The nominal strength was defined as the minimum predicted strength, in either Mode I or II, with the variables set at their nominal values (see Table 3.1). The Mode I results are shown in Figures 2 to 5. These figures correspond to applied transverse stresses equal to 0 (case A), 1/16 (case B), 1/8 (case C) and 1/4 (case D) of the axial stress, respectively. The corresponding results for Mode II are shown in Figures 6 to 9.

For Mode I, the curves for the mean strength and the mean plus and minus one and two standard deviations extend to the range of positive pressures from 0 to 0.035 MPa. Although positive pressures favor Mode II, the panel may still fail under Mode I in this range since panel eccentricity is random. Let us consider a panel that has failed with a negative mean eccentricity, favoring Mode I failure. For values of lateral pressure in the range from 0 to 0.035 MPa each collapse mode has a conditional probability of occurrence (conditioned on the event that the panel has failed), which depends on the pressure and the probability distribution of the eccentricity. The summation of the conditional probabilities of occurrence of the two modes is one for a given value of the pressure. For positive pressures the conditional probability of occurrence of Mode I decreases as the pressure increases because positive pressure favors plate induced collapse (Mode II failure). The interaction curves for Mode II extend to the range of negative pressures for the same reason.

We observe the following from the Figures 2 to 9:

1. The standard deviation of the strength for Mode I changes considerably with pressure. For example, when there is no applied transverse stress, the standard deviation changes from about 11 MPa to 27 MPa when the pressure changes from -0.07 MPa to +0.35 MPa (Figure 2).

2. The range of variation and the magnitudes of the standard deviation of the strength for Mode I is smaller for larger values of the applied transverse stress than for smaller values (Figures 2 to 5).

3. The variability in the strength due to random uncertainty is almost independent of the applied lateral pressure for Modes II. (Figures 6 to 9).

4. The standard deviation for the Mode II strength decreases with increasing lateral pressure. (Figures 6 to 9)

5. The nominal strength is considerably smaller than the mean strength for pressures from -0.07 to -0.0175 MPa. Thus if we predict the strength using the nominal values of the random variables we will be on the conservative side (see Figures 2 to 5). We believe that the main reason for this behavior is that the nominal yield stress of the stiffener is significantly lower than the measured value (Table 3.1).

6. The nominal strength is almost identical to the mean for pressures from -0.0175 to 0.07 MPa (Figures 6 to 9). This is because some of the nominal values used to predict the strength were conservative (e.g., plate and web thickness), and others were non-conservative (e.g., plate yield stress), yet close to the measured values (Table 3.1).

3.3.2 Ranking of Random Uncertainties

We ranked uncertainties in terms of importance using the three methods described in 2.2: Parametric Analysis and the two methods using Sensitivity Coefficients (unweighted and weighted). In the following we present the results:

Parametric Analysis

This method finds the effect of each uncertainty on strength when the corresponding variable is random and the remaining variables are fixed at their means. Uncertainties are ranked using the corresponding parametric coefficients, P_i, that are calculated from equation 2-14.

$$P_i = \frac{\delta_{S_i}}{\sqrt{\sum_{i=1}^{n}\left(\delta_{S_i}\right)^2}} \qquad i = 1 \ldots n \tag{2-14}$$

where δ_{Si} is the c.o.v. of the predicted strength due to the uncertainty in the ith random variable and n is the number of random variables. Table 3.4 presents the c.o.v.'s of the predicted strength due to each uncertainty and the parametric coefficient of each random variable for Modes I and II. Figure 10 shows the contribution of each uncertainty to the sum in equation 2-14, for Mode I. Figure 11 shows the corresponding results for Mode II.

Table 3.4: Ranking of uncertainties using Parametric Analysis for Modes I and II

Random Variable	Mode I: δ_{S_i} (%)	Mode I: P_i	Mode II: δ_{S_i} (%)	Mode II: P_i
Plate Thickness	0.10	0	0.58	0.09
Depth of stiffener	0.33	0.03	0.08	0
Web thickness	0.01	0	0.01	0
Flange thickness	0.04	0	0.01	0
Plate yield stress	0.01	0	5.39	0.87
Stiffener yield stress	4.82	0.48	0.01	0
Young's modulus, PL	0.19	0.01	0.47	0.08
Young's modulus, STF	0.39	0.03	0.04	0
Eccentricity	8.90	0.88	2.86	0.46
Residual stress	--	--	0.76	0.12

The following are observed:

- Mode I:

1. The uncertainty in eccentricity is the most important uncertainty.
2. The uncertainty in the yield stress of the stiffener is the second most important uncertainty.
3. All other uncertainties are unimportant

- Mode II

1. The uncertainty in the yield stress of the plate is the most important.
2. The uncertainty in the residual stress, eccentricity, Young's modulus, and plate thickness are also important.
3. All other uncertainties are unimportant.

Nikolaidis et al. (92) also found that the uncertainty in the yield stress of the plating was the most important among the uncertainties in geometry and material properties, in the case of a stiffened panel failing in Mode II, for which b/t=324, and a/b=1.35.

Sensitivity coefficients

The sensitivity coefficients were calculated the using equations found in section 2.2.2 (equations 2-16, 18, 20, 22, 24, and 26).

Tables 3.5 and 3.6 show the sensitivity coefficients $C_{\mu\mu_i}$, and $C_{\sigma\mu_i}$ for Mode I and Mode II, respectively. Tables 3.7 and 3.8 show the sensitivity coefficients $C_{\mu\sigma_i}$, and $C\sigma\sigma_i$ for Mode I and Mode II, respectively. Tables 3.9 and 3.10 show the sensitivity coefficients $W_{\mu\mu_i}$, and $W_{\sigma\mu_i}$ for Mode I and Mode II, respectively.

Table 3.5: Mode I: ranking based on sensitivity of predicted strength to perturbations of the means of the random variables.

r.v.	$C_{\mu\mu}$
SigY (Stf)	0.860
HSW	0.333
E (Stf)	0.264
TPL	0.175
TSF	0.165
E (PL)	0.130
Eccentricity	0.067
TSW	0.005
SigY (PL)	0.001

r.v.	$C_{\sigma\mu}$
HSW	0.621
E (Stf)	0.487
TPL	0.403
TSF	0.353
E (PL)	0.292
Eccentricity	0.063
SigY (Stf)	0.027
TSW	0.008
SigY (PL)	0

Table 3.6: Mode II: ranking based on sensitivity of predicted strength to perturbations of the means of the random variables.

r.v.	$C_{\mu\mu}$
TPL	0.791
SigY (PL)	0.543
E (PL)	0.261
HSW	0.075
Residual Stress	0.062
E (Stf)	0.027
Eccentricity	0.019
TSF	0.014
TSW	0.003
SigY (Stf)	0

r.v.	$C_{\sigma\mu}$
SigY (PL)	0.864
TPL	0.445
HSW	0.218
TSW	0.063
Residual Stress	0.040
TSF	0.037
Eccentricity	0.032
E (Stf)	0.015
E (PL)	0.015
SigY (Stf)	0

Table 3.7: Mode I: ranking based on sensitivity of predicted strength to perturbations of the standard deviations of the random variables.

r.v.	$C_{\mu\sigma}$
Eccentricity	0.999
SigY (Stf)	0.021
E (Stf)	0.003
HSW	0.002
TPL	0
SigY (PL)	0
E (PL)	0
TSF	0
TSW	0

r.v.	$C_{\sigma\sigma}$
Eccentricity	0.871
SigY (Stf)	0.491
E (Stf)	0.004
HSW	0.002
E (PL)	0.001
TPL	0
TSF	0
SigY (PL)	0
TSW	0

Table 3.8: Mode II: ranking based on sensitivity of predicted strength to perturbations of the standard deviations of the random variables.

r.v.	$C_{\mu\sigma}$
Eccentricity	0.993
SigY (PL)	0.116
Residual Stress	0.006
TPL	0.004
E (PL)	0.003
HSW	0.001
E (Stf)	0.001
TSW	0
TSF	0
SigY (Stf)	0

r.v.	$C_{\sigma\sigma}$
SigY (PL)	0.968
Eccentricity	0.197
Residual Stress	0.153
TPL	0.011
E (PL)	0.008
HSW	0
E (Stf)	0
SigY (Stf)	0
TSF	0
TSW	0

Coefficients $C_{\sigma\sigma_i}$ show the effect of changing the standard deviations of the random variables on the c.o.v. of the strength. It is observed that the most important uncertainties for Mode I, ranked in terms of importance, are in the eccentricity and yield stress of the stiffener. These results are consistent with the results from parametric analysis. For Mode II, the yield stress of the plate is the most important random variable while the eccentricity and residual stress are less important, although they are not negligible. All other uncertainties are negligible.

Table 3.9: Mode I: ranking based on sensitivity of predicted strength to weighted perturbations of the means of the random variables.

r.v.	$W_{\mu\mu}$
SigY (Stf)	0.851
HSW	0.392
E (Stf)	0.253
TSF	0.161
E (PL)	0.129
TPL	0.106
Eccentricity	0.066
TSW	0.006
SigY (PL)	0.001

r.v.	$W_{\sigma\mu}$
HSW	0.729
E (Stf)	0.465
TSF	0.335
E (PL)	0.281
TPL	0.238
Eccentricity	0.060
SigY (Stf)	0.031
TSW	0.008
SigY (PL)	0

Table 3.10: Mode II: ranking based on sensitivity of predicted strength to weighted perturbations of the means of the random variables.

r.v.	$W_{\mu\mu}$
TPL	0.800
SigY (PL)	0.412
E (PL)	0.399
HSW	0.138
Residual Stress	0.093
E (Stf)	0.040
Eccentricity	0.029
TSF	0.022
TSW	0.004
SigY (Stf)	0

r.v.	$W_{\sigma\mu}$
SigY (PL)	0.840
HSW	0.510
TSW	0.132
Residual Stress	0.085
TSF	0.072
Eccentricity	0.063
E (PL)	0.030
E (Stf)	0.024
TPL	0.008
SigY (Stf)	0

A summary of the most important variables in each case is given in Table 3.11 for Mode I and Table 3.12 for Mode II. The three most important variables are listed in the order of greatest impact on the predicted strength mean and coefficient of variation.

Table 3.11: Mode I summary of results for sensitivity coefficient rankings.

Sensitivity Coefficient	Most important random variable	2nd most important random variable	3rd most important random variable
$C_{\mu\mu}$	Stiffener Yield Stress	Stiffener Web Height	Stiffener Young's Modulus
$C_{\sigma\mu}$	Stiffener Web Height	Stiffener Young's Modulus	Plate Thickness
$C_{\mu\sigma}$	Eccentricity	Stiffener Yield Stress	Stiffener Young's Modulus
$C_{\sigma\sigma}$	Eccentricity	Stiffener Yield Stress	Stiffener Young's Modulus
$W_{\mu\mu}$	Stiffener Yield Stress	Stiffener Web Height	Stiffener Young's Modulus
$W_{\sigma\mu}$	Stiffener Web Height	Stiffener Young's Modulus	Stiffener Flange Thickness

Table 3.12: Mode II summary of results for sensitivity coefficient rankings.

Sensitivity Coefficient	Most important random variable	2nd most important random variable	3rd most important random variable
$C_{\mu\mu}$	Plate Thickness	Plate Yield Stress	Plate Young's Modulus
$C_{\sigma\mu}$	Plate Yield Stress	Plate Thickness	Stiffener Web Height
$C_{\mu\sigma}$	Eccentricity	Plate Yield Stress	Residual Stress
$C_{\sigma\sigma}$	Plate Yield Stress	Eccentricity	Residual Stress
$W_{\mu\mu}$	Plate Thickness	Plate Yield Stress	Plate Young's Modulus
$W_{\sigma\mu}$	Plate Yield Stress	Stiffener Web Height	Stiffener Web Thickness

3.4 Results for Modeling Uncertainty

Here the objective was to estimate the uncertainty in predicting strength due to idealizations and approximations in theory. In Section 3.4.1, modeling uncertainty is quantified by evaluating the mean and standard deviation of modeling bias (equation 2-4). Only stiffened panels that are subjected to purely axial load are considered because this is the only case for which sufficient experimental data is available. The three data sets described in Section 3.2 are used: those of Faulkner (77) and of Michelutti and Murray (77). Then, in Section 3.4.2, the results are compared with those of Faulkner's own analysis of the data, and with the results of another study by Bonello.

Uncertainty due to panel end rotational restraint is not addressed here due to the complexity this would introduce. This type of uncertainty creates discrepancy between experimental and actual structural strength, when the structure is part of a ship. This discrepancy may be addressed using experimental bias (equation 2-3). To compare theory to experiment thoroughly would require a large amount of experimental data, which does not exist at this time. The transverse structure is generally weak in torsion in ship structures and provides little rotational restraint to the panel ends. The presence of lateral pressure may cause the panels to behave as if clamped, but the usual design approach is to assume simply supported. This is more often closer to reality and is conservative.

3.4.1 Estimation of modeling uncertainty

There are only two sets of data that are sufficiently complete to obtain predictions of modeling uncertainty - the parametric series and the nominally identical series of Faulkner (77). We first estimated the total bias and then derived the modeling bias using equations 2-1 and 2-13, together with the estimates of random bias from Section 3.3. We did not estimate the modeling bias directly from equation 2-4 because this equation requires prediction of the strength analytically for each panel, and Faulkner did not provide sufficient information on the location of the applied load to do so.

Parametric series

Table 3.2 presents the geometry and material properties of the panels. Two of the panels tripped and the others all failed in Mode II. Three of the latter panels had significantly different geometry than the rest; their stiffeners had no flange. Therefore, we only considered the remaining nineteen panels.

Table 3.13 presents the nominal and measured strength, and the total bias of each of the nineteen panels. The theoretical strengths are not presented. The theory expects the loading to be centered on the elastic neutral axis. As the loading was applied midway between the elastic neutral axis and the neutral axis at failure, consistent predictions with measurements were not forthcoming. Attempts were made to include loading alignment in the panel eccentricity with mixed success. Thus, to preclude adding to the modeling uncertainty through further approximations, we decided to use only total bias results for the parametric series data. Figure 12 shows the correlation between experiments and nominal values of the ultimate stress divided by the yield stress. Table 3.14 presents the nominal values of the parameters of each panel that we used to predict nominal strength.

Table 3.13: Estimation of total bias from parametric series.

Panel	Nominal strength Mode II	Experimental Strength Mode II.	Total bias
1	203.71	255.71	1.26
2	168.31	186.92	1.11
3	134.81	Tripped	
4	121.33	131.54	1.08
5	199.50	196.11	0.98
6	164.72	185.25	1.12
7	131.93	Tripped	
8	118.90	129.78	1.09
9	188.51	179.00	0.95
10	155.42	162.36	1.04
11	124.89	120.54	0.97
12	113.60	114.24	1.01
13		No flange	
14	165.83	190.24	1.15
15	130.84	134.28	1.03
16	116.88	126.50	1.08
17		No flange	
18	162.64	152.85	0.94
19	128.25	145.25	1.13
20	114.72	117.39	1.02
21		No flange	
22	151.92	128.24	0.84
23	119.99	122.26	1.02
24	108.82	94.46	0.87

Table 3.14: Nominal values of material properties and geometry of Panels in Parametric Series.

Model	a (mm)	b(mm)	TPL(mm)	HSW(mm)	TSW(mm)	BSF(mm)	TSF(mm)
1	244.00	88.40	3.00	17.43	4.40	12.70	6.40
2	384.00	147.00	2.50	30.38	4.40	12.70	6.40
3	638.00	221.00	2.50	54.10	4.40	12.70	6.40
4	523.00	236.00	2.00	43.55	4.40	12.70	6.40
5	488.00	88.40	3.00	17.43	4.40	12.70	6.40
6	767.00	147.00	2.50	30.38	4.40	12.70	6.40
7	1275.00	221.00	2.50	54.10	4.40	12.70	6.40
8	1046.00	236.00	2.00	43.55	4.40	12.70	6.40
9	732.00	88.40	3.00	17.43	4.40	12.70	6.40
10	1151.00	147.00	2.50	30.38	4.40	12.70	6.40
11	1913.00	221.00	2.50	54.10	4.40	12.70	6.40
12	1570.00	236.00	2.00	43.55	4.40	12.70	6.40
13	262.00	88.40	3.00	26.40	4.40	0.00	0.00
14	244.00	177.00	3.00	17.45	4.40	12.70	6.40
15	422.00	265.00	3.00	33.90	4.40	12.70	6.40
16	384.00	295.00	2.50	30.48	4.40	12.70	6.40
17	523.00	88.40	3.00	26.40	4.40	0.00	0.00
18	488.00	177.00	3.00	17.45	4.40	12.70	6.40
19	843.00	265.00	3.00	33.90	4.40	12.70	6.40
20	767.00	295.00	2.50	30.48	4.40	12.70	6.40
21	785.00	88.40	3.00	26.40	4.40	0.00	0.00
22	732.00	177.00	3.00	17.45	4.40	12.70	6.40
23	1265.00	265.00	3.00	33.90	4.40	12.70	6.40
24	1151.00	295.00	2.50	30.48	4.40	12.70	6.40

Notes:

1. The following assumptions were made regarding nominal values:
   a. Yield stress of stiffener and plate = 240 N/mm^2
   b. Tension zone parameter due to residual stress = 2.772.
   c. The nominal eccentricity=a/1500
2. Stiffeners of panels 13, 17 and 21 have no flange

The mean value of the samples of total bias in Table 3.13 is 1.0367, the standard deviation 0.10 and the c.o.v. 9.7%. The standard deviation of mean total bias is 0.023 which is only about 2% of the mean. This means that the sample size was large enough for estimating the mean bias accurately. From equations 2-1 and 2-13, we found that the mean value of modeling bias is 1.05 and its c.o.v. 7.4%. Therefore, the analytical method that we used to predict strength was conservative, and, on the average, underestimates strength by approximately 5%.

Nominally identical series

This set consisted of 13 nominally identical panels. Nine of these panels failed in Mode II and four of them (panels 8-11) failed in Mode I. Table 3.15 presents the stress at failure and total bias of the first group of panels. The nominal failure stress was found to be equal to 158.47 N/mm^2. Using the results in Table 3.15 we found that the mean total bias was 1.1562 and its c.o.v. 6.555%. From equations 2-1 and 2-13, we found that the mean modeling bias is 1.17 and its c.o.v. 1.95%. We believe that the c.o.v. of modeling bias is unrealistically low because the panels were nominally identical, which means that the scatter of the ratio of experimental results vs. predictions was too low.

Table 3.15: Experimental results and total bias from nominally identical series.

Panel	Measured Collapse Load (KN)	Measured Stress at Failure (MPa)	Total Bias
1	717	178.5012	1.126368
2	717	178.5012	1.126368
3	786	195.6791	1.234764
4	751	186.9657	1.179781
5	725	180.4928	1.138936
6	646	160.8253	1.104831
7	705	175.5137	1.107517
12	804	200.1603	1.263041
13	773	192.4427	1.214341

The c.o.v. of the measurements of strength of the four panels that failed in Mode II was very low. This is probably because, as explained in Section 3.2.1, these panels were initially very eccentric and they were artificially straightened by heating them. These unusual statistics seem to confirm our decision not to include these panels.

Michelutti's results

Michelutti and Murray (77) tested fifteen panels, thirteen of which were nominally identical. Three panels were axially loaded, and the rest were subjected to combined bending and axial loading. Of the three panels that were axially loaded, two failed in Mode II, while the other panel was designed to fail in Mode I. We analyzed only the results of the two panels that failed in Mode II. The eccentricity of one panel, called A6 by Michelutti and Murray, was equal to a/530. The eccentricity of the other panel, called H, was not reported. We assumed that the eccentricity of panel H was a/1500. Table 3.16 compares predicted and measured failure stresses for panels A6 and H. It is observed that theory underestimated the strength of both panels. Modeling bias was about 1.05 for both panels. Since there were only two samples, we did not try to estimate the statistics of bias from this table. However, this data is used to demonstrate the Bayesian method for estimating bias, as described in Hughes et al. (94).

Table 3.16: Predicted and Measured Strength of Panels Studied by Michelutti.

Panel	Predicted Stress at Failure/Yield Stress	Measured Stress at Failure/Yield Stress	Modeling Bias
A6	0.39	0.41	1.05
H	0.62	0.66	1.06

3.4.2 Comparison of estimates of bias with results from other studies

Faulkner (77)

Faulkner (77) evaluated the total and modeling bias on the basis of the results of the nominally identical series. He analyzed the results of all the thirteen panels together, regardless of the mode in which they failed, and regardless of the artificial straightening of four of them, all of which failed in Mode I. Also he neglected any uncertainty in eccentricity. He found the c.o.v. of the total bias to be 10.9%, and the c.o.v. of the random bias to be 5.7%. Then using equation 2-13, he found the c.o.v. of the modeling bias to be 9.3%.

Our results, which were based on nine of these panels, all of which failed in Mode II, are considerably different. We found that the c.o.v. of the total bias is 6.55%, the c.o.v. of the random bias is 6.26%, and the c.o.v. of the modeling bias is 1.95%.

We believe that Faulkner overestimated total bias because he considered panels that failed in Mode I and II together, and that he underestimated random bias because he neglected eccentricity. Using these in equation 2-13 gives an overestimate of the modeling bias. Also it is important to note that, strictly speaking, nominally identical panels are inappropriate for estimating modeling bias and total bias, because their similarity will cause an underestimate of the c.o.v. of total and modeling bias. Therefore, the estimates of bias from the parametric series, presented in Section 3.4.1., are more realistic.

The results discussed in the remaining of this subsection are for failure Mode II and for the case where panels are subjected to axial loads only.

<u>Bonello et al (92)</u>

Bonello et al (92) developed a computer program for predicting the strength of stiffened, multi-span panels using an inelastic beam-column formulation. They compared predictions using this program with a database of measurements from 85 tests on single and multi-span stiffened panels. The panels were subjected to axial compression only. Bonello et al. (92) found that the mean modeling bias was 1.02 and the c.o.v. of modeling bias 8%. They also compared the computer predictions with some data that they called "numerical data" (63 cases), and found a mean bias of 1.05 and a c.o.v. of 5%. They attributed the difference in the c.o.v.'s to the fact that the c.o.v. corresponding to the experiments included the effect of scatter due to experimental errors.

Bonello et al also calculated the mean and c.o.v. of modeling bias for the strength algorithms used by various authorities, based on 23 tests. (They did not indicate whether these tests were a subset of the 85 tests in the database). Table 3.17 presents the results. The estimates from the present study are also included in this Table.

Table 3.17: Comparison of modeling uncertainties of prediction methods used by various authorities and results from present study.

Reference where method for strength prediction is described	Mean Modeling Bias	c.o.v. of Modeling Bias
Bonello (92)	1.10	0.08
BS5400 (82)	1.10	0.13
DnV (87)	1.10	0.16
ECCS (90) (Column approach)	1.08	0.14
ECCS (90) (Orthotropic plate approach)	1.14	0.15
API RP2V (87)	1.34	0.34
Present study	1.05	0.074

Note:

All of the above values are based on the 23 tests except for those of the Present study, which are based on 19 tests from Faulkner's parametric series.

Guedes Soares and Soreide (83)

Guedes Soares and Soreide (83) estimated the statistics of modeling bias for four different prediction methods: Carlsen (80), Dwight and Little (76), Faulkner (75), and Horne and Narayanan (77). They obtained the experimental values from three test series: Horne and Narayanan (76), Horne, Montague and Narayanan (77) and Faulkner (77) (of the latter they only used the results of the parametric series). They also compared predictions from Carlsen's and Faulkner's methods with data they called "numerical data", which were reported by Carlsen (80).

Faulkner's method (75) is based on a Johnson-Ostenfeld approximation together with the effective width approach for plate behavior. This method was also presented in Faulkner et al (73). Moreover, Faulkner (77) compared predictions of this method with results from parametric series tests. The methods of Carlsen (80), Dwight and Little (76), and Horne and Narayanan (77) are based on a Perry-Robertson formulation.

As it happens, Guedes Soares and Soreide (83) chose to deal with the inverse of modeling bias; that is, they used the ratio of experimental/predicted values. Therefore we repeated their analysis in order to obtain the statistics of modeling bias. Table 3.18 presents these statistics for Faulkner's and Carlsen's methods, which were derived using Faulkner's parametric series (Faulkner 77). The bias of the Standard algorithm estimated in Section 3.4.1 is also presented in Table 3.18. In order to obtain results that can be compared with the estimates of bias of the Standard algorithm we used only 19 panels to derive the results in Table 3.18. Specifically, we discarded two panels that failed in tripping in tests and three panels whose stiffeners had no flange (see Table 3.13). Table 3.19 presents the modeling bias of the methods of Carlsen (80), Dwight and Little (76), Faulkner (75), and Horne and Narayanan (77) for each of the stiffener and plate induced collapse modes. It also presents the statistics of bias of these methods obtained by analyzing data on both failure modes together. The estimates in Table 3.19 were based on results in Horne and Narayanan (76) and Horne, Montague, and Narayanan (77).

Table 3.18: Modeling Bias of Carlsen's, Faulkner's and the Standard methods for the test series of Faulkner.

Method	Mean bias	bias c.o.v.
Carlsen (80)	1.18	0.10
Faulkner (77)	1.01	0.07
Standard	1.05	0.07

Table 3.19: Modeling Bias of Carlsen's, Dwight and Little, Faulkner and Horne and Narayanan's methods for the test series of Horne et al.

Method	Stiffener Induced Collapse (Mode I) mean bias	Stiffener Induced Collapse (Mode I) bias c.o.v.	Plate Induced Collapse (Mode II) mean bias	Plate Induced Collapse (Mode II) bias c.o.v.	Modes I and II mean bias	Modes I and II bias c.o.v.
Carlsen (80)	1.04	0.05	1.09	0.08	1.08	0.07
Dwight and Little (76)	0.98	0.08	1.04	0.07	1.03	0.07
Faulkner (75B)	0.95	0.07	1.00	0.06	0.99	0.07
Horne and Narayanan (77)	1.06	0.06	1.06	0.10	1.06	0.09

It is observed that the mean bias of Faulkner's method is closer to one than that of the other methods and its c.o.v. is small, ranging from 6 % to 7 %. The results of this method correlated particularly well with the parametric series tests (Table 3.18). On the other hand this method is not conservative; its average bias is less than one for some tests, which means that it overestimates strength in these tests. Carlsen's method is the most conservative. The average bias of this method for parametric series is 1.18. The results of this method have larger scatter than those of Faulkner's method and those of the Standard method. Dwight's and Little's method and Horne's method are also conservative, and the latter is slightly more conservative than the former. Both methods have small scatter -- their c.o.v.'s are smaller than 10 %.

Guedes Soares and Soreide (83) also compared predictions of Faulkner's and Carlsen's methods with numerical data by Carlsen (80). They found that Carlsen's method correlated better than Faulkner's method with the numerical data.

4.0 CONCLUSIONS

The uncertainty in structural strength prediction may be a result of ambiguity and vagueness in the system. The thesis focused on the ambiguous component which is the result of random and modeling uncertainty; vagueness was briefly discussed. A methodology was presented by which these uncertainties may be measured (Section 2.1). This methodology is applicable to a well defined, or crisp, failure mode. This includes failures resulting from material yield, buckling, or collapse. Modes of failure such as serviceability can be analyzed, but introduce added uncertainty due to vagueness in the failure definition.

A method of determining the relative impact of the basic strength parameters on the random uncertainty was presented (Section 2.2). Three different ranking methods were presented with a total of seven variations. This method was applied to the compressive failure of a longitudinally stiffened panel in failure modes I and II. The following ranking is for Faulkner's (77) nominally identical series panels only. For stiffener induced collapse (Mode I) the most important basic strength parameters are the stiffener yield strength, the eccentricity of the panel, and the height of the stiffener. The important variables for plate induced collapse (Mode II) are the yield strength of the plate, the thickness of the plate, and the eccentricity of the panel.

The methods of determining the random and modeling uncertainties were demonstrated for the axial compressive failure of longitudinally stiffened panels, for plate (Mode I) and stiffener (Mode II) initiated failure. The random uncertainty was estimated for Faulkner's (77) nominally identical series. For pure axial loading, the c.o.v. of the Mode I strength was found to be 10.2% and for Mode II, a c.o.v. of 6.33%. Plots are presented of the interaction between the axial strength of the panels and the lateral pressure for Modes I and II, for four different applied, transverse in-plane loadings. For these load combinations the random bias ranged from 1.1 to 1.5 for Mode I and from 1.0 to 1.1 for Mode II. The c.o.v.'s ranged from 3 % to 15 % for Mode I and from 2 % to 9 % for Mode II.

The modeling uncertainties were evaluated for Mode II failure of axially loaded, longitudinally stiffened panels. The standard algorithm predictions for Faulkner's parametric series gave a modeling bias mean of 1.05 with a c.o.v. of 7.4 %. The standard algorithm predictions for the Michelutti panels gave a modeling bias of 1.05 also.

A comparison with other studies was undertaken. The results from Bonello (92) gave a mean modeling bias of 1.02 and a c.o.v. of 8 %. In a comparison with other prediction algorithms for a different experimental sample set, Bonello reported mean modeling biases ranging from 1.08 to 1.34. Guedes Soares and Soreide (92) gave results for Faulkner's parametric series. The mean modeling bias for several strength prediction methods ranged from 1.01 to 1.18 with c.o.v.'s ranging from 7 to 10 %. A variety of algorithm predictions for other experimental data were reported. For Mode I and Mode II, the mean modeling bias ranged from 0.99 to 1.08 with c.o.v.'s ranging from 6 to 10 %.

The accuracy of the estimations of random and modeling uncertainty is limited by the availability of appropriate experimental data. The findings discussed above are limited to the specific algorithms and data sets used in the analysis. The results are helpful to gaining insights into levels of uncertainty possible in structural strength design and analysis, whether for use deterministically or in a reliability-based format. Greater efforts in generating experimental test data are needed in order to quantify uncertainty for use by the practician.

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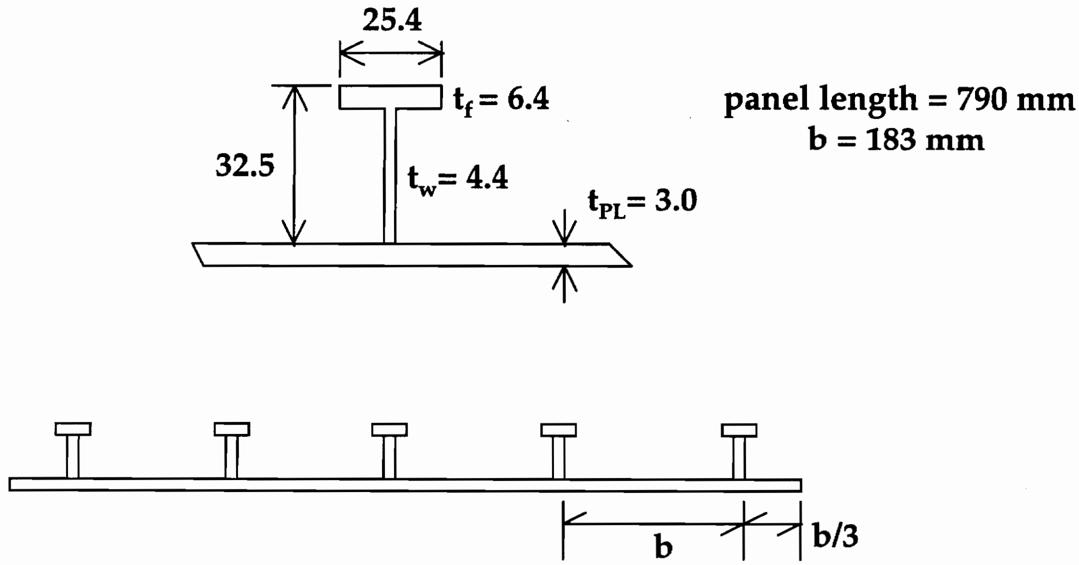
FIGURES

Faulkner's Nominally Identical Series

Cross section



dimensions in mm

Figure 1 Nominally Identical Series Panel Configuration

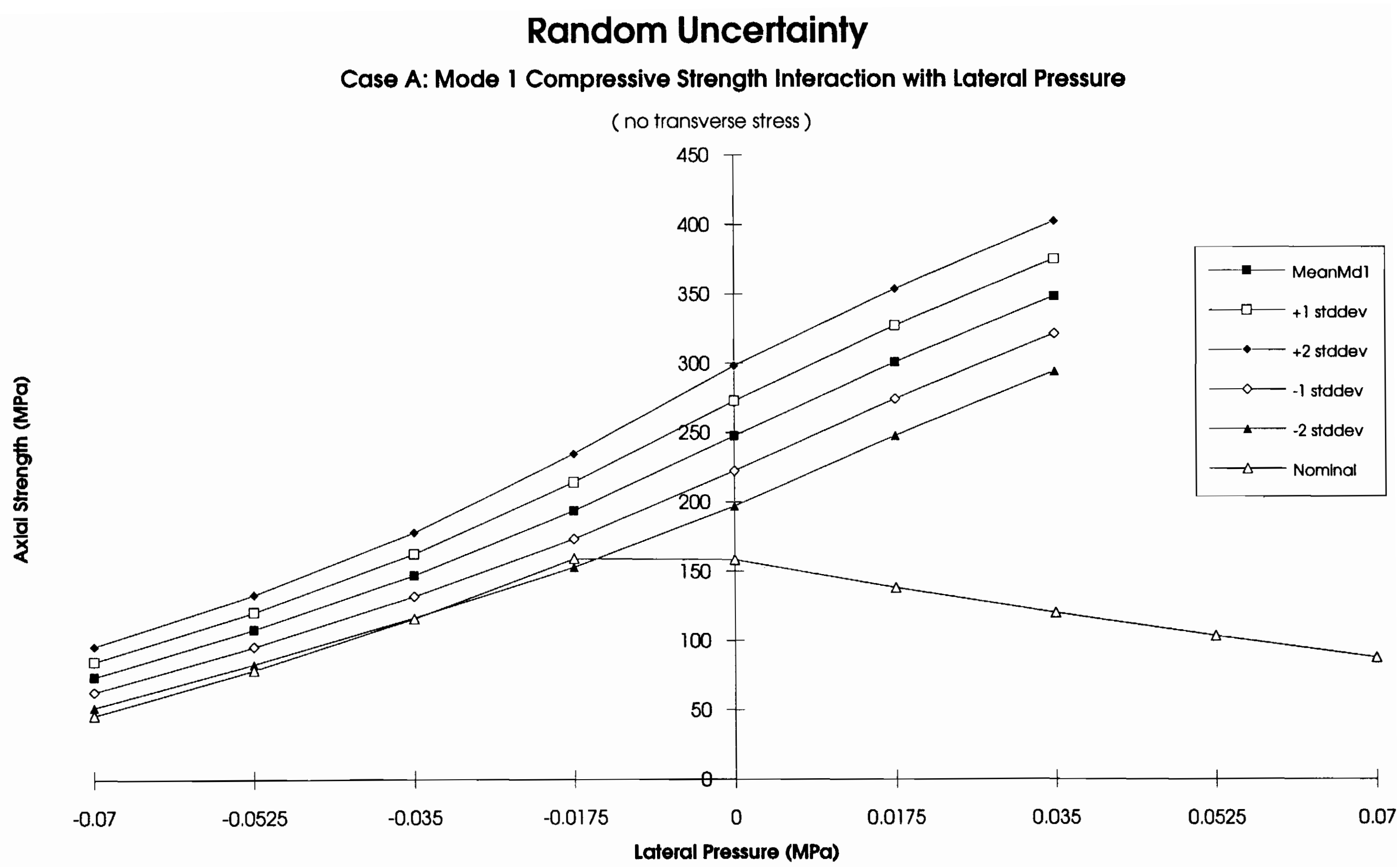


Figure 2 Case A, Mode I Failure: Effect of Random Uncertainties on Strength (negative eccentricity)

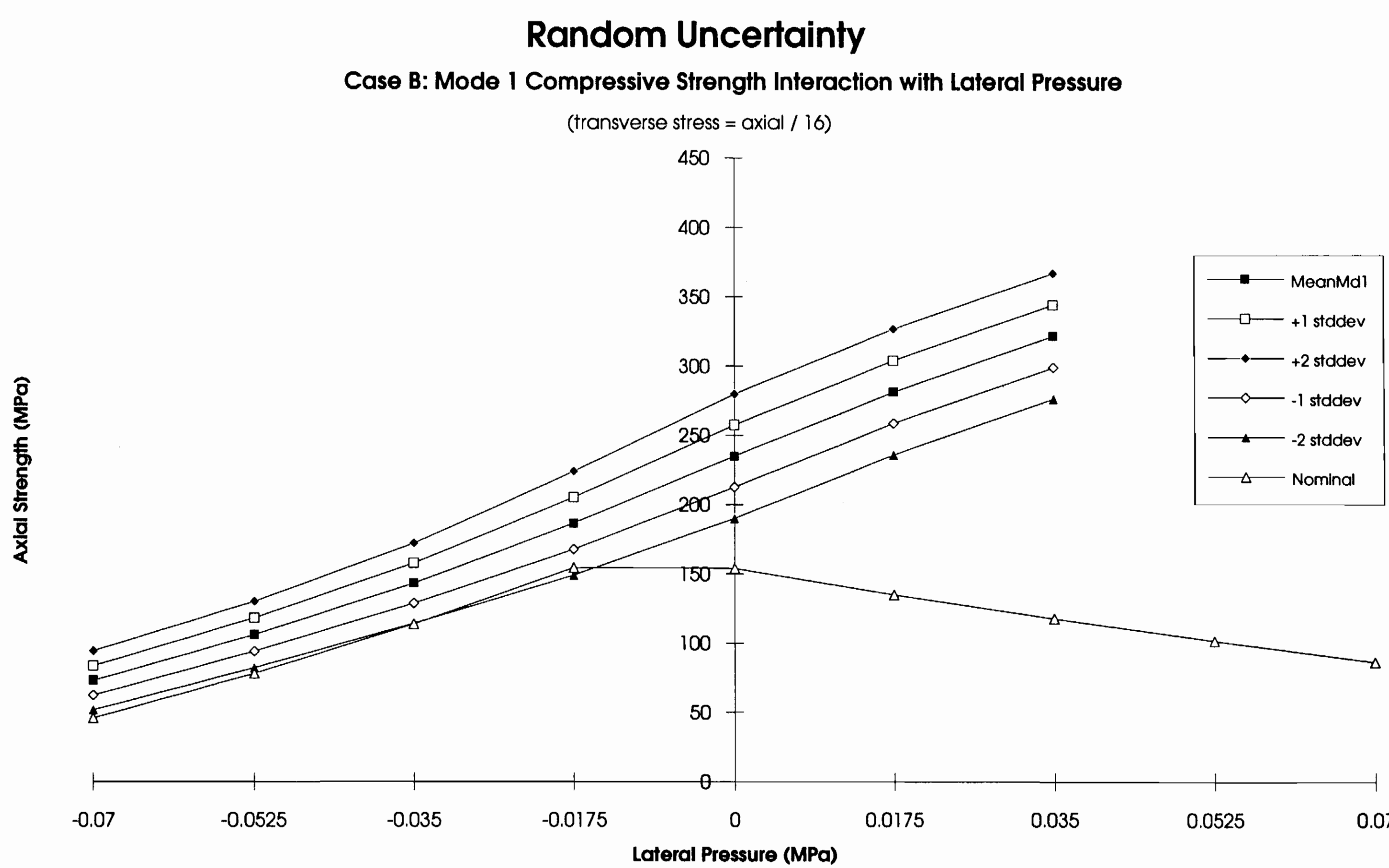


Figure 3 Case B, Mode I Failure: Effect of Random Uncertainties on Strength (negative eccentricity)

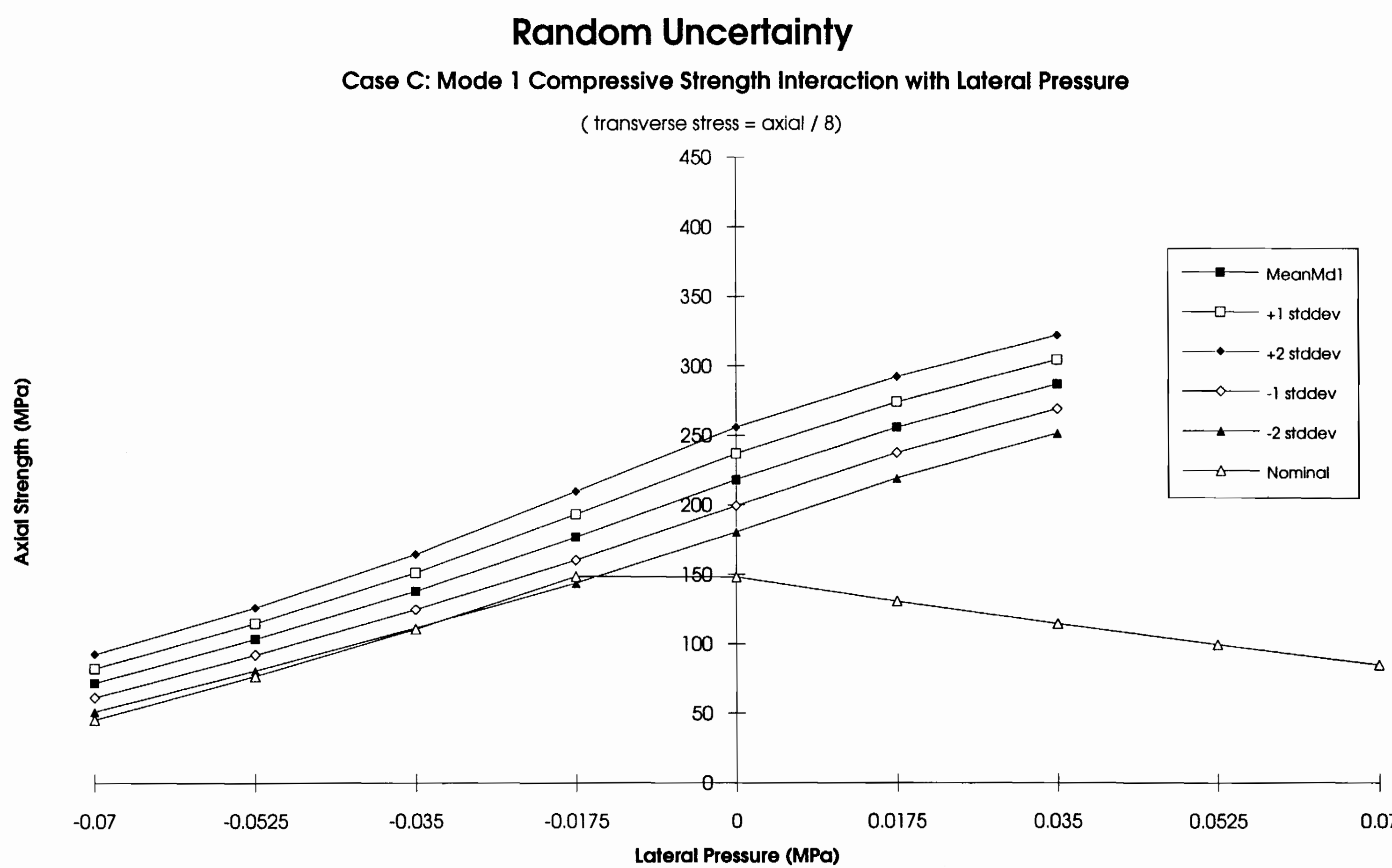


Figure 4 Case C, Mode I Failure: Effect of Random Uncertainties on Strength (negative eccentricity)

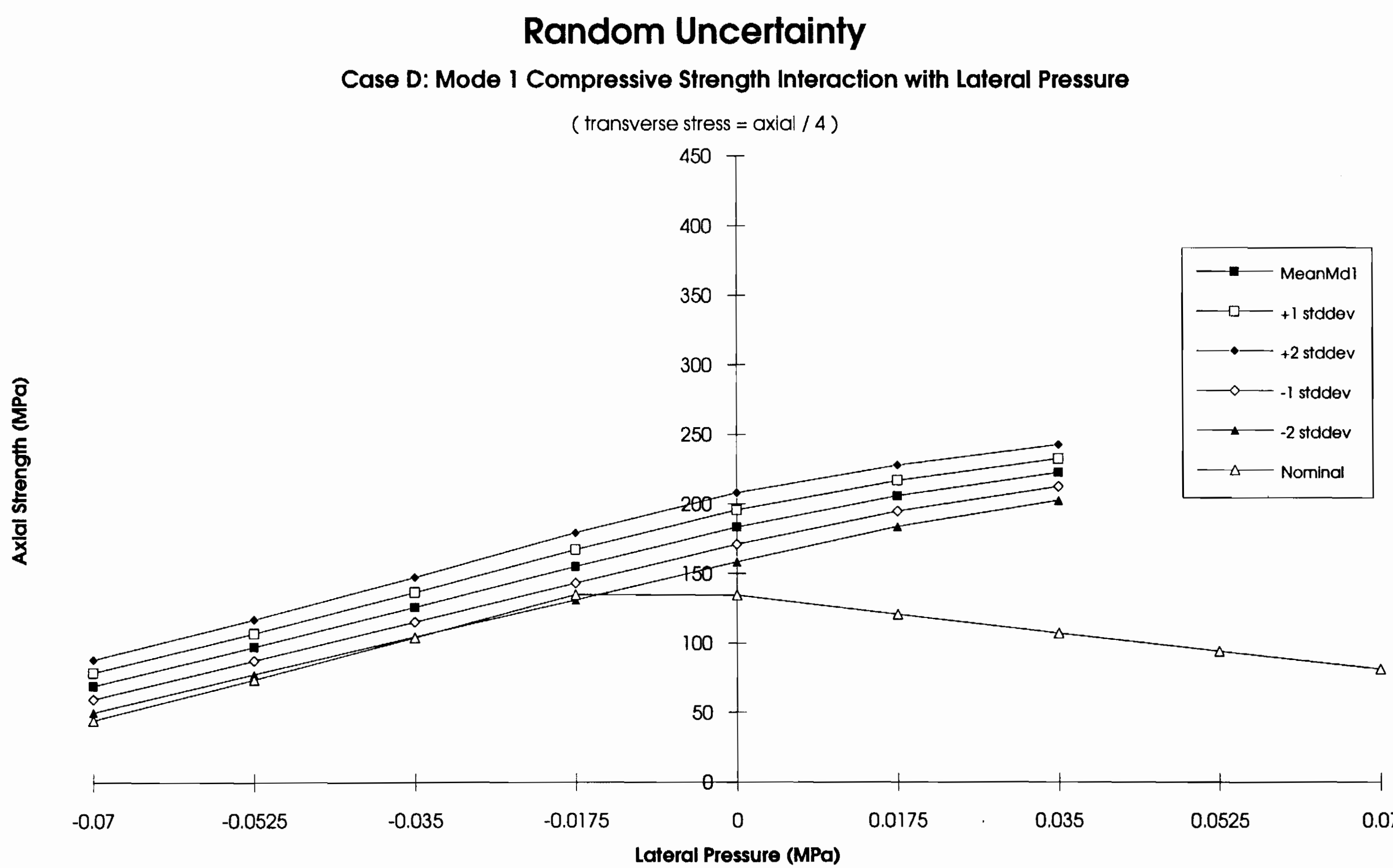


Figure 5 Case D, Mode I Failure: Effect of Random Uncertainties on Strength (negative eccentricity)

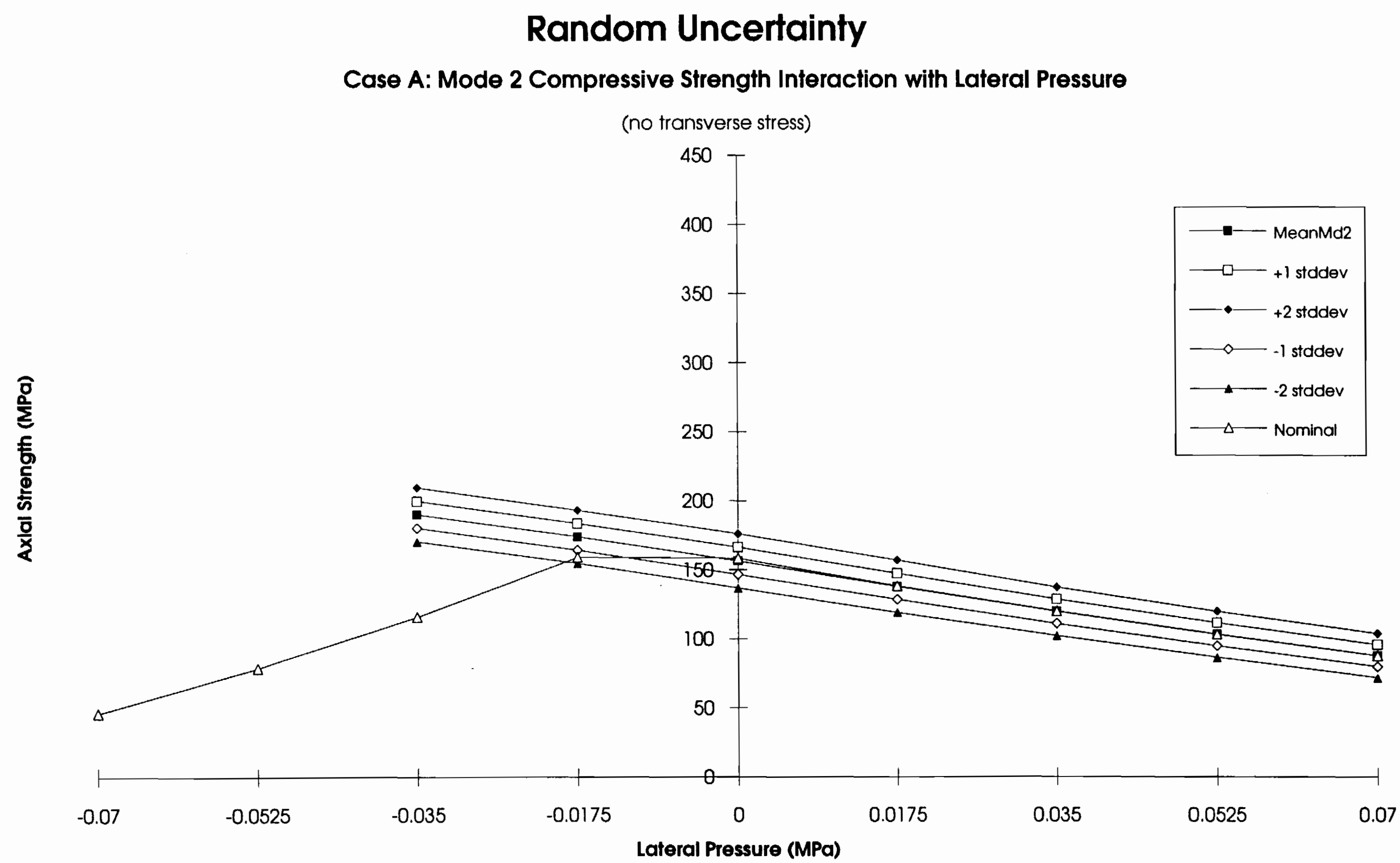


Figure 6 Case A, Mode II Failure: Effect of Random Uncertainties on Strength (positive eccentricity)

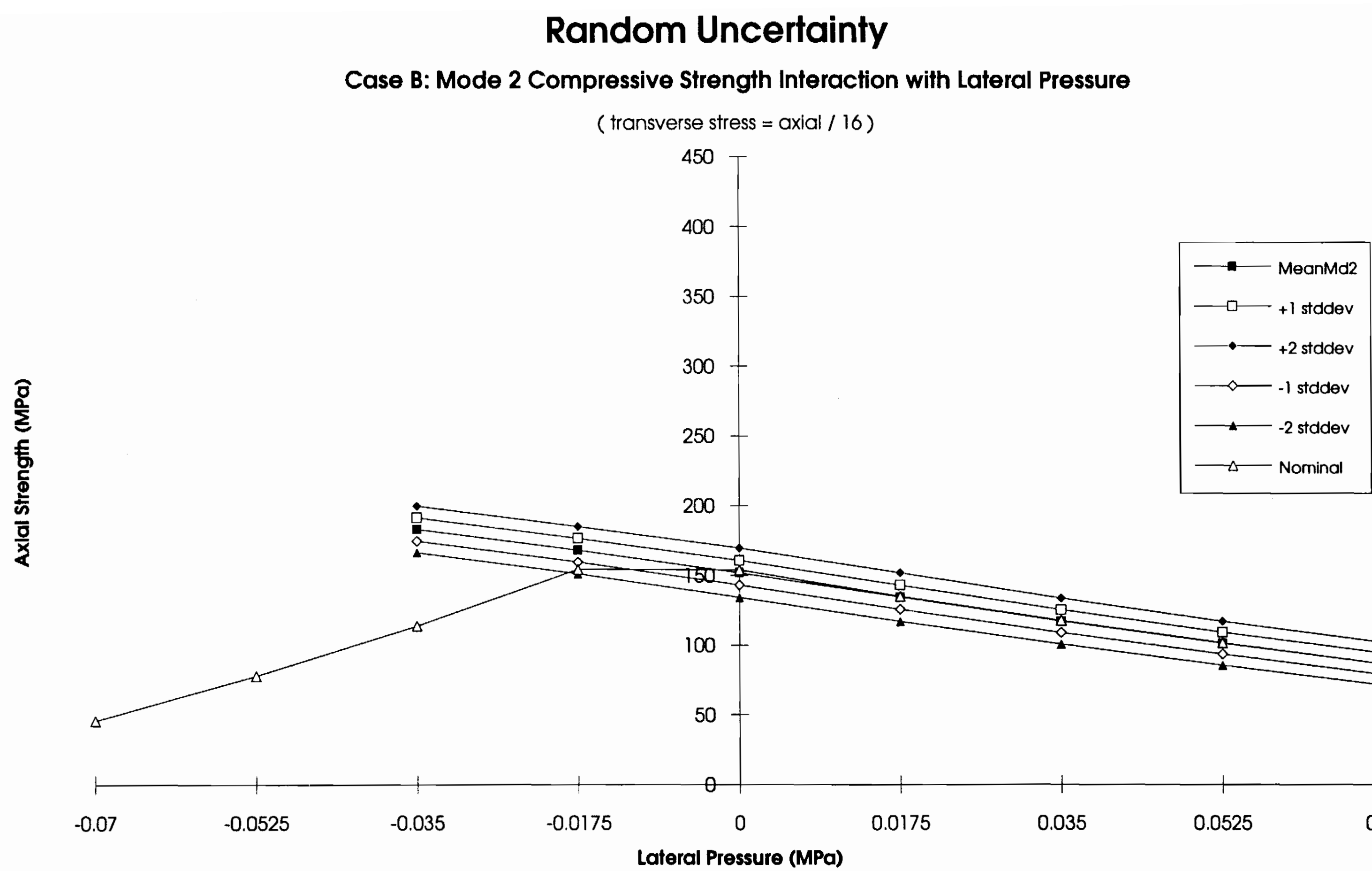


Figure 7 Case B, Mode II Failure: Effect of Random Uncertainties on Strength (positive eccentricity)

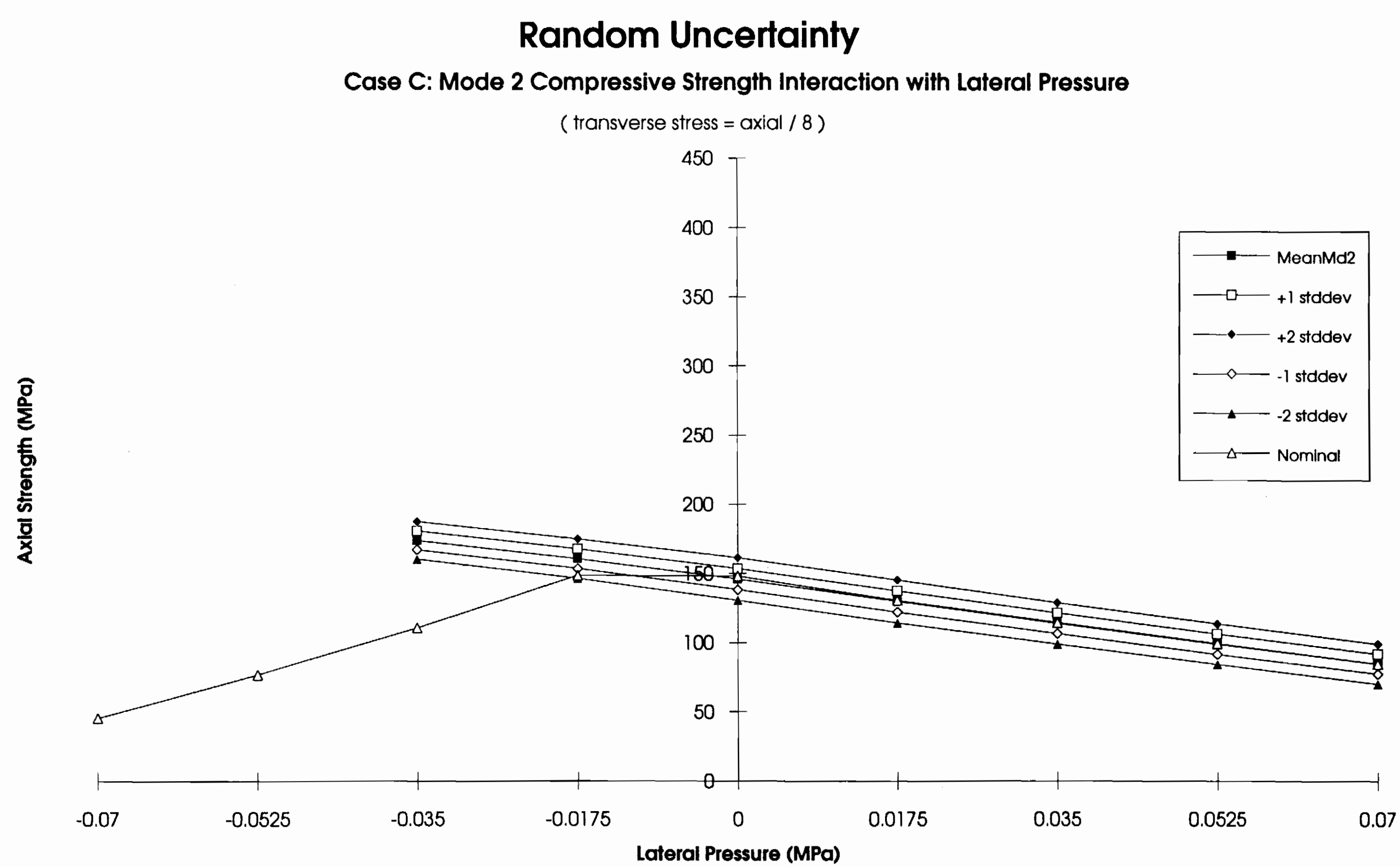


Figure 8 Case C, Mode II Failure: Effect of Random Uncertainties on Strength (positive eccentricity)

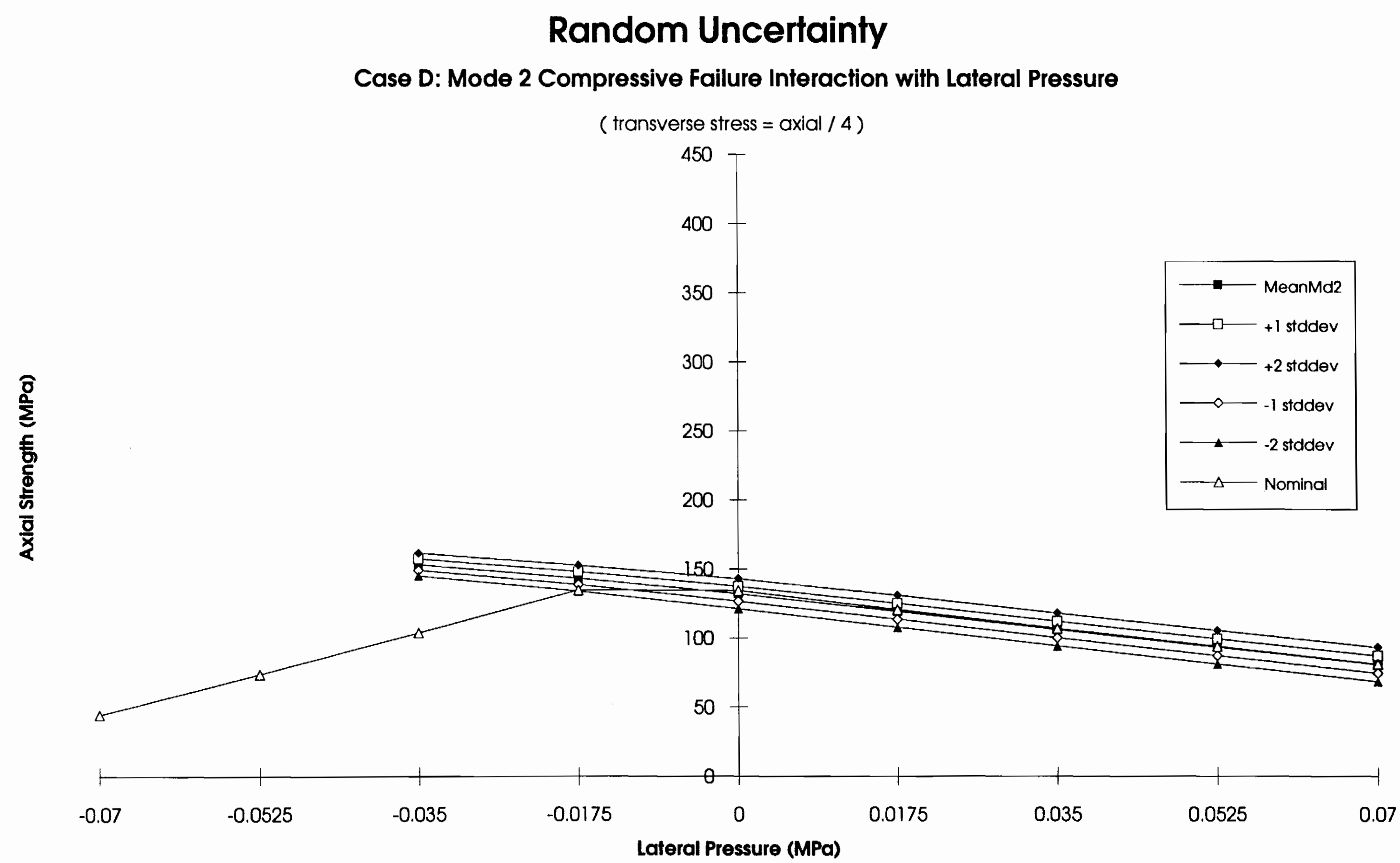


Figure 9 Case D, Mode II Failure: Effect of Random Uncertainties on Strength (positive eccentricity)

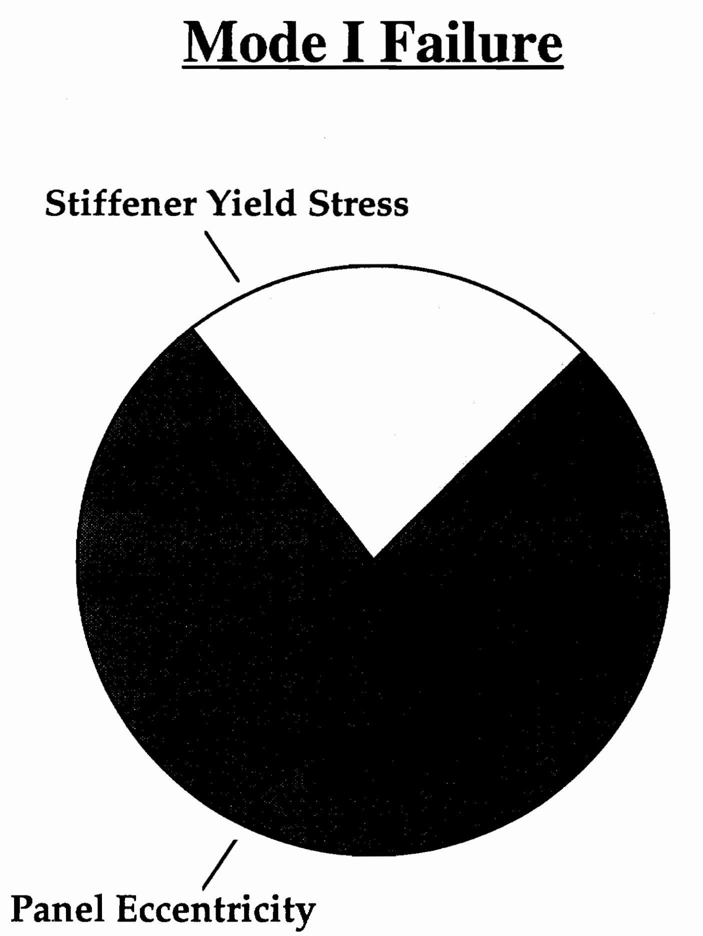


Figure 10 Mode I, Parametric Analysis: Contributions of Basic Strength Parameters to Random Uncertainty in Strength.

Mode II Failure

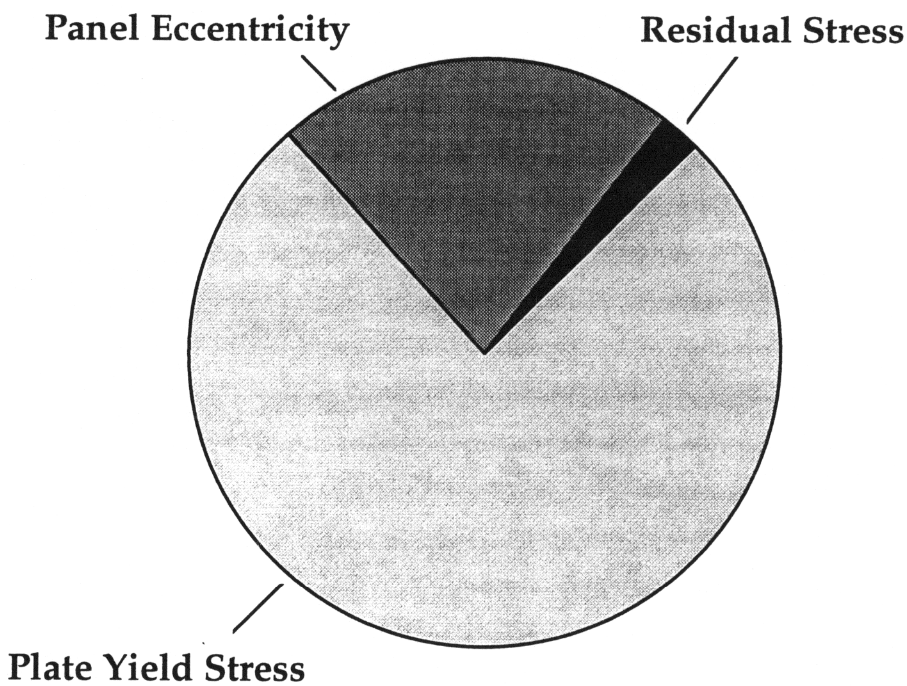


Figure 11 Mode II, Parametric Analysis: Contributions of Basic Strength Parameters to Random Uncertainty in Strength.

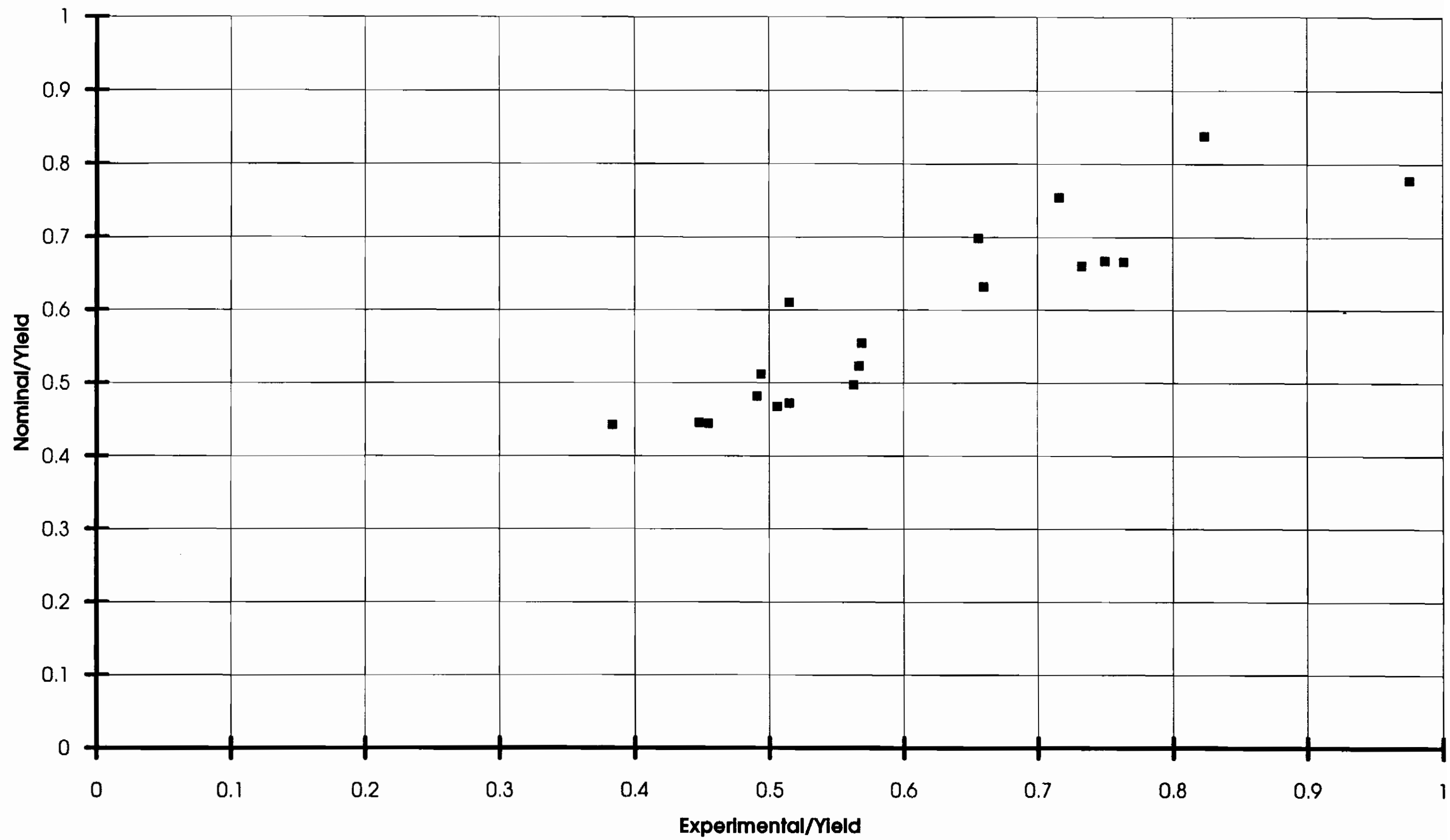


Figure 12 Correlation Between Experimental and Nominal Values of Strength for Parametric Series

VITA

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