Effects of Multiple Presence & Monitoring Period on Bridge Health Monitoring

Transfund New Zealand Research Report No. 175

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Acknowledgments

This project has been greatly assisted by the support and co-operation of many people and organisations. Infratech Systems & Services Ltd (Infratech) acknowledges the assistance of the technical reviewers, Mr Frank McGuire (Transit New Zealand), Mr Howard Chapman (Opus International Consultants Ltd), and Dr John Fenwick (Department of Main Roads, Queensland), for their valuable insight and assistance with the development of this report. The support and assistance of many people were required to complete the field work, in particular Mr Derek Dumbar (TD Haulage), Mr Colin Knaggs (Transit New Zealand), Mr Bill Blair (Worley Consultants), the staff of Scott Technical, and Mr Scott Verevis (Opus International Consultants). The assistance and support of the staff of Deloitte Touche Tohmatsu is also appreciated.

Infratech is grateful for the support of Transfund New Zealand, and of their staff involved in the project.

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Introduction

Bridge Health Monitoring is a method of evaluating the ability of a bridge to perform its required task (also called "Fitness for Purpose") by monitoring the response of the bridge to the traffic loads it has to withstand.

This report is Stage 3 of a research project carried out between 1998 and 2000, that involved the long-term Health Monitoring and Fitness For Purpose assessment of the Atiamuri Bridge over the Waikato River, on State Highway 1N between Tokoroa and Taupo, North Island of New Zealand. The objectives of Stage 3 were to:

1. Understand the effect of multiple-presence events on the Health Monitoring process;
2. Understand the effect of monitoring duration on the Health Monitoring process;
3. Refine and define the Health Monitoring data analysis process.

After considering various bridge sites, the Atiamuri Bridge was selected for long-term health monitoring. This bridge was monitored for approximately 17 months, although only data from approximately 9 months was used in this analysis. Over 95 000 heavy vehicle events were included in the sample population. Data was automatically retrieved from site before it was filtered and processed.

General Health Monitoring Issues

The Health Monitoring process, as applicable to short span bridges, was investigated during the project, and a refined approach is given in the recommendations of this report. Efficient Health Monitoring requires placement of instrumentation in the most appropriate locations (i.e. those having greatest influence on bridge capacity or performance). To identify these locations structural analysis of the bridge was used. While Health Monitoring can be carried out in isolation, it is likely to be more efficient and effective when combined with the results of analytical techniques. The use of a known vehicle during Health Monitoring can add substantial value to the data gathered for a limited additional cost.

While the Fitness for Purpose Evaluation (FPE) provides a convenient means of evaluating and comparing the adequacy of bridges, assumptions are implicit in each FPE. These need to be outlined when an FPE is reported to ensure that Health Monitoring results are correctly interpreted in the broader context of bridge evaluation.

The Health Monitoring process must be managed by an experienced engineer with a sound understanding of the design and behaviour of structures, experimental techniques and the Health Monitoring process. Health Monitoring is different in nature to existing rating and posting evaluation processes, and can be used to complement the total bridge evaluation process, for both asset management and bridge engineering procedures.

Monitoring Duration

Based on the results of this investigation, a population of 1000 single heavy vehicle events is recommended as an appropriate size upon which to base most Health Monitoring investigations. Sample sizes as small as 100 single heavy vehicle events can provide good results, and no major detrimental effects (apart from increased cost) were incurred in obtaining sample sizes much larger than 1000 events. Ideally this population of events should include a spectrum of "heavy vehicles" from light trucks to the heavier vehicles using the route. Where traffic effects are seasonal, the Health

Monitoring programme needs to be designed accordingly. Engineering judgement, and an understanding of Health Monitoring in the context of overall bridge evaluation, are both required in order to gain maximum benefit from Health Monitoring results.

Multiple Presence & Fitness for Purpose Evaluation

Bridge evaluation requires the estimation of the Ultimate Traffic Load Effect (UTLE). The Transit New Zealand Bridge Manual (1994) assumes that the UTLE is the result of multiple-presence events. The spectrum of single heavy vehicle events captured during Health Monitoring can be used to predict the load effects of the "extreme" single heavy vehicle event. In the case of multiple-lane short-span bridges, the load effects for different lanes can then be combined using the principle of superposition to determine the UTLE.

Two methods of estimating UTLE were identified as appropriate. They are:

1. Correlated Upper Bound (CUB) method. This assumes that multiple extreme events with similar probability of occurrence happen simultaneously in adjacent lanes. A reduction factor may be used to adjust the magnitude of this calculated UTLE (in accordance with the Bridge Manual) to allow for the reduced probability of simultaneous occurrence.
2. Independent Upper Bound (IUB) method. This assumes that the magnitude of the UTLE in one lane will be independent of the multiple-presence event in the adjacent lane, and the UTLE estimate is based on the statistical relationships developed during Health Monitoring.

The CUB method is consistent with the existing Bridge Manual method and is the more conservative of the two approaches. The UTLE estimated using the IUB method will be lower than that using the CUB method, but should only be used when events in one lane are known to be statistically independent of events in the other lanes. This will be generally true for two-lane two-way bridges (normal roads), but may not be the case for multiple-lane one-way bridges (typical of motorways, where multiple lanes of traffic travelling in the same direction are carried by a bridge). The IUB method should not be used in this latter case unless further research can substantiate the validity of using it.

Abstract

Bridge Health Monitoring is a method of evaluating the ability of a bridge to perform its required task (also called "Fitness for Purpose") by monitoring the response of the bridge to the traffic loads it has to withstand.

This report is Stage 3 of a research project carried out between 1998 and 2000, that has involved the long-term Health Monitoring and Fitness For Purpose assessment of the Atiamuri Bridge over the Waikato River, on State Highway 1N between Tokoroa and Taupo, North Island of New Zealand.

The investigation had the principal purposes of investigating and refining the Health Monitoring methodology for New Zealand road bridges. Issues such as the necessary sample size, duration of monitoring, effect of multiple-presence events, and appropriate methodologies for determining the Ultimate Traffic Load Effect (UTLE) were investigated.

1. Introduction

Bridge Health Monitoring is a method of evaluating the ability of a bridge to perform its required task. This method involves monitoring the response of a bridge to its normal environment, in particular to the traffic loading. Subsequently this data is processed, and used to evaluate the bridge's "Fitness for Purpose".

Bridge Health Monitoring involves a hybrid mix of instrumentation technology, data processing, and conventional bridge analysis and evaluation techniques. It has not been used previously in New Zealand as a systematic bridge evaluation technique. Consequently a project was conceived with the following objectives:

1. To develop an appreciation of a sample of the existing New Zealand Bridge infrastructure;
2. To develop rational guidelines for evaluating the Fitness for Purpose of New Zealand road bridges based on sound engineering principles;
3. To identify and understand the reasons for differences between the Fitness for Purpose Evaluation (FPE) and traditional analytical ratings;
4. To provide validation and data inputs for improving bridge design and evaluation procedures.

The project was divided into four stages so that the Health Monitoring process could be developed, refined, and documented. Table 1.1 summarises the rationale of each of the four stages of the research project.

Stage 1 of the project involved a preliminary study to plan the remainder of the research project in detail.

Stage 2 involved sampling a range of bridges to allow the investigation of the effect of Health Monitoring evaluations across a representative sample of New Zealand's bridge population. These projects used short-term Health Monitoring, which was believed to be adequate. Evaluation of the Health Monitoring approach required differences between the results of conventional bridge evaluation and those of a Health Monitoring evaluation to be determined for typical bridges.

Stage 2 results for the Atiamuri Bridge showed that composite action between the deck and stringers was breaking down, and that the stringers were governing bridge capacity. The kerbs and guardrails were also found to be contributing to the strength of the bridge.

Stage 3 results are presented in this report, and are of the long-term Health Monitoring of the Atiamuri Bridge, carried out between 1998 and 2000. The objectives of this stage were to:

1. Understand the effect of multiple-presence events on Health Monitoring results;
2. Understand the effect of monitoring duration on Health Monitoring;
3. Refine and define the Health Monitoring data analysis process.

Table 1.1 Summary of overall research project.

Stage	Description	Rationale & Objectives
1	Preliminary study	Identify issues and conduct detailed design of research project.
2	Short-term Health Monitoring	Short-term Health Monitoring was conducted on a total of 10 bridges on New Zealand state highways, covering a range of bridge types, ages, conditions and environments. This population of 10 bridges was selected to be representative of the New Zealand bridge population, thus providing an appropriate basis to compare conventional bridge evaluation with the bridge Health Monitoring techniques under development. Specific objectives were: • Evaluate a sample of the existing infrastructure stock; • Compare conventional fitness for purpose rating of a sample of bridges with health monitoring ratings.
3	Long-term Health Monitoring	One of the 10 bridges (Atiamuri) was monitored over a 1-year period to: • Identify the effect of multiple-presence events on health monitoring results; • Evaluate the effect of monitoring time on health monitoring results; • Investigate variation in traffic effects over a longer time base; • Refine the Health Monitoring approach.
4	Consolidation of study	Consolidate results of research project, and develop Health Monitoring Guidelines.

After considering various alternative bridge sites, the Atiamuri Bridge over the Waikato River, on State Highway 1N (SH 1N) between Tokoroa and Taupo, in the North Island of New Zealand, was selected for long-term Health Monitoring. While the emphasis in Stage 3 was on developing and refining the Health Monitoring process, issues involving bridge behaviour were also investigated and are discussed.

The report discusses theoretical and practical background issues, before presenting the long-term health monitoring results. These have led to a review of the Health Monitoring process and, as a result, a refined Health Monitoring methodology is recommended. This methodology is focused on short span bridges where the critical loading corresponds to one heavy vehicle per lane. The methods presented require extension to be applicable to bridges where the critical load cases correspond to multiple heavy vehicles per lane.

2. Evaluation Procedures & Theory

This section describes evaluation procedures and the theoretical basis for Health Monitoring. Health Monitoring relies heavily on data processing and presentation based on the use of Inverse Normal plots. Consequently the development and interpretation of Inverse Normal plots is discussed in some detail because this background is important to an understanding of the concept of Health Monitoring.

2.1 Bridge Manual Evaluation Procedure

The Transit New Zealand Bridge Manual, 1994 and amendments (hereafter called the Bridge Manual), sets out the criteria for the design of new structures and evaluation of existing structures. Evaluation of existing structures is dealt with in Section 6 of that Manual, in which existing bridges are evaluated at two load levels. These levels are outlined below.

1. *A **Rating Evaluation** using parameters to define the bridge capacity using overload factors and/or stress levels (i.e. appropriate for overweight vehicles).*

This evaluation is primarily concerned with evaluating the bridge's ability to carry overweight permit vehicles that comply with the Transit New Zealand Overweight Permit Manual (1995) (i.e. the Overweight Permit Manual). However it is also used as a means of ranking and evaluating bridges for their capacity. This evaluation involves assessing the bridge's ability to carry a specific overweight vehicle load (0.85 HO Loading).

2. *A **Posting Evaluation** based on parameters to define the bridge capacity using live load factors and/or stress levels (i.e. appropriate for conforming vehicles).*

This evaluation is primarily concerned with evaluating the bridge's ability to carry conforming vehicles. The evaluation involves assessing the bridge's ability to carry a reference loading of 0.85 HN that is representative of the effects of the maximum vehicles and loads complying with the Heavy Motor Vehicle Regulations 1974. If the bridge is unable to carry this loading, then the bridge is posted with the allowable load that the bridge can safely carry.

The first evaluation is a set of loads intended to represent the worst-case effects from overloaded but permitted vehicles (HO loading, in the Bridge Manual). The second is a set of loads intended to represent worst-case effects from normal legally loaded heavy vehicles (HN loading, in the Bridge Manual). New bridges and their components are designed for the most severe effects resulting from both HN and HO loadings. This approach is intended to ensure that new bridges can accommodate current and foreseeable legal loads.

When evaluating existing bridges there is often little scope to modify a bridge to change its capacity to accommodate future loads. However there is a strong need to understand its capacity to accommodate existing legal loads. The Bridge Manual empirically links legal loads with design loads for evaluation purposes. Essentially bridge evaluation loads are 85% of the design loads. Bridges are **rated** with a Class relative to their overload capacity, in accordance with the Transit Overweight Policy. This rating will be used to approve or reject permit applications from transport operators requesting permission to cross the bridge with an overloaded (permitted) heavy vehicle. If a bridge evaluation reveals that a given bridge cannot safely sustain 85% of the HN (normal legal heavy vehicle) loading, it will be **posted** with a load limit consistent with its actual capacity to resist such a load.

2.2 Member Capacity & Evaluation using the Bridge Manual Criteria

The Bridge Manual deals with main members of the bridge and decks separately. The evaluation approach described in Section 6 of this Manual is summarised in this section.

2.2.1 Main Members

Equation 1 calculates the available vehicle live load capacity (or overload capacity) for a particular component of the bridge. This is the capacity available to carry unfactored service loads. A value of 1.49 for the overload factor is used for rating evaluations and a value of 1.9 is used for posting evaluations (Transit 1994). These factors reflect the degree of uncertainty associated with the actual vehicle loads that will be applied to the bridge in each case. The higher the overload factor, the greater the degree of uncertainty.

$$R_o = \frac{\phi R_i - \gamma_D(DL) - \sum(\gamma(Other\ \ Effects\ ))}{\gamma_o} \qquad \text{(Equation 1)}$$

where:

R_o = Overload Capacity

ϕ = Strength Reduction Factor

R_I = Section Strength

γ_D = Dead Load Factor

DL = Dead Load Effect

γ = Load factors on other effects

γ_0 = Overload Factor

From the overload capacity, the ability of the bridge to carry the desired loads (i.e. its Class) is calculated from Equation 2, which divides the overload capacity by the rating load effect. The rating load effect is the effect of the evaluation vehicle on the bridge (85% of HO load for one-lane bridges, or 85% of HO load + 85% of HN load for two or more lane bridges), including the effects of eccentricity of load and impact. A value of 100% for the Class represents a bridge that can safely withstand these rating loads. Values for Class greater than 120% are recorded as 120%. The final Load Rating is found by first determining the Class for each main component (e.g. stringers). The minimum Class then becomes the rating for that bridge.

$$Class = \left(\frac{R_o \times 100}{Rating\ Load\ Effect}\right)\% \qquad \text{(Equation 2)}$$

A similar formula (Equation 3) applies for posting evaluations[1] (R_L being the live load capacity) with the posting load effect represented by 85% of the HN vehicle loading, including the effects of eccentricity of load and impact. There is an allowance for reducing impact if speed restrictions apply or are imposed.

$$Gross = \left(\frac{R_L \times 100}{Posting\ Load\ Effect} \right) \% \qquad \text{(Equation 3)}$$

2.2.2 Decks

The general principles for assessing the capacity of the deck to resist wheel loads are similar to those for the main members.

The Bridge Manual sets out procedures for calculating the strengths of concrete and timber decks, and the various wheel loads to be considered.

Generally the deck is then assessed based on similar principles to the main members along the lines of Equation 4, with the output being a DCF (Deck Capacity Factor). A DCF of 1.0 represents a deck that can safely resist the applied loads using the criteria in the Bridge Manual.

$$DCF = \left(\frac{Overload\ Capacity\ of\ Deck}{Rating\ Load\ Effect} \right) \qquad \text{(Equation 4)}$$

2.3 The Health Monitoring Approach

Health Monitoring utilises ambient traffic to investigate the effect that actual loads have on the in-situ structure[2]. Thus the results of Health Monitoring provide an integrated measure of both the actual loads applied to the structure, and the effects of these loads on the structure.

As outlined in the Introduction to this report, bridge Health Monitoring is a method of evaluating the ability of a bridge to perform its required task or Fitness For Purpose by evaluating the response of the bridge to its loading environment[3].

Bridge evaluation procedures are generally undertaken at the strength, serviceability, and fatigue limit states. Strength and serviceability limit states are normally defined in probabilistic terms, and Health Monitoring concepts utilise these fundamental

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[1] Posting evaluation applies to conforming traffic (as defined in the Heavy Motor Vehicle (HMV) Regulations 1974). Note that 0.85HN relates closely to the HMV Regulations 1974 Class I axle weights and loadings.

[2] The Health Monitoring approach presented in this document is built around the measured bridge response to single vehicle events per lane. Consequently the methods require extension to be applied to longer span structures where multiple vehicles in each lane are critical.

[3] Health Monitoring compares the results of in-service measurements with corresponding failure criteria. Engineering experience and judgement may be required to interpret those quantities. For example, care must be exercised when interpreting strains in concrete structures whether these are average surface strains or strains in the reinforcement.

definitions. For the purpose of assessing the probabilistic effects of loading, the Bridge Manual recommends a bridge design life of 100 years[4]. Obviously, measuring the traffic effects for 100 years is not feasible or practical. Monitoring the traffic effects for a shorter period of time, and extrapolating this data using statistical and probability methods, provides an economic and viable alternative for assessing a bridge using its measured response to ambient traffic loading.

The understanding developed as part of Health Monitoring allows better predictions of structural response. This must be compared with the ultimate (strength) limit state defined by the Bridge Manual and by NZS 4203 (NZS 1992). The ultimate limit state is based on estimating the magnitude of an event that is unlikely to be exceeded during the life of the bridge. The Bridge Manual (1994) and the AUSTROADS Bridge Design Code (1996) define this as having a 5% probability of being exceeded in the design life of 100 years or, if defined according to NZS 4203 for a building-type structure, of 50 years.

The AUSTROADS Bridge Design Code (1996) defines the serviceability limit state as an event that has a 5% probability of being exceeded in any 1 year. This corresponds to an event with an average recurrence interval (ARI) of 20 years[5].

Statistical procedures are necessary to enable the Health Monitoring data to be compared with the limit state requirements. To allow an assessment of a bridge using Health Monitoring techniques which is consistent with the Bridge Manual requires the standard equations to be combined with Health Monitoring principles. Re-arranging Equation 1 by moving the Overload Load Factor to the left-hand side gives Equation 5, with $\gamma_o R_o$ representing the capacity available for factored load effects (ultimate live load capacity) imposed by heavy vehicles.

$$\gamma_o R_o = \phi R_i - \gamma_D (DL) - \sum (\gamma (Other\ Effects)) \qquad \text{(Equation 5)}$$

The posting evaluation can then be calculated in terms of ultimate load effects using the ultimate traffic load effect extrapolated from the Health Monitoring data, rather than the posting load effect, as demonstrated in Equation 6. In this way the bridge's ability to safely carry the actual traffic using the bridge during its design life (based on the traffic data obtained during the monitoring period) is calculated. The evaluation that is derived from this procedure has been defined as the Fitness for Purpose Evaluation (FPE).

$$FPE = \left(\frac{\phi R_i - \gamma_D (DL) - \sum (\gamma (Other\ Effects))}{UTLE} \right) \times 100\% \qquad \text{(Equation 6)}$$

where:

FPE = Fitness for Purpose Evaluation; $\gamma_o R_o$ = Ultimate Traffic Live Load Capacity
$UTLE$ = Ultimate Traffic Load Effect derived from Health Monitoring data

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[4] Note however that NZS 4203 (1992) assumes a design life of 50 years.

[5] Evidence suggests that in these serviceability and strength limit state definitions, the live loads and load factors specified in both Transit and AUSTROADS design codes are not consistent. A review of the Health Monitoring results and the expected values for serviceability and ultimate limit states will illustrate that the serviceability load effect (95% 1 year) is high compared with the ultimate load effect (95% 100 years). A review of the serviceability limit state definition is recommended.

Generally an FPE greater than 100% indicates that the structure is "Fit for Purpose", while an FPE of less than 100% indicates that intervention is required.

2.4 Health Monitoring & the Inverse Normal Plot

Section 2.3 presented the fundamental theory used to calculate FPE results from Health Monitoring data. Converting raw data into a statistical form consistent with Bridge Manual provisions requires considerable data processing, and the Inverse Normal plot is the key component of that process. This section describes theory associated with Inverse Normal plots and some other issues associated with data processing.

Estimating the probability that a response level will be exceeded requires a method for estimating the shape of the "tail" of the statistical distribution. Once the parameters of the distribution tail are determined, estimating the limit states can be undertaken utilising statistical techniques. It is convenient to assume that events recorded during Health Monitoring are random, and that the statistical distribution type is "Normal" (Gaussian).

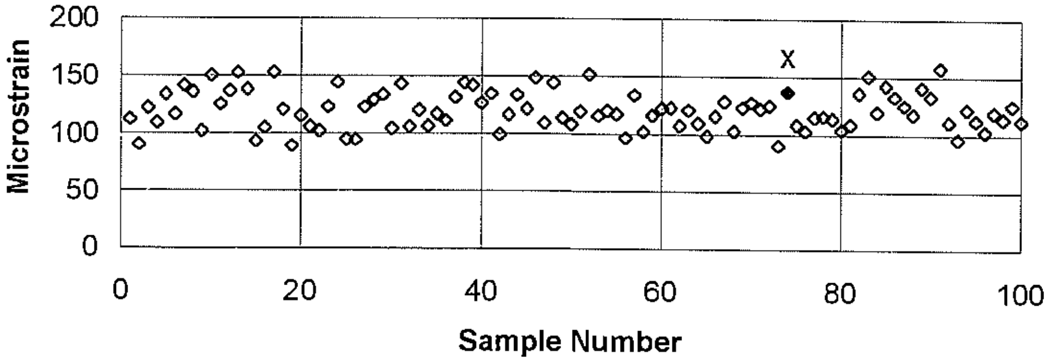
The central limit theorem suggests that, when many random variables are added, the resulting distribution will be Gaussian (Normal distribution). The response of a bridge depends on many variables (surface profile, vehicle loading, spacing between axles, vehicle speed, vehicle suspension characteristics, lateral position, bridge frequency and damping). Bridge response is therefore likely to be normally distributed. Normal distributions are generally characterised by the mean and standard deviation. The Inverse Normal plot uses these parameters and provides a graphical presentation tool to facilitate prediction and interpretation of results in statistical terms.

Application of the Health Monitoring concept integrates both the load and response aspects of the bridge. The response of any element of the structure will depend on where it is in the structure, and what loads are applied to it. For example, the most influential loads with respect to deck components will be wheel loads. Axle or axle group loads are likely to govern stringers (supporting the deck), while vehicle or lane loads are likely to be important for cross-girders and headstocks. The load paths and tributary areas (size of area over which the particular load applies) for these different components often vary significantly. Consequently the Inverse Normal plot may vary between different structural elements for the same loading (as Inverse Normal plots represent the integration of loading and response). The Atiamuri Bridge was chosen partly because diverse tributary areas could be monitored on the same bridge.

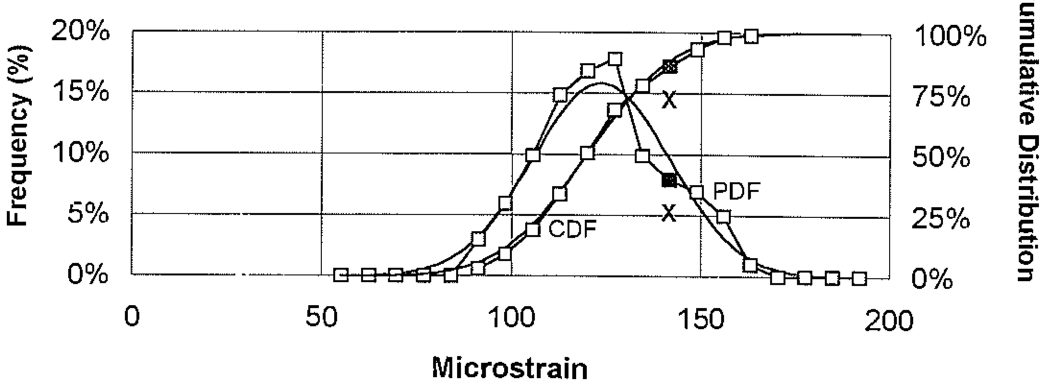
2.4.1 The Inverse Normal Plot

During Health Monitoring, peak events, and the times that peak events occur are recorded routinely. These data are often presented as a scatter plot of event magnitude versus time, which provides valuable information about the largest events and are useful for identifying patterns in the loading and extreme events. The transformation from a scatter plot to the Inverse Normal plot is illustrated in Figure 2.1.

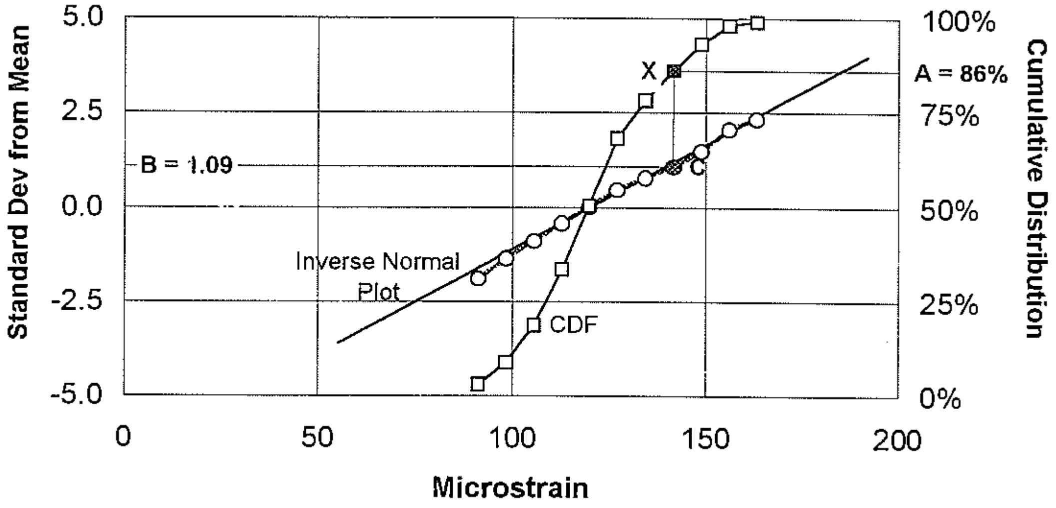
(a) Scatter Plot



(b) Probability and Cumulative Distribution Functions



(c) Cumulative Distribution Function and Inverse Normal Plot



Parameters: Mean = 120 Std Dev = 18 COV = 0.15 No. of Samples = 100

Figure 2.1 Development of the Inverse Normal plot.

PDF	Probability distribution function	CDF	Cumulative distribution function
COV	Coefficient of Variation	X	sample no. 74

The series of graphs have been derived from a sample of 100 strains generated randomly from a population that is normally distributed (mean = 120 με, standard deviation = 18 με) using Monte Carlo simulation techniques.

The scatter plot (Figure 2.1a) presents a fairly narrow band of strains between 90 με and 160 με. The probability distribution function (PDF) is presented in Figure 2.1b, and this has at least some resemblance to the expected "bell curve" associated with the Normal distribution. The classical "bell curve" is superimposed on the PDF and illustrates the "lumpiness" which is a consequence of the relatively small sample size. The cumulative distribution function (CDF) is also presented. The "lumpiness" evident in the PDF is less noticeable in the CDF. Once again the theoretical result is superimposed on the CDF.

Sample number 74 is marked with an "X" in the scatter plot, and corresponds to a strain of 137 με. This event contributes to the PDF and CDF at the locations marked with an "X" in Figure 2.1b. The CDF is represented in Figure 2.1c and indicates an 86% probability that an event is less than event "X" (X–A in Figure 2.1c).

The Inverse Normal plot is also presented in Figure 2.1c. The Inverse Normal plot is the CDF plotted to a different vertical scale that transforms the S-shaped CDF to a straight line should the distribution be normally distributed. Note that the theoretical line is superimposed on the Inverse Normal plot.

Some general observations regarding Inverse Normal plots follow:

- The intercept with the horizontal axis corresponds to the mean (Figure 2.2). Note that this point is where the CDF and the Inverse Normal plot cross in Figure 2.1c.
- The vertical limits of the Inverse Normal plot depend on the number of samples. The vertical limits grow with the greater number of samples. The rate of growth diminishes rapidly with increasing sample size (Figure 2.2).
- The inverse of the slope of the Inverse Normal distribution corresponds to the standard deviation (Figure 2.2).
- The ends of the Inverse Normal distribution correspond to the smallest and largest events. The ends of the Inverse Normal plots are less reliable than their central regions (Figure 2.2), because this data is based on a smaller number of samples.
- Figure 2.2 suggests that a sample size of 100 to 1000 events provides a reasonable basis for determining the distribution parameters. A sample population of 10 000 events approximates well with the actual distributions, but offers only a limited improvement in results.

The vertical scale represents the probability in terms of the number of standard deviations from the mean. This transformation is illustrated for the event "X". The probability of 86% corresponds to an event that is 1.09 standard deviations above the mean (refer "B" in Figure 2.1c). Thus, point "X" on the CDF is transformed to point "C" on the Inverse Normal plot. Repeating this process for each point results in the relatively straight line being presented as the Inverse Normal plot.

The fact that this line is approximately straight is confirmation that the 100 samples were generated from a Normal distribution.

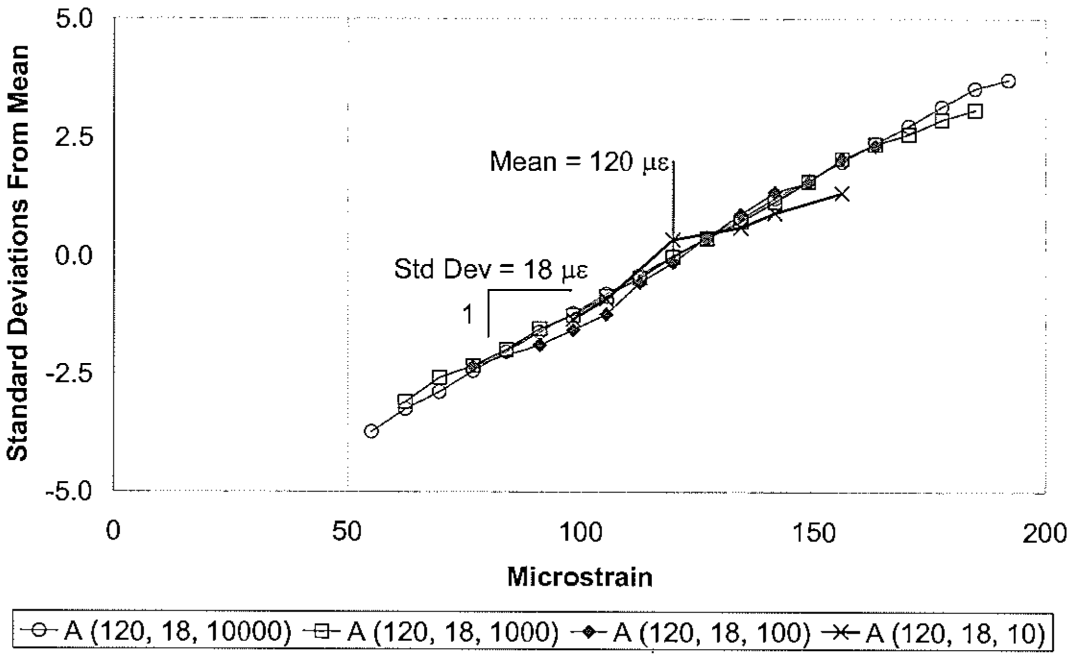


Figure 2.2 Effects of sample size on the Inverse Normal plot.

The Inverse Normal plot provides a graphical method of presenting statistical data and evaluating how close a data set is to a Normal distribution. It also provides the opportunity to approximate complex distributions with a series of Normal distributions.

In the case of the bridge Health Monitoring data, the distributions can become quite complex. For example, the traffic consists of laden and unladen heavy vehicles. Multiple vehicles, on infrequent occasions, will cross a bridge at the same time leading to the summation of vehicle effects. The following discussion illustrates some of these effects on the shape of the PDF and the Inverse Normal plots.

The PDFs and Inverse Normal plots for the two distributions, the parameters of which are summarised in Table 2.1, are presented graphically in Figure 2.3. Some possible scenarios corresponding to these distributions are also presented.

Table 2.1 Parameters for Normal Distributions A and B.

Distribution	**Mean (με)**	**Standard Deviation (με)**	**Possible scenario**
A	120	18	Peak strain in an element due to fully laden heavy vehicles travelling north
B	60	9	Peak strain in an element due to empty heavy vehicles travelling north; or Peak strain in an element due to fully laden heavy vehicles travelling south

Note that the mean and standard deviation of distribution B are half those for distribution A. Consequently the Inverse Normal plot for distribution B has a smaller intercept and a steeper slope compared with those for distribution A. The PDFs also change shape and this reflects the changes in mean and standard deviation.

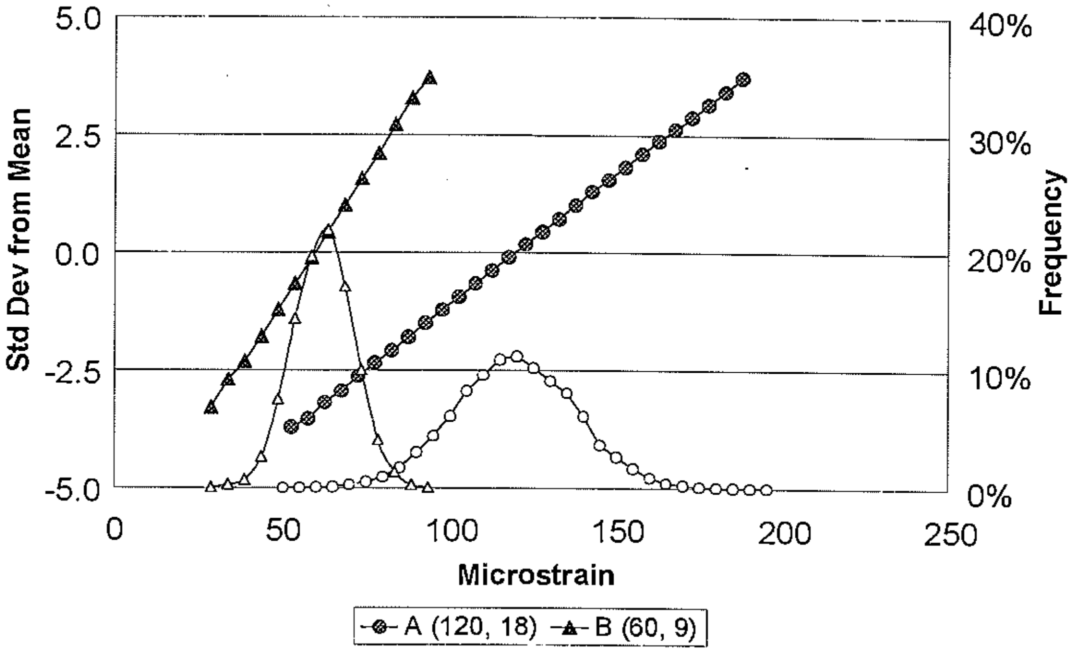


Figure 2.3 PDFs and Inverse Normal plots for two distributions A and B.

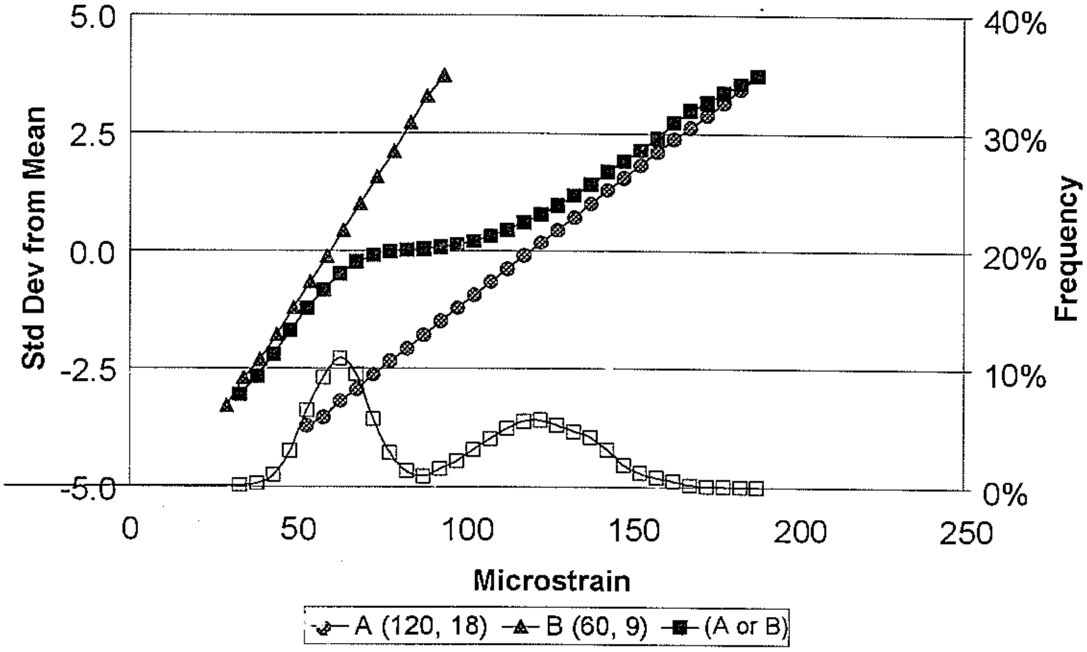


Figure 2.4 Inverse Normal plots for the distributions A, B, (A or B), and PDF for (A or B).

Another scenario is that of a bridge where only one laden heavy vehicle is on the bridge at a time. This heavy vehicle can either be northbound (distribution A) or southbound (distribution B), but two vehicles cannot be recorded at one time. Assuming that the northbound and southbound traffic volumes are similar, leads to the combined distribution (A or B) presented in Figure 2.4 (PDFs on Figure 2.4 corresponding to (A or B) have open symbols). Similar distributions can arise from laden and unladen heavy vehicles travelling north.

The PDF of the resulting distribution of (A or B) has a double hump (Figure 2.4). The Inverse Normal plot for (A or B) has a characteristic S curve with each end tending towards being asymptotic with the base distributions. Note that the S curve crosses the horizontal axis about midway between the means for the base distributions. This is consistent with the 50-50 split in the traffic. Should the number of vehicles corresponding to the distribution A increase, then the shape of the (A or B) curve will change. The transition from distribution A to B will reduce, and the mean will increase.

2.4.2 Multiple Presence

Another scenario is that vehicles corresponding to distribution A and B always occur simultaneously. This useful upper limit scenario is illustrated in Figure 2.5. Note that events A and B have been assumed to be statistically independent. The resulting Inverse Normal plot is a straight line, indicating a Normal distribution for A+B, as expected. This A+B result can be considered as an Independent Upper Bound (IUB solution) because a maximum combined event is predicted, based on the events in each lane being independent of each other.

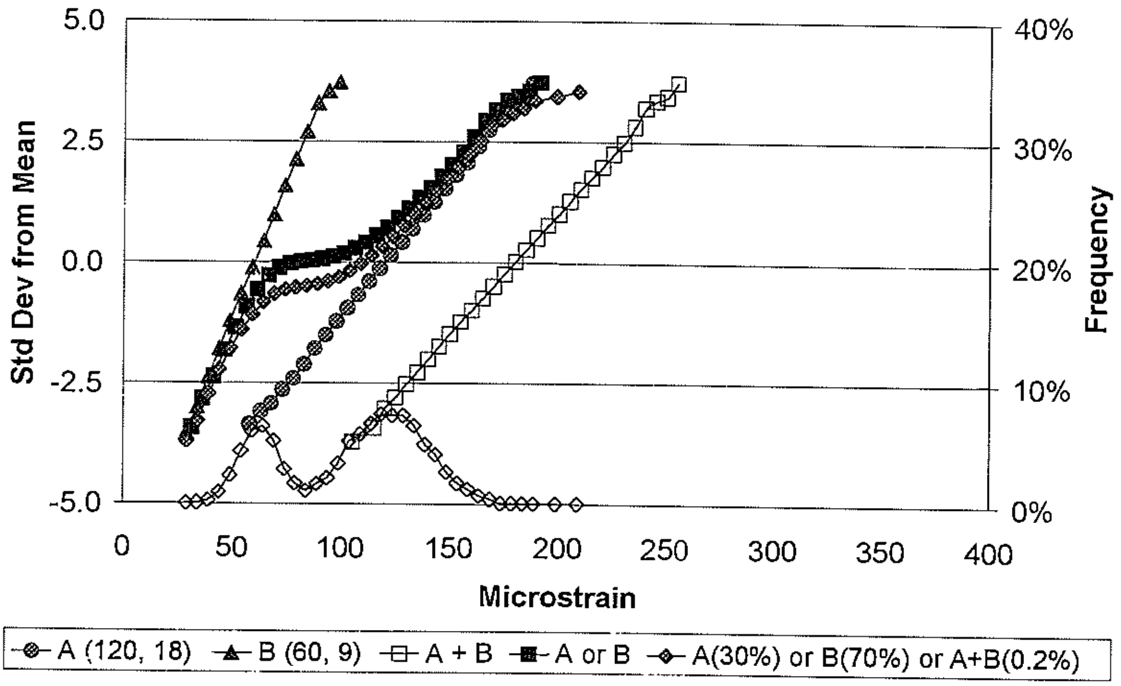


Figure 2.5 **PDFs and Inverse Normal plots for the distributions A, B, A+B, (A or B), A(30%) or B(70%) or A+B(0.2%).**

Figure 2.5 includes a further scenario where 30% of the vehicles correspond to distribution A, and 70% to distribution B. The scenario is further complicated by the additional restraint that every 500th vehicle (0.2%) corresponds to a multiple-presence event where the effects of vehicles of A and B distributions are added. The resulting Inverse Normal plot and PDF (A(30%) or B(70%) or A+B(0.2%)) are similar in shape to the A or B distribution except that the transition is lower and, importantly, the upper tail crosses the base distribution B due to the effects of multiple presence.

Note that the evidence of this kink in the upper tail is not readily evident in the PDF. This kinked tail is almost entirely related to the 0.2% of vehicles assumed to be on the bridge simultaneously. The Monte Carlo simulations used to generate these distributions were curtailed at 10 000 samples. For very large sample sizes, this tail will become asymptotic to the A+B distribution (IUB), but the kinked tail is only likely to be evident after an extended period of sampling.

If Inverse Normal data can be obtained for each lane, then the multiple-presence (combined) event curve can be calculated using basic algebra. The magnitude of the average multiple-presence event will be the sum of the averages for each lane. On the Inverse Normal curve, this means that the horizontal axis intercept for multiple-presence events will be the sum of the horizontal intercepts for each lane. The slope of the multiple-presence event is the standard deviation of the multiple-presence population. This standard deviation can be calculated by taking the square root of the sum of the squares of the each lane slope.

2.4.3 Determination of Extrapolation Limits

Inverse Normal plots facilitate statistical presentation of data and allow extrapolation to pre-determined confidence limits. Consideration of the sample size, and of the required confidence limit (for the specific purpose), allows the confidence limit to be calculated in terms of the number of standard deviations from the mean. This limit can be conveniently plotted on Inverse Normal plots and used as the limit of extrapolation to predict "extreme" event magnitudes.

The relationship between probability of exceedance and the number of standard deviations from the mean is documented in various statistical texts (Moore & McCabe 1993). The process used to calculate the standard deviation corresponding to as known confidence limit is as follows:

Step 1 – Calculate the frequency of event occurrence (E_D):

$$E_D = \frac{Count\ of\ sample\ events}{Duration\ of\ monitorng}$$

where an "event" is a recorded heavy vehicle.

Step 2 – Calculate the Average Recurrence Interval (ARI) for the pre-determined confidence limit of the appropriate period;

95% in 1 day has an ARI of 20 days

95% in 1 month has an ARI of 610 days

95% in 1 year has an ARI of 7 305 days

95% in 100 years has an ARI of 730 500 days

Step 3 – Calculate the probability of exceedence for the events associated with the ARI as follows.

$$P = \frac{1}{(E_D ARI) + 1}$$

Step 4 – Convert probability (P) to the number of standard deviations from mean (assuming Normal distribution). Statistical tables can be used for this standard conversion. Although spreadsheets also have this functionality, Infratech Systems & Services Ltd (Infratech) uses its own algorithm, based on statistical fundamentals, which is more accurate than the spreadsheet functions.

2.5 Summary

The Inverse Normal plot is a very useful method for presenting statistical distributions. The examples provided illustrate the background to the characteristic shapes of the Inverse Normal plot that are often observed in Health Monitoring data.

Real data may include multiple data populations. For example, identifying empty and loaded vehicle populations in the data, or small populations of overloaded vehicles, is sometimes (but not always) possible. These variations can affect the Inverse Normal plots. Since sub-populations can be difficult to separate reliably using Inverse Normal plots, Health Monitoring methodologies have been developed in this report that deal with total populations which include such sub-populations.

3. Short-term Health Monitoring Results

Short-term Health Monitoring of Atiamuri Bridge was conducted as part of Stage 2 of this project (TNZ Research Report No. 173, Andersen et al. 2000). In this Section 3 of this report the Atiamuri Bridge is described, as is the rationale for its selection for long-term Health Monitoring, and the instrumentation of the bridge required for such monitoring. Previously derived theoretical evaluation, and short-term Health Monitoring results for Atiamuri Bridge are also summarised.

3.1 Description of Atiamuri Bridge

The Atiamuri Bridge is located on State Highway 1N over the Waikato River, and is a twin-cantilevered steel-truss structure hinged at the centre of the centre span. The span arrangement is 27.4 m/54.9 m/27.4 m. The deck comprises a cast in-situ reinforced-slab composite, with four longitudinal stringers spanning 5.5 m between steel cross girders. Construction of the bridge was completed in 1957 and the structure is illustrated in Figure 3.1.

Figure 3.1 Atiamuri Bridge over the Waikato River.

Atiamuri Bridge was chosen for long-term Health Monitoring for a number of reasons including:

- Heavy vehicles regularly use the bridge;
- Heavy vehicle loadings produce significant and measurable structural responses;
- The configuration of the bridge means that various structural elements on the bridge have significantly different tributary loading areas (important to the statistical evaluation process).

3.2 Instrumentation of Atiamuri Bridge

The instrumentation installed on the bridge for long-term monitoring included eight Foil Strain Gauge (FSG) transducers. Figure 3.2 illustrates the locations of the four transducers installed at the midspan of the four stringers (S1 to S4) in the first segment of the structure. The first two cross-girders (CG) were also instrumented, as were two of the bottom chords (BC) of the truss. The positions of the instrumented segments are illustrated in Figure 3.3.

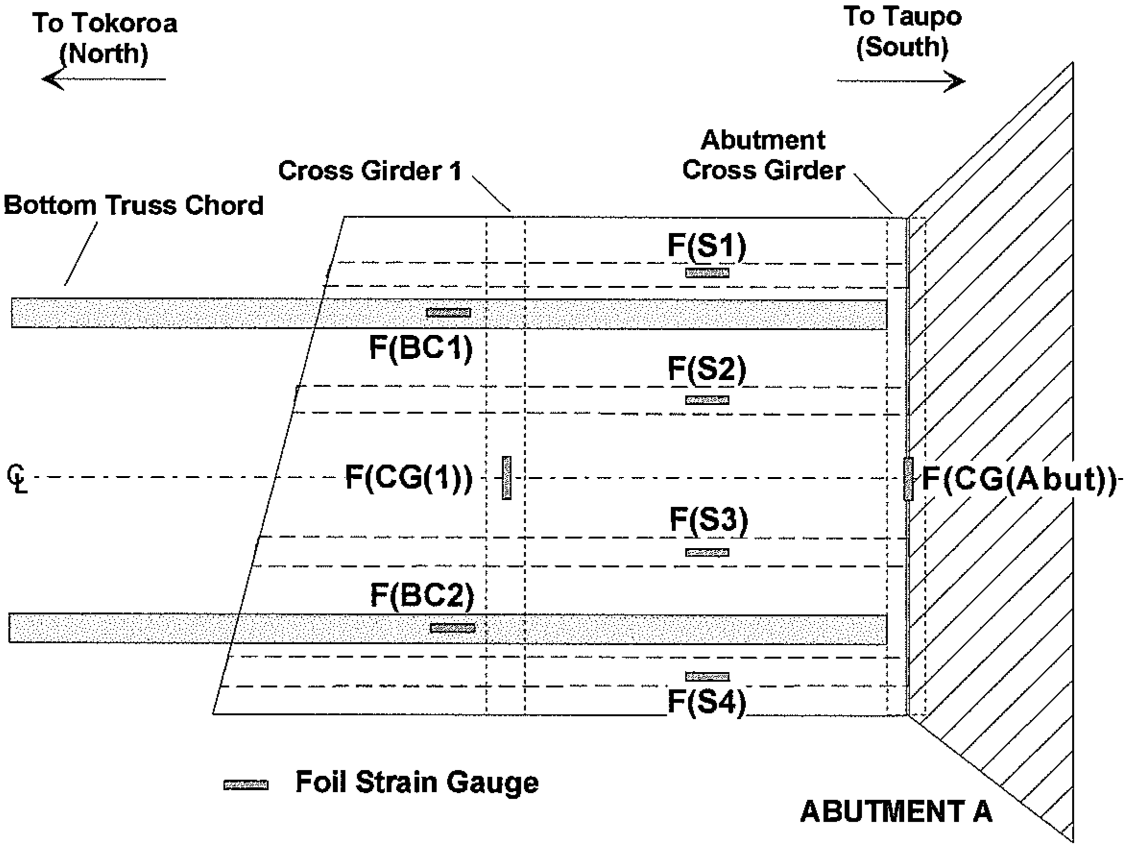


Figure 3.2 Instrumentation plan for Atiamuri Bridge.

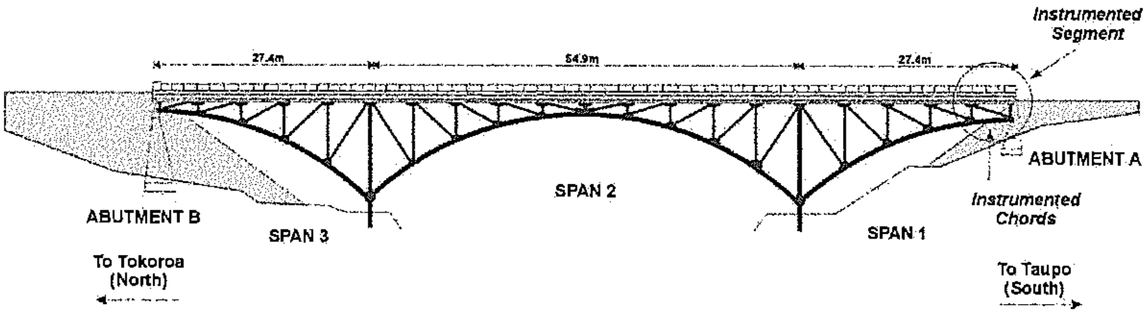


Figure 3.3 Elevation of the Atiamuri Bridge showing the position of the instrumented segment of the truss.

3.3 Previous Evaluations based on Short-term Health Monitoring

The current rating of the bridge in the Transit Structural Inventory (Transit 1999) is:

Bridge Classification	104%
Deck Capacity Factor (DCF)	1.02

These ratings are based on the evaluation methods set out in Section 6 of the Bridge Manual.

In 1998, short-term Health Monitoring of the Atiamuri Bridge was conducted using a similar instrumentation configuration to that shown in Figure 3.2. This data was used to evaluate the Fitness for Purpose of the bridge using the technique developed by Infratech.

3.3.1 Theoretical Structural Evaluation

The structure was analysed using the rating and posting loads. It was also analysed using a grillage analysis to determine the bending moment and shear in the stringers, and the bending moment in the cross girders of a typical span based on various vehicle loadings. The bending moment in the stringers was found to govern the strength and therefore it determines the rating of the superstructure. The grillage analysis assumed simply supported stringers. The dimensions of the structure used in the analysis were those detailed on the "as constructed" plans and were confirmed by on-site measurements.

The material properties for the concrete deck and steel members were not available, but instead were obtained from Section 6.3.4 of the Bridge Manual. The material properties used in the analysis of this bridge are as follows:

- Concrete Deck – $f'_c = 21$ MPa, $E = 22\ 100$ MPa
- Steel Members – $f_y = 230$ MPa, $E = 200\ 000$ MPa

The results of the bridge load rating analysis are presented in Table 3.1. The rating was assessed for the bending and shear in the stringers, and for bending in the cross-girder. The rating was based on the assumption that partial composite action exists between the stringers and deck. The table also presents a comparison of the load rating calculated by Andersen et al. (2000) and the load rating found in the Structural Inventory compiled by Transit.

A value of 1.3 was used for the impact factor and a value of 1.3 was used for the dead load factor in calculating the load ratings. However, the rating and posting load effects presented in Table 3.1 do not include impact factors. The Impact Factor is included in the ratings and postings (percentage values). In this case the mid-span stringer bending is the critical failure mode with a rating of 90%. This compares with the rating of 104% that is documented in the Structural Inventory.

This comparison (90% compared with 104%) illustrates the differences that can occur when different assumptions are made during theoretical evaluations. Nominally both evaluations should be the same, although assumptions regarding material characteristics and boundary conditions can cause variation in theoretical evaluations.

Table 3.1 Summary of theoretical ratings for the main stringers.

Mode of Failure	ϕ x Ultimate Capacity	0.85 HO + 0.85 HN Rating Load	0.85 HN + 0.85 HN Posting Load	Dead Load	0.85 HO + 0.85 HN Rating (Infratech)	0.85 HN + 0.85 HN Posting (Infratech)	Rating (Structural Inventory)
Stringer Bending	340kNm	165kNm	110kNm	45kNm	90%	105%	104%
Stringer Shear	380kN	110kN	70kN	30kN	160%	195%	
Cross-girder Bending	366kNm	195kNm	116kNm	5kNm	95%	125%	

Based on the results from this analysis, the Health Monitoring programme concentrated on evaluating the Fitness for Purpose for the stringers based on midspan bending. The Fitness for Purpose for the cross-girders (based on midspan bending) was also investigated.

3.3.2 Fitness for Purpose Evaluation

The short-term Health Monitoring of the structure began on Thursday 1 October, 1998, and continued until Saturday 3 October, 1998, giving a total monitoring period of approximately 40 hours. During the monitoring period the response of the bridge to 934 heavy vehicles was recorded.

The Atiamuri Bridge carries two lanes of traffic and therefore the effects of more than one vehicle being on the bridge at any one time must be considered (multiple-presence events). The effect of multiple presence was evaluated using the Bridge Manual approach which simulates a multiple-presence event by summing the 95% in 100-year event for both lanes.

Midspan bending was identified as the critical mode of failure for the stringers and this was used to evaluate the Fitness for Purpose of the bridge. Results showed that the loss of composite action had occurred. Therefore, by conservatively assuming zero composite action, the strength of the section is based on the steel stringer only. The yield stress of the steel is 230 MPa (as specified by the Bridge Manual) giving a yield strain (0.85 ε_u) equal to 980 $\mu\varepsilon$. The highest projected strain caused by a multiple-presence event occurred in Stringer 3 and was 925 $\mu\varepsilon$ (95% in 100 years). Therefore allowing for dead load, the FPE based on the yield strength of a typical stringer for this bridge was 80%. This evaluation can be compared with the 0.85 HO + 0.85 HN rating evaluation (90%), and suggests that the actual performance of the bridge is not as good as theoretically predicted.

3.3.3 Issues arising from Previous Evaluations

The evaluation methodology used for Stage 2 was:

1. Validate peak event data;
2. Sort data into lanes based on whether the peak maximum strain occurred in Stringer 2 (southbound traffic) or Stringer 3 (northbound traffic);
3. Extrapolate line-of-best-fit of lane data (based on all data) to the 95th percentile (in 100 year) limit and obtain the expected peak strain;
4. Use expected peak strain to determine FPE.

The known vehicle results from Stage 2 showed that higher strains were recorded in Stringer 3 compared with Stringer 2 for similar events. This was attributed to variations in composite action between the two stringers. The result of this outcome was that the lane sorting (step 2 above) incorrectly sorted some data. It is possible that a vehicle travelling south may cause a slightly higher strain in Stringer 3 than Stringer 2, because Stringer 3 has a higher normal response than Stringer 2.

Consequently, the simple lane-sorting routine may have classified some southbound events as if they were northbound events. The net result of incorrect lane classification is to modify the Inverse Normal curve for the lane traffic that does not travel over the stringers that are being considered (i.e. Stringers 1 and 2 for northbound traffic and Stringers 3 and 4 for southbound traffic). Little effect was evident on the Inverse Normal for vehicles travelling over the stringers under consideration (Stringers 1 and 2 for southbound traffic and Stringers 3 and 4 for northbound traffic).

The effect of incorrect lane classification on the projected maximum strain for traffic from each lane also depends on the methodology used for extrapolation. The methodology used for Stage 2 was a line of best fit for all strain values with a positive standard deviation. A straight line on an Inverse Normal graph represents a normally distributed population. The Stage 2 extrapolation used all data gathered, rather than the straight-line data, and this approach can have the effect of increasing the projected maximum strain, which in turn affects the FPE.

3.4 Investigation of Stringer Composite Action

During Stage 2, a DSG (demountable strain gauge) was fixed between the deck and top flange of Stringer 3 near the abutment. A limited amount of data was gathered with the transducer in this position (309 events). Data was processed, and the results are presented on Figures 3.4 and 3.5. One interpretation of Figure 3.4 is that the composite action behaves differently for north- and southbound traffic. The lane-sorted data will be affected at low strain levels by the trigger level (100 $\mu\varepsilon$ in Stage 2), and it may therefore distort results.

In addition, the slip characteristics associated with mobilisation of composite action are more likely to be associated with the magnitude of induced moment in the stringer than the lane in which heavy vehicles are travelling.

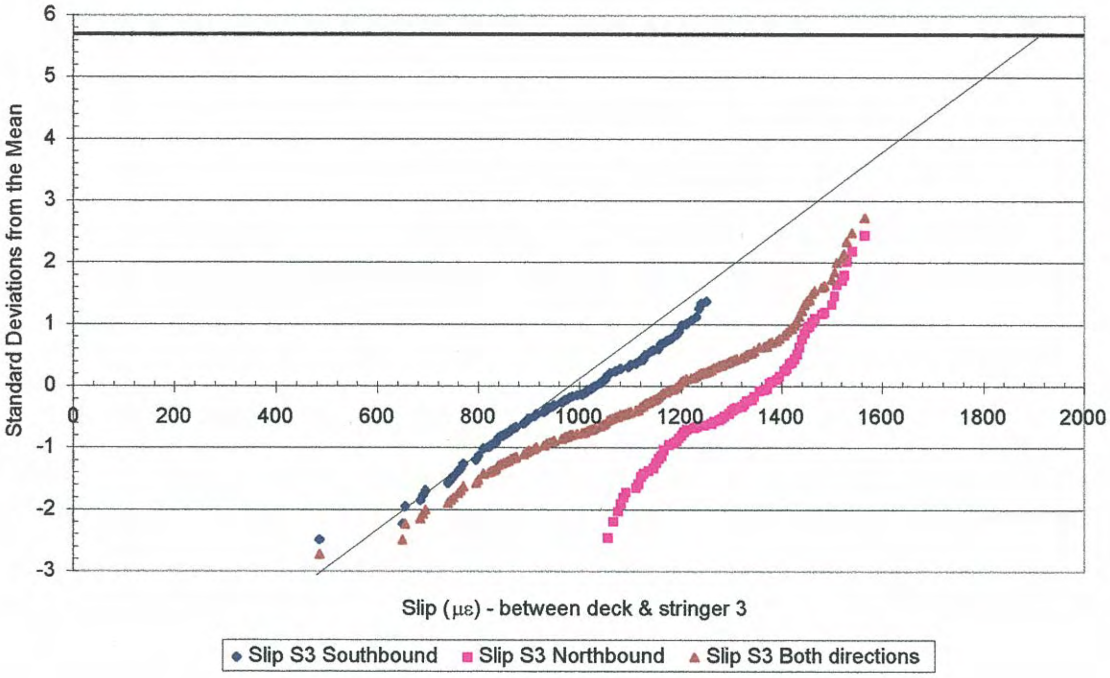


Figure 3.4 Lane-sorted slip results for Stringer 3 from short-term Health Monitoring.

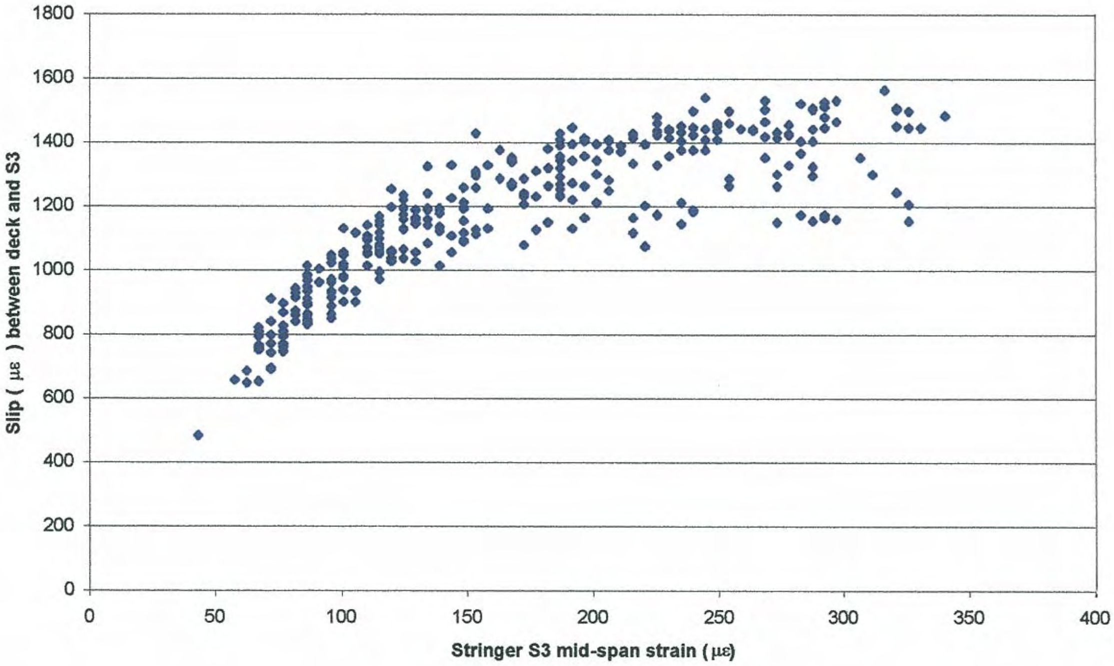


Figure 3.5 Slip versus mid-span bending strain in Stringer 3.

The mid-span strain in Stringer 3 was plotted against the slip measurement for the recorded Stage 2 events, and the results are given in Figure 3.5. This shows that, for events that cause a mid-span stringer strain of less than 130 με, the relationship between slip and stringer strain is relatively linear. Slip associated with events above this value is largely independent of stringer strain, and the results are also more scattered.

The linear relationship at low strain levels (<130 με indicates that slip is occurring between the deck and Stringer 3. The lack of correlation between strain and slip at higher strain levels suggests that, once sufficient movement has occurred, the shear capacity between the deck and Stringer 3 becomes mobilised, and composite action begins to occur. As the load increases, slip does not appreciably increase once the shear mechanism has been engaged. The effect of this is to increase the slope of the Inverse Normal plot, because the member stiffness increases (assuming the traffic distribution remains normally distributed).

3.5 Issues arising from Short-term Health Monitoring Results

Issues arising from the short-term Health Monitoring results that required further consideration are:

- The effect of the loss of composite action between the steel stringers and the concrete deck;
- The lane separation methodology used during data processing.
- Possible revision of the FPE rating, once the above issues have been resolved.

4. Analysing Health Monitoring Data

Fundamentally, Health Monitoring relies on the determination (by statistical extrapolation) of an appropriate Ultimate Traffic Load Effect (UTLE) based on measured bridge response. This UTLE is then compared with estimated resistance (capacity) of bridge components and members. The Fitness for Purpose Evaluation (FPE) described in Section 2 of this report represents the ratio of estimated resistance to estimated UTLE.

Carrying out long-term Health Monitoring (Stage 3 of the project) provided the opportunity to refine and define the process to determine the UTLE. Background issues associated with bridge evaluation, Health Monitoring, and the Atiamuri Bridge in particular, have been discussed in Sections 2 and 3. Issues affecting the Health Monitoring process, in particular those issues influencing the determination of the UTLE, are discussed in this section. These issues include:

- Data processing procedures;
- Conceptual basis for determining the UTLE;
- Effect of tributary area of monitored member on Inverse Normal results;
- Effect of sampling threshold (trigger level) on Inverse Normal results;
- Effect of Health Monitoring duration on Inverse Normal results.

4.1 Data Processing for Long-term Health Monitoring

Post-processing is necessary to convert Health Monitoring data into information suitable for bridge evaluation. This involves first organising and verifying the adequacy of data. Subsequently the data must be sorted and converted into an Inverse Normal plot. The short-term data processing approach has been described in Section 3 and, as a more detailed data reduction process was used for Stage 3, this data reduction and interpretation process is discussed in this section.

4.1.1 Initial Data Reduction

Initial reduction of the Atiamuri Health Monitoring data organised the large volume of data into manageable components, and removed any erroneous data. Essentially:

- All data was sorted into calendar months;
- Events with large strains, i.e. greater than 1000 $\mu\varepsilon$ for tension gauges and less than -1000 $\mu\varepsilon$ for compression gauges, were removed: signal errors typically cause such results;
- Data was sorted into lanes (process similar to Stage 2);
- An Inverse Normal distribution was generated for each transducer within each calendar month. A global bin size increment of 5 $\mu\varepsilon$ was adopted for all Inverse Normal distributions.

Data integrity was then investigated in more detail. This mainly involved considering whether the strains recorded by each of the four stringers (S1 to S4) represented a lateral distribution of load, consistent with structural principles. In particular;

- Southbound events where Stringer S3 values were less than 10% of Stringer S2 values were deleted (large strain in S2 would be inconsistent with little or no strain in S3).
- Southbound events where S4 values were greater than S3 values were removed.
- Likewise northbound events where S1 values were larger than S2 were also deleted. It is very unlikely that the load was concentrated in an outside girder.

In each case, only one channel was likely to be in error. However the data from all channels were rejected for these events to ensure the integrity of the final data set.

Data integrity was further investigated as follows:

- The offset drift (background strain recording) for each transducer was investigated. In some cases, the offset values were fixed at either the top or bottom of the recording range. Under these circumstances, the transducer that is "out of range" cannot record events correctly, so results for periods when these transducers were considered out of range were deleted.
- Preliminary investigation identified that all events after 11.48.07am on 22 December 1999 for channel F(S2) were suspect and these were removed from the data set. Further investigation of data around this date indicated similar trends in the other channels. Consequently, all data after this date was deleted from the data set.

The decision to remove data after 11.48.07 on 22 December 1999 was based on the following evidence:

- A distinct change occurred in values on this date on the S3 scatter plot. Removal of this data improved the Inverse Normal plots for the yearly distribution on channel F(S3);
- Using the waveforms for the April 2000 data, the percentage of corrupt waveforms was reduced after filtering, but the suspect data was not completely removed;
- Comparing scatter plots for data from April 1999 and April 2000 highlighted a distinct difference in patterns and extreme values.
- A similar difference in extreme values was also observed in the waveform files for April 2000.

While much of the data collected during the period from December 1999 to April 2000 was good, a reliable method of separating out the bad data was not found. Hence all data collected during the period was removed from the data set. Loss of data (Nowak et al. 1993) resulting from instrumentation problems is not uncommon. This emphasises the need for data interrogation during both monitoring and data processing.

Yearly statistics were subsequently determined from the above monthly results. Maximum values and average values were obtained by taking a weighted average with respect to numbers of events of monthly values.

Yearly projected values were determined from Inverse Normal distributions. These distributions were obtained from a combined histogram of monthly data sets.

4.1.2 Final Data Reduction

The diagnostic test (with the known vehicle) conducted during short-term Health Monitoring revealed that the behaviour of Stringer S3 varied and the magnitude of events was larger than Stringer S2. Consequently, a comparison of recorded strains in S2 and S3 was not the most reliable method of sorting results into lane data. Inconsistencies in some of the initial Inverse Normal plots highlighted problems with the lane-sorting approach adopted during initial data reduction. Consequently, a new lane-sorting approach was developed and applied for the final data reduction. This technique also utilised each of the four stringer transducer values, but a quadratic curve of best fit was obtained for each record. The quadratic was expressed by the three coefficients of the equation: $y = C_1 + C_2x + C_3x^2$.

Lane sorting was then conducted as follows:

- All records with a positive curvature, i.e. $C_3 > 0$ were deleted;
- Distribution factors were determined for each record, and a corresponding load centroid position with respect to the bridge centreline was obtained;
- Events were divided into lanes (north- and southbound) by the quadratic (C_2) term. This differed to the previous method (Section 3.3.3) of determining the lane in which an event occurred. This result was checked against the lateral load position estimates and good correlation was found between both approaches.

Yearly statistics were subsequently determined from the monthly results. Maximum values and average values were obtained by taking a weighted average with respect to number of events of monthly values. Yearly projected values were determined from Inverse Normal distributions. The results of this final data reduction process are presented in Appendix A, and represents the "good" data collected during the monitoring period.

4.1.3 Comparison of Short-term & Long-term Data Processing

Some variation was found between the data processing techniques used for Stage 2 and Stage 3 of this project, and the effect of data processing method on UTLE estimates was worth considering. Consequently, the raw data for Stage 2 was re-processed using the Stage 3 data processing method, and the results from both methods using the same raw data are presented in Appendix B. Generally the difference in the UTLE predicted for each lane by both methods is similar, particularly for stringers when the loaded lane is over the stringer of interest. Some variation in northbound traffic for Stringers 1 and 2 is mostly associated with the incorrect lane classification of traffic that had been used in Stage 2. The more refined (Stage 3) method corrects this problem.

The major difference between the Stage 2 and Stage 3 methods is associated with extrapolation of all data (Stage 2) compared to extrapolation of the main heavy vehicle population (Stage 3). This is most evident on Figure B3 (Appendix B), where the UTLE predicted for Stringer 3 (northbound traffic) by the refined (Stage 3) process is significantly smaller than that predicted by the Stage 2 process. Coincidentally this is the UTLE that governed the FPE in the Stage 2 report. The refined data processing method used for Stage 3 would therefore predict a lower UTLE than that predicted using the Stage 2 method. Therefore the FPE predicted by the Stage 3 results would be expected to increase, compared to that predicted in the Stage 2 report.

4.1.4 Summary of Data Reduction Issues

While Health Monitoring equipment is relatively robust, interpretation of Health Monitoring data must include interrogation to determine the validity of data. This process is aided by an understanding of structural behaviour, likely traffic effects, and instrumentation. Much of the data reduction process can be automated, but each site requires individual assessment to determine appropriate validation tests. To this end, the results of diagnostic testing (using a known vehicle) can be very helpful when conducted as part of a Health Monitoring project.

Once the equipment has been commissioned on a site, most data will be valid. However interference in various forms can occur which can result in a relatively small number of erroneous events. Alternatively abnormal structural behaviour can occur. Validation tests must distinguish between these two possible sources of unusual data.

Validation of data for extended monitoring periods (such as Stage 3) can require considerable human resource, both because of the volume of data to be validated, and because a greater range of "unknown" effects can influence data over extended monitoring periods. This activity can be particularly difficult when only a small amount of data is "unusual" because the large quantity of "normal" data tends to mask the aberrations. Consequently a robust Heath Monitoring data interpretation process should emphasise the large quantity of easily validated data, rather than rely on small sub-populations of potentially abnormal data, especially as the cause of such abnormal data cannot often be precisely determined.

4.2 Estimation of Ultimate Traffic Load Effect

Multiple-presence events are relatively infrequent, but they are important because they often govern design or evaluation processes. Accepted procedures usually predict the UTLE based on multiple-presence events. It may be possible to measure UTLE (including multiple presence) if monitoring were to occur for a suitably long period (many years). However a number of assumptions are implicit in this proposition, including the concept that traffic population characteristics remain constant over time. Historically this assumption has been demonstrated to be incorrect in that the number and mass of vehicles likely to contribute to the UTLE tends to increase over time.

Therefore the magnitude of the UTLE increases with time. The estimate of the UTLE will be dependent on when the estimate is made, and this in turn will be based on contemporary traffic characteristics and projections. This situation applies to both theoretical and testing-based evaluation procedures.

Even though the estimation of the UTLE is somewhat arbitrary (even using analytical techniques), a consistent and justifiable approach must be developed for Health Monitoring purposes. In particular, the approach should be consistent with alternative evaluation methods (e.g. as defined by the Bridge Manual). The method used in the Bridge Manual bases estimation of the UTLE on the simultaneous occurrence of multiple evaluation vehicles (0.85HN in each of the two most adverse lanes) on a multi-lane bridge (multiple presence). As these events are rare a relatively long Health Monitoring duration is required to collect a representative sample of multiple-presence events. Alternatively, the extreme single-vehicle-event effects can be deduced from the Health Monitoring data, and these can be analytically combined to estimate the UTLE.

Conventional analytical investigations consider possible “overload” events based on the legal requirement for vehicles with other than legal mass and configuration to obtain permits. The “normal” heavy vehicle population is assumed to comply with legal loading requirements. Significant illegal overloading of heavy vehicles is known to occur on some routes. These events will be recorded by Health Monitoring but will be difficult to distinguish from multiple-presence events, unless the illegal overloading is substantial in both number and frequency and obviously shows in the data.

One issue that arises when determining UTLE based on the concept of multiple presence, is selecting the events of appropriate magnitude that are to be combined. If a single-vehicle event of large magnitude is rare, then the simultaneous combination of two such events will be extremely rare. The need to design or evaluate structures for such rare events at the same level of risk as “normal” events can be questioned. Alternative rationales for determining UTLE include combining one extreme event with one typical event, or combining typical events, then factoring them to provide a “margin of safety”.

These methodologies assume that the principle of superposition applies. This in turn assumes that the structural system remains linear in the loading range. The Stage 3 data was used to investigate the use of seven different methods to predict the UTLE. The concept of each of the seven alternative methods is described in the following sections. The purpose was to use a combination of algebraic and statistical manipulation in order to generate a practical approach to bridge evaluation. Health Monitoring data was required (including multiple-presence events) to investigate the adequacy of the various methodologies. Since multiple-presence events are rare, a relatively long monitoring period is required to obtain a sufficient sample.

4.2.1 Multiple-Presence at Atiamuri Bridge

The situation at Atiamuri Bridge is typical of many bridges worldwide (i.e. a two-lane two-direction road bridge with moderate heavy vehicle traffic in both directions). If 250 heavy vehicles are assumed to cross the bridge in each direction each day, then the probability that a truck will have an effect on a cross-girder at any given instant is approximately 1 in 170 (assuming the duration of a truck on the cross-girder is approximately 1 second). In simple terms, the probability that two trucks will influence the same cross-girder at the same time is approximately 1 in 120 000, or once every 1.4 days. Thus, multiple-presence events are relatively infrequent, and it is quite likely that none will occur during a monitoring period of one day. The average recurrence interval of multiple-presence events decreases as the time taken for a heavy vehicle to cross the bridge increases. For example, the average recurrence interval between multiple-presence events is 1.4 days and 0.3 days for a cross-girder and the entire bridge respectively.

4.2.1.1 *Estimate using Correlated Upper Bound (CUB)*

The Bridge Manual considers both "normal load" (HN) and "overload" (HO) cases. In the case of two-lane bridges, the Bridge Manual requires multiple-presence events to be estimated by combining HN loading in each lane, and combining HN loading in one lane with HO loading in the other. The worst calculated effects then govern the design or evaluation.

This approach could be considered "conservative" in that it presumes that two "extreme" events will occur simultaneously, and that this should be the governing load case. However this assumes that "gross overloading" of heavy vehicles does not occur, i.e. the load effect of the worst illegally overloaded vehicle will still be less than the effect of two legal heavy vehicles. This may seem to be a reasonable assumption, and is probably appropriate in the case of Atiamuri Bridge. However some routes may have traffic characteristics where this is not the case. Therefore the concept of FPE may require clarification.

This Bridge Manual approach to estimating UTLE was used during Stage 2 to complete the FPE. In probabilistic terms, this could be considered to be a correlated upper bound (CUB) method, in which the magnitude of the event in the second lane is directly correlated to the magnitude of the event in the first lane.

As discussed previously in this Section, a maximum event in a single lane is considered to be rare. A probabilistic approach would suggest that the chances of two very rare events occurring simultaneously are so remote that the approach is unnecessarily conservative. Other codified approaches allow for a reduction in the UTLE to account for the small chance that it may occur (e.g. AUSTROADS 1996 provides for a 0.9 reduction factor). The Bridge Manual provides for no such reduction factor for a two-lane bridge.

4.2.1.2 *Estimate using Turkstra & Madsen method*

The method proposed by Turkstra & Madsen (1980) implies that an "extreme" event should be combined with a "typical" event to determine the UTLE. Based on the

Inverse Normal plots used in Health Monitoring, an interpretation of this approach is to combine an extrapolated maximum event in one lane with an average event in the adjacent lane. This method is relatively easy to calculate using the Inverse Normal plot, and was used for both Stages 2 and 3.

4.2.1.3 *Estimate by summing average lane events, & multiplying by 2*

Another approach to estimate the UTLE is to take the load effect caused by an "average" heavy vehicle and multiplying by a load factor. This load factor is statistically based, and often has a magnitude of 2. Thus the hypothesis was that the average event for each lane should be summed to estimate an average multiple-presence event. A load factor of 2 should then be applied to this UTLE. This approach (also used in Stage 3) is broadly consistent with normal design methods but, as presented, does not have a rigorous theoretical basis.

4.2.1.4 *Estimate by summing 2 average events, & multiplying by 2*

An alternative to the method to that proposed Section 4.2.1.3, is to select the average event for all data (both directions) and use this as the average event. Using similar rationale to that of Section 4.2.1.3, this number is then multiplied by 2. This approach was also used and evaluated for Stage 3.

4.2.1.5 *Estimate based on extrapolation of line of fit for all data*

If the Inverse Normal is generated from the data without lane separation, then this could be considered to be the normal population of data. If this Inverse Normal data is extrapolated, its value at the appropriate number of standard deviations from the mean could be considered as the UTLE. This approach was evaluated in Stage 3.

While this approach appears to be rational, the combined data curve asymptotes to the lane data for the lane that is causing the greatest effect on the member being monitored. Multiple-presence events tend to form a new population on the upper tail of the distribution (see Section 2).

4.2.1.6 *Estimate by extrapolation of the extreme event data*

The upper tail of the Inverse Normal plot generated from the combined data theoretically represents the population of multiple-presence events although, as discussed, it is also likely to contain other abnormal events such as those caused by overloaded vehicles. One apparently rational approach is to extrapolate this "upper tail" population to estimate the UTLE. This should overcome the difficulties associated with the method of Section 4.2.1.5. However, some of the issues arising from using this approach include:

- The population in the upper tail is relatively small;
- A long monitoring period is required to obtain values in the upper tail (the events themselves are rare);
- Statistically this approach places heavy emphasis on extreme events that may not be a robust practice.

4.2.1.7 *Estimate using Independent Upper Bound (IUB)*

An Independent Upper Bound (IUB) estimate based on lane extrapolation was described in the theory presented in Section 2 of this report. The average event for each lane is determined from the lane-separated Inverse Normal plots, as is the slope (standard deviation) for each lane. The average lane events are summed to find the average combined event. The square root of the sum of the squares for each lane is then calculated to determine the slope (standard deviation) of the combined distribution.

Using this horizontal intercept and slope, a combined Inverse Normal distribution can be estimated, and this distribution represents the upper bound of expected results, assuming that the events in each lane are statistically independent. This IUB can be extrapolated to determine the UTLE. The approach is consistent with the statistical theory presented in Section 2.4.2.

4.3 Effect of Tributary Area on Inverse Normal Plots

The governing traffic load effect (for either design or evaluation) varies for bridges and their components, based on a series of parameters including tributary area of traffic load to the component under consideration (see Section 2.4). The frequency of occurrence of events that cause the UTLE for different types of components will vary. Since this affects the form of Inverse Normal plots, a bridge that enabled data to be gathered from components having different tributary areas needed to be identified for long-term Health Monitoring. In addition, traffic load effects had to be discernible from background effects on the bridge. From the short-term Health Monitoring undertaken in Stage 2 of the project, Atiamuri Bridge was known to fit this requirement.

The long-term monitoring stage of this project was intended to provide a comprehensive database to investigate the behaviour of Inverse Normal plots for different types of structural elements. Section 3.2 described the instrumentation installed on the bridge, which consisted of eight Foil Strain Gauges. The components monitored on this bridge were:

- Four stringers (tributary area approximately 10 m^2);
- Two cross-girders (tributary area approximately 40 m^2);
- Two truss chords (tributary area approximately 200 m^2).

Thus the Inverse Normal plots derived from this project provide data from components attracting load from a range of tributary areas, which allows the effect of tributary area on the Inverse Normal plot to be investigated.

4.4 Effect of Trigger Level on Inverse Normal Plots

4.4.1 Data Gathering Process

Infratech's HMX bridge Health Monitoring system was used to collect data for this project. Understanding the data collection process is important to understanding data processing issues. The HMX system consists of a monitor (processor) and up to eight instruments (transducers).

The transducers are continuously sampled during Health Monitoring, because a "sudden" change in the reading of a transducer can be caused by a traffic effect (vehicle crossing the bridge), or a range of other influences such as background noise, thermal and other climatic effects. Health Monitoring is based on the collection of these records that are intended to represent heavy vehicle events. The monitoring system must therefore be capable of discerning a vehicle event. A threshold, that is set by the user, records events (waveforms) that exceed the threshold, and nothing when the threshold is not exceeded.

Waveforms (records of response versus time) represent a large volume of data, and it is impractical to store all waveforms recorded by each channel for every event. Consequently, the monitor that is collecting data from the instruments post-processes the data after each event is recorded. The monitor is programmed to interrogate each waveform to determine whether it is "large" or "small" (a user-defined parameter, based on the peak magnitude recorded). If the waveform is "small" then the waveform is interrogated to determine some important parameters such as peak positive and peak negative values for each channel. These values are stored, but the remainder of the waveform is deleted. If the event is "large" then the waveform is stored, and the peak values are also stored.

Inverse Normal plots are generated from the stored peak values (Section 2.4.1). The database of peak values represents all events larger than the trigger threshold, including those events for which waveforms are stored. There is little value in storing events caused by cars, because storage of these events would consume storage space and add little or no value to the data. The trigger threshold is therefore used to eliminate unnecessary small events such as cars.

"Significant" events (in terms of the Limit States of the bridge) are caused by the ambient heavy vehicle population. If the threshold is set too high, important events can be eliminated from the event database. Since the Inverse Normal plot is generated from this database, the selection of the sampling (trigger) threshold has the potential to influence the Inverse Normal plot. In Section 4.4.2, a simulation is used to investigate the effect of trigger level on an Inverse Normal plot. The Stage 2 Atiamuri Bridge data was also re-processed to investigate the effect of trigger level on the bridge, and this is discussed in Section 4.4.3.

4.4.2 Effect of Trigger Level by Simulation

A computer was used to generate 870 random numbers with a mean of 100 and a standard deviation of 20. The random numbers could be considered to represent recorded strain in a bridge member. An Inverse Normal plot was then generated as shown in Figure 4.6. An Inverse Normal was generated from the full data set.

All data less than 100 was then excluded and the Inverse Normal was re-generated. Next all data less than 120 was excluded and the Inverse Normal was again re-generated. Clearly changing the recording event threshold changes the Inverse Normal plot (Figure 4.6). In particular:

- More curvature is introduced into the Inverse Normal plot when the threshold is raised;
- The slope of the Inverse Normal increases with an increased threshold level;
- The effect on extrapolated strain depends on the extent of extrapolation.

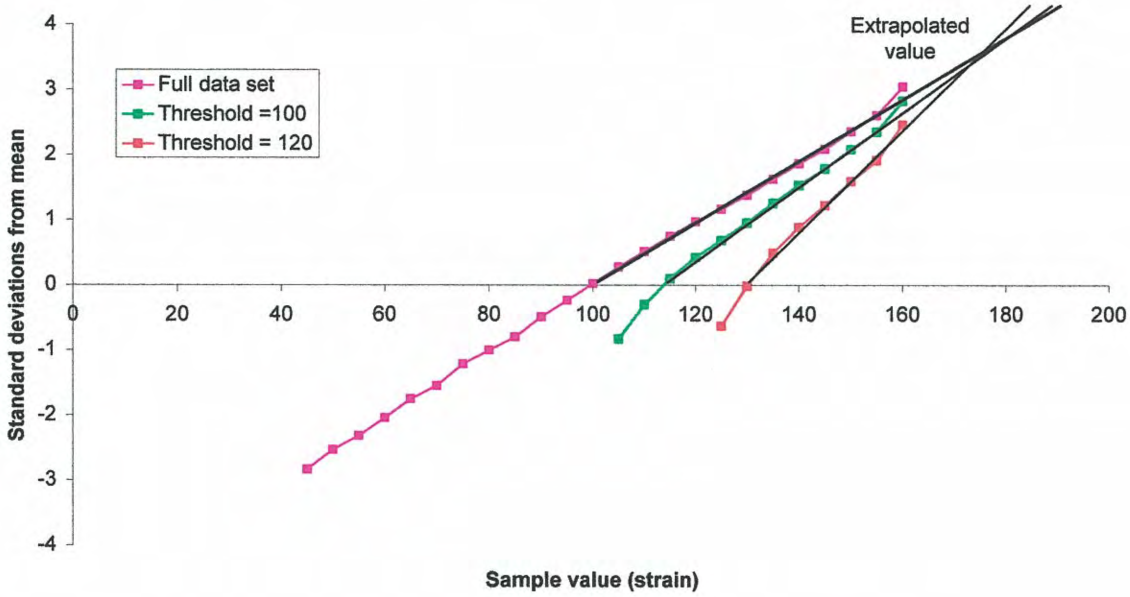


Figure 4.6 Simulation to investigate the effect of change in trigger level.

While the extrapolation level changes as the threshold increases because of reduced sample size, this effect has not been specifically considered since it is the form of the curves that is of interest. An important observation from Figure 4.6 is that a similar change in slope occurred when the threshold was increased from 0 to 100 (pink to green) as occurred when the threshold was increased from 100 to 120 (green to red). Since the average value of the population was 100, changes in threshold level appear to be more significant when the threshold value is set above the average population value, compared with when the threshold is set below the average population value.

In practical terms, this suggests that relatively light vehicles causing less than half of the maximum load effect should be included in the "heavy vehicle population" to ensure that the trigger level does not adversely affect the estimate of UTLE. Typically the trigger level is set (on site) so that all events greater than 2- to 4-tonne trucks are included in the data set.

4.4.3 Effect of Trigger Level using Short-term Health Monitoring Data

During Stage 2 of this research project, the Atiamuri Bridge was health monitored for a short period (Section 3.3.2). A strain threshold was set in the monitor of the HMX system, and when a traffic event caused the threshold to be exceeded on any transducer, the responses of all transducers were recorded for a period of approximately 10 seconds.

During this time each gauge was sampled at a frequency of 200 Hz. Thus each time the system was "triggered", eight "waveforms" (strain v time) were generated. The trigger level of the HMX system was set at 100 με for short-term Health Monitoring (Stage 2). Consequently once the strain sensed in any of the transducers had increased in excess of 100 με above the background strain, the HMX system recorded the strain results for all transducers for a period of approximately 10 seconds. During Stage 2, a total of 934 of these events were collected. Only a limited number of these waveforms were stored, and the rest were deleted after their peak values had been stored.

The long-term Health Monitoring (Stage 3) required large volumes of data to be collected, transferred internationally through the telecommunications network, and then processed. A decision was taken at the beginning of Stage 3 to limit the amount of data collected by increasing the trigger threshold to 170 με (with other monitoring configuration parameters remaining essentially unchanged). The effect that this trigger level adjustment would have on Health Monitoring results needed to be understood.

Consequently the Stage 2 Atiamuri Bridge data was re-processed. All data that would not have triggered the system in Stage 2 if a 170 με threshold had been used, were removed from the data set. This caused an approximate 25% reduction in the number of events, giving a total number of events of 696. Inverse Normal plots were then generated from this data set using the Stage 3 evaluation process, and the results are presented in Appendix C.

The main heavy vehicle population (lane-separated) is represented by the Inverse Normal plot from approximately 0.5 to 2.5 standard deviations from the mean. However it is important to understand that the main heavy vehicle fleet has been defined by other means at different sites. For example, the population from 0 to the standard deviation corresponding to 90% of the maximum event was used recently (Heywood & Welch 2000). The critical issue is to understand the data presented for a given site, and this is often assisted by diagnostic test results.

As discussed above, the range of results from 0.5 to 2.5 standard deviations was found to be representative for this site and has been used to extrapolate results in Appendix C to the 95% confidence limit in 100 years. Appendix C shows that the effect of increasing the trigger threshold is to move the lower end of most plots to the right (demonstrated in Section 4.4.2), while leaving the upper portions relatively unchanged.

Review of Figures C1 to C6 (Appendix C) shows that the sub-set of results resulting from the increased trigger level generally has little influence on the extrapolated strain (provided the population lies within 0.5 to 2.5 standard deviations). In some cases the trend is to reduce the magnitude of the extrapolated value. This reduction results from the removal of small events from the data set, which is consistent with the simulation discussed in Section 4.4.2.

4.5 Effect of Monitoring Duration on Inverse Normal Plots

The trade-off between the cost of obtaining information, and the value of information is an important practical consideration in the development of a Health Monitoring programme. An appropriate monitoring duration must be determined in each case so that sufficient data can be collected to ensure confidence in the results. However the cost of monitoring increases with time, as does the cost of data analysis (i.e. more data to analyse).

A monitoring duration of 1 to 3 days has often been used as the basis for health monitoring bridges, and this duration assumes that temporal patterns that may exist for a bridge are likely to occur within a period of approximately 24 hours. Thus seasonal effects could not be determined from such a short monitoring period.

Although this 1 to 3 day duration has been used in Stage 2, a rigorous investigation had not been conducted by Infratech to investigate the effect of monitoring period on health monitoring results. This was one of the main objectives of the long-term (Stage 3) Health Monitoring project. The "clean" complete data set obtained from this project was taken as a nominally continuous data set, sample populations were extracted from the data set, and they were analysed to investigate the effect of monitoring duration on health monitoring results.

Instead of considering the monitoring period, the number of heavy vehicle events can be used as the basis for considering sample size. Clearly monitoring duration and the number of heavy vehicle events recorded are connected, because a typical number of heavy vehicles would use a route per day. Thus the same issue (of sample size) can be addressed by considering either monitoring duration or the number of events recorded. Rather than sampling the data based on time, sampling was based on the number of events. Ten different starting events were randomly selected from the data set, simulating the commencement of ten different and random monitoring programmes. For each starting event, sample populations of the following sizes were selected:

- 10 events;
- 100 events;
- 10 000 events.

Thus for each starting event, three different monitoring durations were simulated. All data from all monitoring simulations were processed, and Inverse Normal plots were generated in the same manner as described in Section 4.1.2. Thirty different monitoring populations were simulated using the same data set, and each was considered as an independent health monitoring exercise. The UTLE was estimated for each simulation, and the results were compared to determine the effect of monitoring duration on health monitoring results (discussed in detail in Section 5 of this report).

4.6 Summary

A summary of the data processing used for Stage 3 is as follows:

- Organise the data into manageable components on the basis of time;
- Remove clearly erroneous data: for example, events with large strains (i.e. greater than 1000 με), or cases where the transducer offset has exceeded the maximum range of the transducers;
- Separate events into lanes: a parabolic curve-fitting approach was adopted in this case;
- Remove clearly erroneous data: for example, cases where edge-stringer strains are substantially greater than centre-stringer strains;
- Transform data into Inverse Normal form: adopt a global bin size increment (in this case 5 με) for Inverse Normal distributions;
- Extrapolate the heavy vehicle population data to determine the UTLE.

Table 4.4 Methods used to predict ultimate traffic load effect (UTLE).

Method	Rationale
1 CUB	Correlated Upper Bound approach used in the Bridge Manual combines two extreme single events.
2 Turkstra & Madsen's approach	This approach combines an extreme event with a typical event. In this case an average-lane event was chosen as the typical event.
3 2 x sum of lane averages	Typical (average) lane events are determined. These are summed (to allow for multiple presence), and multiplied by a load factor of 2 to provide a margin of safety.
4 2 x sum of two average events	An average event (no lane separation) is determined. This is doubled to allow for two lanes, and then multiplied by a load factor of 2 to provide a margin of safety.
5 Line of fit (all data)	The main heavy vehicle population (no lane separation) is used to extrapolate to a maximum event.
6 Extreme event extrapolation	The extreme event tail (no lane separation) is extrapolated for the heavy vehicle population to predict a maximum event.
7 IUB	Independent Upper Bound estimate. The data is first lane-separated. The lane averages are summed to estimate a combined average event. The standard deviations are summed as vectors, and extrapolated to estimate the UTLE.

Various techniques were proposed to estimate the UTLE and these are summarised in Table 4.4 as the intention was to compare these approaches using the long-term data (and discussed in Section 5). In each case the data set was used to generate projections of the UTLE using the range of techniques summarised in Table 4.4, and described in more detail in Section 4.2.

Stage 3 data was interrogated in considerable detail in an attempt to ensure that erroneous events were excluded from the result set. Where doubt existed regarding the validity of data, it was excluded from the data set. Substantial amounts of data were eventually excluded.

Health Monitoring relies on the determination (by statistical extrapolation) of an appropriate UTLE based on measured bridge response. This UTLE is then compared with estimated resistance (capacity) of bridge components and members. The Bridge Manual places considerable emphasis on the concept of multiple presence to determine the UTLE, and a similar approach has been adopted in this research project. Other "events" can possibly occur during Health Monitoring that may appear to be multiple-presence events. In particular, overloaded vehicles and some erroneous signal "events" can appear in the "upper tail" of the Inverse Normal plot, and these can be almost indistinguishable from multiple-presence events (despite data validation techniques). Both have the potential to affect Health Monitoring results, and the estimation of UTLE in particular.

The Fitness for Purpose Evaluation (FPE) described in Section 2 represents the ratio of estimated resistance to estimated UTLE, and is an important output of the Health Monitoring process. Since a range of factors can affect both the estimation of resistance and UTLE, it is important to define clearly the concept of FPE, so that Health Monitoring results can be correctly interpreted. Stage 4 of the project will deal specifically with applying FPE values, and the implementation of bridge Health Monitoring.

5. Long-Term Health Monitoring Results

The long-term Health Monitoring (Stage 3) of the project was intended to answer two fundamental questions:

- What is an appropriate monitoring duration?
- How should the issue of multiple presence be considered when evaluating bridges using Health Monitoring techniques?

Long-term Health Monitoring of the Atiamuri Bridge commenced in December 1998 and ceased in April 2000 in order to gather one year of data for analysis. Some problems were initially experienced with telecommunication incompatibilities between Australia and New Zealand. Subsequently, other problems were experienced with contaminated signals (high levels of electrical noise in the data).

While the duration of monitoring was approximately 17 months, the final "clean" data set consisted of a total of 246 days (9 months) during which time a total of 95 651 events were recorded. The lowest heavy vehicle daily traffic counts were recorded in June, July and August (280 heavy vehicles per day). The highest heavy vehicle daily traffic counts were recorded in March, April and May (480 heavy vehicles per day). No "clean" data were retained from the months of January and February from either 1999 or 2000.

The numerical data for the monitoring period were imported into spreadsheets and contained approximately 130 MB of raw data. The data were first sorted, then interrogated for validity before being analysed and presented as described in Section 4.1 of this report. The full result set and bridge behavioural issues are discussed in this Section 5. Results of estimating the UTLE, following procedures outlined in Section 4.2, are presented, before issues associated with monitoring duration are discussed. The last step was to carry out the FPE of the Atiamuri Bridge.

5.1 Bridge Response

Results from Stage 2 suggested some inconsistencies in the behaviour of the Atiamuri Bridge. With the benefit of the Stage 3 data, this behaviour was explored in greater detail.

5.1.1 Behaviour of Cross-Girders

Figure 5.1 illustrates the Inverse Normal plots for both instrumented cross-girders, i.e the abutment cross-girder (CG(Abut)) and the centre cross-girder (CG(1)). The following features of these girders should be noted:

1. The slope of the regression lines for the northbound and southbound traffic on both cross-girders are similar to each other.
2. The average strain value associated with southbound traffic is greater than that for northbound traffic for both cross-girders.

3. A greater differential exists between average strain values for north- and southbound traffic on CG(Abut) compared with that for with CG1. While the cause of point 2 is not immediately apparent, it may result from traffic–bridge interaction associated with the boundary condition at the end of the bridge (also associated with the road profile).
4. Deviation from a normally distributed population associated with southbound traffic is more evident compared with that associated with northbound traffic.
5. No real evidence of deviation is shown from a normally distributed population associated with northbound traffic on the abutment cross-girder.

Deviations from Normal distribution on the upper tail of the Inverse Normal plots are caused by a combination of overloaded vehicles, multiple-presence events, and signal errors.

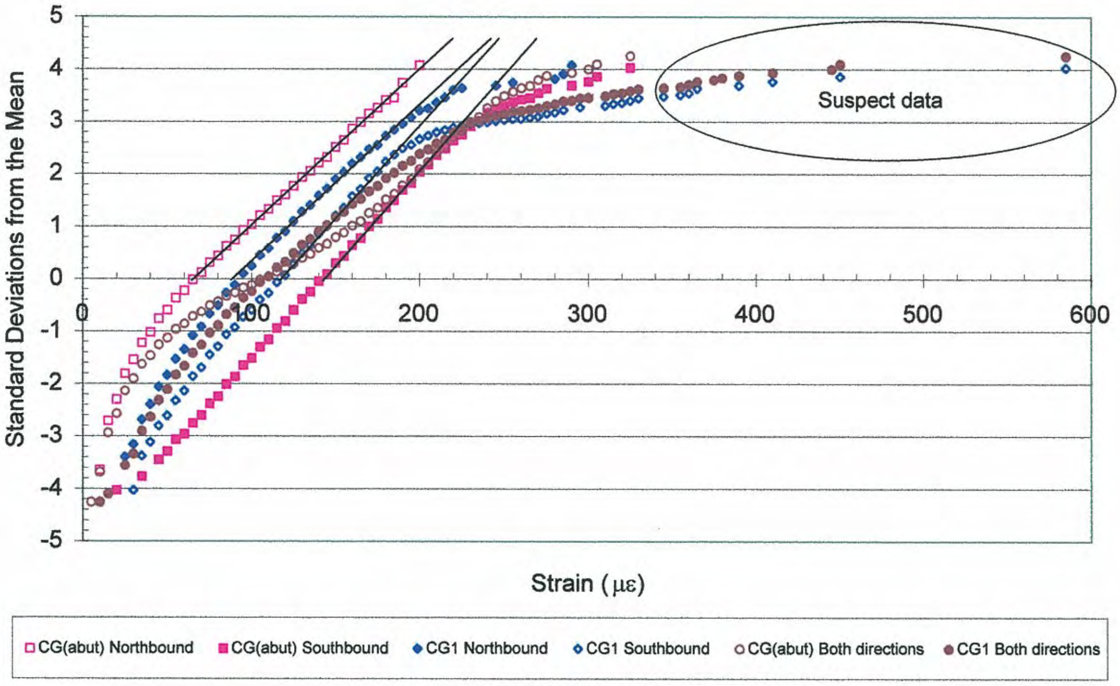


Figure 5.1 Comparison of behaviour for CG(Abut) and CG(1) cross-girders.

Figure 5.1 implies that the standard deviations (slope) of both north- and southbound traffic populations are similar for both cross-girders, but that southbound traffic induces a greater effect than northbound traffic. This differential effect is more pronounced on the abutment cross-girder than the internal cross-girder, which may be associated with traffic–bridge interaction effects at the end of the bridge.

The apparent UTLE population becomes evident between 2.5 and 3 standard deviations from the mean for southbound traffic on cross-girder CG1. This effect occurs at just over 3 standard deviations from the mean for the abutment cross-girder. Multiple-presence events are more likely to occur on the internal cross-girder which has a greater tributary area than on the abutment cross-girder.

Some of the data in the UTLE population appeared to be suspect, and further investigation showed a small number of events associated with CG1 that had very high strain readings, but very little strain in the stringers. The data filtering process did not target this type of data, and the result is that part of the apparent UTLE population is erroneous. This illustrates both the need for data validation, and the potential problems associated with projecting the small (and unrepresentative) UTLE data population.

5.1.2 Behaviour of Inside Stringers

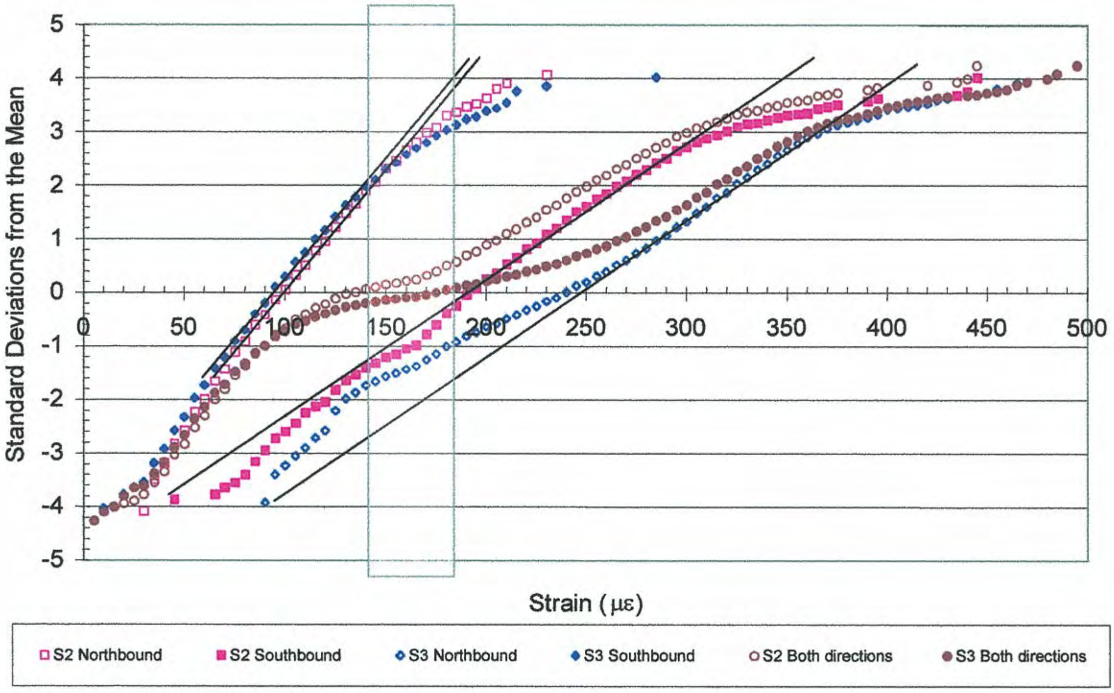


Figure 5.2 Comparison of behaviour of inside Stringers S2 and S3.

Results for the inside Stringers S2 and S3 are given in Figure 5.2. Nominally the response of these stringers should be similar, but the figure shows differences in the responses of S2 and S3, and the following features should be noted:

1. Stringer strains are similar in both stringers when loading occurs in the opposite lane to the stringer being considered (i.e. S2 northbound, and S3 southbound);
2. The response of the stringers is significantly different (S2 southbound, and S3 northbound) when the load is applied over the stringer. The standard deviations for both stringers are similar (i.e. have similar slopes). However the average value is significantly higher for S3 compared to S2. S2 has a “dip” in the shaded zone on Figure 5.2. This seems to be associated with a change in response of S3.

Section 3.4 illustrated that slip occurs between the deck and Stringer 3 (S3), and Figure 5.2 suggests that the behaviour of S3 begins to change when the bottom flange strain is approximately 140 με. This behaviour changes gradually up to approximately 250 με, above which it is consistent until the curve deviates to the right. This deviation occurs for strain magnitudes greater than 360 με.

The likely explanation for the behaviour of S3 between 0 με and 140 με is that for bottom flange strains less than 140 με, slip continues to occur. For bottom flange strains in excess of 250 με, the composite action between the deck and the stringer has been fully engaged. For bottom flange strains between these values, the system is in transition between the two cases (i.e. composite action is in the process of being engaged).

The maximum strain in Stringer S3 recorded during diagnostic testing in Stage 2 was 280 με. The diagnostic test vehicle had legally loaded tandem-axle groups, and a legally loaded tridem-axle group was calculated to have an effect 1.22 times greater than the effect from a tandem set. Thus "Normal" heavy vehicle events would be expected to result in S3-event magnitudes that are up to approximately 340 με. Consequently events in S3 with magnitudes above 360 με are likely to result from an overloaded vehicle, multiple presence events, or from signal errors (assuming no significant deterioration in composite action has occurred since the Stage 2 monitoring).

5.1.3 Behaviour of Outside Stringers

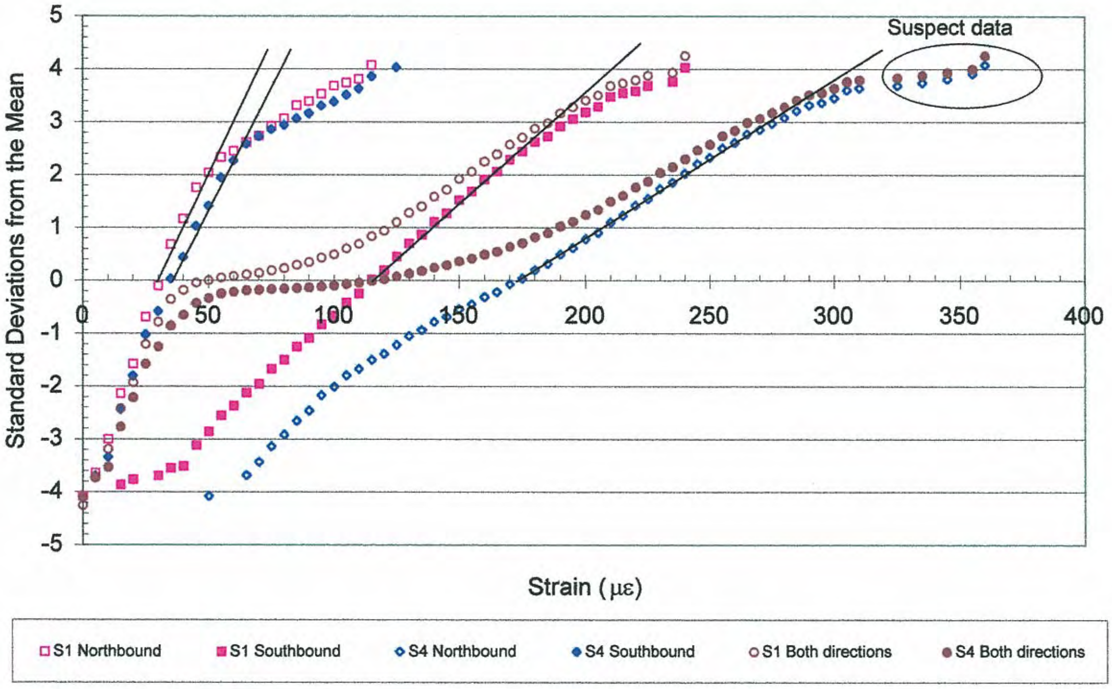


Figure 5.3 Comparison of behaviour of outside Stringers S1 and S4.

The standard deviation is greater for Stringer S4 with northbound traffic, compared with S1 with southbound traffic. This is most likely associated with the loss of composite action in S3 discussed above. The reduced stiffness in S3 will tend to re-distribute load into S4, thus increasing the range of load (and hence standard deviation) recorded in S4. The results obtained from the known-vehicle testing using the slip gauge helped to confirm this mechanism and hence the bridge behaviour. This example demonstrates the advantage of adopting known-vehicle testing to a Health Monitoring programme.

Some similarities are noted between Figure 5.2 and Figure 5.3, in particular:

1. Stringer strains are similar in both S1 and S4 stringers when loading occurs in the opposite lane to the stringer being considered (S1 northbound, and S4 southbound). This also occurs in S2 and S3.
2. The response of the stringers is significantly different (S1 southbound, and S4 northbound) when the load is applied over the stringer. The standard deviation (slopes) associated with S3 and S4 are different to each other in this circumstance.

5.1.4 Behaviour of Truss Chords

Figure 5.1 implies that southbound traffic causes greater load effects than northbound traffic. However, Figures 5.2 and 5.3 suggest that the opposite is the case. To investigate this effect, the behaviour of the western and eastern truss chords was compared, and is illustrated in Figure 5.4.

Since the Inverse Normal has a greater magnitude for the western chord compared with the eastern chord, the northbound traffic (on average) seems to produce a greater structural response than southbound traffic.

A range of factors can affect this apparent difference in behaviour including:

1. The loss of composite action in Stringer 3, which increases the recorded strain in Stringers 3 and 4. Thus greater load effects would be expected for northbound traffic;
2. The interaction of road profile, bridge, and vehicle response may affect cross-girder behaviour, causing an apparent greater response as a result of southbound traffic.

5.1.5 Summary of Bridge Behaviour

It is difficult to draw general conclusions from these results other than that the responses of bridge elements vary, and that variations in traffic characteristics and bridge response can influence the recorded response.

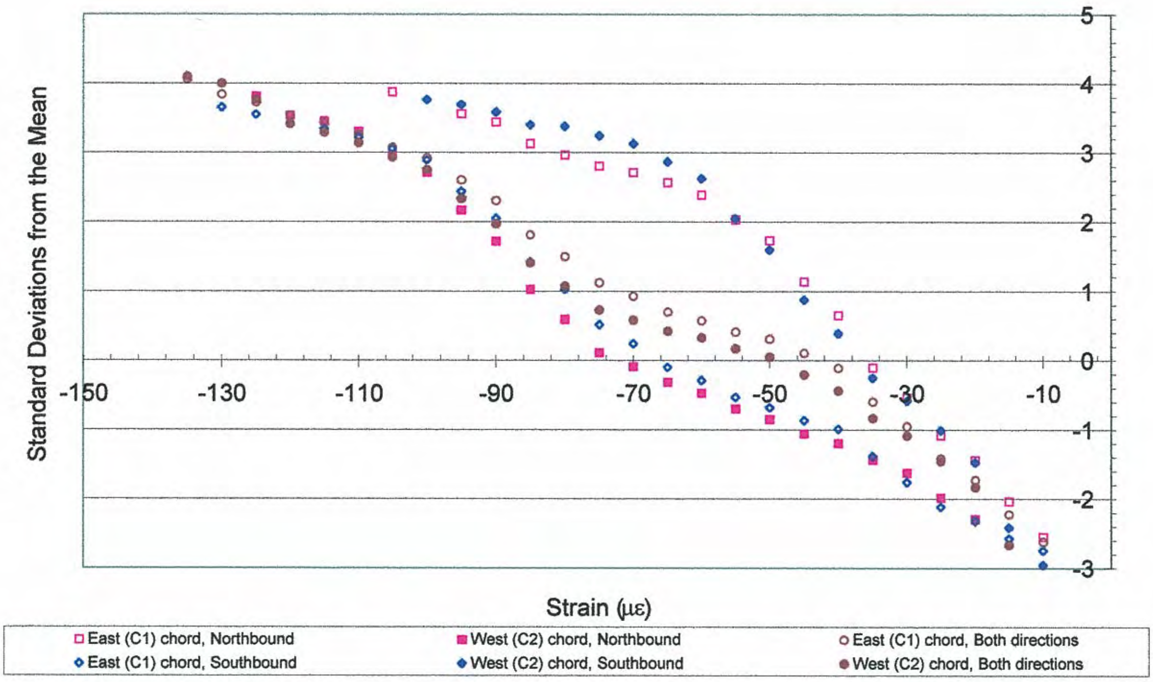


Figure 5.4 Comparison of behaviour of the outside truss chords C1 and C2.

Suspect data is indicated on Figures 5.1 and 5.3, and is associated with traffic flow in opposite directions, and results predominantly from lane events (as opposed to multiple-presence events). In the case of Figure 5.1, some of the CG1 events associated with southbound traffic have produced strain events of magnitudes twice those produced in the abutment cross-girder (CG(Abut)). These high CG1 strains are also associated with relatively low stringer strains. This suspect data may be the result of electronic effects, abnormal bridge response, or unusual vehicle effects so the validity of this data is questionable. This data would normally have been deleted, but has been retained to illustrate the need for appropriate data interpretation.

5.2 Estimation of the Ultimate Traffic Load Effect

The sampling methodology used to investigate the effect of monitoring duration on UTLE was described in Section 4 of this report. The methodology used was to sample the large database obtained from the Atiamuri Bridge. Sampling occurred on the basis of the number of events rather than monitoring duration. Ten start times were randomly selected (based on a combination of date and time) during the monitoring period. Using the event that occurred closest to this date and time as the starting event, sample populations of 10, 100, 1000, and 10 000 sequential events were chosen. Thus, 10 independent samples were selected for each of the above number of samples. In each case the data set was used to generate projections of the UTLE using the seven techniques described in Section 4. These projections were then analysed to evaluate the effect of sample size on the consistency of results.

The long-term Health Monitoring data was also used to compare the validity of the estimates of UTLE obtained, using each of the seven methods proposed for predicting UTLE (Section 4.2). The UTLE was calculated for each transducer using the correlated upper bound (CUB) as required by the Bridge Manual (Method 1), based on the full data set, and to be used as the reference value.

The UTLE was then calculated for the sample sizes (10 samples for each sample size) using each of the remaining six methods under consideration. The mean and standard deviation of these UTLE estimates were calculated. The mean value estimates were then divided by the reference values (based on CUB) to facilitate comparison between the methods, and the results are given in Appendix E.

5.2.1 CUB Method (Method 1)

The CUB method (Method 1, Table 4.4) was used as the reference value for the full data set, and hence all results converge on a fixed value for all the data (Figure E1, Appendix E). Consequently, Figure E1 provides an indication of the change in mean value as the number of samples increases. The figure also illustrates that a sample size of 1000 events provides a reasonable estimate of the UTLE, and that little apparent advantage is gained in monitoring for 10 000 events.

5.2.2 IUB Method (Method 7)

Figure E6 (Appendix E) was generated from UTLE projections based on the independent upper bound (IUB) approach (Method 7, Table 4.4) as described in Section 2.4.2. The form of this figure is reasonably similar to that of Figure E1.

5.2.3 Methods 3, 4 & 5

Figure E3 presents results from calculating the UTLE based on twice the sum of the average data for each lane (Method 3, Table 4.4), while Figure E4 was based on calculating the UTLE based on twice the average value of all data (Method 4). These two approaches produce quite different numerical results, but exhibit similar (though less pronounced) grouping to that of Figure E2 which is based on member type. This grouping appears to be the result of the relationship between average and extreme events for given member types.

Similar grouping is evident on Figure E5, where the population of all data was extrapolated from the full data set (independent of lanes) (Method 5, Table 4.4). A review of Appendix A shows that Methods 4 and 5 are unconservative, so they have been rejected as valid evaluation methods.

5.2.4 Extreme Event Extrapolation (Method 6)

Prediction of the UTLE using extrapolations of the extreme events (Method 6, Table 4.4) was not possible in some cases, so these data are not presented in Appendix E. Figures A4 and A6 (from which Figures 5.1 and 5.2 have been derived) illustrate situations where recorded events exceed predictions resulting from Method 1. Two likely causes were suspected, namely:

- Erroneous measurements;
- Non-linear member behaviour.

Erroneous measurement caused this result (as discussed in Section 5.1). The specific events that produce the exceedance in the given member are not consistent with results in other members for the same event. While the concept of using extreme projections may seem to be appropriate, discussions in Section 5.1 show that using extreme event projections can be problematic. This would appear to be an inappropriate technique unless a very large number of events (significantly larger than that of the Atiamuri database) are available. Method 6 was therefore rejected since it is unreliable (as it is reliant on a small number of extreme events with dubious statistical validity).

5.2.5 Turkstra's Method (Method 2)

The approach recommended by Turkstra (Method 2, Table 4.4: Turkstra & Madsen 1980) was used to generate Figure E2. This figure in Appendix E illustrates that:

- Increasing sample size above 1000 events has little effect on results (the slope of the plot for each transducer is relatively flat and constant);
- Results predicted by Turkstra's approach are less than those predicted by the Bridge Manual approach;
- Results predicted by Turkstra's approach are dependent on the nature of the member being monitored and its loading characteristics. For example, results for stringers tend to be grouped, those for cross-girders tend to be grouped, etc.

Again the implication is that 1000 events is an appropriate sample. The second item listed above follows from the theoretical basis of Turkstra's method compared with the CUB method. The former is based on combining an average event with an extreme event, while the latter is based on combining two extreme events. The tendency for results for similar members (e.g. S1 and S4) to group together suggests a consistent relationship between average and extreme events for a given member configuration and traffic population.

In some cases a substantial economic advantage is associated with adopting Turkstra's approach. The UTLE predicted by Turkstra's approach is only 65% of that predicted by the CUB method. Therefore, lower ULTE estimates will produce higher FPE, indicating that more bridges are "fit for their purpose" (than calculated using the CUB, as in the Bridge Manual). While Turkstra's approach generally appears to be reasonable, Figures A5 and A6 suggest that this approach may be unconservative, and further investigation into the practical application of Turkstra's principle may be warranted. Consequently the current interpretation for applying Turkstra's method is not appropriate.

5.2.6 Recommended Methods

Both Figures E1 and E6 have less dependency on member type than the other methods, and they produce similar predictions when based on sample sizes of 1000 events.

The recommended method for determining the UTLE is the CUB method that is already used by the Bridge Manual.

In some circumstances, the IUB method may be appropriate, particularly where there is confidence that heavy vehicle events will be independent of each other. The IUB method will produce smaller estimates of UTLE than the CUB method, and therefore will tend to indicate that bridges are "fit for their purpose" compared with the indications obtained by the CUB method.

5.3 Effect of Monitoring Duration

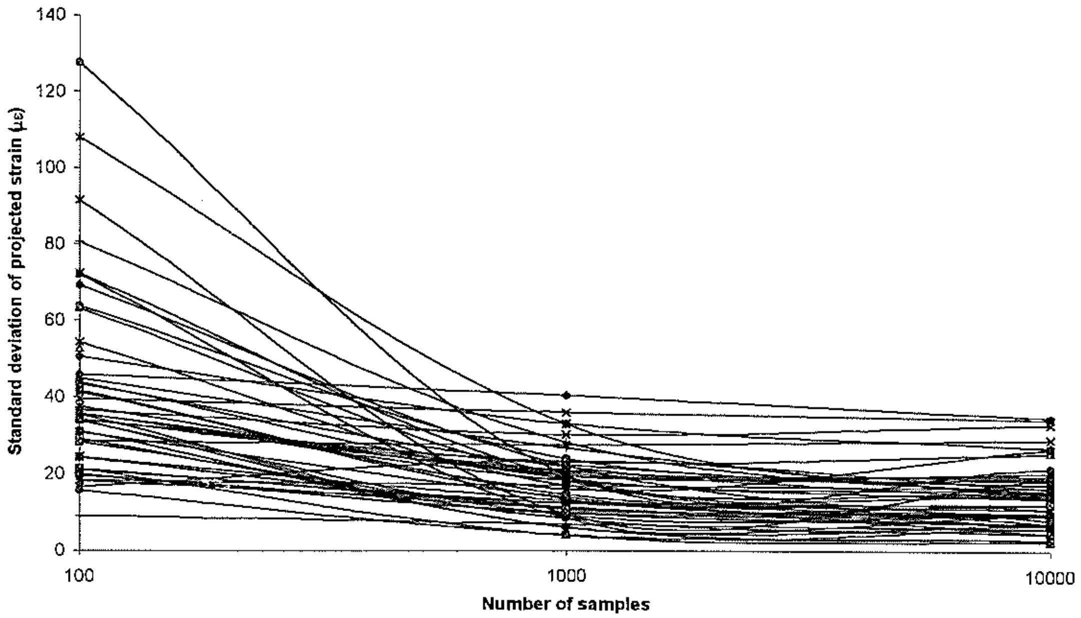


Figure 5.5 Standard deviation of projected strain versus number of samples.

Results presented in Section 5.2 suggest that a sample population of 1000 events is adequate to predict the UTLE (based on mean values). The standard deviations of these same samples were calculated, and they have been plotted against sample size for all methods on Figure 5.5. A sample size of 10 events was found to be too small to create meaningful Inverse Normal plots, so these results have not been plotted. Figure 5.5 shows that the standard deviations of all projection methods behave in a similar manner (with the exception of some extreme event projections which were not plotted). Little change occurs in the standard deviation between taking 1000 and taking 10 000 samples, with the upper bound of standard deviation in this range being 40 με.

Figure 5.5 also shows that considerable benefit can be gained in increasing the sample size from 100 to 1000, in that this can substantially reduce the standard deviation of results. Again, the evidence therefore suggests that a sample population of 1000 events is appropriate for general health monitoring purposes (excluding seasonal or similar traffic effects). There may be some benefit (from an economic perspective) in reducing the sample population to below 1000 events, but further research would be required to investigate the implications of a reduced sample population, particularly for other types of bridges.

5.4 Fitness for Purpose Evaluations

Data-processing methodology can affect the UTLE estimate. Consequently the FPE calculated for Stage 2 (both for data set and processing method) is compared with the FPE for Stage 3 (also for data set and processing method). The two methods considered appropriate for estimating the UTLE were the CUB (essentially the Bridge Manual method), and the IUB (described in Section 2.4.2). Because the UTLEs estimated using these two methods are different, both methods have been applied to calculate the FPE to compare their effects.

5.4.1 Comparison of FPE from Short-term & Long-term Monitoring

An FPE was completed for the Atiamuri Bridge as part of Stage 2 using short-term Health Monitoring data (Andersen et al. 2000). An FPE was also completed using the long-term Health Monitoring data and the Stage 3 methodology (described in Section 4.1) to compare the results of Stage 2 with Stage 3. These results are summarised in Table 5.1. The Stage 3 strain results are based on the maximum values and extrapolated values corresponding to a 5% probability of being exceeded in 100 years (95% 100 years) as shown on the figures in Appendix A.

Table 5.1 Comparison between FPE obtained for Stage 2 with that for Stage 3.

	Results from Short -Term HM (Stage 2)							Results from Long Term HM (Stage 3)						
Element	Max test truck	Max HM	Extrapolated 95 % in 100 year limit			Short term HM		Max HM		Extrapolated 95 % in 100 year limit			Long term HM	
			N	S	MP	LLC	FPE	N	S	N	S	MP	LLC	FPE
Col #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
S1	160	190	249	**270**	519	730	80%	115	**242**	78	**262**	340	730	104%
S2	220	335	367	**450**	817			232	**446**	230	**412**	642		
S3	280	445	**580**	345	**925**			**484**	284	**473**	229	**702**		
S4	185	255	**390**	202	592			**357**	123	**364**	92	455		
CG (abut)	120	285	**450**		**900**	959	106%	202	**323**	256	310	566	959	170%
CG1	120	250	**350**		700			290	**585**	276	**276**	**552**		
BC1	80	110	**165**					-107	**-133**	-109	**-155**	-264		
BC2	80	120	**180**					**-125**	-99	**-152**	-106	-257		

Shaded results from TNZRR 173 (Andersen et al. 2000).
Unshaded results are from this present report.
All figures in Micro-strain (με) or percentage (%).
HM – Health Monitoring

Element Definitions:

S1 to S4 – Stringers 1 to 4 (Figure 3.2)

CG (abut) – Abutment cross-girder

CG1 – Cross-girder 1

BC1 & BC2 – Bottom chords 1 and 2

Column# Definitions:

1 - Maximum known heavy vehicle strain

2 (also 8, 9) - Maximum HM strain

3, 4 (also 10, 11) - Extrapolated limit for single lane

5, 12 - Calculated multiple presence (MP) strain (worst lane1+worst lane2)

6, 13 - Calculated live load capacity (LLC)

7, 14 - FPE (%)

5.4.1.1 *Effect of monitoring duration*

The same live load capacity strains (LLC, columns 6 & 13 in Table 5.1) were used in both Stage 2 and Stage 3 evaluations. The strains corresponding to a 5% probability of being exceeded in 100 years were significantly less when based on the long-term health monitoring data, compared with those based on the short-term data. Overall the FPE rose from 80% in Stage 2 to 104% in Stage 3, which is a significant difference.

A number of factors (other than variations in traffic and bridge behaviour) were likely to influence such changes in the data including:

- Variations in evaluation methodology;
- Variations in monitoring system trigger level;
- Replacement of demountable strain gauges with foil strain gauges;
- Different durations of monitoring periods.

5.4.1.2 *Effect of evaluation methodology*

The Stage 2 evaluation methodology was to:

1. Validate peak event data;
2. Sort data into lanes based on whether the peak maximum strain occurred in Stringer 2 (southbound traffic) or Stringer 3 (northbound traffic);
3. Extrapolate line of best fit of lane data to obtain the expected peak strain corresponding to 5% probability of being exceeded in 100 years (95% 100 years);
4. Use expected peak strain to determine FPE.

As discussed in Section 3.3.2, the known vehicle results from the Stage 2 report showed that higher strains were recorded in Stringer 3, compared with Stringer 2 for similar events. This was attributed to variations in composite action between the two stringers (Section 3.4). The outcome was that the lane-sorting (step 2 above) incorrectly sorted some data. A vehicle travelling south may have caused a slightly higher strain in Stringer 3 with its higher than Normal response, compared with Stringer 2.

Consequently, the simple lane-sorting routine may have classified some southbound events as northbound events. The net result of incorrect lane classification was to modify the Inverse Normal curve for the lane traffic that did not travel over the stringers under consideration.

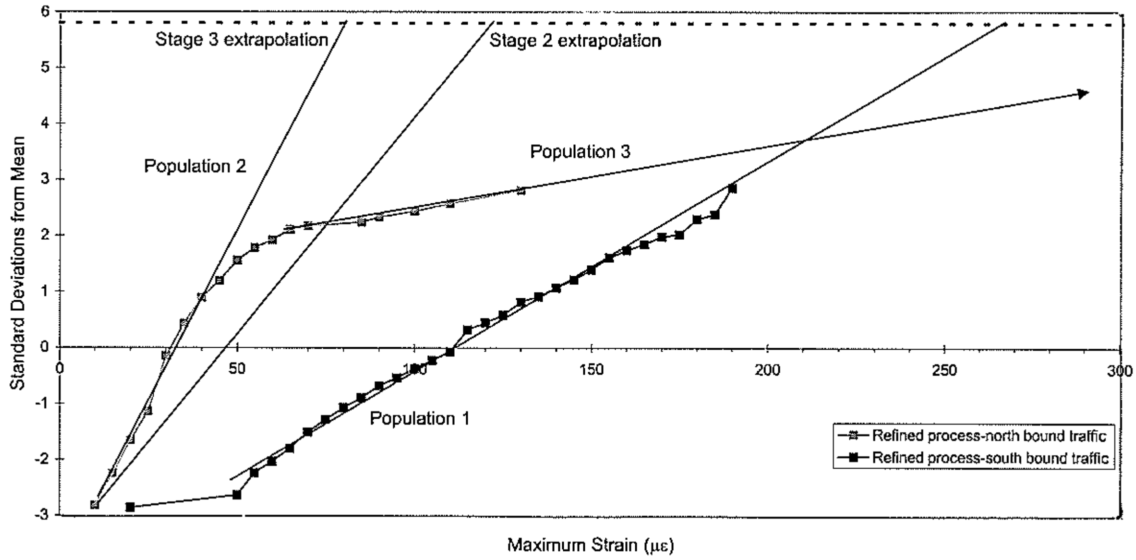


Figure 5.6 **Simplified Inverse Normal plot for Stringer 1 (Figure B1, Appendix B) to compare effect of evaluation methods on Stages 2 and 3 results.**

The effect that incorrect lane classification has on the UTLE for traffic data from each lane also depends on the methodology used for extrapolation. The methodology used for Stage 2 was a line of best fit for all strain values with a positive standard deviation. Recalling that a straight line on an Inverse Normal plot will represent a Normally distributed population, two different populations would be represented by lines of different slope on an Inverse Normal plot. This is illustrated on Figure 5.6.

Stringer 1 is the edge-stringer under the southbound lane. Therefore the heavy vehicle population is a straight line (population 1, Figure 5.6). Northbound traffic causes much lower strains in Stringer 1 compared with southbound traffic, but still remains a straight line (population 2, Figure 5.6). When a heavy vehicle travels in the northbound lane at the same time that a lighter vehicle travels in the southbound lane (a multiple presence event), the event will appear to result from a northbound event. However, the strain that results will be the sum of a northbound heavy vehicle and a southbound light vehicle. This will appear as a separate population on the Inverse Normal (population 3, Figure 5.6), and this effect is evident on Figures B1 and B4 (Appendix B). The effect is not apparent on Figures B2 and B3 because of the relative magnitudes associated with the multiple-presence events (i.e. a small vehicle in the opposite lane has little influence on internal stringer response when a large vehicle is present in the lane of primary interest).

As stated previously, the Stage 2 extrapolation was based on the line-of-best-fit through the lane data. According to the above discussion this is not the most appropriate extrapolation. Instead populations 1 and 2 (Figure 5.6) should be used for the extrapolated lane events, and this approach was used during Stage 3. This approach can have a significant effect on the derived extrapolated value, and therefore on the FPE rating.

5.4.1.3 *Effects of other factors*

The effect of trigger level on Inverse Normal plots was discussed in Section 4.4. Since the trigger level was higher in Stage 3 compared with that used in Stage 2, the lower end of the Inverse Normal should be rotated to the right. In addition, the top portion of the Inverse Normal for the stringers in the lane opposite to the stringer under consideration would be expected to be rotated to the right (the result of modified trigger level). A review of the figures in Appendix D reveals that these effects are generally apparent.

While trigger level can affect the Inverse Normal plot, the above methodology makes estimation of UTLE relatively insensitive to trigger level settings, because the upper portion of the positive distribution is used, and trigger level does not greatly influence this portion of the distribution.

DSGs were used to measure the strain on Stringers 1 to 4 and the Abutment cross-girder during Stage 2, whereas FSGs were used during Stage 3. The mounting geometry of the DSGs means that, for this bridge, they would tend to read values between 3% and 5% higher than those recorded by foil gauges.

Thus, the Inverse Normal curves for the stringers and the abutment cross-girder would be expected to be shifted to the right by 3% to 5%. However as the Stage 2 report included an adjustment of this effect, it should not affect the results.

Neither the different trigger levels, nor the difference in transducers used in Stages 2 and 3, have therefore influenced the difference in results. None of the main aberrations in results between the two stages is evident on Figure D5 (Abutment cross-girder). Substantially larger strains were recorded during the Stage 2 monitoring compared with the Stage 3 monitoring, though the reasons for this are not clearly evident.

The longer monitoring period used in Stage 3 could possibly result in variations in traffic characteristics compared with Stage 2. Both the number (280 to 480 heavy vehicles per day) and distribution of events varied throughout the Stage 3 monitoring period. Total load histograms were calculated by summing the four stringer strains for valid events for each month. The histograms for the months of March 1999 and July 1999 are illustrated in Figures 5.7 and 5.8 respectively. Significant variations in traffic characteristics are evident in these figures that are representative of the greatest variation between months. The Stage 2 data was recorded in October, and the corresponding Stage 3 data showed that October traffic characteristics were representative of the combination of Figures 5.7 and 5.8. Thus the short-term FPE should not have been significantly affected by traffic variation with respect to the long-term Stage 3 FPE.

5.4.1.4 *Summary of factors affecting these differences*

Of the factors that may have affected the FPEs calculated from Stage 2 and Stage 3 data, the evaluation methodology (Table 4.4) that is used is the most likely cause of variation. In particular, discrepancies in lane sorting and extrapolation have affected the results.

The Stage 3 results should be preferred over the Stage 2 results, because the former are obtained from more rigorous and robust evaluation.

5.4.2 Comparison of FPE from CUB & IUB methods

The Independent Upper Bound (IUB) method was proposed as a method of estimating the UTLE in Section 5.2.2). Details of calculating this FPE for the Atiamuri Bridge are given on Figure 5.9, while the results of the CUB method (Section 5.2.1) are compared in Table 5.1. This shows that the performance of Stringer 3 still determines the FPE rating, but that the rating has increased from 104% to 120%.

Use of the IUB method for Atiamuri Bridge is appropriate because traffic events can be considered to be independent. This increase can be quite significant in the context of bridge evaluation.

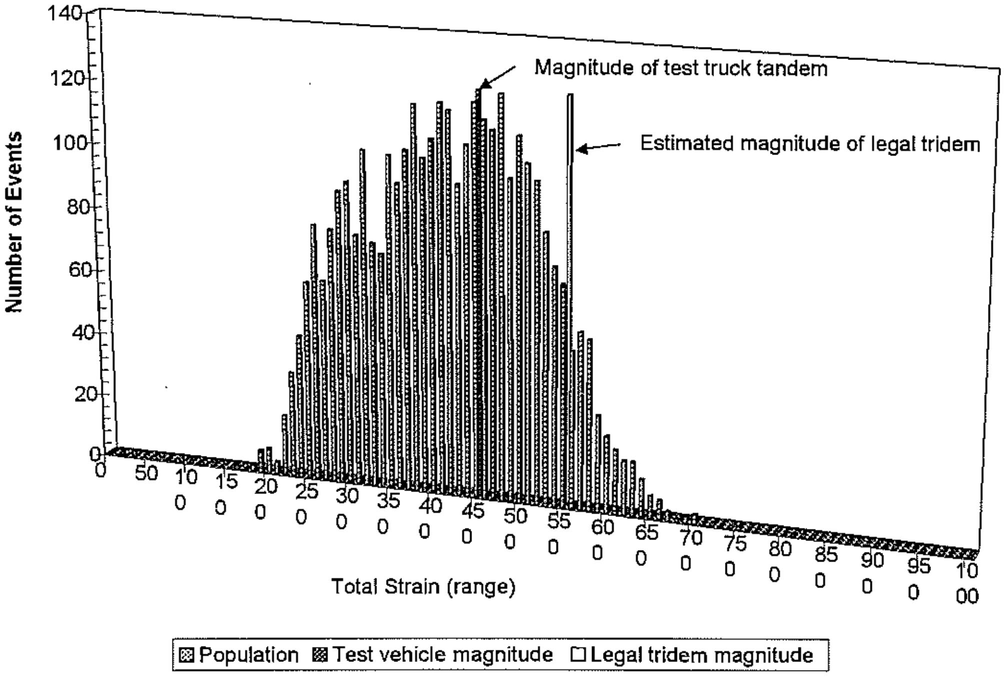


Figure 5.7 Total load histogram for March 1999 – southbound traffic.

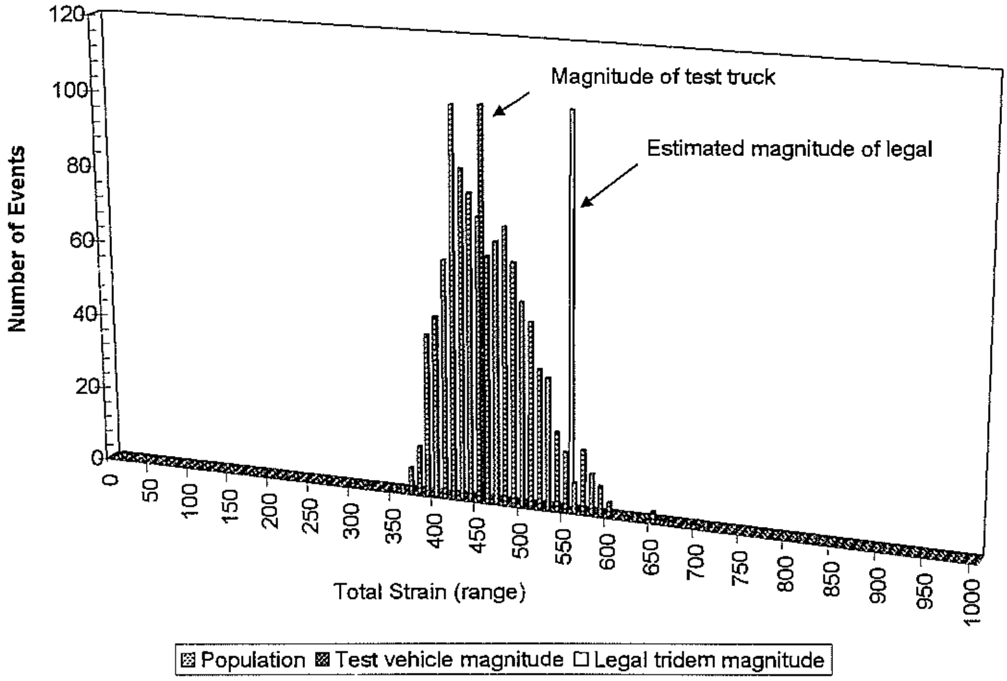


Figure 5.8 Total load histogram for July 1999 – southbound traffic.

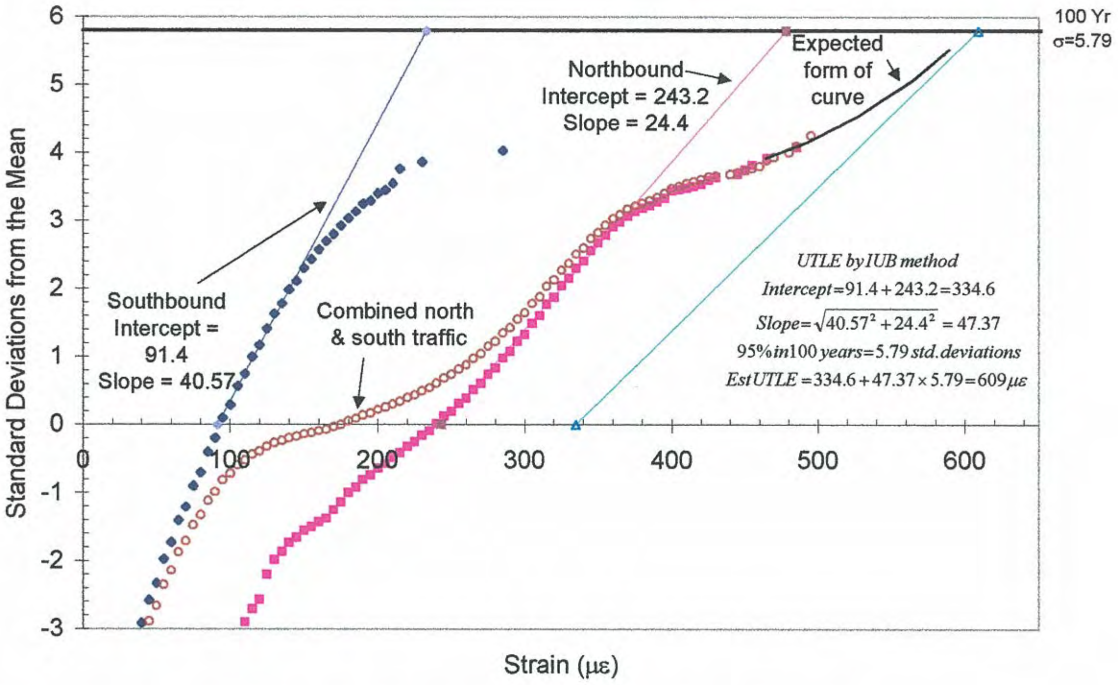


Figure 5.9 **Determination of FPE using IUB method for Stringer 3.**

			Results from Long-Term HM (Stage 3) TNZ (1994)					Results from Long-Term HM (Stage 3) Section 3.1		
Element	**Max HM**		**Extrapolated 95 % in 100 year limit**			**Short-term HM**		**Extrapolated 95 % in 100 year limit**	**Long-term HM**	
	N	S	N	S	MP	LLC	FPE	MP	LLC	FPE
Col #	1	2	3	4	5	6	7	8	9	10
S1	115	**242**	78	**262**	340	730	104%	304	730	120%
S2	232	**446**	230	**412**	642			552		
S3	**484**	284	**473**	229	**702**			**609**		
S4	**357**	123	**364**	92	455			411		
CG (abut)	202	**323**	256	**310**	566	959	170%	**467**	959	200%
CG1	290	**585**	276	**276**	**552**			457		
BC1	-107	**-133**	-109	**-155**	-264			-219		
BC2	**-125**	-99	**-152**	-106	-257			-215		

Table 5.2 **Comparison between FPE predicted by CUB with that by IUB methods.**

In some bridge codes, a load factor of 0.9 is applied to multiple-presence events to allow for the low probability of occurrence of two extreme events in opposite lanes (AUSTROADS 1996). If a load factor of 0.9 were applied to the CUB estimation method, then the FPE would be 116%. Further investigation may be required on other types of structures to investigate the validity of a possible 0.9 load factor, particularly in cases where events should not be considered to be independent (i.e. when both lanes of the bridge carry traffic in a single direction).

In some bridge codes, the strength limit state is defined in terms of the structural reliability index β. Although procedures to calculate the structural reliability of a bridge are not developed here, it is the next logical step in the application of Health Monitoring data.

Other issues that require further investigation with respect to UTLE and multi-lane bridges include various combinations of multiple-presence, such as:

- multiple lane bridges where traffic is travelling in the same direction (rather than in opposite directions);
- medium span bridges where vehicles following closely behind each other are supported by the same span;
- long span bridges supporting queues of stationary vehicles.

5.5 Use of Health Monitoring Results

The objectives of Stage 3 of this project were given in Section 1 of this report, and they deal with the development of appropriate analytical techniques for Health Monitoring data. Practical use of these (analytical) Health Monitoring results will require the consideration of a range of qualitative issues not specifically considered in this document. These issues include:

1. Health Monitoring results are based on measured quantities. Engineering experience and judgement may be required to interpret some quantities.
2. The Health Monitoring procedures presented in this report estimate live load effects from moving traffic streams. Thus, its greatest application will be with short to medium span bridges, or in smaller components of long span bridges. Hence the methodologies presented are applicable to the majority of New Zealand's bridges.
3. The upper tails of the statistical distribution of bridge live load effects tend to be normally distributed, and this is generally reflected in Health Monitoring data. However in some cases (e.g. Stringer 3, Atiamuri bridge) there is evidence that data is not normally distributed. In such cases it is important to develop an understanding of what has caused the effect before making full use of the data.
4. Health Monitoring provides estimates of traffic load effects for vehicles travelling in typical lane positions (i.e. it is strongly influenced by traffic behaviour patterns). Where critical cases for evaluation are outside what might be considered typical traffic behaviour (vehicles travelling in "out of lane" locations), Health Monitoring alone is unlikely to provide estimates of structural response. In such cases, bridge responses for these load cases can be investigated by conducting a concurrent behavioural testing programme to ensure that such issues are addressed.
5. Fundamental to Health Monitoring is the extrapolation of results to estimate live load effects. There is clearly some uncertainty associated with extrapolation beyond measured behaviour, particularly since non-linear effects and partial failures can occur. Uncertainties associated with linear extrapolation beyond measured responses must be considered when using Health Monitoring results.

6. Kerbs and guardrails often make significant contributions to bridge stiffness and strength. There is concern that the effectiveness of kerbs and concrete handrails may break down at higher load levels, or that they could be damaged before a large live load effect event. This concern is reflected in the Bridge Manual, which requires the contribution of concrete handrails to be ignored and limits the contribution of kerbs in some circumstances. Health Monitoring includes their effects as a matter of course.

   The most practical approach to deal with this issue appears to be the use of adjustment factors that consider the magnitude of kerb and guardrail contributions, the extent of extrapolation required to resist likely live load effects, and the risk that these elements may not be fully functional at the occurrence of an extreme live load effect.

7. In most cases, Health Monitoring results will be used as a means to address ultimate limit state effects. The technology can be equally used to evaluate serviceability (deflection) issues, but a methodology to compare actual and predicted responses with accepted benchmarks requires development.

Health Monitoring data must be used with knowledge and engineering judgement. Thus the Health Monitoring process must be managed by an experienced engineer with a sound understanding of the design and behaviour of structures, experimental techniques, and the Health Monitoring process.

Health Monitoring is different in nature to existing rating and posting evaluation processes. As such, it can be used to complement the total bridge evaluation process as an integral part of both asset management and bridge engineering procedures. Stage 4 of this project aims to produce a "Guide for Health Monitoring of New Zealand Bridges", and will further address these issues.

6. Summary of Long-term Health Monitoring Results

Long-term Health Monitoring of the Atiamuri Bridge was conducted for a period of approximately 17 months during which approximately 9 months of "clean" data were acquired. The key objectives of this Stage 3 were to:

- Refine and define the Health Monitoring process;
- Determine an appropriate sample size for Health Monitoring;
- Determine the appropriate methodology to predict the UTLE.

The results of the long-term Health Monitoring are summarised in this Section, as well as the behaviour of the Atiamuri Bridge.

6.1 Data Processing & Health Monitoring

Generally the Health Monitoring results for Stages 2 and 3 are consistent with each other, with the following exceptions:

- The simple lane-classification approach used in Stage 2 did not adequately classify all lane data;
- An improved selection of the line-of-best-fit for lane data was used for Stage 3, compared with that used for Stage 2;
- The trigger level used for Stage 3 was approximately 170 $\mu\varepsilon$, compared with 100 $\mu\varepsilon$ for Stage 2 (although this did not significantly affect results);
- Some data recorded on the Abutment cross-girder during Stage 2 is inconsistent with the Stage 3 data. Greater confidence should be placed in the Stage 3 data.

As the methodology used to generate the Stage 3 Inverse Normal plots was more refined than that used on the Stage 2 data, the Stage 3 results should be preferred. Despite the reasonably comprehensive data processing used during Stage 3, a number of erroneous records still existed, in particular, the high strain levels recorded in Stringer 4 and Cross-girder 1. Problems with this data were only revealed when the results for individual events were considered. This provides further evidence that the extrapolation of data from the upper tail of lane distributions is not a robust methodology and therefore should not be used. Such unusual distributions should serve as a cue to further investigate the data, bridge response, or both.

6.2 Sample Size

The relatively small sample size of 1000 single heavy vehicle events was identified as adequate to achieve reliable Health Monitoring results, and to quantify the response of a bridge to ambient traffic. However as temporal patterns (other than diurnal) are not likely to be recorded in monitoring using such small sample sizes, this characteristic should be considered when establishing Health Monitoring projects.

Once the statistical behaviour of load effect from a representative population of heavy vehicle events has been determined, the effect of "extreme" single heavy vehicle events can be estimated. For most bridges, the estimation of UTLE will require the analytical combination of extreme multiple events. This can be done using conventional techniques such as the principle of superposition.

6.3 Estimation of Ultimate Traffic Load Effect

Two appropriate methods to estimate the UTLE were identified:

1. Correlated Upper Bound (CUB) method; and
2. Independent Upper Bound (IUB) method.

The CUB method is generally consistent with the method used in the Bridge Manual, and with Health Monitoring concepts when events are assumed to be fully correlated (i.e. the magnitude of an event in one lane is the same as the magnitude of the event in the adjacent lane).

The IUB method is consistent with Health Monitoring concepts when events are assumed to be independent of each other (i.e. the magnitude of an event in one lane is totally independent of the magnitude of the event in the adjacent lane). Thus the IUB method is more appropriate for the Atiamuri Bridge for which events can be considered to be independent.

For the Atiamuri Bridge, the estimate of UTLE using the IUB method has a magnitude of approximately 0.9 times the CUB estimate. This factor is consistent with the AUSTROADS' (1996) Accompanying Lane Factor (ALF). However further research would be required before this factor could be adopted as a general approach in New Zealand.

6.4 Estimation of Fitness for Purpose Evaluation

The FPE method described in Section 2.3 has been used for both Stage 2 and Stage 3 Health Monitoring. This relies on estimating member or component capacity based on an understanding of structural details, and estimating a response based on the ambient heavy vehicles recorded during the monitoring period. Thus the Fitness for Purpose rating is based on the assumption that both capacity and load effects have been appropriately interpreted.

Issues and assumptions associated with the estimation of capacity for an FPE are similar to those encountered with conventional evaluation approaches. The estimation of load effects will be based on the traffic recorded, even though in some cases, the recorded traffic may not be representative of all traffic using the bridge. In particular:

- Illegal overloading events may not be recorded during monitoring. This will not cause a problem in most cases since illegal overload events will be less than UTLE events predicted using the Health Monitoring data. If gross overloading occurs on the route, the UTLE predicted by Health Monitoring methods may possibly be less than that which actually occurs. In this case significant traffic management issues will be associated with the route;
- Significant variation in the heavy vehicle population can occur on a route over time (e.g. the seasonal traffic variation typical in grain-growing areas).

Where either of the above is suspected, the Health Monitoring report should comment on the implications with respect to the FPE. Thus, although a Health Monitoring procedure has been developed, it must be combined with engineering judgement to gain maximum benefit from the results. This will be discussed in greater detail in the report on Stage 4 of this project.

6.5 Performance of Atiamuri Bridge

The long-term Health Monitoring of the Atiamuri Bridge began in December 1998 and ceased in April 2000. While the duration of monitoring was approximately 17 months, the final "clean" data set consisted of a total of only 246 days (9 months). A total of 95 651 heavy vehicle events were recorded over that time, and the daily traffic counts ranged between 280 and 480 heavy vehicles per day.

6.5.1 Fitness for Purpose Evaluation

Midspan bending was the critical mode of failure for Stringer 3 and this was used to evaluate the Fitness for Purpose of the bridge. Both the CUB (as per Bridge Manual) and the IUB methods were used to evaluate the UTLE, simulating the effect of multiple presence by summing the events with a 5% probability of being exceeded in 100 years for both lanes. FPEs were then calculated for the bridge using both techniques, and they are as follows:

- by the CUB method = 104%;
- by the IUB method = 120%.

The FPE based on the IUB method (120%) was considered the most appropriate result.

6.5.2 Structural Behaviour

Results showed that the loss of composite action had occurred. Therefore, by conservatively assuming that there is zero composite action, the strength of the section is based on the steel stringer only. The assumed yield stress of the steel was 230 MPa (as specified by the Bridge Manual) giving a yield strain (0.85 ε_u) equal to 980 $\mu\varepsilon$. The highest projected strain related to a multiple-presence event occurred in Stringer 3 and was 605 $\mu\varepsilon$ (with a 5% probability of being exceeded in 100 years). Therefore allowing for dead load, the FPE based on the yield strength of a typical stringer for this bridge was 120%.

This evaluation is significantly better than the theoretical 0.85 HO + 0.85 HN rating evaluation (Class - 90%) determined during Stage 2.

The Health Monitoring evaluation suggests that the bridge is performing substantially better than the predictions made by theoretical evaluations, including that indicated in the Transit Structural Inventory (i.e. 104%). Full composite action between Stringer 3 and the deck has broken down so that only partial composite actions currently exist at this time (year 2000) (although full composite action appears to be present with some of the other stringers that were monitored). This affects the Inverse Normal distribution.

Some composite action occurs for Stringer 3 particularly under heavy vehicle loading. Since the rating of 120% assumes stringer capacity with no composite action, the rating may appear relatively conservative, although further monitoring may reveal that composite action has broken down completely on some of the stringers that were not monitored.

There is no immediate cause for concern regarding the capacity of the Atiamuri Bridge superstructure, but it is likely that the composite action on the bridge will continue to deteriorate.

Health Monitoring could be used to monitor this deterioration, by periodic re-evaluation of the performance of the Atiamuri Bridge. This may also provide an improved understanding of the composite behaviour of bridges built in that era, which may be useful for understanding the behaviour of similar New Zealand road bridges.

7. Conclusions

The Health Monitoring evaluation process has been investigated in some detail using the Atiamuri Bridge, and has been refined and improved using the long-term Health Monitoring results.

7.1 Sample Size

Based on the results of this investigation, a sample of 1000 heavy vehicle events is considered to be a suitable population upon which to base most Health Monitoring investigations. Sample sizes as small as 100 heavy vehicle events can provide good results, and sample sizes much larger than 1000 events offer no greater advantage, but do incur increased costs.

Ideally this population of 1000 events should include a spectrum of heavy vehicles from light trucks to the heavier vehicles using the route. The lighter vehicles are important to ensure that the variability of the heavy vehicle population is truly represented. With a population of 1000 events, it is likely that:

1. Only a limited number of overloaded vehicles will be recorded;
2. Temporal variations other than diurnal are unlikely to be recorded;
3. Few, if any, multiple-presence events will be recorded.

7.2 Estimation of UTLE & FPE

While (3) above is accounted for in the estimation of UTLE, and hence FPE, (1) and (2) are not likely to be accounted for in the FPE results. Consequently the FPE should be qualified if either effect is considered to be significant. The capacity calculations associated with FPEs are often subject to similar assumptions to those used in theoretical calculations. Where appropriate, FPEs should also be qualified if some uncertainty is associated with these assumptions.

The spectrum of single heavy vehicle events captured during Health Monitoring can be used to predict the load effects of the extreme single-heavy-vehicle event. In the case of multiple-lane bridges, the load effects for different lanes can then be combined using the principle of superposition to determine the UTLE

Two methods of estimating UTLE identified as appropriate in this investigation are:

- Correlated Upper Bound (CUB) method;
- Independent Upper Bound (IUB) method.

The CUB method is consistent with the method given in the existing Bridge Manual and is the more conservative of the two approaches.

The UTLE estimated using the IUB method will be lower than that using the CUB method, but should only be used when events in one lane are known to be independent of events in the other lanes. This will be generally true for two-lane two-way bridges, but may not be the case for multiple-lane one-way bridges. Issues associated with multiple presence and Health Monitoring could benefit from further investigation.

From a bridge evaluation perspective, considerable advantages may accrue in using the IUB method to estimate UTLE because the magnitude of the predicted event will be smaller than that predicted using the CUB method.

7.3 Performance of Atiamuri Bridge

The Structural Inventory (Transit 1999) gives a rating (Class) for the bridge of 104% and a Deck Capacity Factor (DCF) of 1.02. Infratech's theoretical assessment of the superstructure of the bridge found that the rating evaluation (0.85 HO + 0.85HN loading) was 90% and was governed by stringer-bending capacity. This assumed partial shear connection between the stringers and the deck in accordance with the Bridge Manual. The cross-girders were also assessed, and their rating evaluation was 95%, governed by mid-span bending of the cross-girder when the 0.85 HO evaluation vehicle travels along the centre of the bridge.

The FFP rating for this bridge from Stage 2 was 80% (based on the response of Stringer 3). This lower rating was largely related to the method used to extrapolate the UTLE from the short-term monitoring data.

Based on the CUB method and Stage 3 data, the FPE for Atiamuri Bridge superstructure is 104% (governed by the response of Stringer 3). The theoretical posting evaluation for the bridge is 105%, which agrees well with the FPE based on the CUB method from Stage 3.

The IUB method, however, predicts an FPE of 120% for the bridge. The IUB method is appropriate for this bridge, though the composite action between Stringer 3 and the deck is likely to deteriorate, and thus this FPE will probably reduce over time. Monitoring of this deterioration would be beneficial both for the Atiamuri Bridge, and for similar bridges with composite deck systems that may be subject to similar deterioration.

Theoretical rating showed that cross-girders had limited capacity above the stringer rating. The FPE of the cross-girders based on short-term Health Monitoring was 106%, but FPE based on long-term results from Stage 3 indicated that it was 200%. This suggests that the cross-girders are either performing substantially better than theoretical predictions, or that the actual vehicle live load effects are less severe than theoretical predictions.

The worst theoretical load case for the cross-girder was when an 0.85 HO vehicle travelled down the centre of the bridge. This would be an infrequent occurrence. The chance that this vehicle is a heavily overloaded permit vehicle is even less likely to occur. Therefore, since a very specific and unlikely set of events governed the theoretical rating evaluation of the cross-girders, it is not surprising that the monitored FPE was significantly better than the theoretical rating. This may partly explain the high FPE for the cross-girders compared with conventional theoretical evaluation results.

7.4 General Health Monitoring Issues

Efficient Health Monitoring requires placement of instrumentation in the most critical locations (i.e. those having greatest influence on bridge capacity or performance). Structural analysis of the bridge is used to identify these locations. While Health Monitoring can be carried out on its own, it is more effective when combined with the results of analytical techniques.

The Stage 2 Health Monitoring data indicated that the ambient traffic produced structural responses that were significantly greater than the response produced by a known heavy vehicle configured with tandem axles and operating at legal load levels. Legally loaded tridem-axle groups produce greater effects in the stringers than tandem-axle groups. Long-term Health Monitoring showed a significant number of events had occurred that produced effects significantly greater than predicted for legal tridem vehicles. These events are likely to have been the result of multiple presence, overloading, or both. Legitimate Health Monitoring results recorded during Stage 3 did not exceed the estimates of UTLE calculated using the IUB method. Consequently, while these events have not been investigated in detail, there is no reason to believe that excessive overloading occurs on this route, based on the data gathered.

The use of a known vehicle during Health Monitoring can add substantial value to the data gathered, and at only a limited additional cost. It provides a reference to confirm that the bridge is actually experiencing heavy vehicle events and to identify if overload management is reasonable. Clearly the known vehicle data used for Stage 2 was useful in interpreting the Stage 3 results, particularly for the loss of composite action in Stringer 3. In addition, the known vehicle results allowed the dynamic increment characteristics of the bridge to be determined.

8. Recommendations

Based on the results of long-term Health Monitoring of the Atiamuri Bridge, recommendations can be made regarding:

- Data processing and evaluation for Health Monitoring purposes;
- Monitoring duration for Health Monitoring purposes;
- Methods to estimate Ultimate Live Load Effect (UTLE) from Health Monitoring;
- Fitness for Purpose Evaluation (FPE);
- Further research;
- Performance of the Atiamuri Bridge.

It should be noted that these recommendations apply specifically to short span bridges where the critical loading corresponds to one moving vehicle per lane. Extensions of the following recommendations are required to apply them to longer span structures.

8.1 Data Processing & Evaluation

Post-processing of data is necessary to convert Health Monitoring data into useful information. The recommended process based on Stage 3 of this project is as follows:

- Organise the data into manageable components on the basis of time.
- Remove clearly erroneous data: for example, transducers that are out of range, malfunctioning, or subject to electronic interference.
- Separate events into lanes. A parabolic curve-fitting approach is recommended, as this has several advantages including a filtering function that identifies "events" with highly improbable curvature.

  Other techniques may also be used provided they give accurate separation of lanes, and "event" filtration is adequate (for example: the use of load distribution factors calculated from relative transducer values).
- Present the summary statistical data as Inverse Normal plots for single vehicle events in each lane. Extreme single-vehicle-event data can be estimated from these results. Estimating the combined effect of multiple vehicles can be done using conventional techniques such as the principle of superposition.
- Extrapolate the heavy vehicle population data to determine the UTLE. For this project the main heavy vehicle population was represented by results in the range from 0.5 to 2.5 standard deviations from the mean.

  The magnitude of events represented on the Inverse Normal plot, and diagnostic test results (derived from the effect of a known vehicle) are important to understand Health Monitoring results.

  It is not appropriate to include data from the upper tail of the distribution in the extrapolation.

- Determine the UTLE, by using either the CUB method recommended by the Bridge Manual, or the IUB method.
- Calculate the FPE based on the method set out in Section 2 of this report.
- Compare FPE with analytical ratings, and understand and quantify the differences.

This approach has been shown to give reliable results. However it is important to review results and compare Inverse Normal plots with expected theory. Where the shapes of Inverse Normal plots appear unusual, further processing of the results may reveal additional understanding about the behaviour of the bridge.

Care is required when sorting data to ensure that extraneous events are excluded from the data set. As the above methodology is relatively robust, any small amounts of extraneous data that may exist are unlikely to affect the validity of evaluations.

8.2 Monitoring Duration

One key objective of long-term Health Monitoring was to determine the number of events (or monitoring duration) required to ensure that reliable results are obtained.

The recommendation is that the recording of 1000 events is adequate to complete an FPE. Since the number of heavy vehicles per day is normally stable, and can be estimated with reasonable accuracy, an appropriate monitoring duration can be determined. Where seasonal traffic variations are known or likely to occur, the Health Monitoring programme should be designed to take account of these, because 1000 events is very unlikely to include seasonal variation effects.

A sample size as small as 100 heavy vehicle events has been demonstrated to give good estimates of UTLE and satisfactory Health Monitoring can be carried out with such small samples. This may be appropriate when the heavy vehicle fleet is known to be very uniform (i.e. most heavy vehicles are of similar mass and configuration), or when heavy vehicle traffic counts are low (i.e. isolated rural roads). Thus, while a general target sample size of 1000 heavy vehicle events should be used, site or traffic characteristics, and project requirements should also be considered when determining sample target size.

8.3 Estimation of Ultimate Traffic Load Effect

Two methods were identified as appropriate for estimating the UTLE using Health Monitoring data:

- Correlated Upper Bound (CUB) – essentially the method required by the existing Bridge Manual;
- Independent Upper Bound (IUB) – described in Section 2.4.2.

Both methods require the separation of Health Monitoring data into lanes, and the UTLE is then determined from the lane data. If traffic characteristics are such that events in each lane can be considered to be independent of each other, then use of the

IUB method to predict UTLE has some advantage, because it is likely to have a magnitude of approximately 90% of that estimated by the CUB method. This reduced UTLE can represent a significant advantage for the purposes of bridge evaluation.

Where multiple-presence lane events are not likely to be independent (e.g. if both lanes support traffic in the same direction), the recommendation is that the CUB method should be used because the IUB method may be unconservative.

Both the IUB and CUB methods assume that the UTLE is created by multiple-presence events. While this is reasonable in most cases and is consistent with the approach recommended by the Bridge Manual, a substantial illegally overloaded vehicle population (if it occurs) could influence the actual UTLE. Health Monitoring techniques can be used to quantify some overloading issues, but more research is required to understand the relationship between overloading and multiple presence.

8.4 Fitness for Purpose Evaluation

One of the main outcomes of a Health Monitoring project is an FPE. This term must be understood in its correct context. Health Monitoring requires an analytical assessment to be made of the bridge before such a programme is initiated. This establishes the most appropriate locations to place instrumentation based on an understanding of the expected response of the bridge. Therefore measurements taken during Health Monitoring quantify behaviour at these specific critical locations.

It is possible that other critical locations exist on a bridge which are not monitored. In the case of Atiamuri Bridge, only the stringers in one span were monitored, and considerable variability can exist between spans due to variations in dynamic wheel force. FPE can only be based on the results of the components that are monitored, so engineering judgement is required to determine the appropriate monitoring locations, and also to interpret the numerical results. It would be inappropriate to base decisions purely on the numerical FPE result, and in this respect, FPE results must be treated in a similar manner to analytical ratings.

The objectives of Stage 3 of this project were given in Section 1 of this report, and these deal with the development of appropriate analytical techniques for processing and interpreting Health Monitoring data. Practical use of Health Monitoring results will require the consideration of a range of qualitative issues not specifically considered as part of Stage 3. Health Monitoring can be used to complement the total bridge evaluation process, and therefore the use of Health Monitoring results could be an integral part of both asset management and bridge engineering procedures. Stage 4 of this project will further address these issues.

The Health Monitoring process must be managed by an experienced engineer with a sound understanding of the design and behaviour of structures, experimental techniques and the Health Monitoring process.

Economic monitoring programmes will, in most cases, not be of long enough duration to record results from traffic where seasonal variability exists, although multiple short-term monitoring projects may overcome this problem. Such issues must be accounted for when making decisions using Health Monitoring data. Qualitative information may indicate when the worst traffic effects occur and monitoring could be scheduled to occur during this period. Other alternative strategies can be used, but it is important to consider the issues when interpreting results.

8.5 Further Research

While this research project has quantified some issues associated with Health Monitoring, further research is required in a number of areas including:

- Characteristics of multiple-presence events in different lane configurations;
- The relationship between overload events and multiple-presence events;
- The effect of component tributary area on Inverse Normal plots;
- Health Monitoring of structures on routes with low traffic volumes, and routes with high seasonal variability;
- Health Monitoring of structures on routes where multiple-presence events occur with traffic travelling in the same direction.

8.6 Performance of Atiamuri Bridge

Advantages of the long-term Health Monitoring programme regarding the condition of the Atiamuri Bridge include the following:

- The deterioration of composite action between stringers and decks in the Atiamuri Bridge may represent a good opportunity to monitor such composite behaviour.

- A better understanding of the phenomenon will be gained from such monitoring, and this will also be relevant to other New Zealand bridges.

- A correctly designed monitoring programme could achieve the following objectives:
  - Manage the risk of failure at the Atiamuri bridge by continuous monitoring;
  - Obtain an improved understanding of this deterioration phenomenon so that it can be used to manage the greater population of bridges on New Zealand roads;
  - Determine the most appropriate rehabilitation strategy to ensure that maximum service life is obtained from the existing Atiamuri bridge.

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10. Glossary

5% probability of being exceeded in 100 years	An event that has a 5% probability of being exceeded (or a 95% probability of being smaller) in a 100-year design life. This corresponds to an event with an average recurrence interval of 2,000 years or the Ultimate Limit State. This is consistent with NZS 4203:1992), the Bridge Manual (1994), and the AUSTROADS Bridge design Code (1996).
5% probability of being exceeded in any 1 year	An event that has a 5% probability of being exceeded in 1 year. This corresponds to an event with an average recurrence interval of 20 years or the Serviceability Limit State (NZS 4203:1992, AUSTROADS 1996).
95% 100 years	As for *5% probability of being exceeded in 100 years.*
95% day	An event that has a 95% probability of being smaller (or a 5% probability of being exceeded) in a day.
95% month	An event that has a 95% probability of being smaller (or a 5% probability of being exceeded) in a month.
95% year	As for *5% probability of being exceeded in any 1 year.*
CDF	Cumulative Distribution Function: an expression generated to determine the cumulative frequency of occurrence of events.
Class	A measure of a bridge's rating. See *Rating.*
Composite Action	The structural response associated with two different structural elements behaving as an equivalent single element bonded together.
CUB	Correlated Upper Bound: a means of combining two statistical populations to produce a *UTLE*; this method adopts the summation of extreme events as an approach.
DCF	Deck Capacity Factor: a measure of current deck capacity to resist the calculated UTLE. See *FPE.*
DSG	Demountable Strain Gauge.
Extrapolated Limit State	The resultant load effect of an event associated with the probability of a given limit state.
FPE	Fitness for Purpose Evaluation: an estimate of current capacity of a structure to resist the calculated UTLE; typically expressed as a percentage.
FSG	Foil Strain Gauge.
Gaussian Distribution	A statistical distribution generated from a random variable, centred on a mean value. Also known as a *Normal Distribution.*
Gross	Gross capacity: an estimate of the capacity for bridge posting purposes. See *Posting.*
Health Monitoring	The evaluation of structures using ambient loading, specifically used for bridge evaluation using normal traffic loading.
HMX	Monitoring system includes monitoring hardware and software, along with transducers required to monitor bridges or similar structures.

Inverse Normal	A representation of a Gaussian or Normal distribution, plotted on a statistical scale. Consequently, a Normal distribution generates a linear Inverse Normal.
IUB	Independent Upper Bound: a means of combining two statistical populations to produce a UTLE. This method generates a combined distribution from two independent Normal distributions.
Monte Carlo Simulation	A means of simulating a random variable, used to test theories and postulations.
Multiple Presence	More than one truck within the tributary area for a member at a given point in time.
Normal Distribution	See *Gaussian Distribution.*
PDF	Probability Distribution Function: an expression generated to determine the frequency of occurrence of events.
Posting	A means of estimating the bridge capacity to resist the design actions of conforming vehicles.
Rating	A means of estimating the bridge capacity to resist the design actions of permit overload vehicles.
Sampling Threshold	See *Trigger Threshold.*
Superposition	A principle which allows the effect of multiple individual effects to be numerically added to estimate the combined effect of these events.
Tributary Area	A surface that bounds an area to which an applied load is resisted by a given member.
Trigger Threshold or Level	An operator-selected event magnitude that causes the Health Monitoring system to record an event. Also called *Sampling Threshold.*
Turkstra (& Madsen) Method	A means of combining two statistical distributions to produce an UTLE. Based on the principle of combining a typical event from one population with an extreme event in the other population.
UTLE	Ultimate Traffic Load Effect: an estimate of the largest load effect that is statistically likely to occur during the life of the bridge.

Appendix A

Inverse Normal Plots for Full Data Set

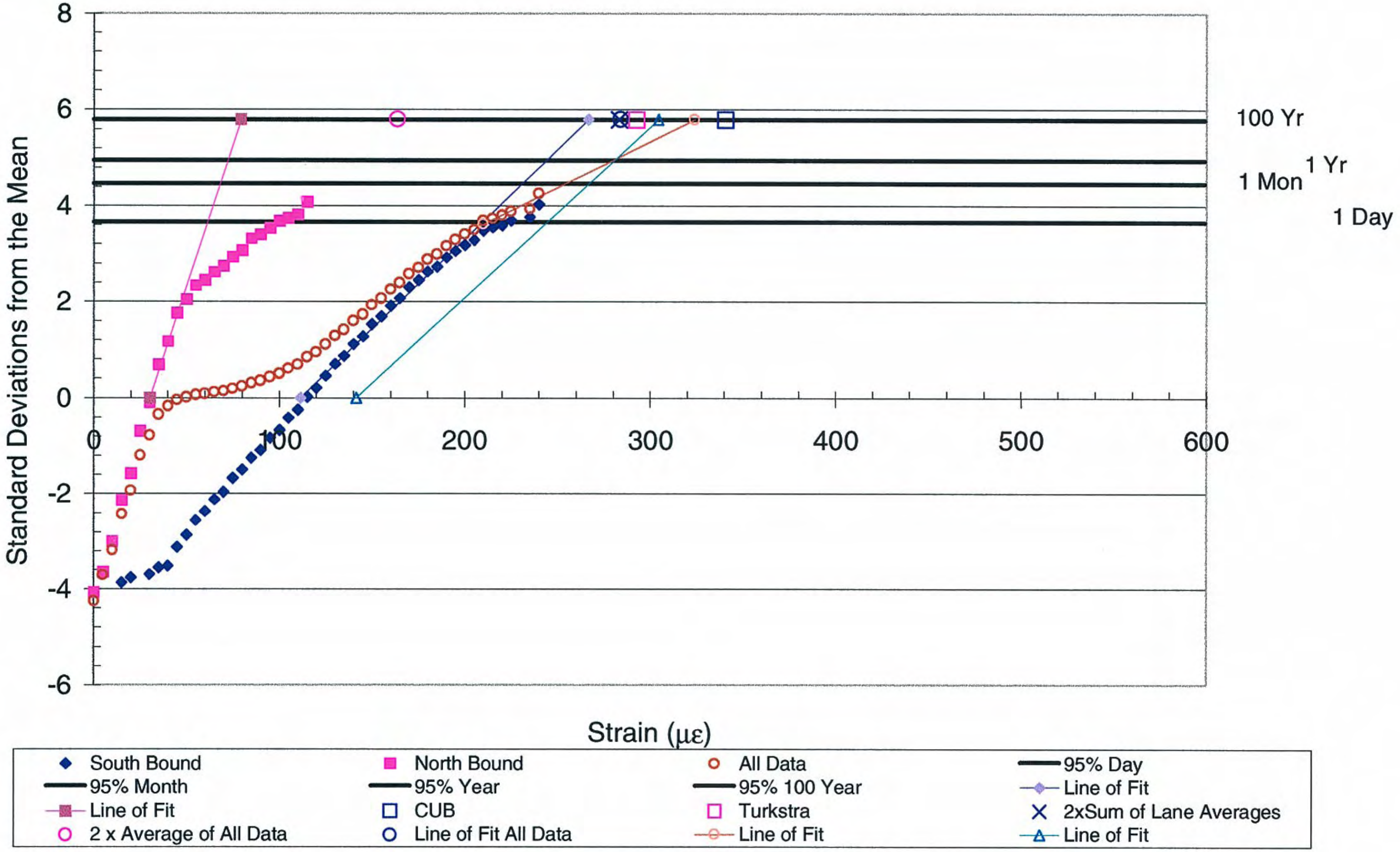

Figure A1. Inverse Normal Plot for Stringer 1

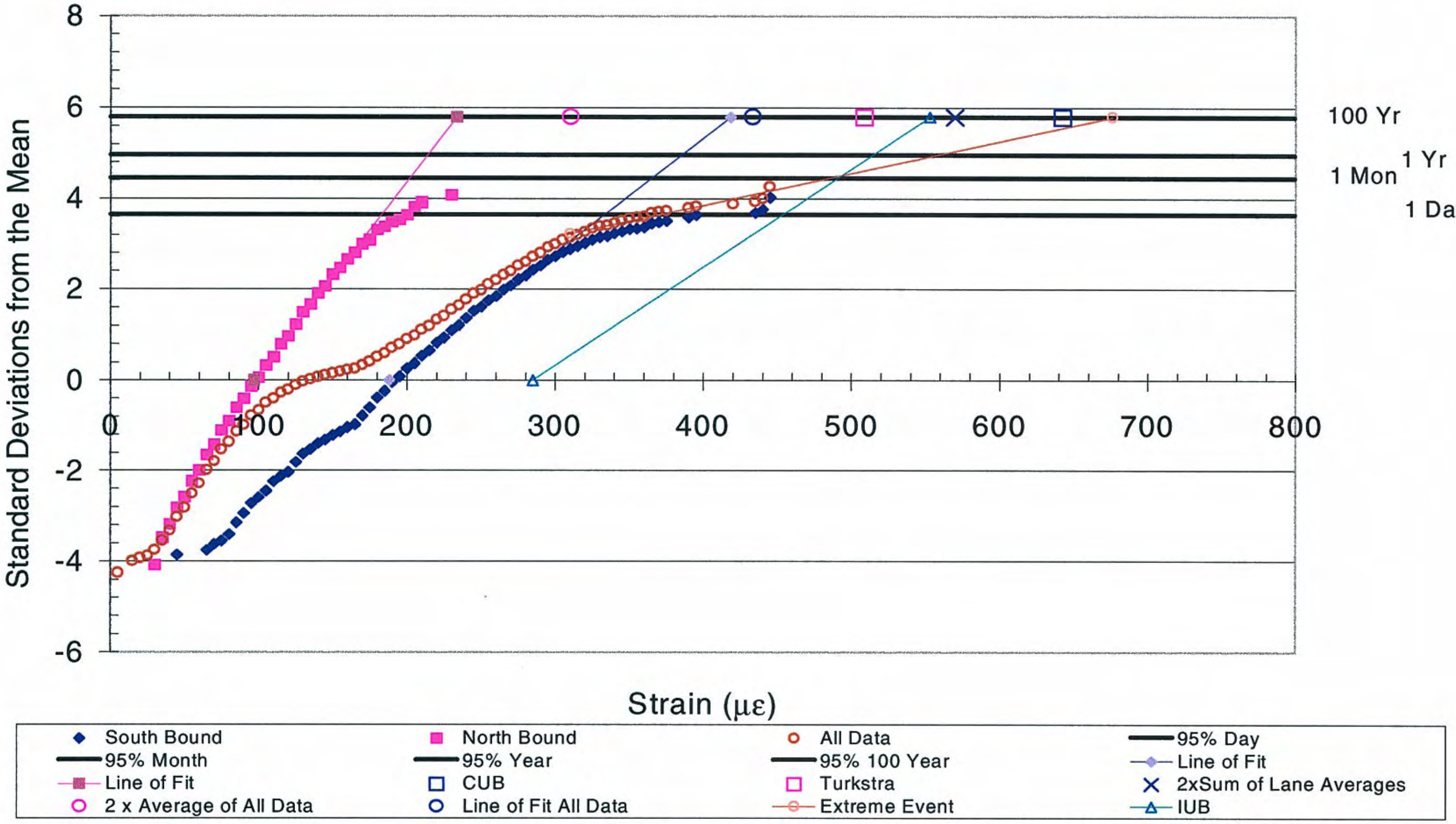

Figure A2. Inverse Normal Plot for Stringer 2

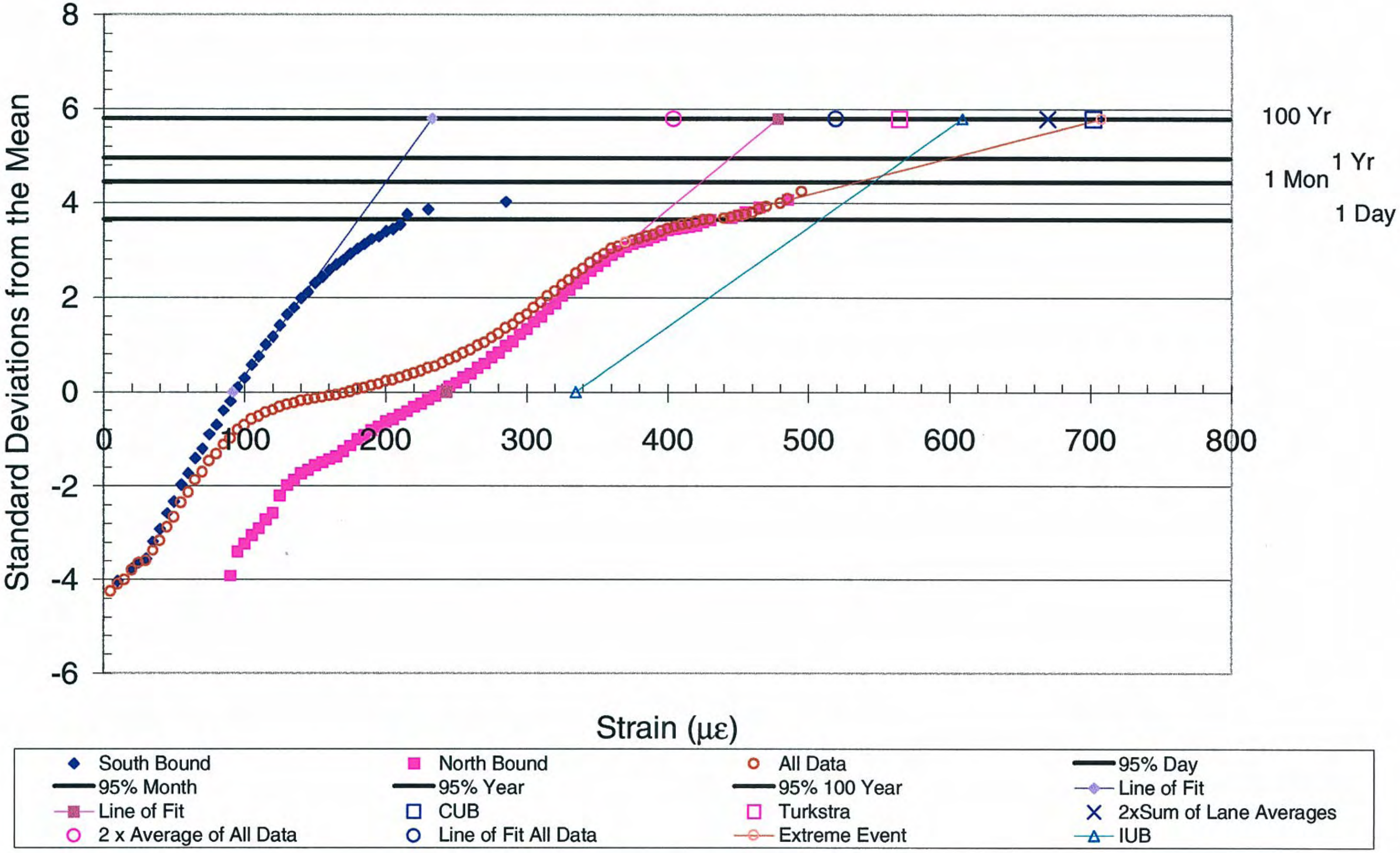

Figure A3. Inverse Normal Plot for Stringer 3

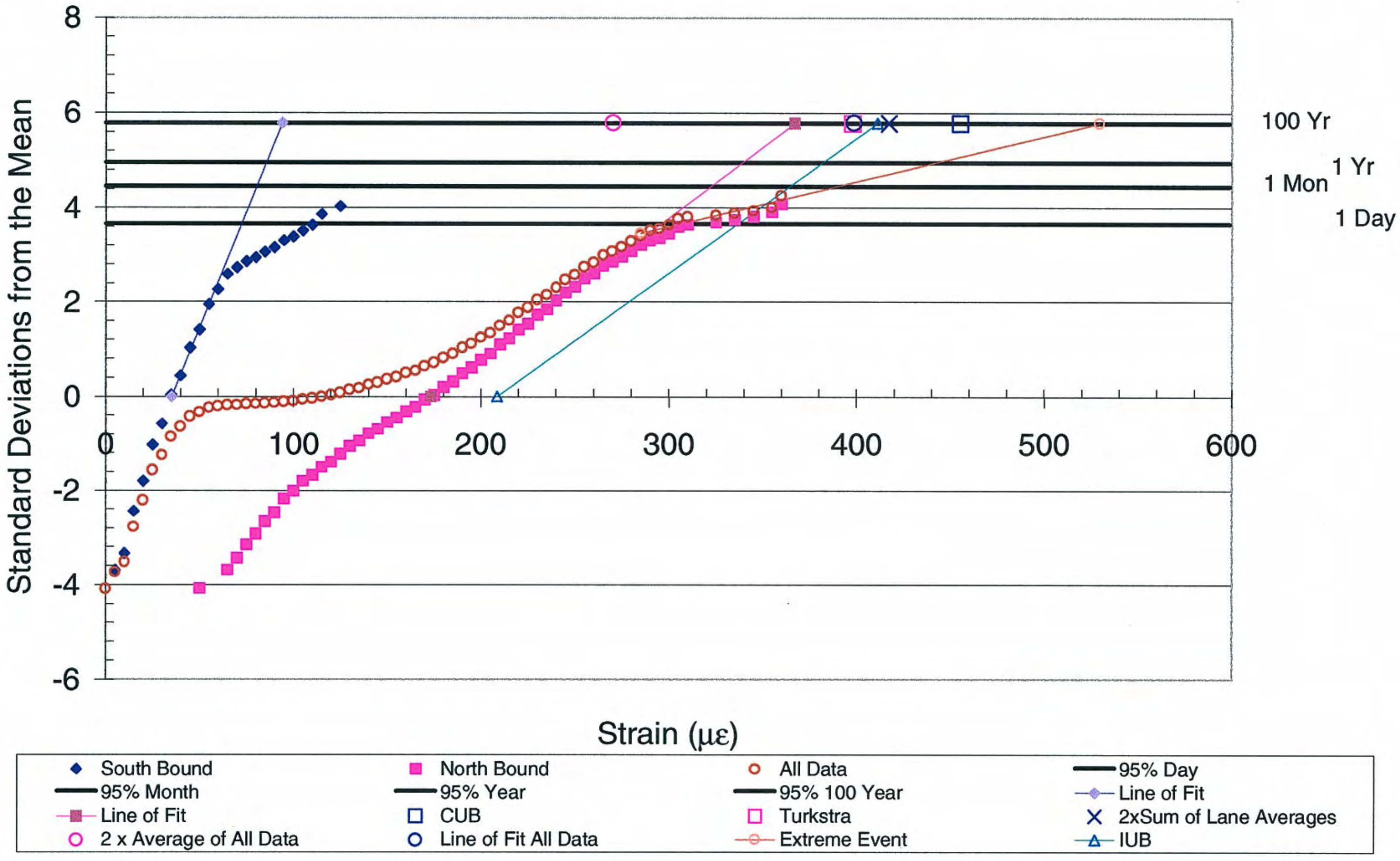

Figure A4. Inverse Normal Plot for Stringer 4

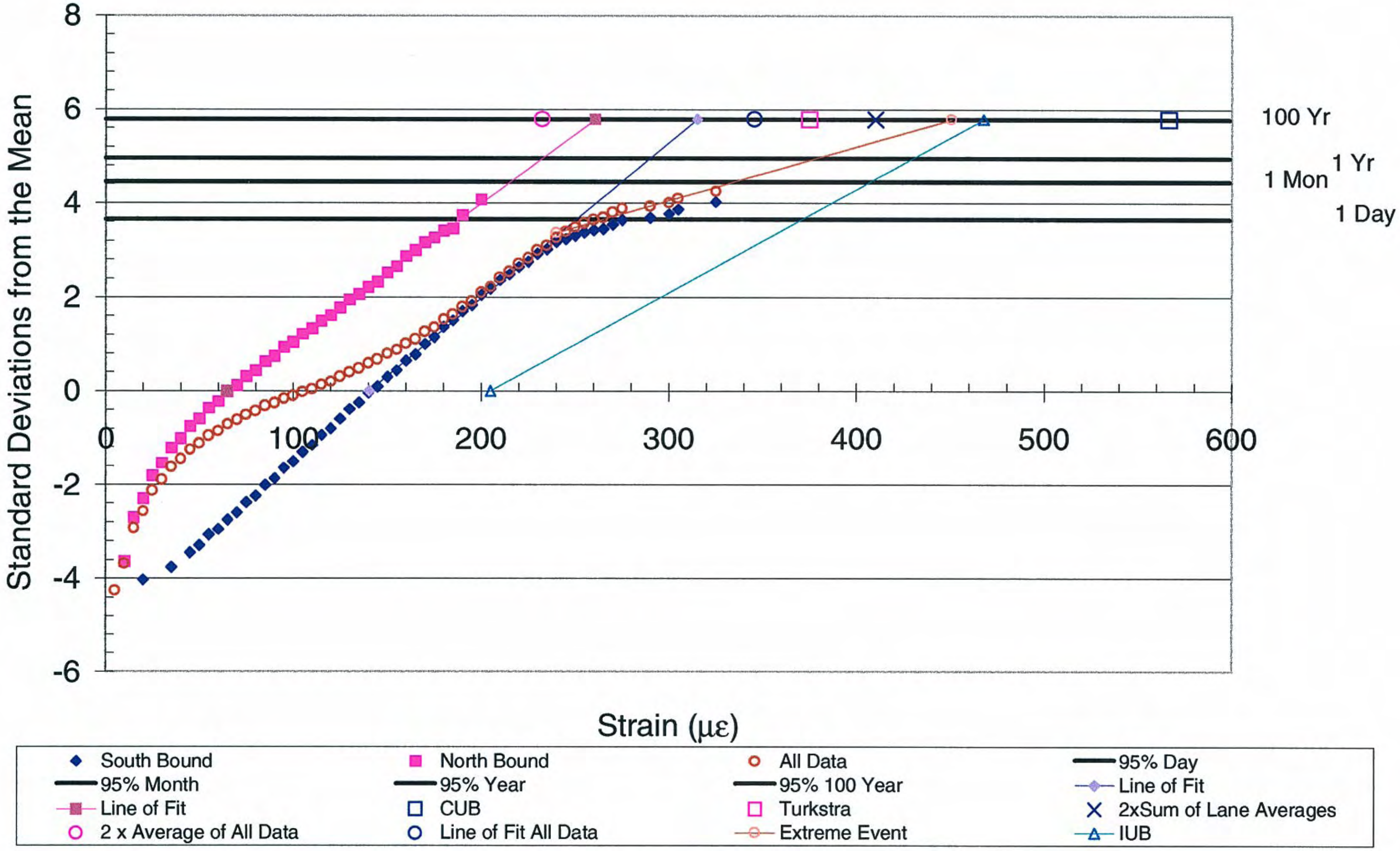

Figure A5. Inverse Normal Plot for southern abutment cross-girder

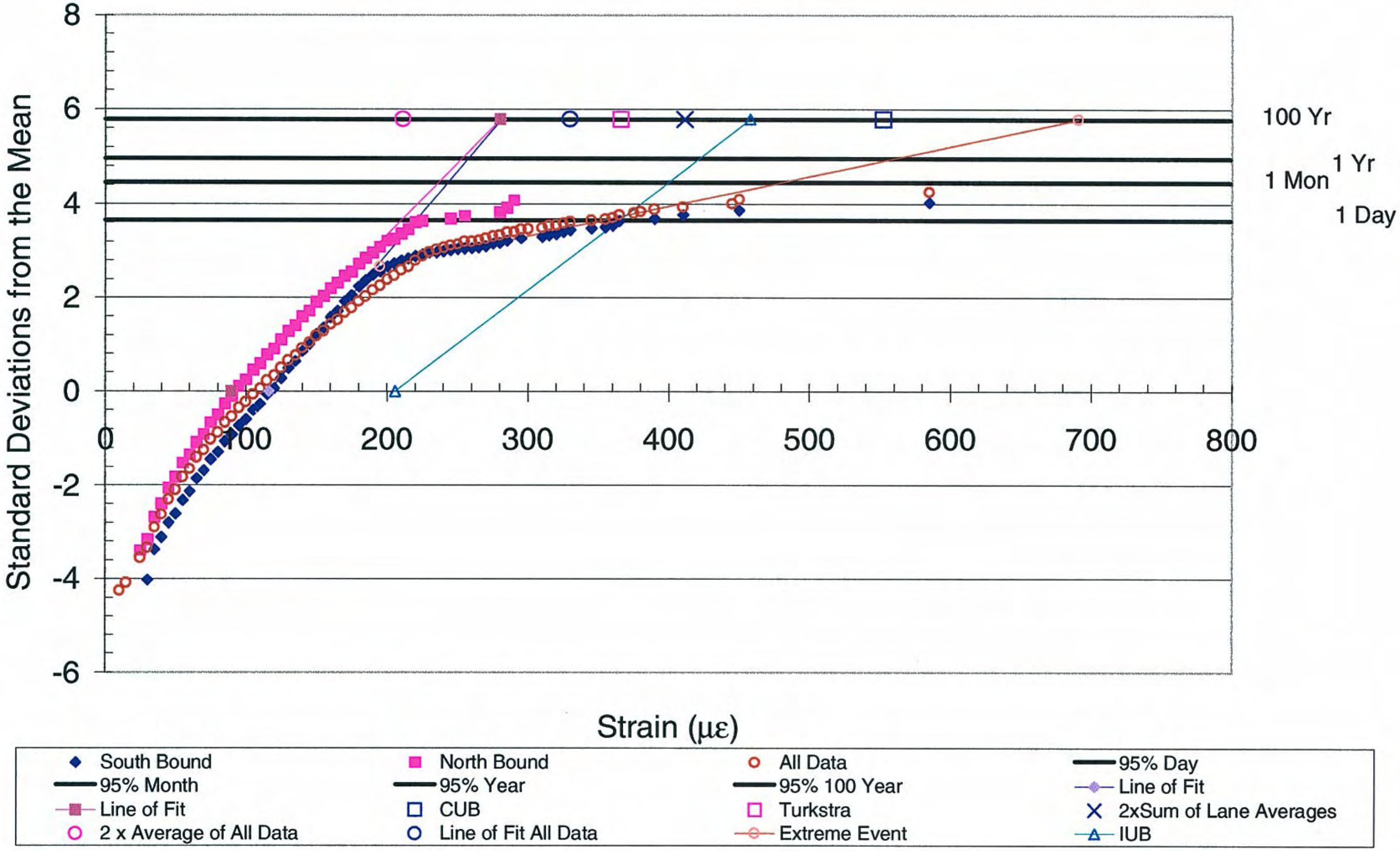

Figure A6. Inverse Normal Plot for cross-girder 1

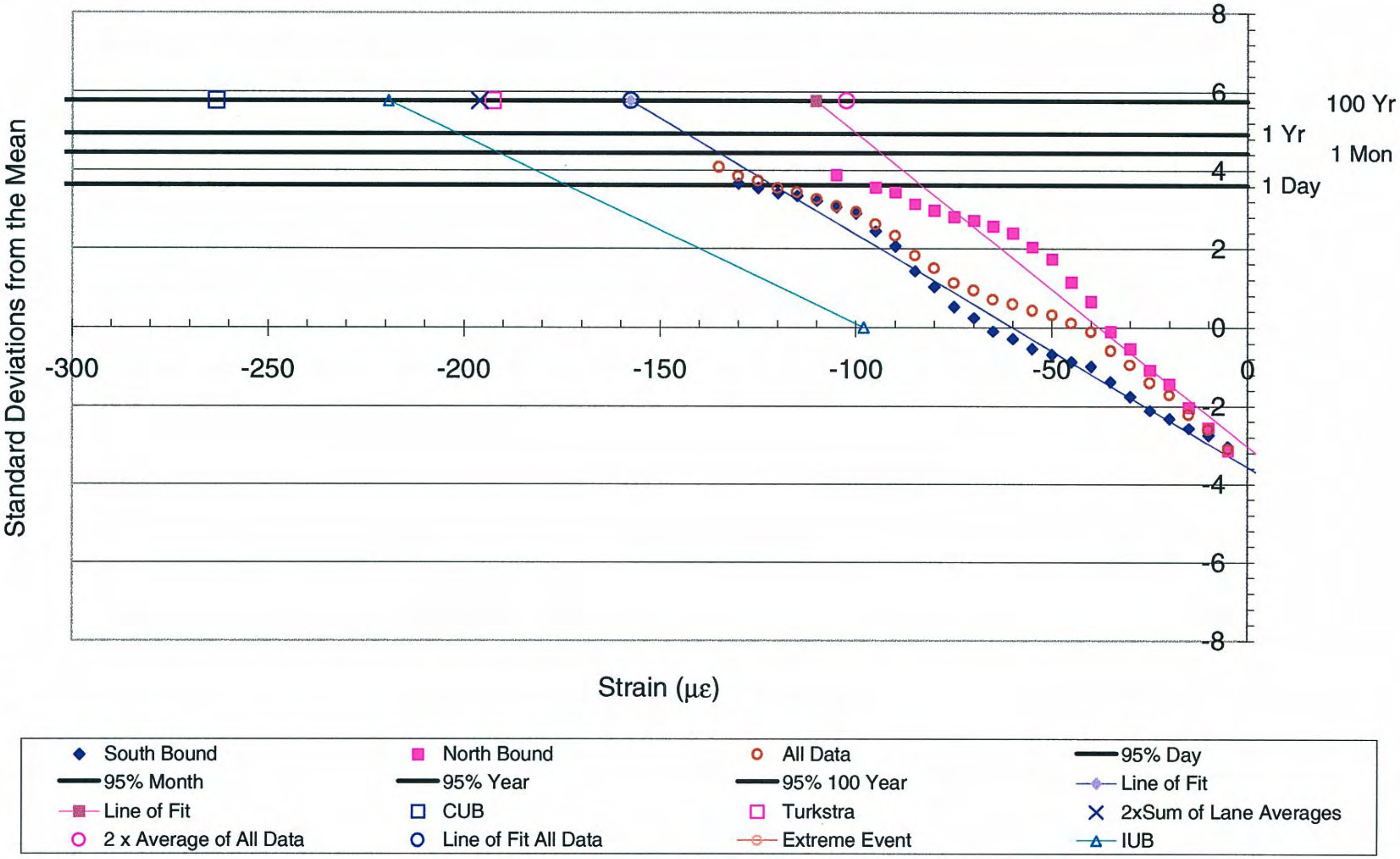

Figure A7. Inverse Normal Plot for eastern arch chord

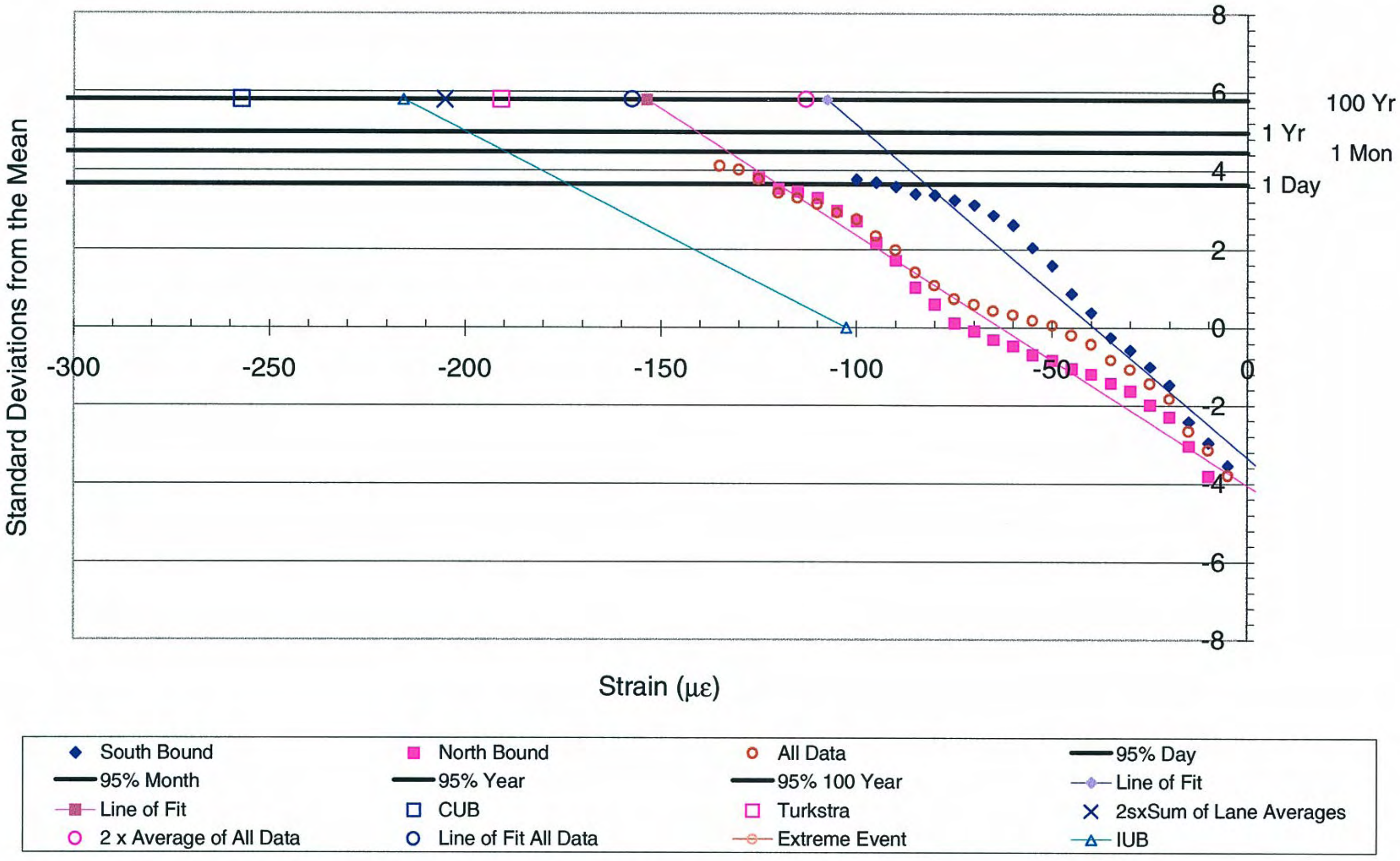

Figure A8. Inverse Normal Plot for western arch chord

Appendix B

Inverse Normal Plots for Stage 2 Results: Comparison between Short-term (Stage 2) & Long-term (Stage 3) Data Processing Methods

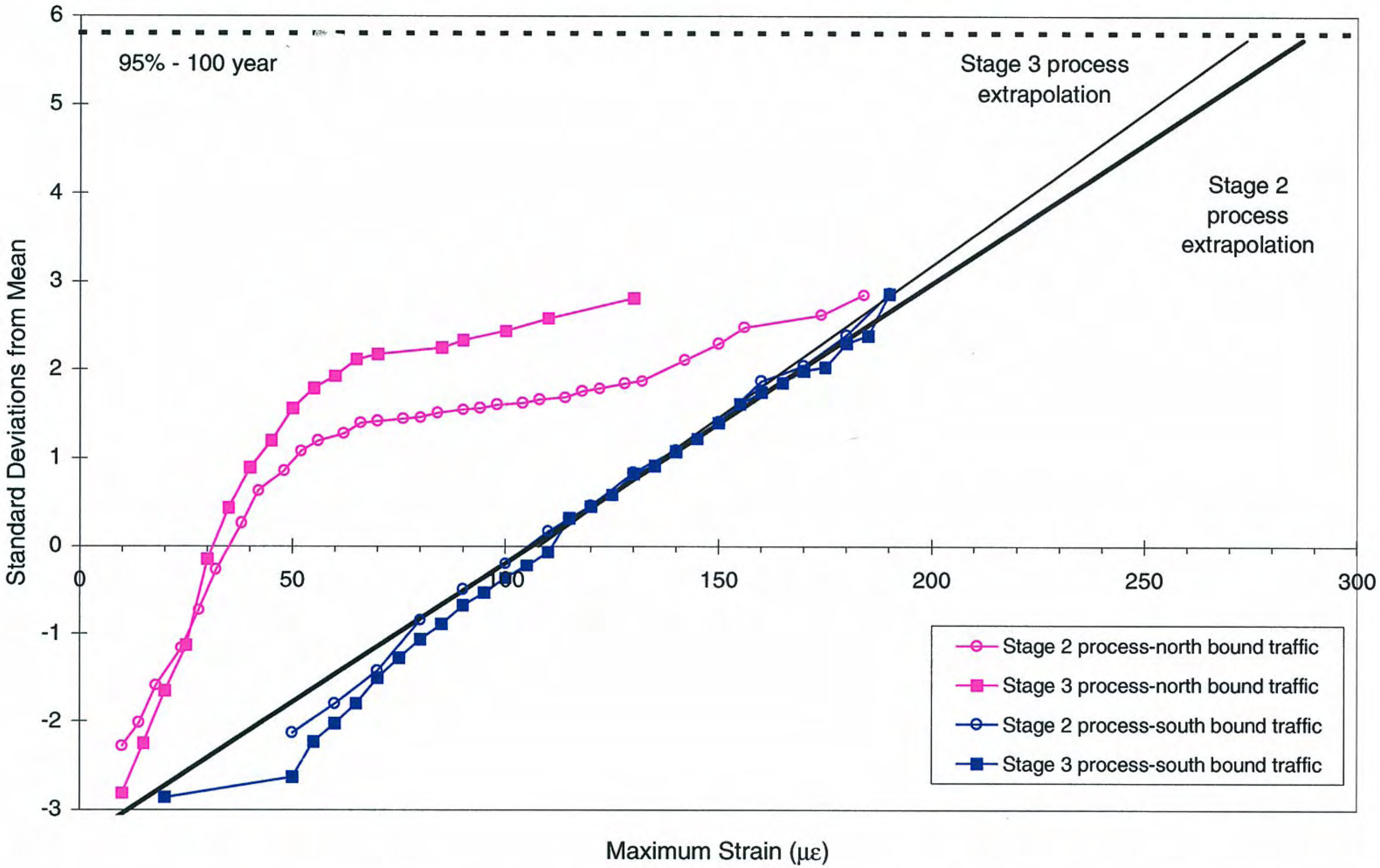

Figure B1. Inverse Normal Plot for Stringer 1 (Comparing Stage 2 and 3 evaluation methods)

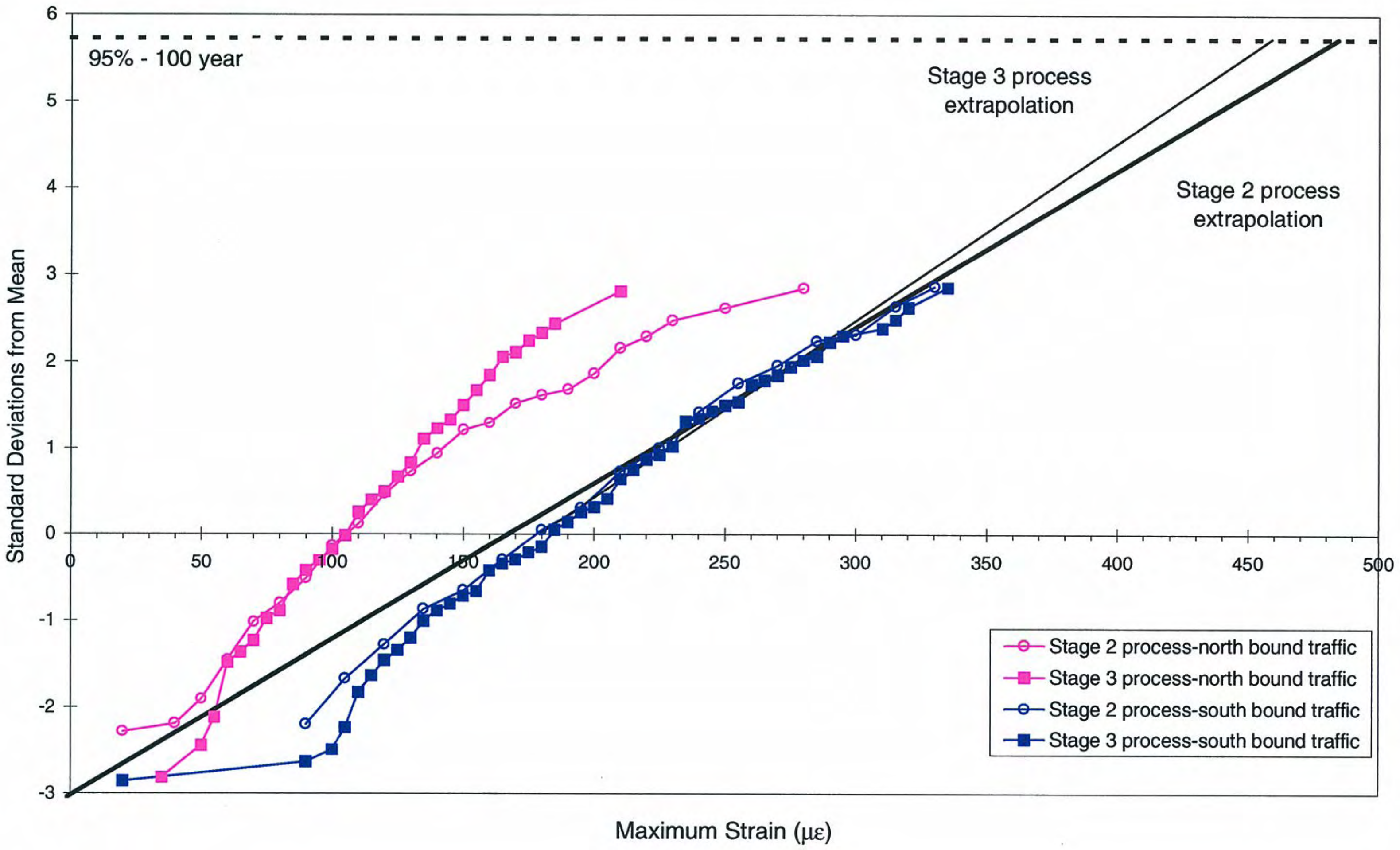

Figure B2. Inverse Normal Plot for Stringer 2 (Comparing Stage 2 and 3 evaluation methods)

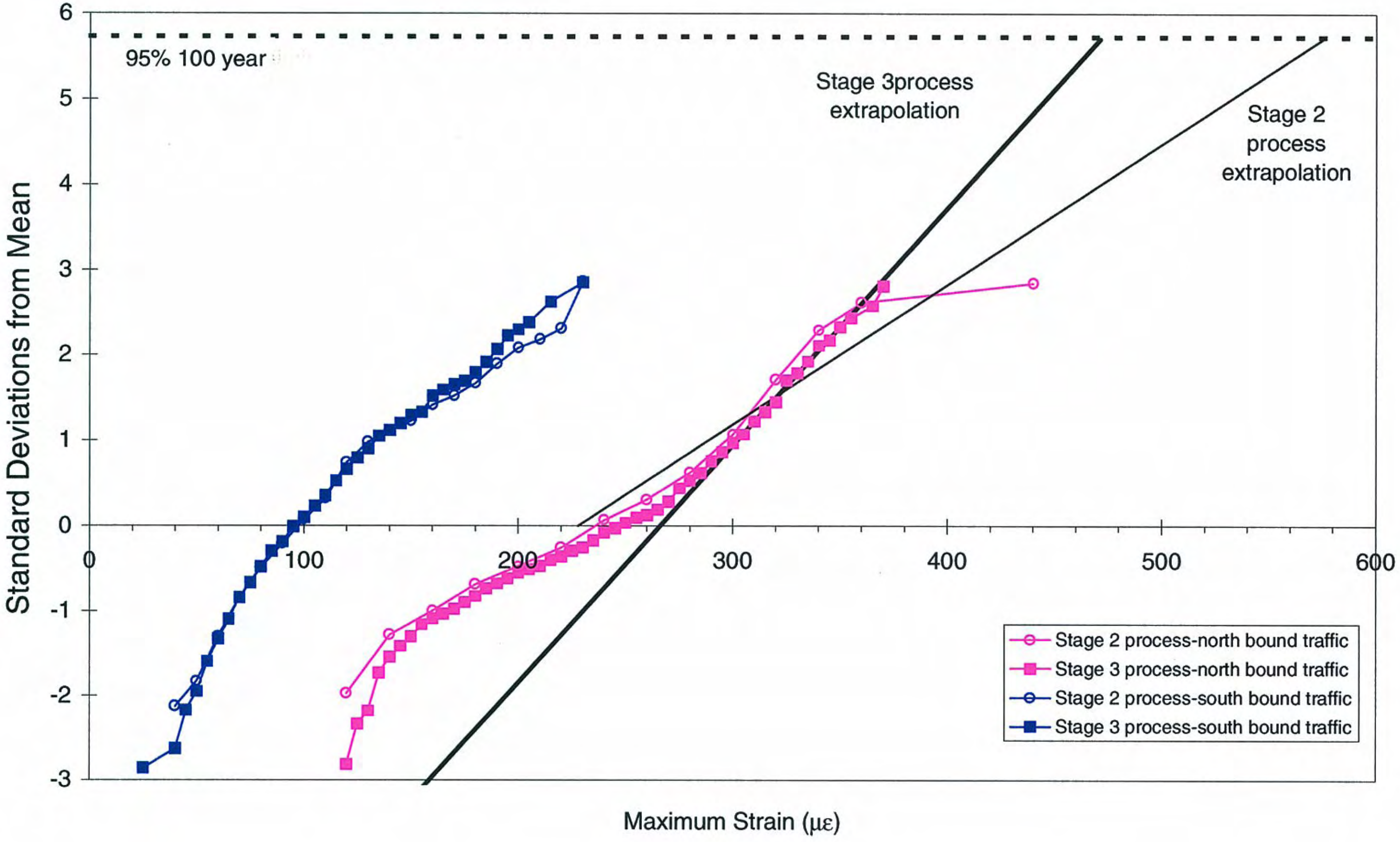

Figure B3. Inverse Normal Plot for Stringer 3 (Comparing Stage 2 and 3 evaluation methods)

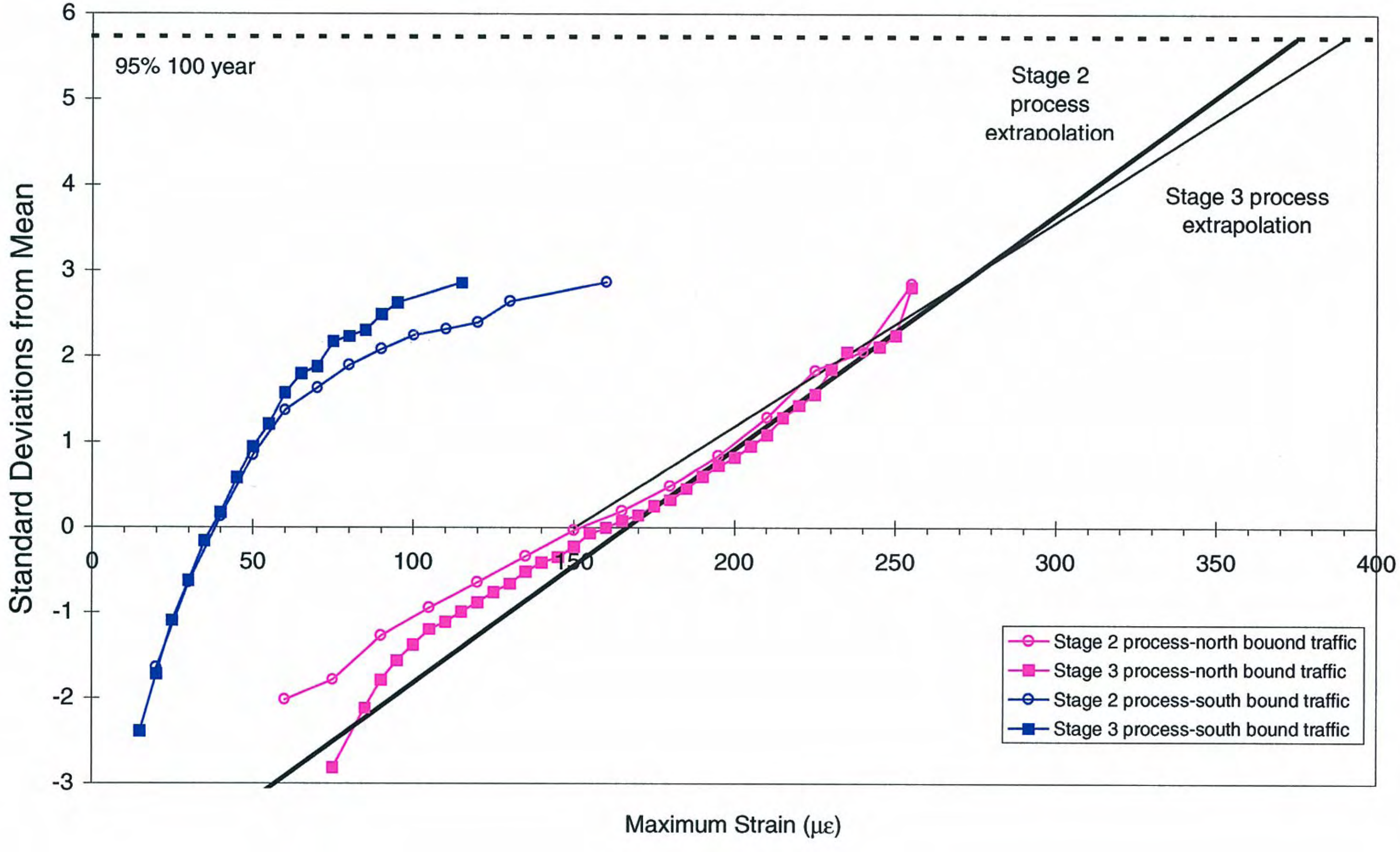

Figure B4. Inverse Normal Plot for Stringer 4 (Comparing Stage 2 and 3 evaluation methods)

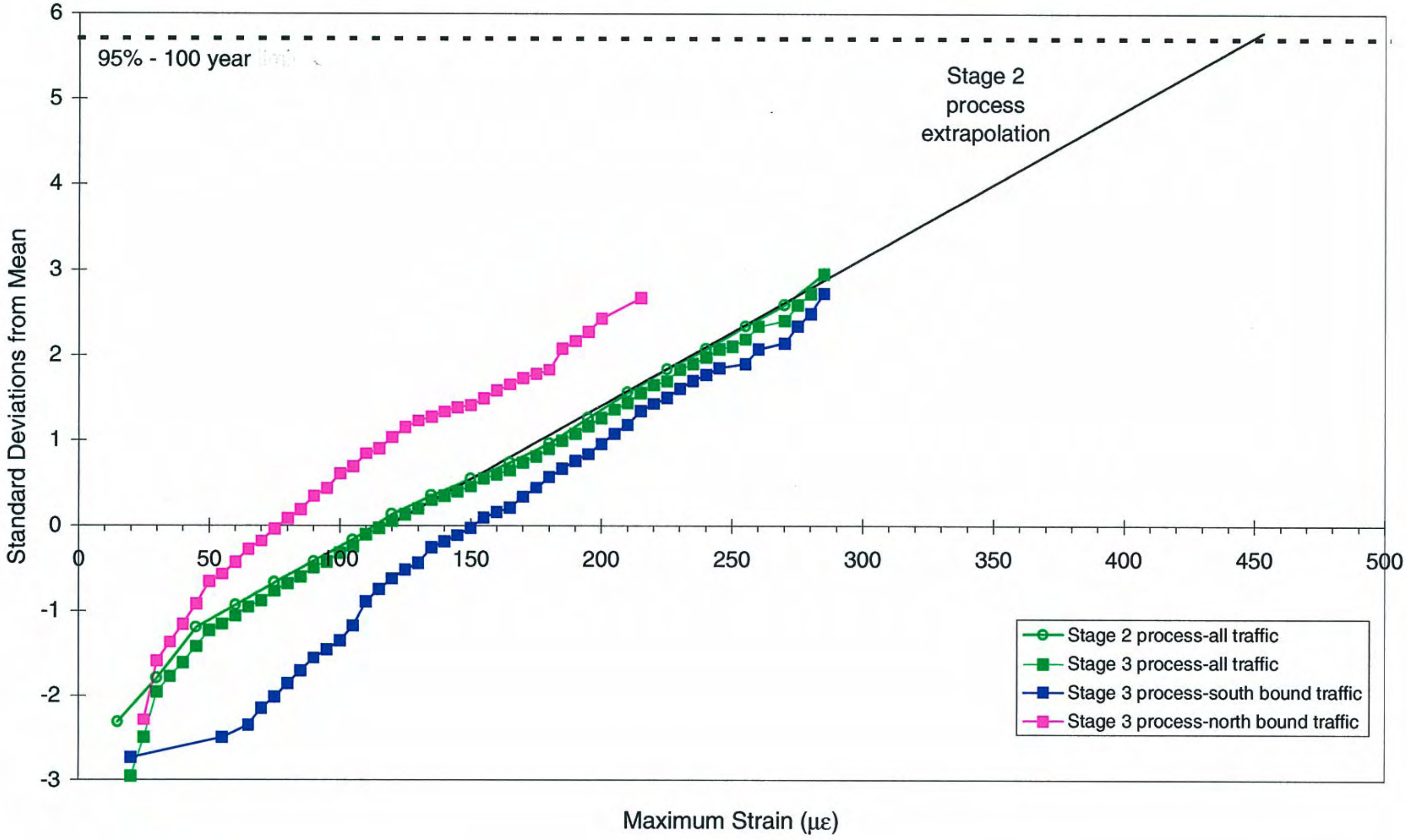

Figure B5. Inverse Normal Plot for southern abutment cross-girder (Comparing Stage 2 and 3 evaluation methods)

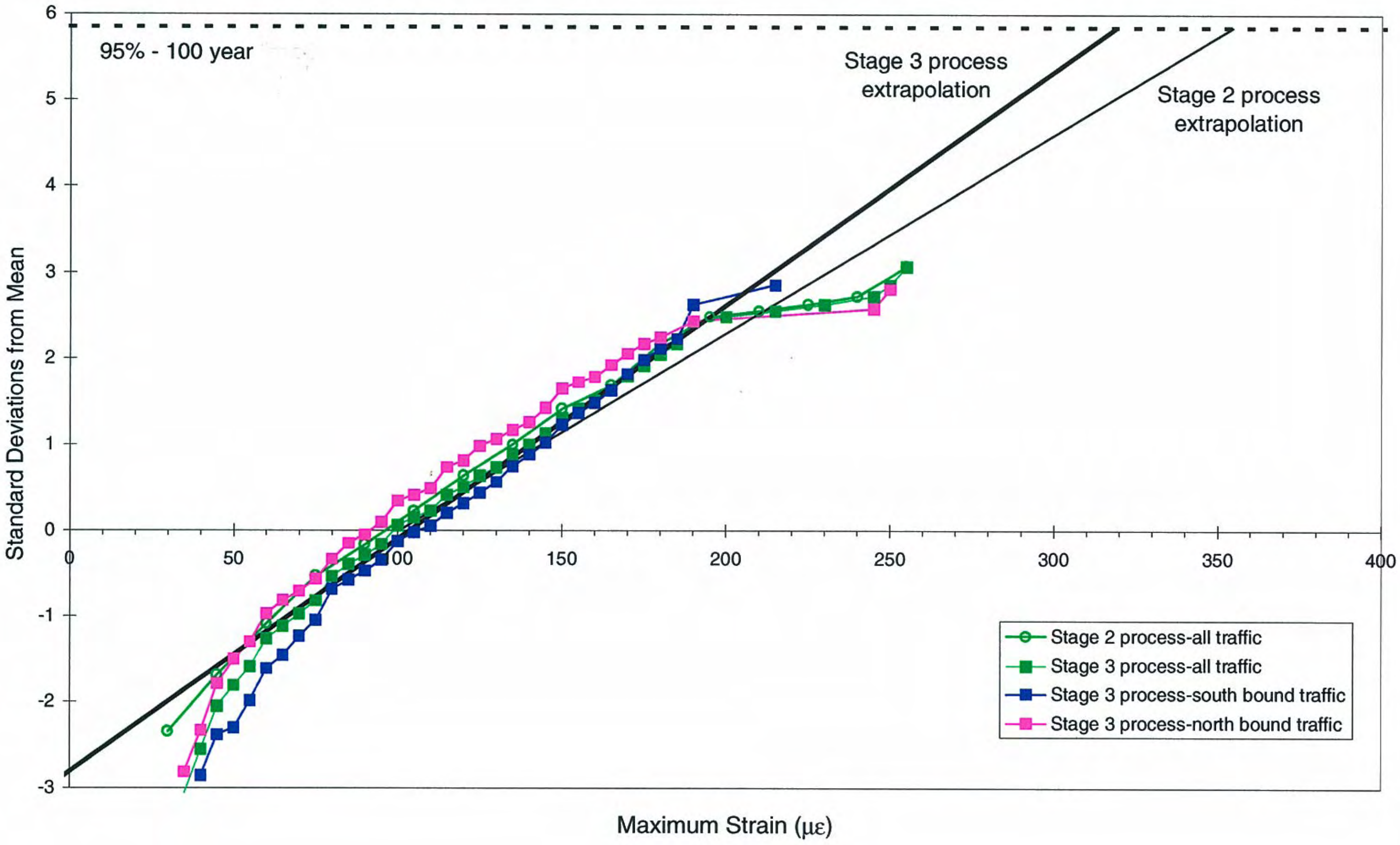

Figure B6. Inverse Normal Plot for cross-girder 1 (Comparing Stage 2 and 3 evaluation methods)

Appendix C

Inverse Normal Plots for Full Data Set: Investigation on Effect of Trigger Level on Health Monitoring Results

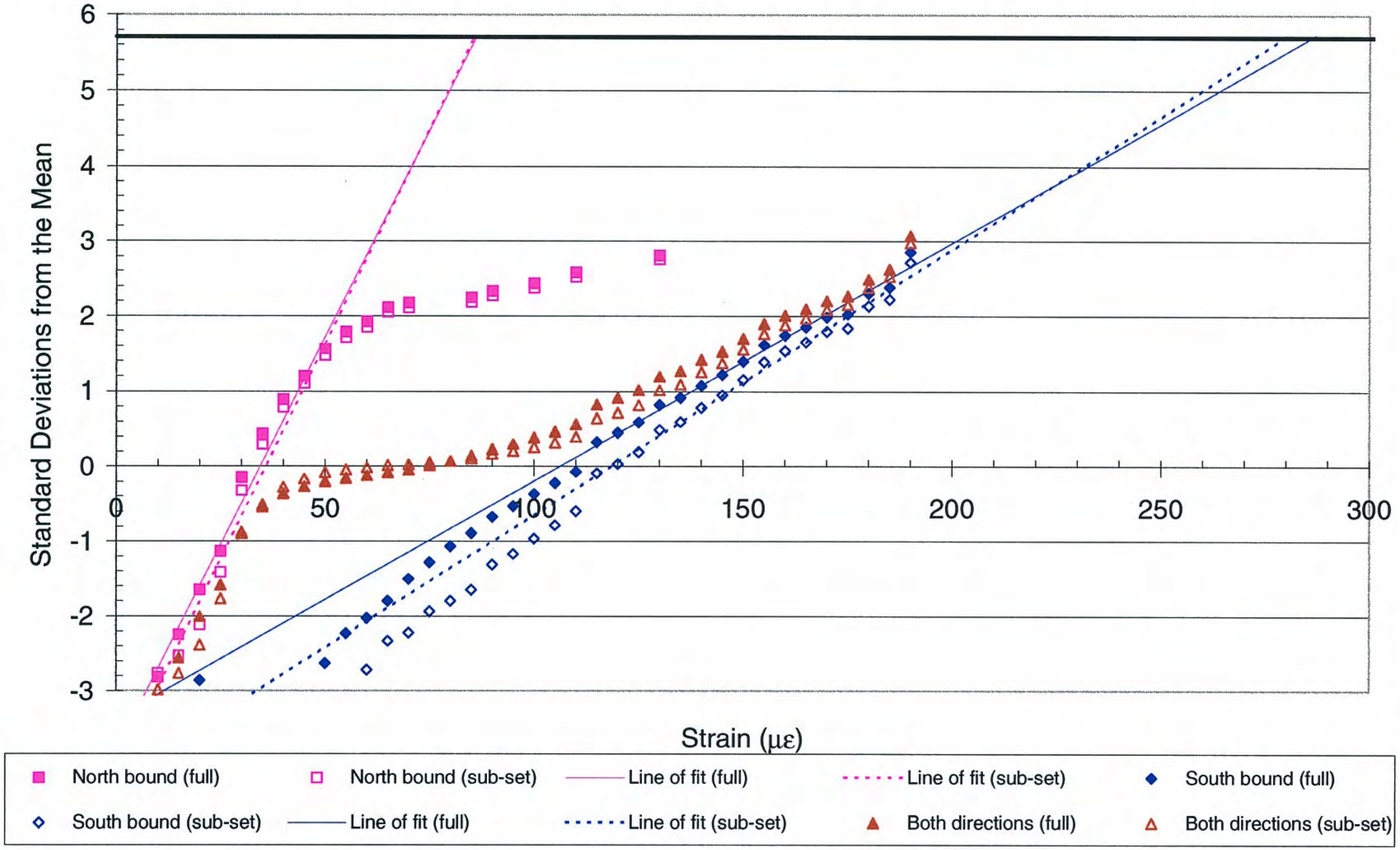

Figure C1. Inverse Normal Plot for Stringer 1 (Comparing the effect of trigger level)

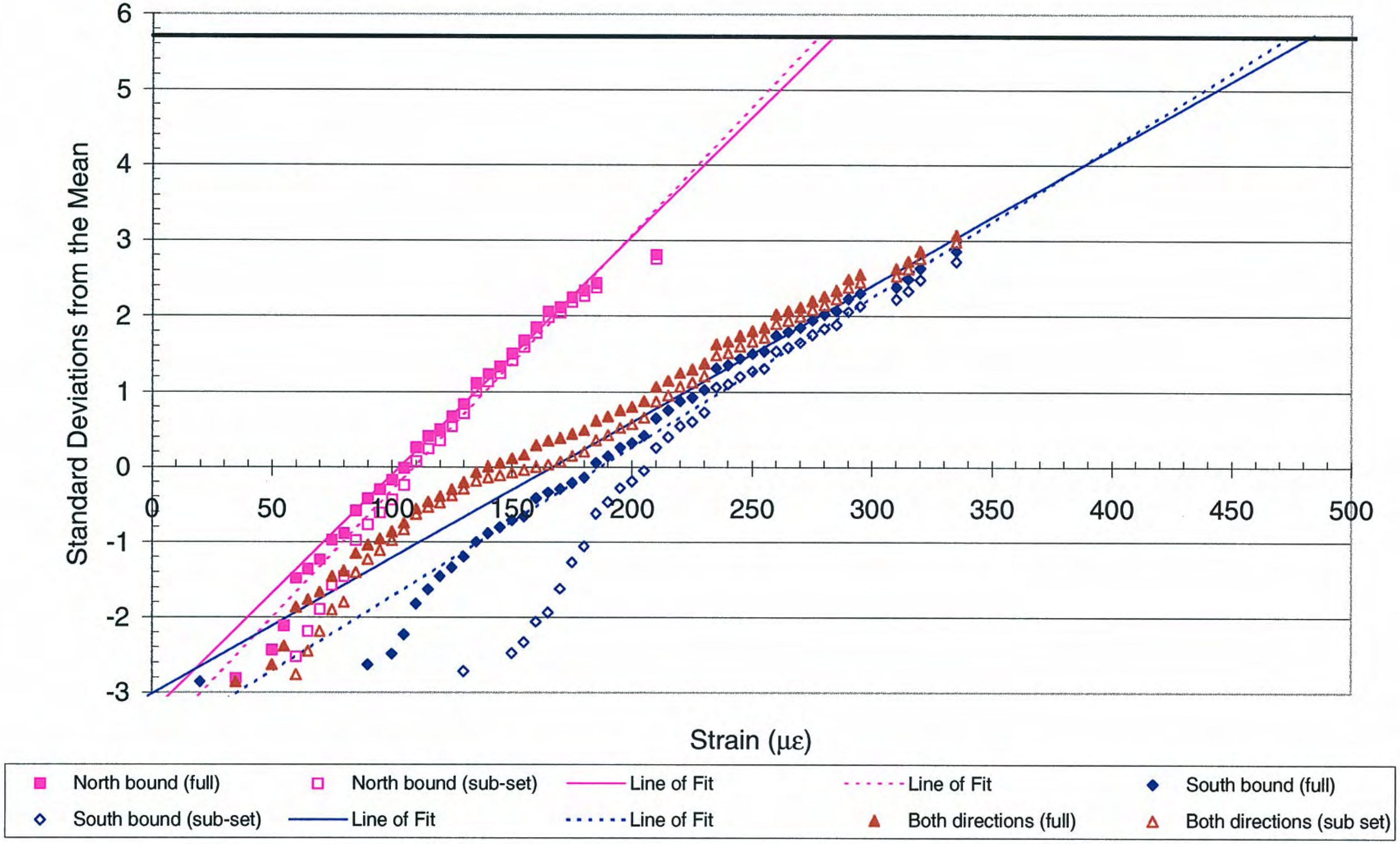

Figure C2. Inverse Normal Plot for Stringer 2 (Comparing the effect of trigger level)

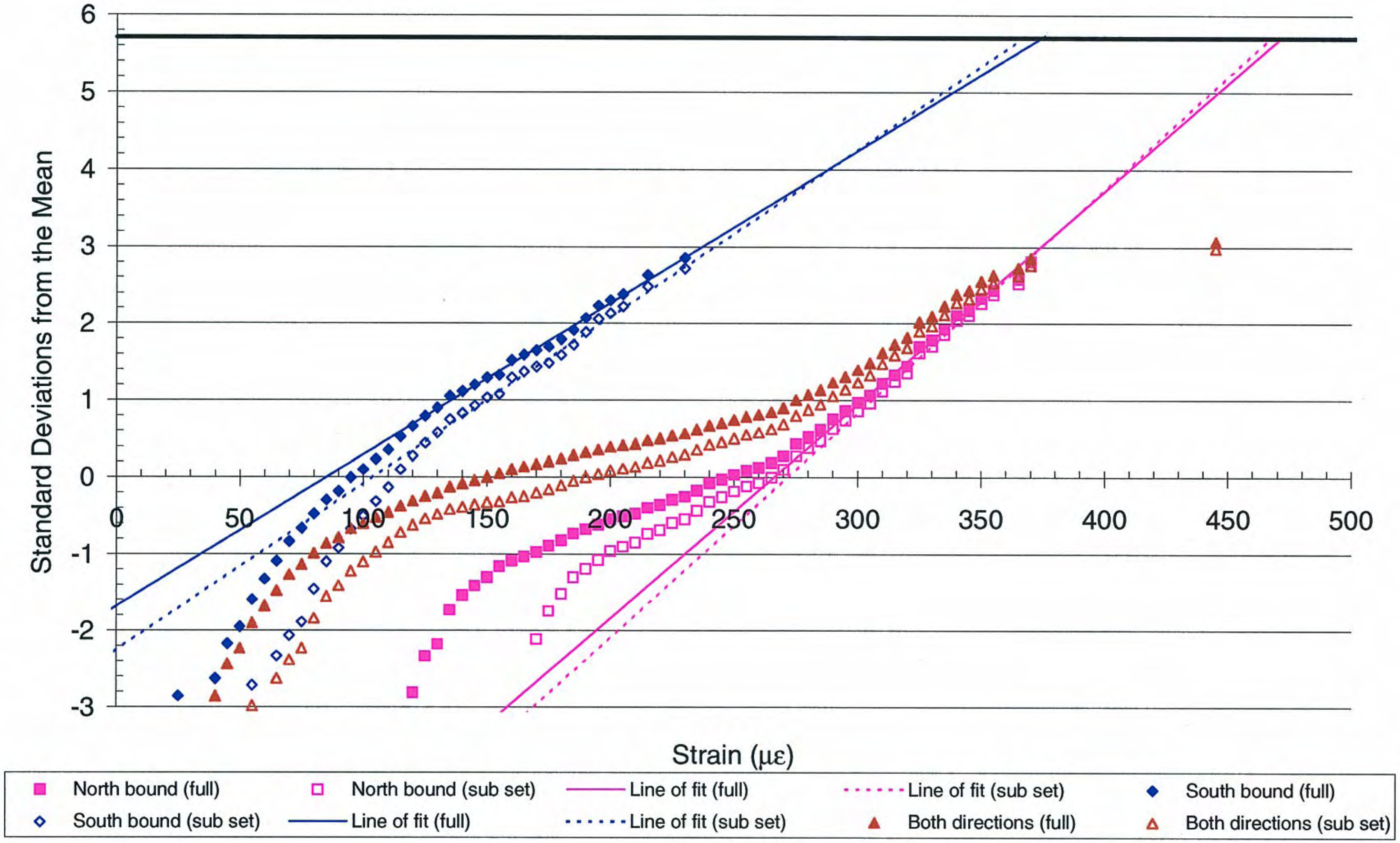

Figure C3. Inverse Normal Plot for Stringer 3 (Comparing Stage 2 and 3 evaluation methods)

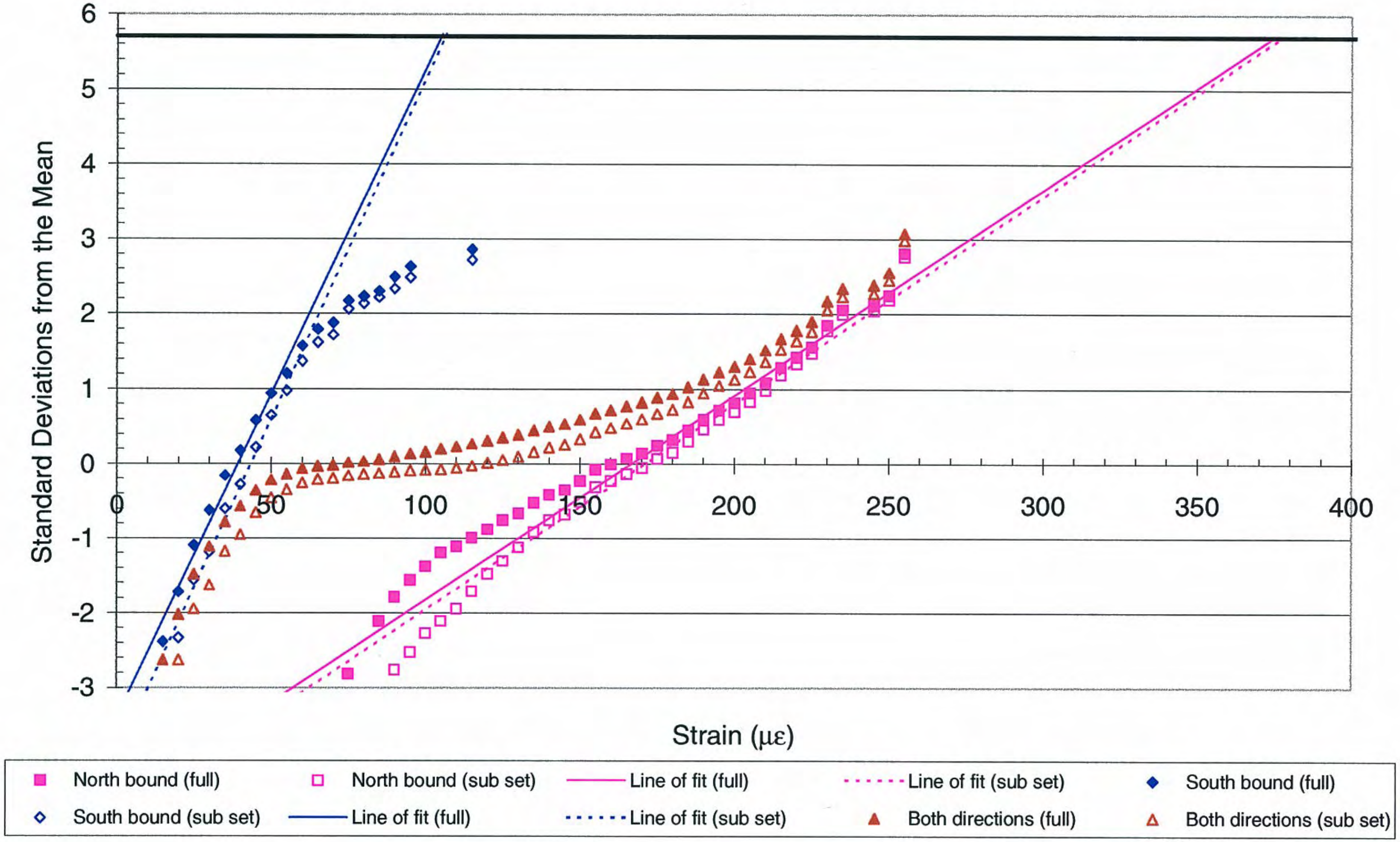

Figure C4. Inverse Normal Plot for Stringer 4 (Comparing the effect of trigger level)

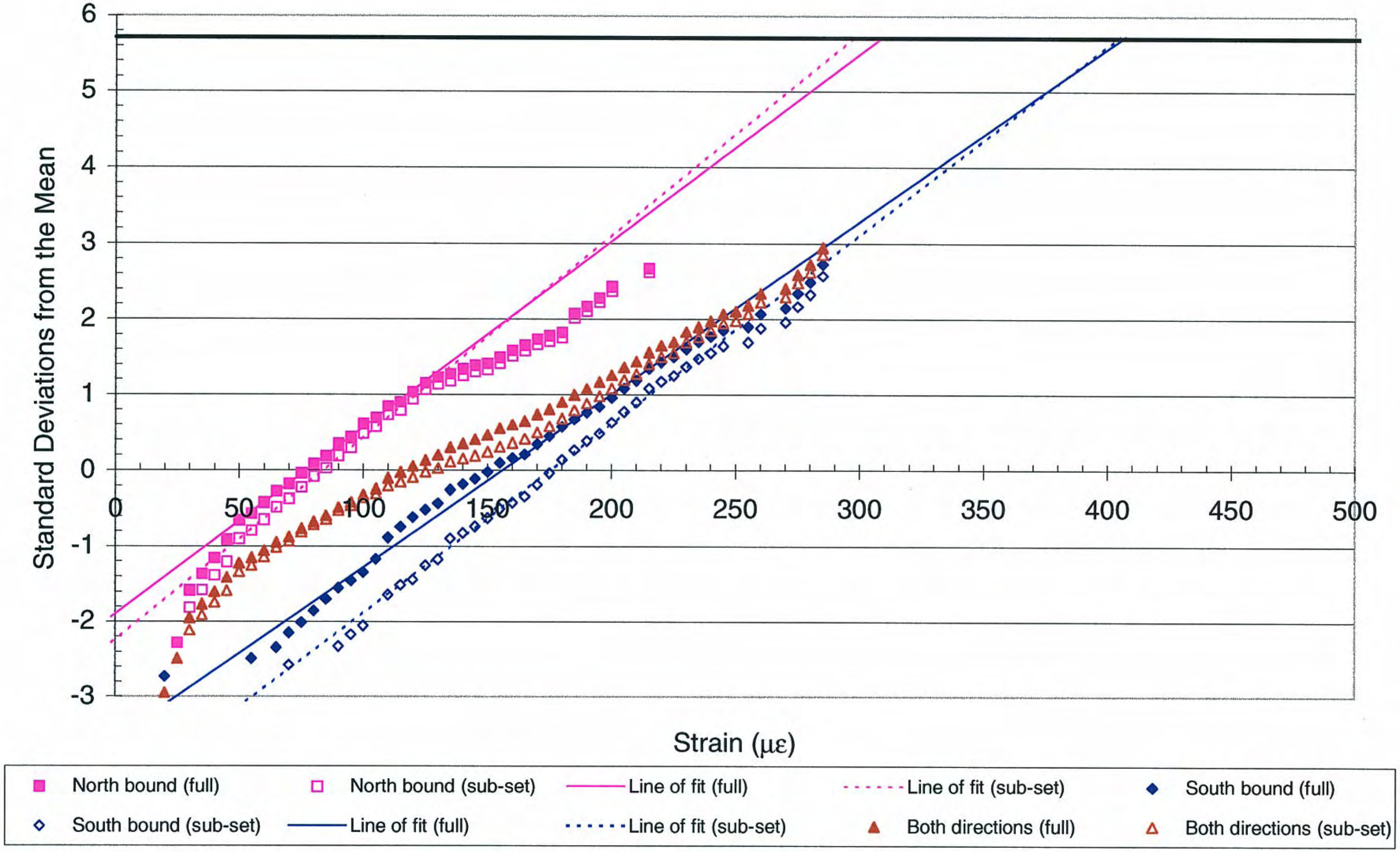

Figure C5. Inverse Normal Plot for southern abutment cross-girder (Comparing Stage 2 and 3 evaluation methods)

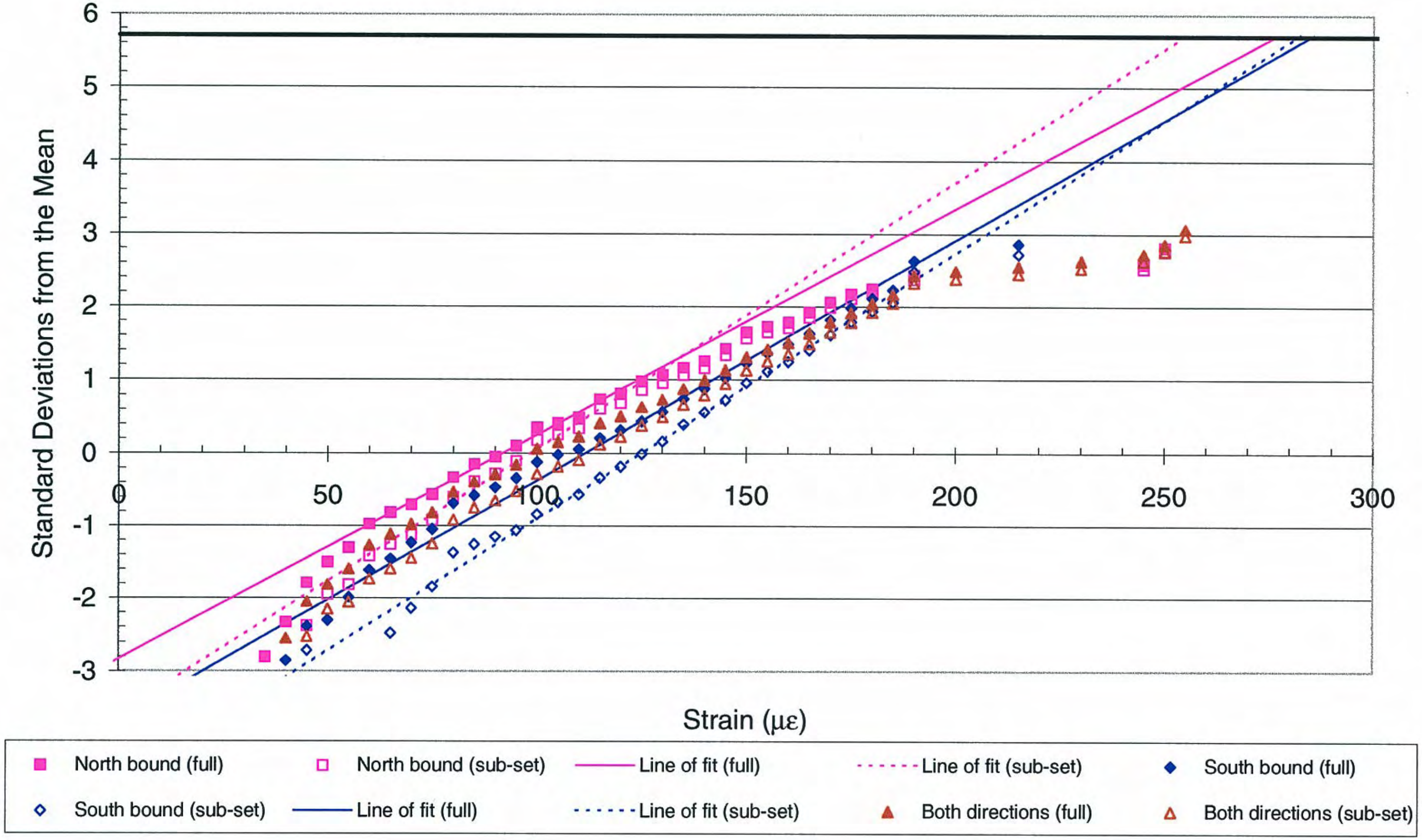

Figure C6. Inverse Normal Plot for cross-girder 1 (Comparing the effect of trigger level)

Appendix D

Inverse Normal Plots for Short-term (Stage 2) & Long-term (Stage 3) Results

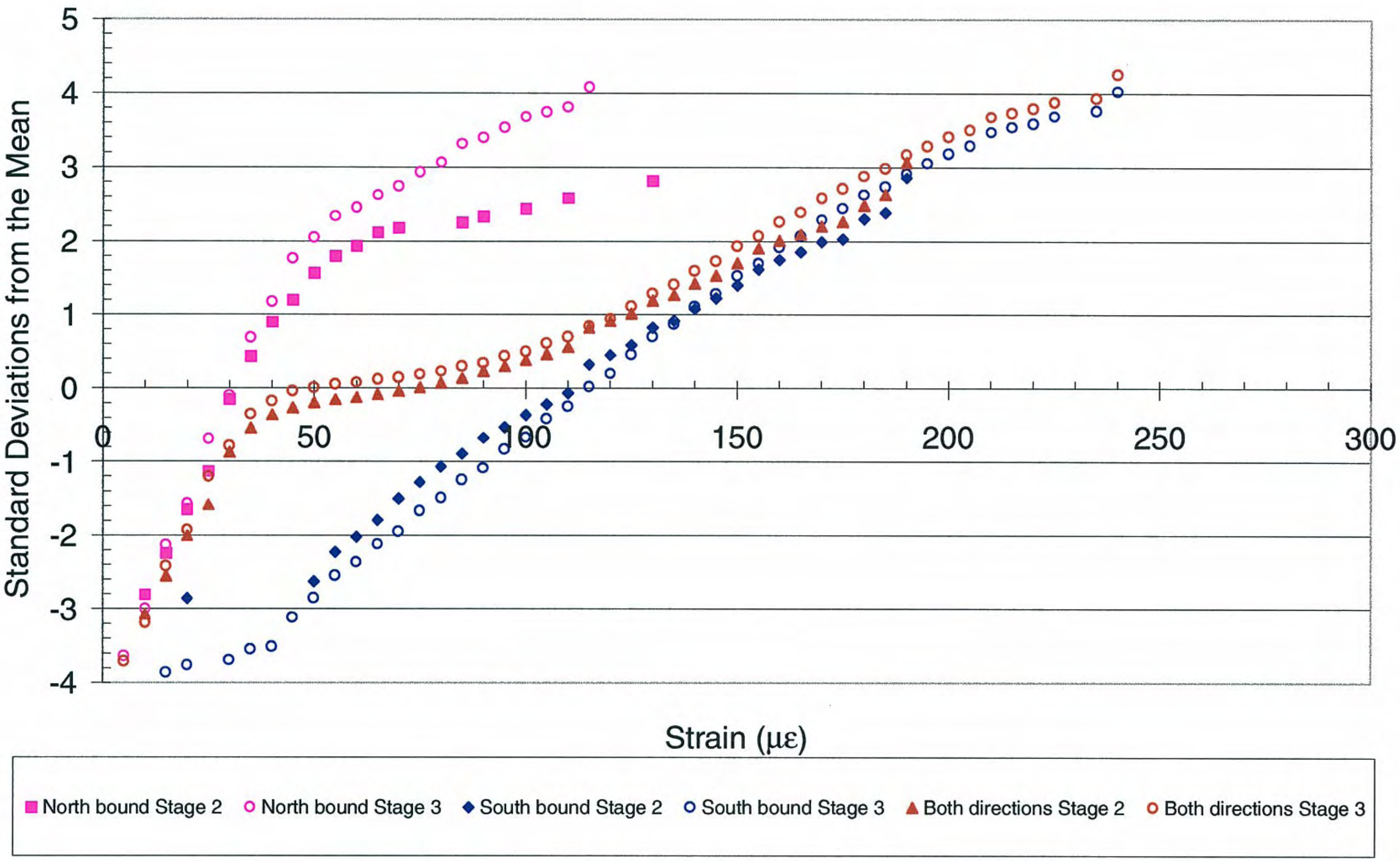

Figure D1. Inverse Normal Plot for Stringer 1 (Comparing Stage 2 and 3 results)

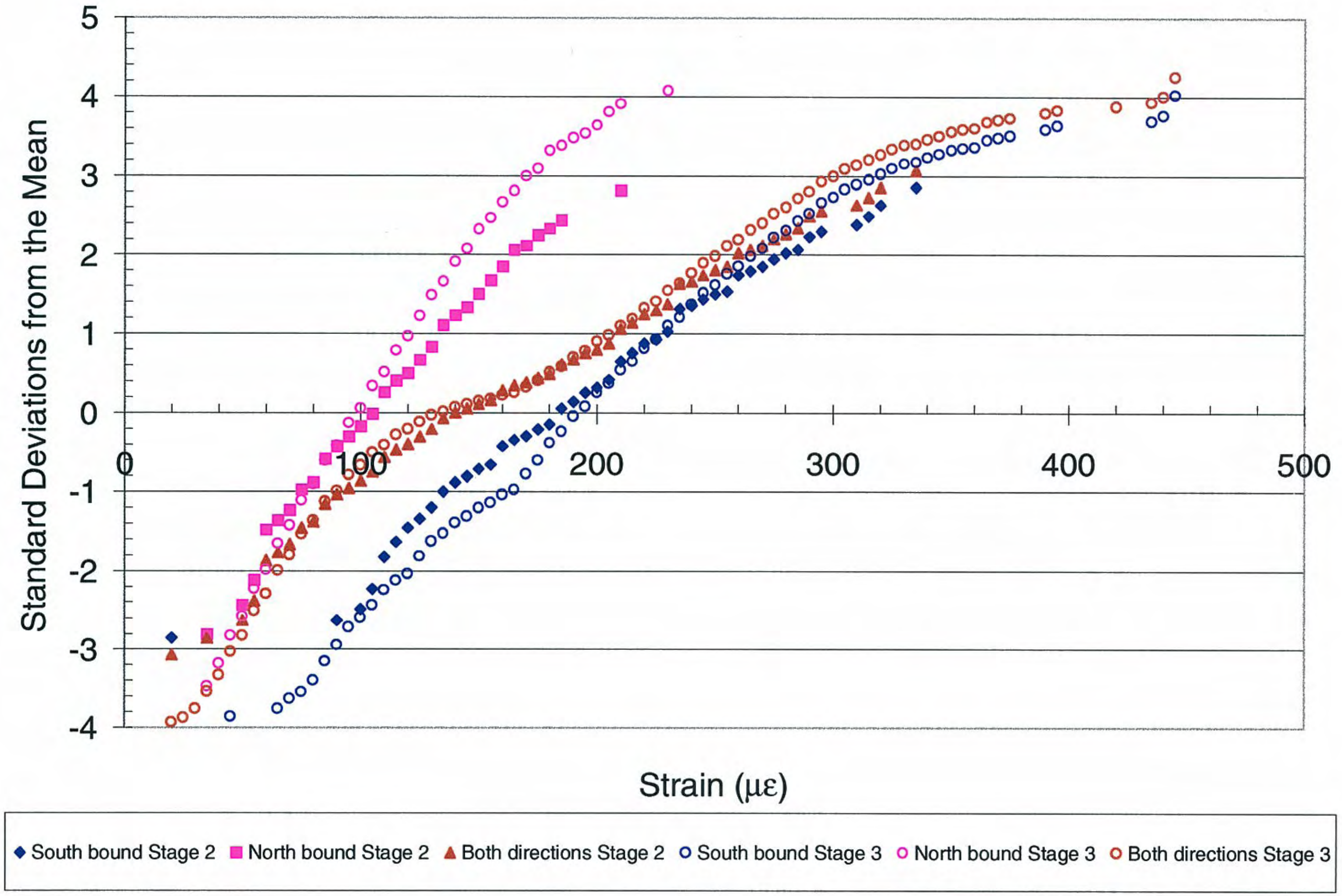

Figure D2. Inverse Normal Plot for Stringer 2 (Comparing Stage 2 and 3 results)

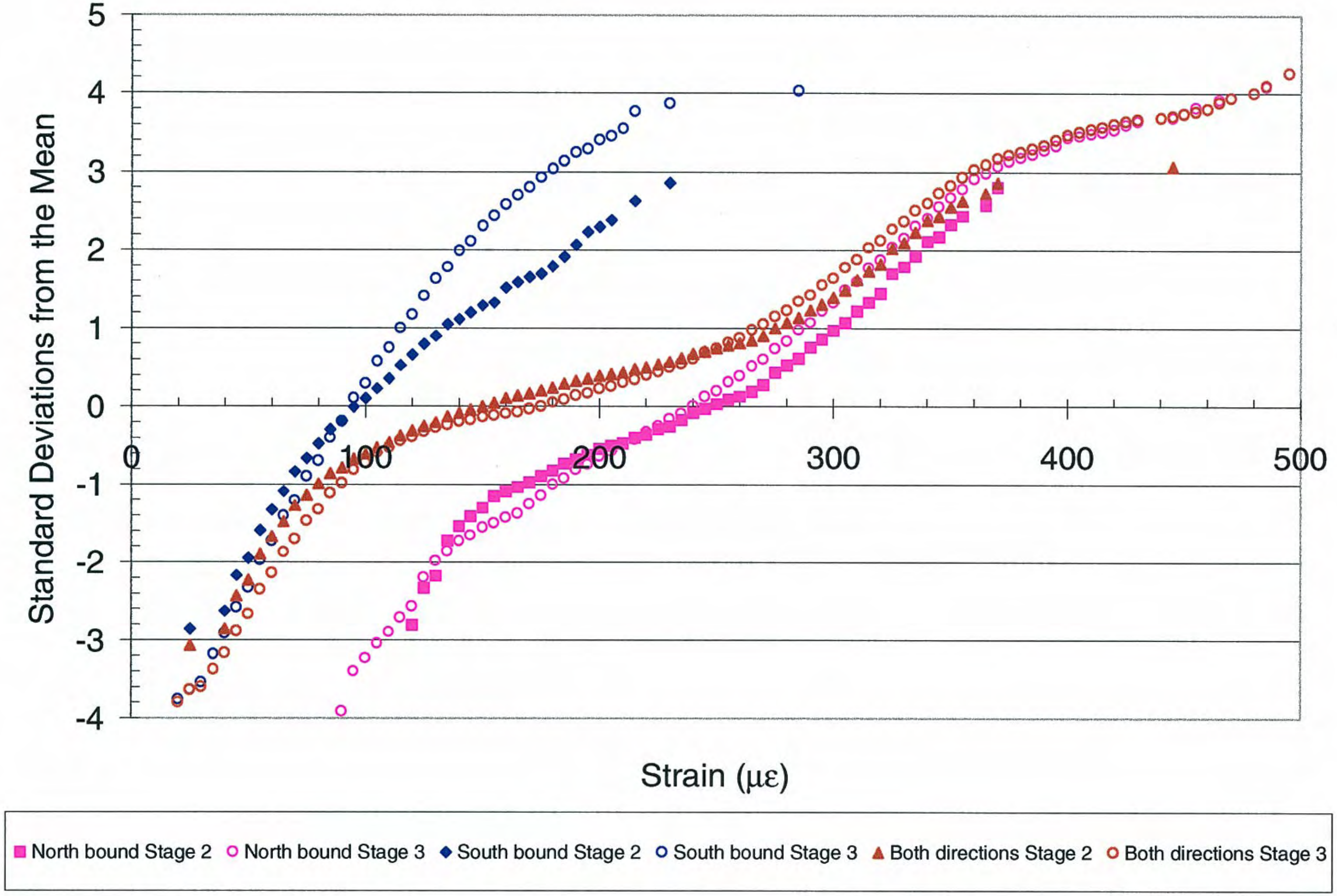

Figure D3. Inverse Normal Plot for Stringer 3 (Comparing Stage 2 and 3 evaluation methods)

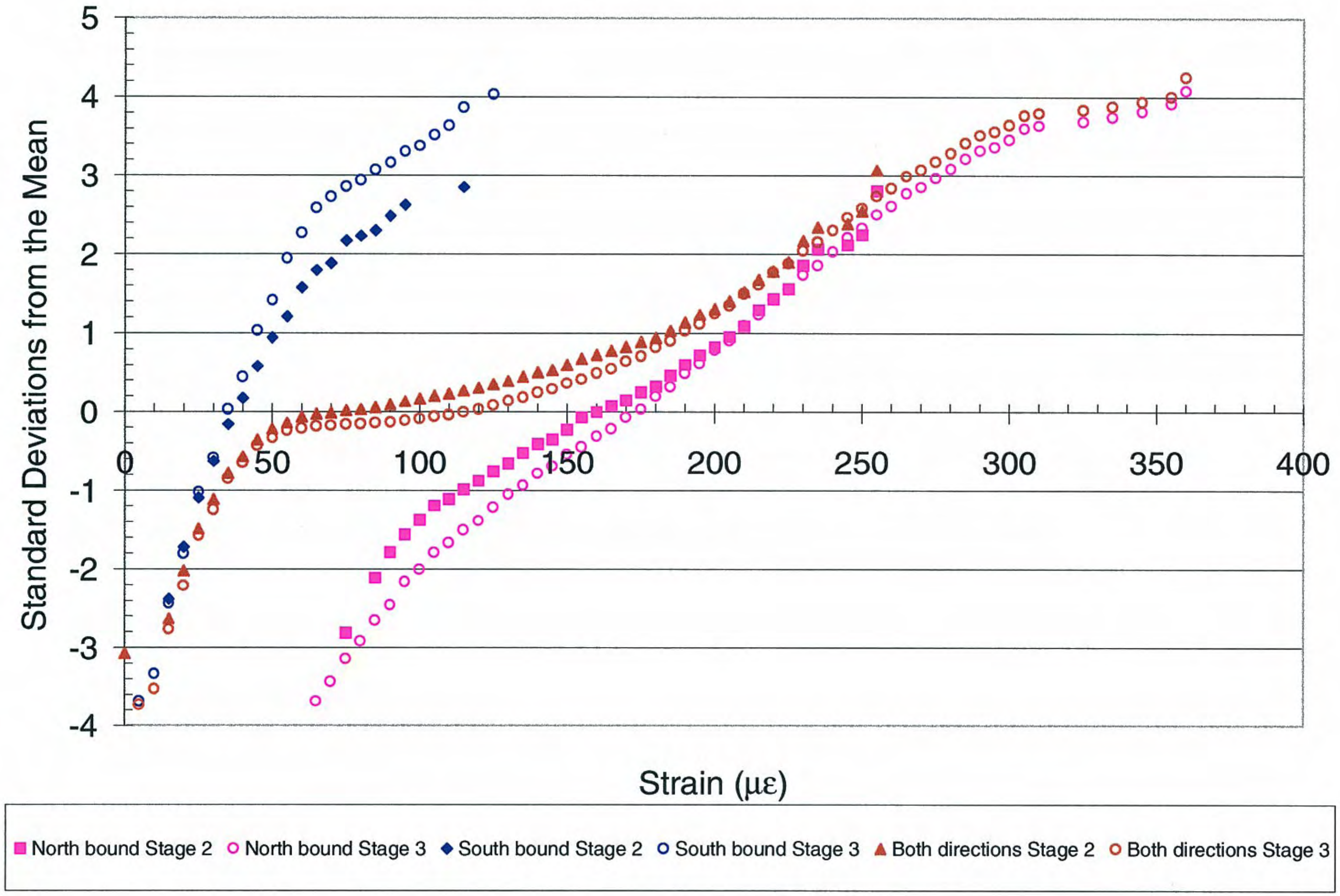

Figure D4. Inverse Normal Plot for Stringer 4 (Comparing Stage 2 and 3 results)

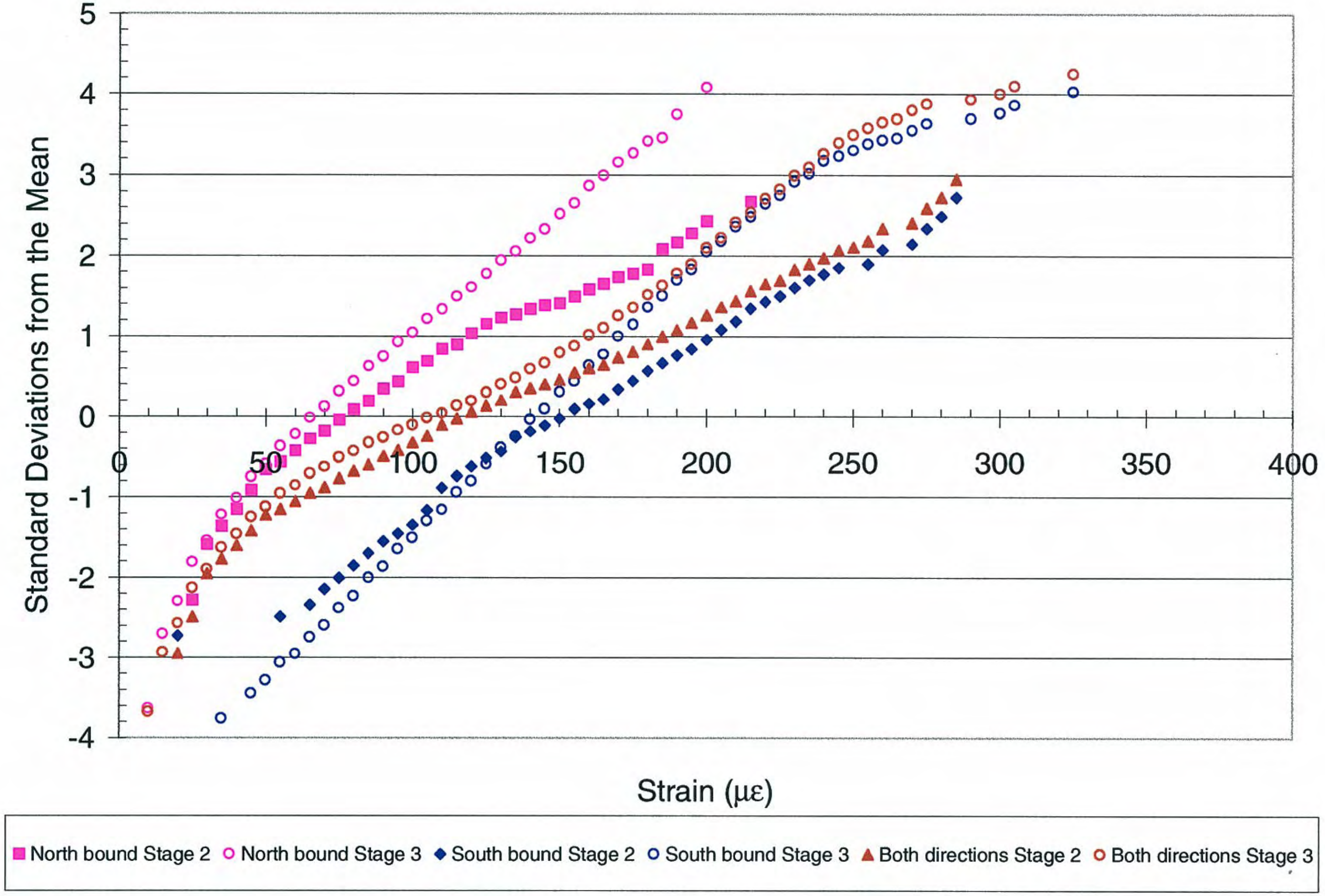

Figure D5. Inverse Normal Plot for southern abutment cross-girder (Comparing Stage 2 and 3 results)

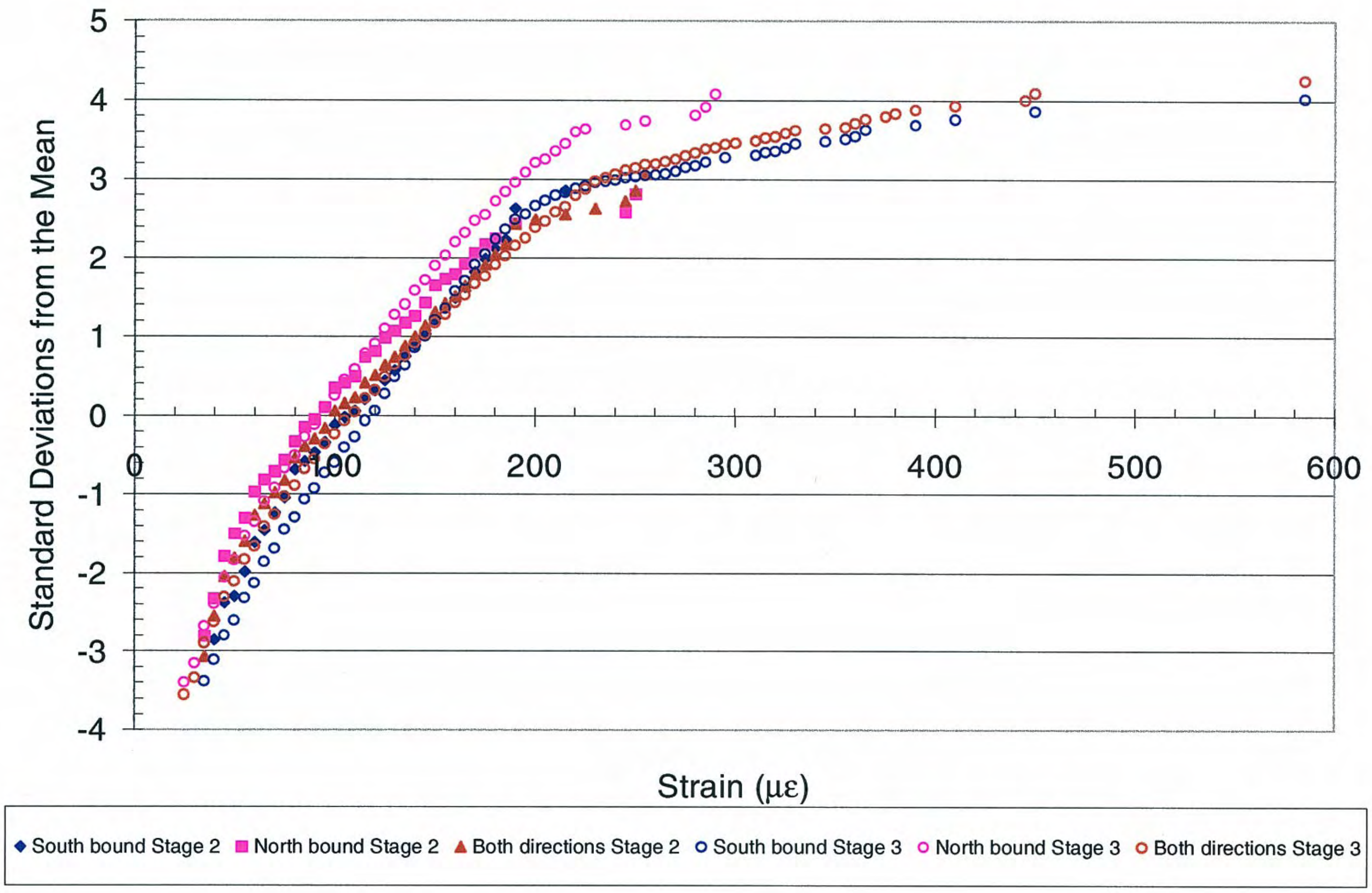

Figure D6. Inverse Normal Plot for cross-girder 1 (Comparing Stage 2 and 3 results)

Appendix E

Ratio of Predicted Maximum Strains: Various Approaches

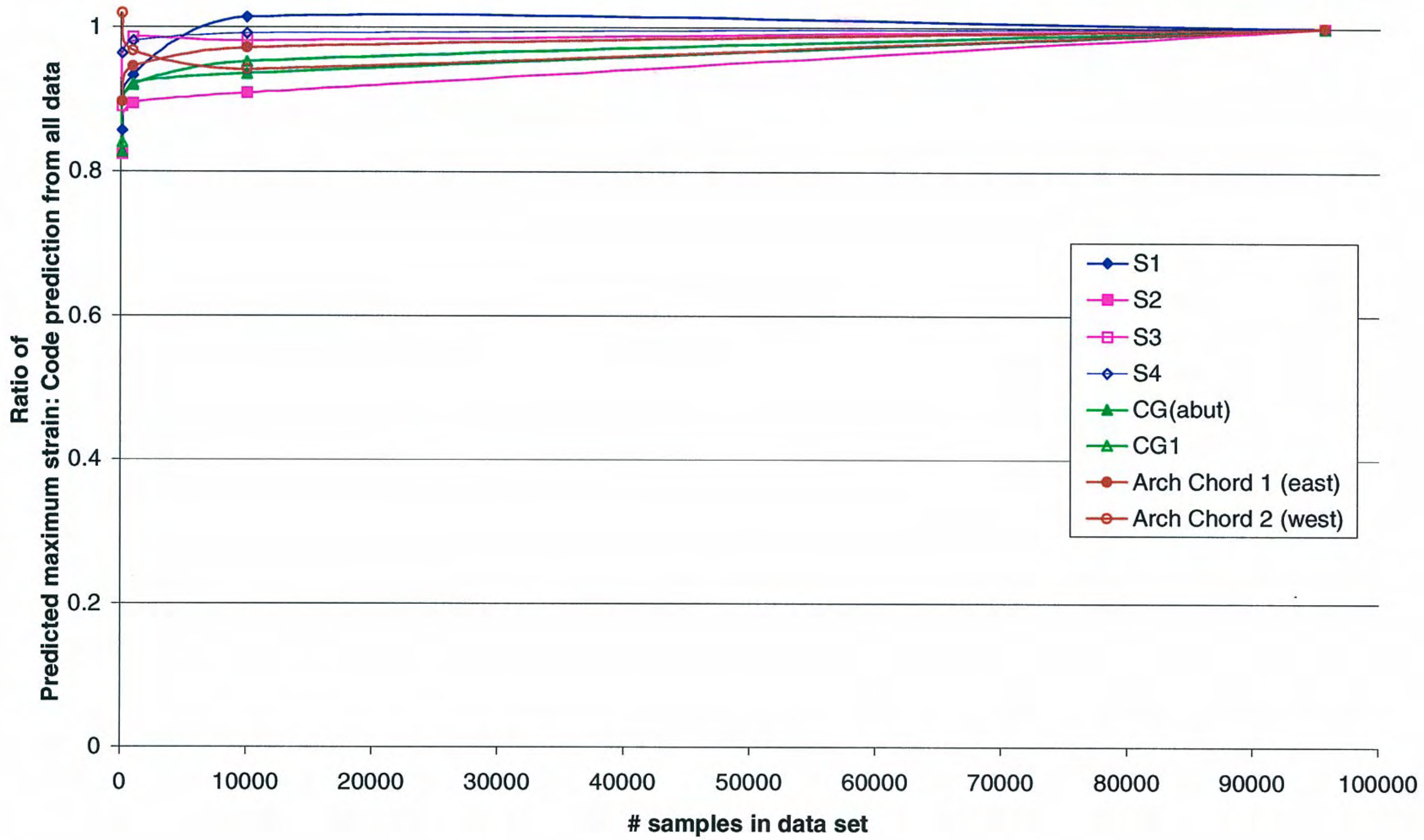

Figure E1. Ratio of predicted maximum strain (CUB)

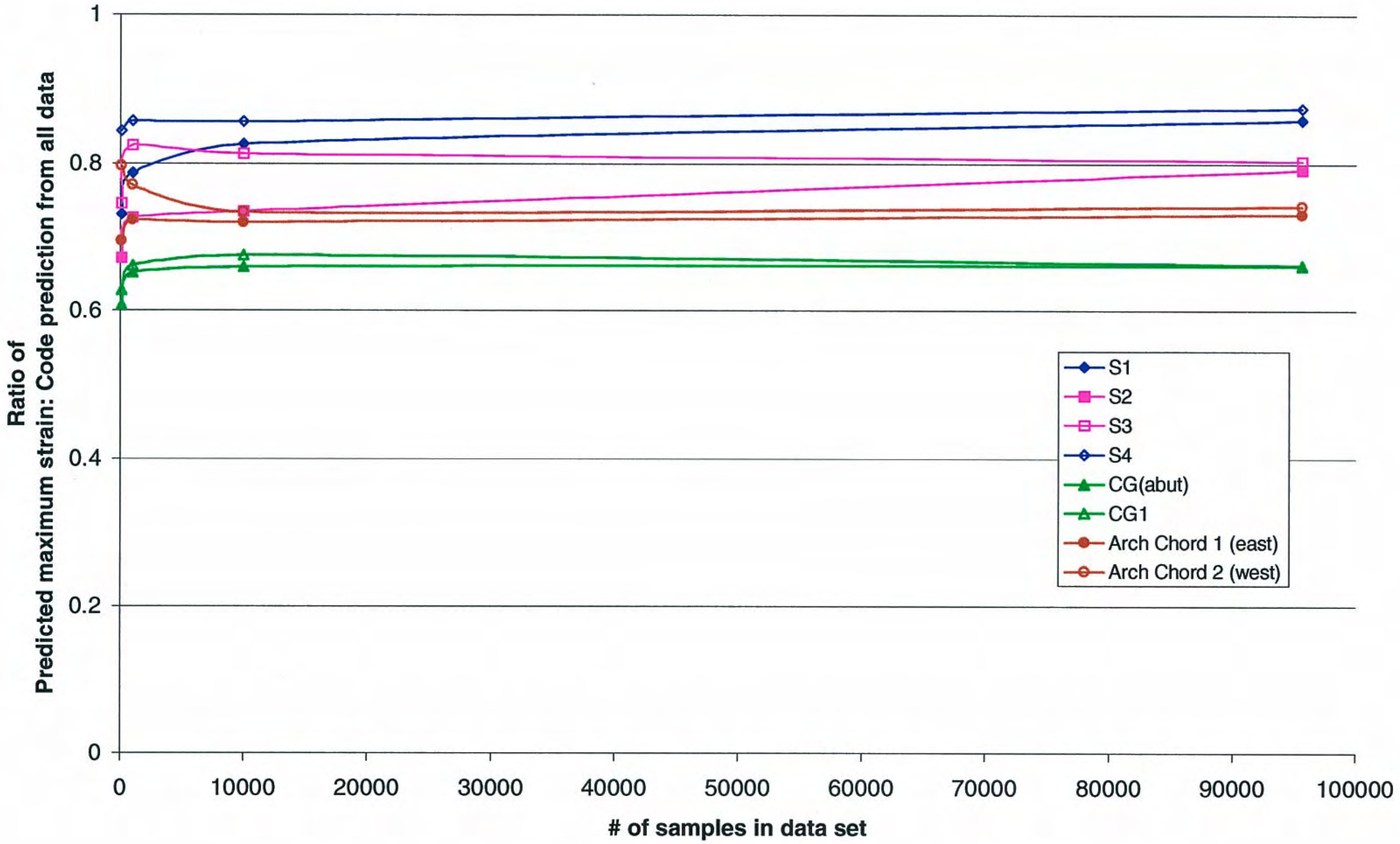

Figure E2. Ratio of predicted maximum strain (Turkstra's approach)

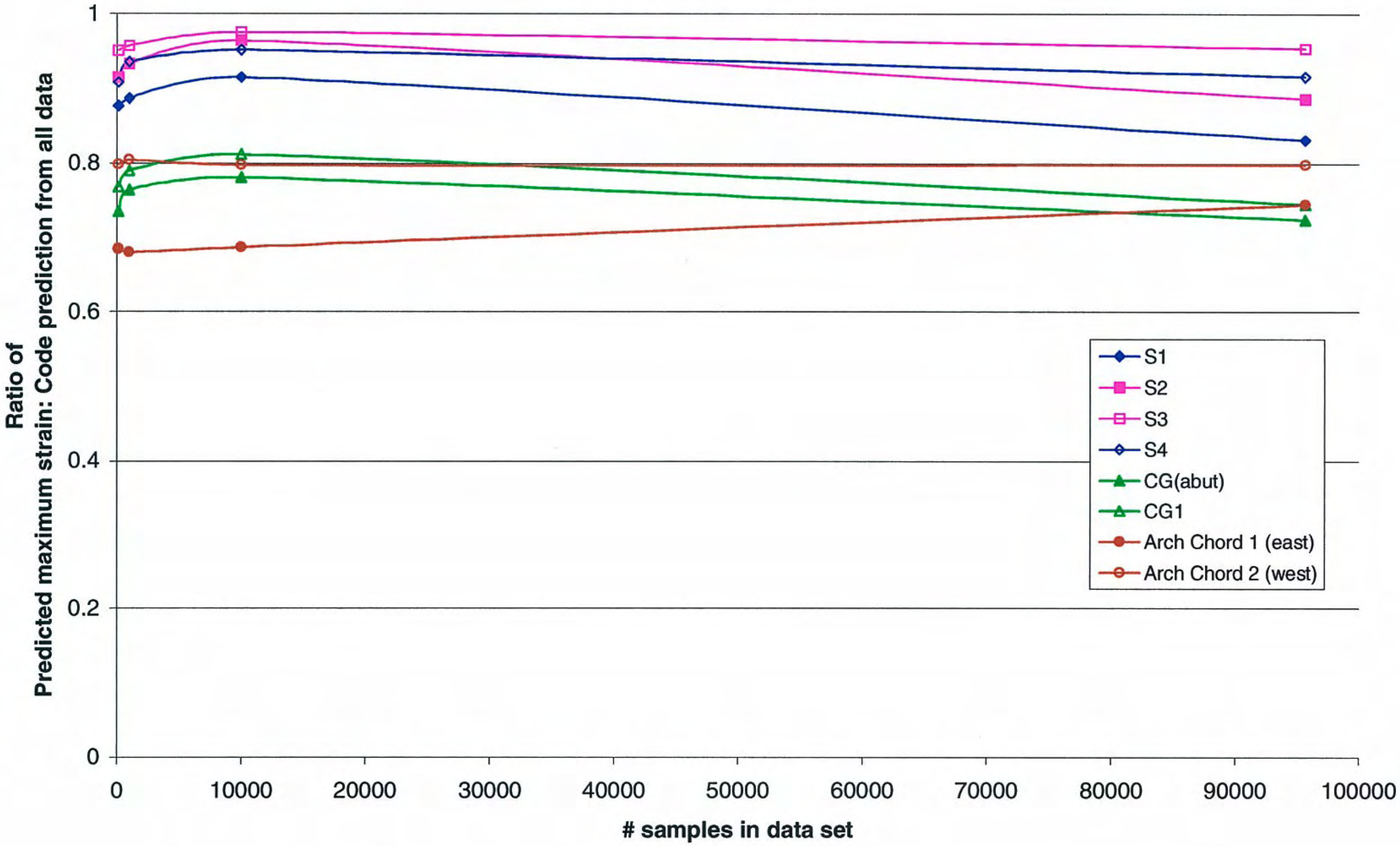

Figure E3. Ratio of predicted maximum strain (Twice the sum of lane average approach)

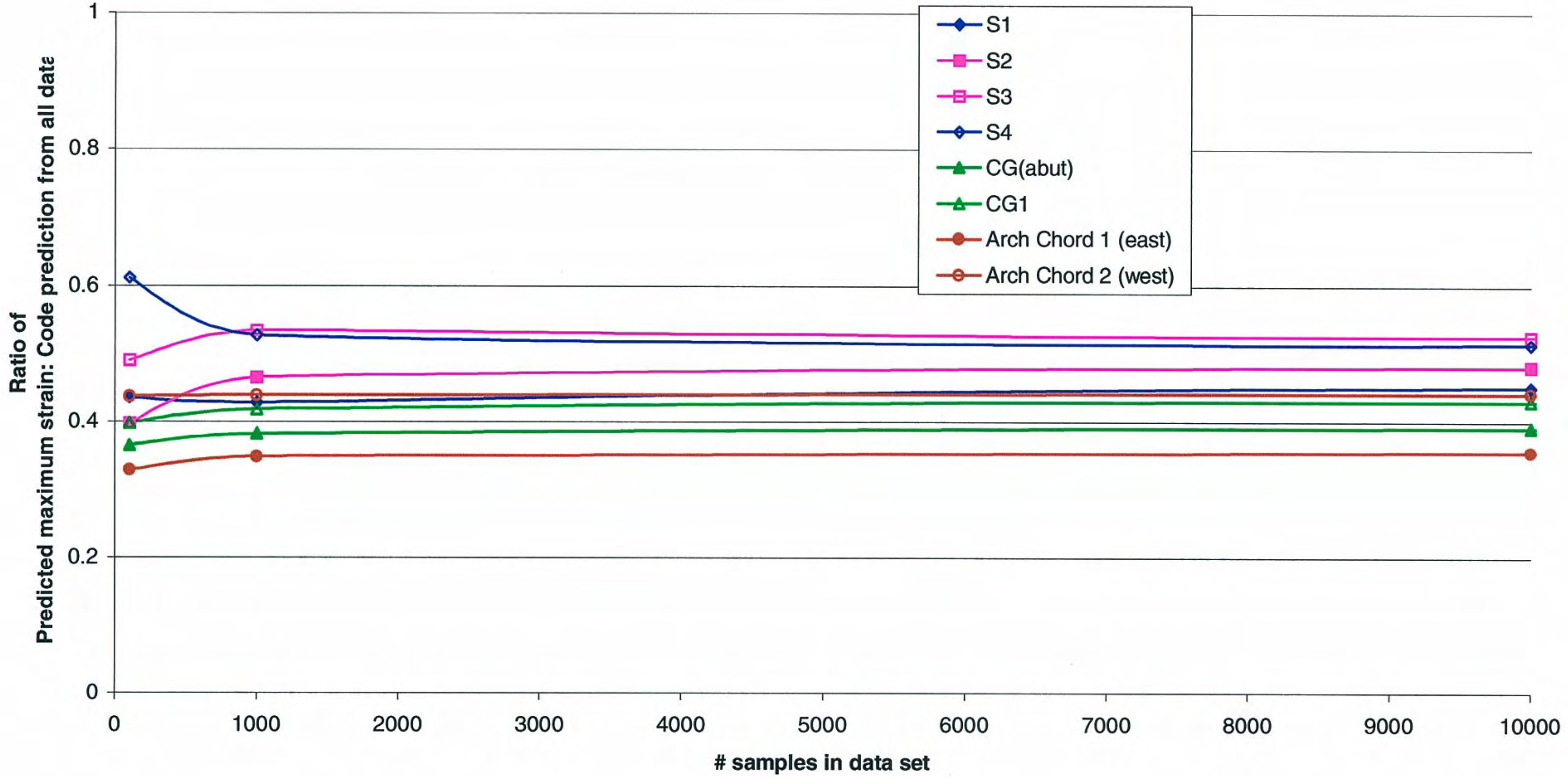

Figure E4. Ratio of predicted maximum strain (Twice the sum of average (all data) approach)

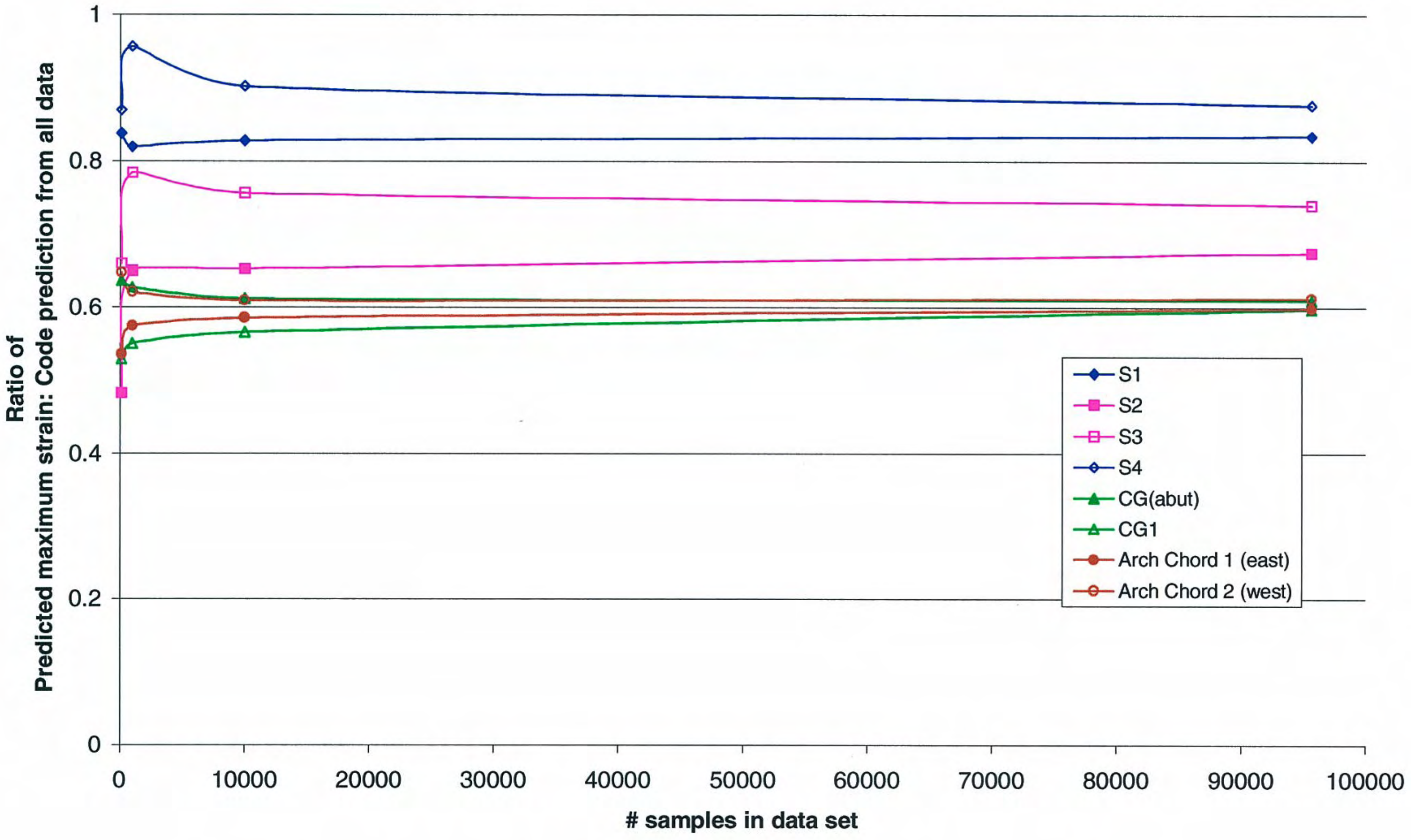

Figure E5. Ratio of predicted maximum strain (Line of fit – all data approach)

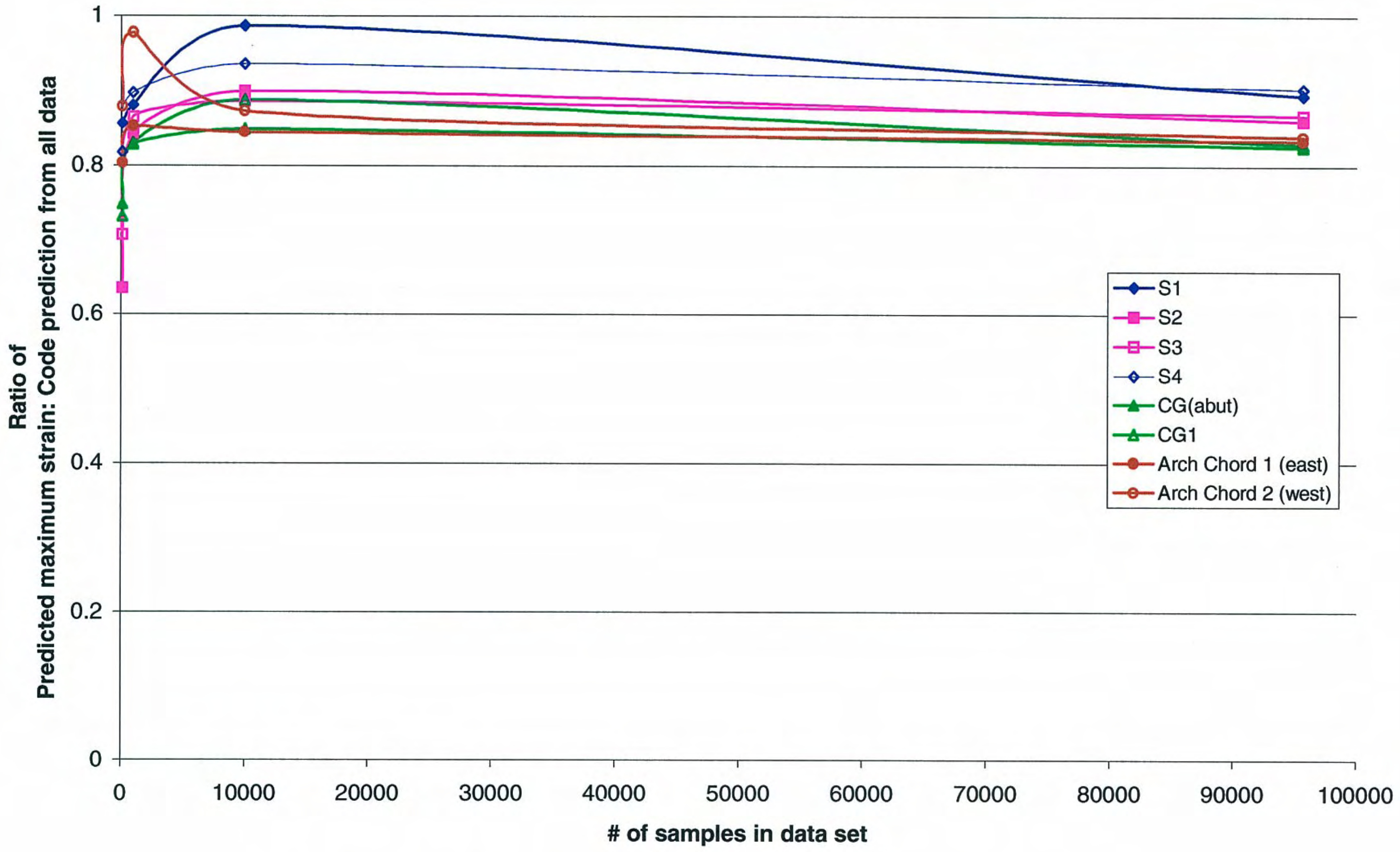

Figure E6. Ratio of predicted maximum strain (IUB Method)

ISBN 0-478-11583-0
ISSN 1174-0574

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Heldt, T.J., Welch, M.J., Heywood, R.J., Roberts, W.S. 2002. Effects of multiple presence and monitoring period on bridge health monitoring. *Transfund New Zealand Research Report No. 175.* 116 pp.

Keywords: bridges, bridge dynamics, bridge health, heavy vehicles, loading, monitoring, New Zealand, performance, roads, structures, traffic