Health Monitoring of Superstructures of New Zealand Road Bridges:

Tuakopai Bridge, Bay of Plenty

Transfund New Zealand Research Report No.174

Health Monitoring of Superstructures of New Zealand Road Bridges:

Tuakopai Bridge, Bay of Plenty

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An Important Note for the Reader

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Executive Summary

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 part of Stage 2 of a research project carried out in 1998-1999, which involves the *Short-Term Health Monitoring and "Fitness for Purpose" Assessment* of ten bridges on New Zealand highways, in order to develop and evaluate the methodology.

The Tuakopai Bridge crosses the Tuakopai Stream, on State Highway 29 which leads to the Port of Tauranga, Bay of Plenty Region, North Island. It was selected as one of these ten, because it is representative of a large number of bridges in New Zealand built between the early 1930s and late 1940s. The span is typical of many of these bridges, and the removal of the original reinforced concrete guardrails has decreased the stiffness of the structure. It therefore provides an example that represents a lower bound for bridges without guardrails and a similar form of construction.

Theoretical Analysis

As the existing drawings for this bridge were incomplete, it has been assessed by comparing its performance with two other bridges (Rakaia and Waitangi Washout) that have similar characteristics, and have also been monitored as part of this project. The bridge has a Class of 87% in the 1999 Transit New Zealand Structural Inventory and a Deck Classification Factor of 1.05.

Health Monitoring Results

The findings of the Health Monitoring of the Tuakopai Bridge are that:

- The girders on this bridge should have a bending strength of approximately 1200 kNm. The assumption was made that midspan bending was the critical failure mode for the bridge.
- The results of the Health Monitoring programme show evidence of significant overloading on this bridge, with some of the ambient heavy traffic inducing responses up to 75% higher than the known heavy vehicle. The known vehicle is equivalent to around 85% of the 0.85 HN*-type vehicle on this bridge.
- The dynamic effects of heavy vehicle traffic are high and an impact factor of around 35% is appropriate for this bridge.
- The actual strains and deflections induced by heavy vehicles on this route are much lower (approximately 50%) than the strains and deflections predicted by the grillage analysis (using assumed structural properties). The maximum strain recorded was 140 $\mu\varepsilon$ and the maximum deflection was 2.9 mm.

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* HO Highway overweight vehicle; HN Highway normal vehicle

In summary, overloading occurs on the Tuakopai Bridge but the structural response is lower than expected, probably because of end restraint provided at the abutments to the girders. This improves the load carrying capacity of the bridge.

Fitness for Purpose Evaluation

Because the drawings and other data concerning the bridge's structure were incomplete, the Fitness for Purpose Evaluation could not be calculated.

Instead a comparison of the performance of this bridge was made with the Rakaia Bridge, which has a Fitness for Purpose Evaluation of 137%.

This comparison found that the Tuakopai Bridge would have a Fitness for Purpose Evaluation similar to or higher than 137%.

It also means that the Tuakopai Bridge has adequate strength capacity to resist the effects of the heavy vehicle traffic it has to withstand.

Recommendations

Recommendations for the Tuakopai Bridge are:

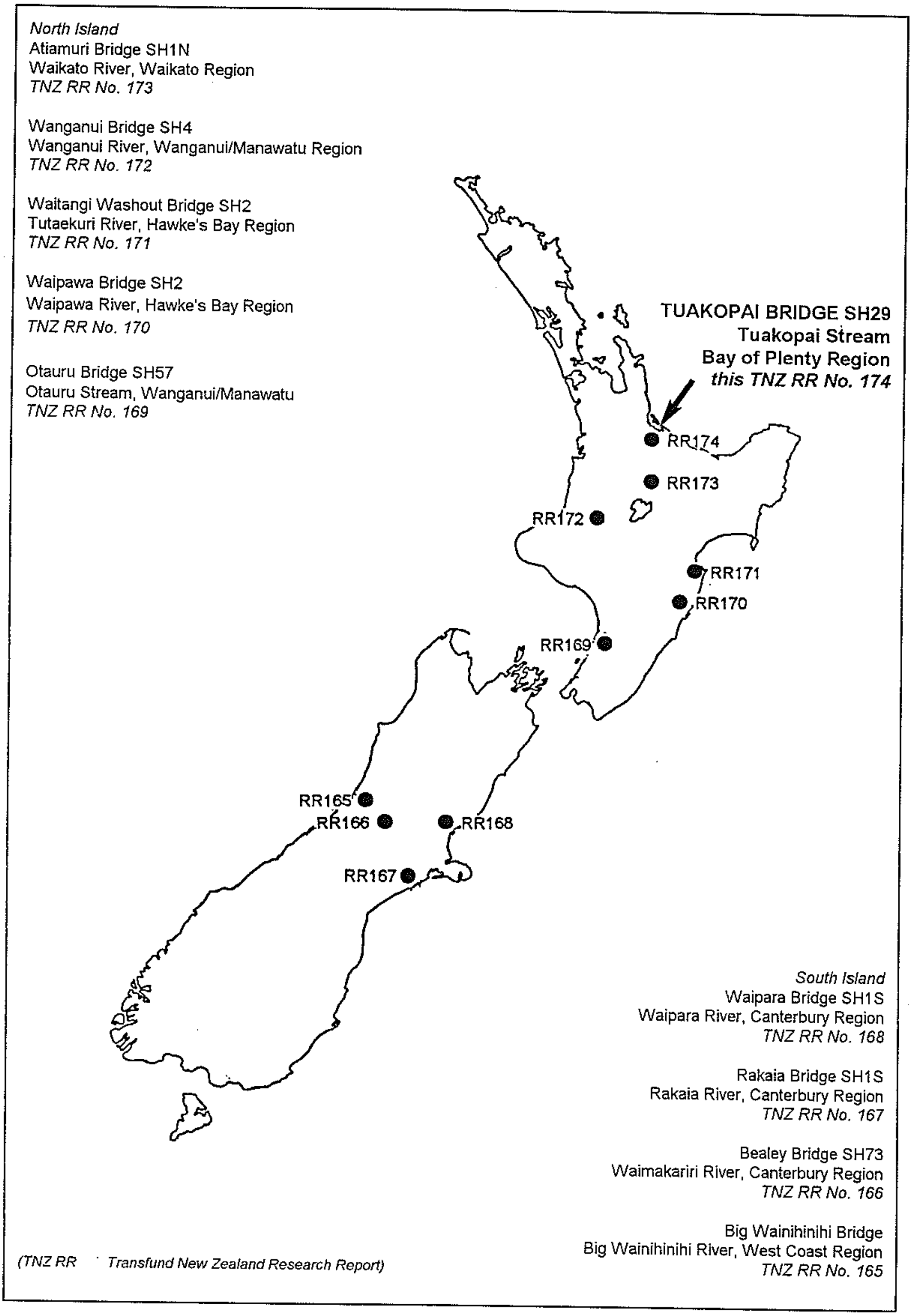
- Posting of the bridge is not necessary.
- The apparent overloading on this route should be investigated further.
- Methodology for using Health Monitoring results in the comparative manner used for this bridge should be further developed.

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 research project, carried out in 1998-1999, is part of Stage 2 of the *Short-Term Health Monitoring and "Fitness for Purpose" Assessment* of ten bridges on New Zealand highways, in order to develop and evaluate the methodology. The Tuakopai Bridge, on State Highway 29 that leads to the port of Tauranga, Bay of Plenty Region, North Island, was selected as one of these ten. It is representative of a large number of bridges in New Zealand built between the early 1930s and late 1940s. The span is typical of many of these bridges, and the removal of the original reinforced concrete guardrails has decreased the stiffness of the structure. It therefore provides an example that represents a lower bound for bridges without guardrails and a similar form of construction.

Figure 1.1 Location of Tuakopai Bridge, on SH29, Bay of Plenty, North Island, New Zealand, one of the ten bridges selected for the Bridge Health Monitoring project.



1. Introduction

1.1 Background

Bridge Health Monitoring is a method of evaluating the ability of a bridge to perform its required task, also called its "Fitness for Purpose". This method involves monitoring the response of a bridge to its normal environment, in particular to the traffic loads it has to withstand. Subsequently these data are processed and used to evaluate the bridge's Fitness for Purpose.

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

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

The project, conducted in 1998-1999, was divided into four stages, of which Stage 2 was entitled *Short-term Health Monitoring and "Fitness for Purpose" Assessment.* Short-term Health Monitoring was conducted on a total of ten New Zealand bridges on state highways, covering a range of bridge types, ages, conditions and environments. This population of ten bridges was selected to be representative of the New Zealand bridge population. It thus provided an appropriate basis to compare conventional bridge evaluation with the bridge Health Monitoring techniques under development. Not every aspect of every bridge has been considered, but rather the monitoring has typically focused on critical components of the superstructure of each bridge.

This report is part of Stage 2 of the project, and presents results for the Tuakopai Bridge across the Tuakopai Stream, on State Highway (SH) 29 that leads to the Port of Tauranga, Bay of Plenty Region, North Island of New Zealand (Figure 1.1). The reasons for choosing this bridge for the representative sample were:

- It is representative of a large number of bridges in New Zealand built between the early 1930s and late 1940s.

- The configuration of this reinforced concrete beam and slab bridge is typical of a large number of these bridges.
- The removal of the original reinforced concrete guardrails may have decreased the stiffness of the structure.
- It therefore provides an example that represents a lower bound of performance for bridges without guardrails.
- This type of structure also often benefits from the continuity effects provided by the support conditions, which may not have been considered in the original design.
- Because of this, benefits often arise in evaluating these types of structures using the Health Monitoring procedure.

The objective of this investigation was to evaluate the Fitness for Purpose of the superstructure of the Tuakopai Bridge using the conventional evaluation technique and the proposed Health Monitoring technique, and to compare the results of both techniques. The fitness of the bridge to carry heavy vehicle traffic loadings was specifically investigated.

1.2 Applying Health Monitoring Technology

The Transit New Zealand Bridge Manual (TNZ 1994) procedure was used to complete the conventional evaluation. The Health Monitoring procedure involved the following steps:

- Performing a structural analysis on the superstructure of the bridge to determine the critical mode of failure and to determine the locations for health monitoring instrumentation.
- Monitoring the response of the structure to the ambient heavy vehicle traffic passing over the bridge for at least 24 hours (Health Monitoring).
- Recording the response of the structure to the passage of a heavy vehicle of known mass and dimensions to provide a reference for the health monitoring data.
- Evaluating the Fitness for Purpose of the superstructure based on health monitoring data, and comparing this with conventional evaluation methods.

This evaluation is based principally on the following components of the Tuakopai Bridge structure:

- Midspan bending capacity of the main reinforced concrete girders.
- Shear strength of the main reinforced concrete girders.

The substructure was not evaluated in this investigation.

2. Evaluation of Bridges using Health Monitoring Techniques

2.1 Introduction

This section looks at the traditional approach to evaluating bridges as set out in the Bridge Manual (TNZ 1994). The advantages of a Health Monitoring approach are outlined, and a method to integrate the advantages of Health Monitoring in the existing evaluation procedures is also proposed.

Both bridge design and bridge evaluation involve ensuring that the probability of the load being greater than the resistance (i.e. the bridge fails) is acceptably small. This is illustrated graphically on Figure 2.1.

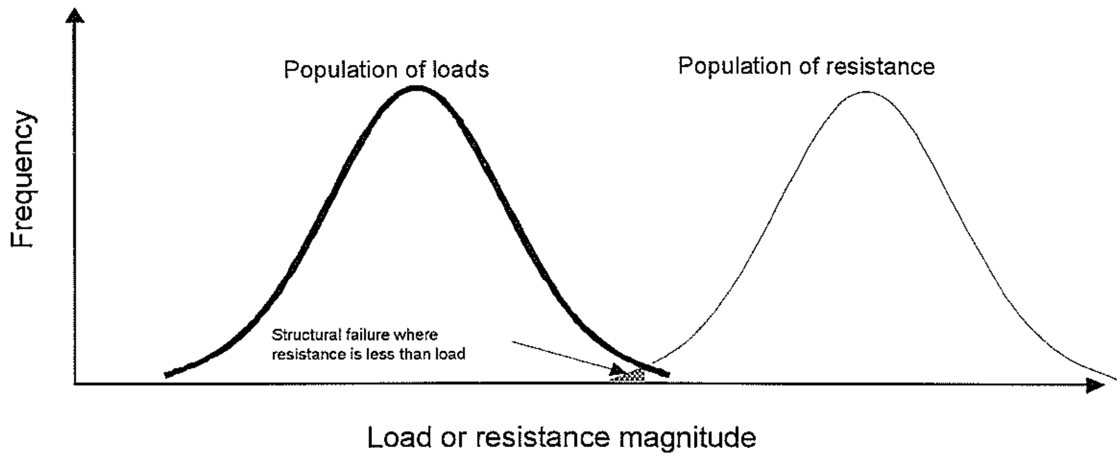


Figure 2.1 Statistical representation of structural failure.

Normally theoretical models are used to predict the magnitudes of loads and resistances in both design and evaluation processes. However, Health Monitoring utilises ambient traffic to investigate the effect that actual loads have on the in-situ structure. Thus the results of Health Monitoring provide an integrated measure of both the actual loads applied to the structure, and the effects that these loads have on the structure.

The objectives of bridge design and evaluation are similar, however the processes differ in some significant ways including:

- Bridge evaluation is more constrained than bridge design, since the infrastructure already exists in the latter case;
- Constraints are better understood during evaluation compared to design;
- Evaluation is usually associated with shorter time spans (typically 20 years compared to 100 years);
- Management options are often available and well understood during evaluations.

The estimation of structural resistance usually applies theoretical models based on engineering mechanics. Models of various levels of complexity are available, and these produce estimates of capacity with different levels of accuracy. Input data (material strengths, boundary conditions, etc.) are required for theoretical models, regardless of the model chosen. Much of these input data are based on a knowledge of construction procedures and tolerances. In the case of design, specific tolerances and parameters can be specifically controlled and confirmed where necessary.

When conducting evaluations however, greater uncertainty is usually associated with parameters (for example material strength). Conservative values can be chosen for the input data to allow for this, but will lead to under-estimation of capacity. Uncertainty may be reduced by testing all or part of the structure in some cases. Testing may also be important, because the resistance of an existing structure may decrease with time as physical deterioration progresses. In significantly deteriorated structures, this must be accounted for in the evaluation process.

Quantification of representative loads is generally more difficult than quantification of resistance, mainly because there is less control over bridge loading than there is over bridge construction and maintenance. In addition, design loads and legal loads are at best only indirectly linked. Design loads are generally developed by code writers who consider the worst-case loads likely to occur within the design life of structures. These loads are normally considered in two categories. The first is a set of loads intended to represent worst-case effects from normal legally loaded heavy vehicles (HN loading; TNZ 1994). The second is a set of loads intended to represent the worst-case effects from overloaded but permitted vehicles (HO loading; TNZ 1994). 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 limited 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 New Zealand Bridge Code (in TNZ 1994 Bridge Manual) empirically links legal loads with design loads for evaluation purposes. Essentially bridge evaluation loads are 85% of the design loads. If a bridge evaluation reveals that a given bridge cannot safely sustain 85% of the HO (overloaded/permitted legal heavy vehicle) loading, it will be **rated** consistent with its actual capacity to resist load. This rating will not be publicised, but 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 load.

2.2 Bridge Manual Evaluation Procedure

The Bridge Manual (1994) 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. Existing bridges are typically evaluated at two load levels which are outlined below.

1. *A **Rating Evaluation** based on 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 (TNZ 1995), in a consistent and logical manner. 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 vehicles which are characteristic of typical heavy vehicle traffic and comply with the TNZ Overweight Permit Manual (TNZ 1995). These vehicles comply with normal legally loaded vehicles. The evaluation involves assessing the bridge's ability to carry a design loading which is somewhat characteristic of typical heavy vehicle traffic (0.85 HN loading). If the bridge is unable to carry this loading, then the bridge is posted with the allowable load that the bridge can safely carry.

2.3 Member Capacity & Evaluation using TNZ Bridge Manual Criteria

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

2.3.1 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 (TNZ 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 number 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_o = Overload Factor

2.3.1.1 *Rating Evaluations*

From the overload capacity, the ability of the bridge to carry the desired loads (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 the HO) including the effects of eccentricity of load and impact. A value of 100% for the Class represents a bridge which can safely withstand the applied loads according to the Bridge Manual. Values of Class greater than 120% are recorded as 120%. The final Load Rating is found by first determining the Class for each girder (main component). The minimum Class then becomes the rating for that bridge.

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

2.3.1.2 *Posting Evaluations*

A similar formula (Equation 3) applies for posting evaluations with the Posting Load Effect represented by 85% of the 0.85 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.

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

2.3.2 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 which can safely resist the applied loads using the criteria in the Bridge Manual.

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

2.4 The Health Monitoring Approach

2.4.1 Theory of this Approach

As outlined in section 1 of this report, 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.

Traditional methods of evaluation, as outlined in section 2.3, use a design load to represent vehicle effects (which may or may not accurately represent the traffic) and a series of factors to represent other load-related factors. There is also a series of assumptions regarding the strength of the structure and how it resists the loads.

Health Monitoring, which involves monitoring the response of the bridge to the ambient heavy vehicle traffic, has the advantage of measuring and considering the overall system including the bridge, road profile, type of traffic and the level of overloading. In fact, Health Monitoring of the bridge allows the influence of all these factors to be assessed for a specific site. By monitoring the response of the bridge for a short period of time and extrapolating these results using statistical and probability techniques, the health or Fitness for Purpose of a bridge can be assessed.

The Bridge Manual is based on limit-state design principles with the requirement for bridges to be designed for both strength and serviceability. For the purpose of assessing the probabilistic effects of loading, the Bridge Manual recommends a design life of 100 years. If the traffic effects were recorded for 100 years on a bridge, then the full spectrum of loads applied to the bridge would be measured and the bridge's ability to withstand these loads could be assessed.

Obviously, measuring the traffic effects for 100 years is not feasible or practical. Monitoring the traffic effects for a short period of time and extrapolating these data using statistical and probability methods provides an economic and viable alternative for assessing a bridge. Stage 3 of this research project will quantify the appropriate duration for monitoring, but this Stage 2 is based on short-term monitoring, and previous experience has shown that 1 to 3 days is normally an adequate period for Health Monitoring purposes.

Extrapolating short-term health monitoring data for periods of time that are representative of the design life of the bridge provides an effective ultimate live load strain for the bridge caused by heavy vehicle effects. In the case of the Bridge Manual, an extrapolation out to a 95% confidence limit in 100 years is appropriate to represent an ultimate live load strain. For the serviceability limit state, an extrapolation out to a 95% confidence limit in one year is appropriate. This is also consistent with the AUSTROADS Bridge Design Code (1992).

To allow an assessment of a bridge using Health Monitoring techniques which is consistent with the Bridge Manual requires an integration of the standard equations 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 during the monitoring period) is calculated. The evaluation that is derived from this procedure has been defined as the Fitness for Purpose Evaluation.

$$FPE = \left(\frac{\gamma_o R_o}{UTL \quad Effect} \right) \times 100 \ \% \qquad \text{(Equation 6)}$$

where:

FPE = Fitness for Purpose Evaluation
$\gamma_o R_o$ = Ultimate Traffic Live Load Capacity
$UTL\ Effect$ = Ultimate Traffic Load Effect derived from health monitoring data

Generally a Fitness for Purpose Evaluation greater than 100% indicates that the structure is "Fit for Purpose", while an Evaluation of less than 100% indicates that intervention is required. This intervention could include repair, rehabilitation, replacement, risk management, or a load limit.

2.4.2 Behavioural Test using a Known Vehicle

The Health Monitoring approach relies on statistical techniques to provide a rating for bridges. This involves installing an instrumentation system on the bridge. It is often possible, with little extra effort, to record the response of the bridge to several events generated by a heavy vehicle of known mass and configuration (i.e. a known vehicle). This vehicle can be any legally loaded heavy vehicle. It can then be modelled and used as a load case in the analytical model required for a theoretical evaluation. While this activity is technically not required for Health Monitoring, it has a number of benefits. For example, results from the known vehicle can be used to calibrate the health monitoring data. These can provide:

- A mechanistically derived indicator of the extent of overloaded vehicles in the health monitoring data, which can be used to confirm the statistical indicators of the presence of overloading;
- An indication of whether the bridge behaviour is adequately predicted by the analytical model used for evaluation; where there is significant variation, it can provide a general indication of the source of variation;
- Quantification of the dynamic increment that actually exists at the bridge;
- Greater detail of the transport task to which the bridge is subjected.

Behavioural tests using a known vehicle were conducted at the Tuakopai Bridge during the Health Monitoring programme, and the results are given in section 4.4 of this report.

3. Bridge Description & Assessment

This section outlines the description of the Tuakopai Bridge and its classification based on the guidelines set out in the Bridge Manual. The results of an assessment of the bridge capacity are also presented to determine the predicted mode of failure and identify critical locations for health monitoring instrumentation. The results of a grillage analysis to determine the effects of various design heavy vehicle loads on the structure is included.

3.1 Bridge Description

The Tuakopai Bridge (RP 29-24/14.85) is located on State Highway (SH) 29, which is a heavily trafficked route leading from the Waikato Region to the Port of Tauranga, Bay of Plenty Region. The bridge (Figure 3.1) consists of three reinforced concrete beam and slab spans, 12.19 m in length. Each span has four girders at 2 m centres, that essentially are simply supported on reinforced concrete piers. However the detail at the abutments may provide some moment capacity at member ends. The detail over the pier and abutments is illustrated in Figure 3.2. The bridge was constructed in 1938 and the original drawings for the bridge show a concrete guardrail. However this was removed and has been replaced with a standard metal guardrail. The deck slab is nominally 200 mm thick.

Figure 3.1 Tuakopai Bridge on SH 29, in Bay of Plenty region.

(a) *(b)*

Figure 3.2 (a) Abutment detail and (b) Pier detail of Tuakopai Bridge.

The bridge is located on an open highway section of two-lane road with a carriageway width of 7.32 m. The road over the bridge is illustrated in Figure 3.3.

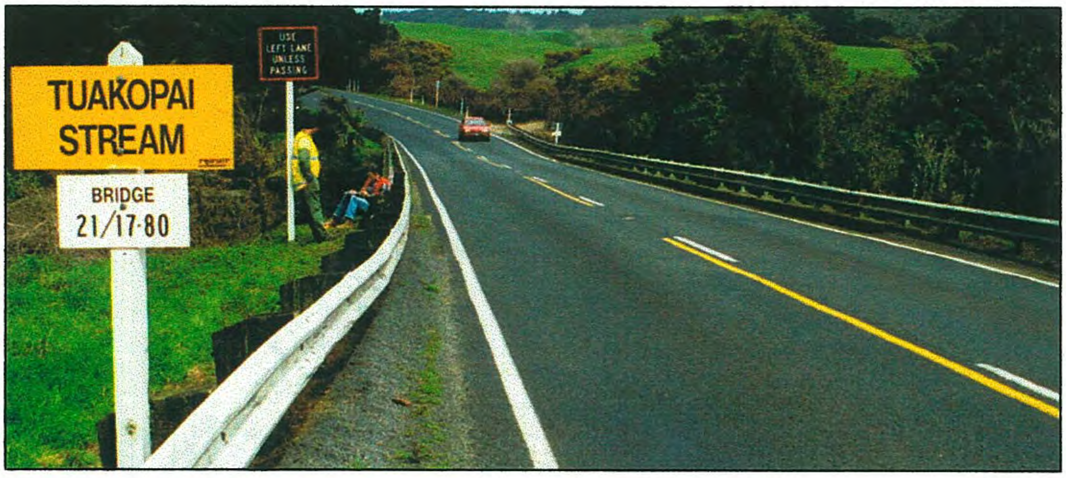


Figure 3.3 Road over the bridge (note the metal guardrail that replaces the original guardrail).

Considering the age of the structure (c.60 years) the bridge is generally in good condition. The bridge is located in a moist environment and the soffit of the structure has some moss and other growth. The concrete is in good condition with little cracking, and no spalling or rust staining. This indicates that the reinforcement has not corroded significantly.

The Tuakopai Bridge has a classification of 87%, calculated in accordance with the method set out in the Bridge Manual (Section 6), with a Deck Capacity Factor of 1.05. This indicates that the bridge deck can safely resist the appropriate (posting) evaluation load (0.85 HN) but that the girders are under-capacity by around 10% for the 0.85 HO rating load.

The current theoretical load rating of the bridge listed in the TNZ Structural Inventory (1999) is:

- Bridge Classification (superstructure) 87%
- Deck Capacity Factor (DCF) 1.05

These ratings are based on the evaluation methods set out in Section 6 of the Bridge Manual, which are outlined in Section 2.3 of this report.

3.2 Structural Assessment

The drawings available for this structure were not complete. They showed overall dimensions, beam dimensions, and pier and abutment reinforcement details, but no details of the beam reinforcement. Because of this, a different approach has been used for this bridge compared with the other bridges studied in this project. This approach has involved back-calculating the strength of the bridge using the Class listed in the 1999 TNZ Structural Inventory and comparing the performance of this bridge with two other bridges that have similar characteristics and have been health monitored. The two are the Rakaia Bridge[1] and the Waitangi Washout Bridge[2]. Both these bridges are of similar construction and span, with the Rakaia Bridge having four girders, and the Waitangi Washout having three girders, but they still have the original reinforced-concrete guardrail intact.

A typical span of the bridge superstructure was investigated using a "grillage analysis"[3]. The grillage analysis assumed that the girders are simply supported, and the kerbs were included in the model. The dimensions of the structure used in the analysis were taken from the "as constructed" plans, and were confirmed by on-site measurements.

The following material properties (nomenclature as in the Bridge Manual) were adopted for the strength of the concrete and reinforcement in the grillage analysis:

- Concrete $f'_c = 17$ MPa, E = 25 200 MPa
- Steel Reinforcement $f_y = 250$ MPa, E = 200 000 MPa

The loads applied to the grillage analysis included the 0.85 HO rating evaluation load and 0.85 HN posting evaluation load, along with that of the known vehicle used in the Health Monitoring programme. Details of this vehicle are included in section 4.4 of this report.

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1 Infratech 2000a: Transfund New Zealand Research Report No. 167.

2 Infratech 2000b. Transfund New Zealand Research Report No. 171.

3 Grillage analysis: analytical model using a 2–dimensional idealisation of the bridge superstructure as beam elements.

3.2.1 Girder Bending

The distribution of moment into each girder, calculated from the grillage analysis, is shown in Table 3.1. The differences in the bending moments for the dead load for each girder are caused by the additional load of the kerbs on the outside girders. For the known vehicle, results are presented for two cases: with the known vehicle in the normal lane position, and with the known vehicle at the maximum eccentricity.

Table 3.1 Results of grillage analysis for midspan bending moment (kNm) of girders.

Load	Girder 1	Girder 2	Girder 3	Girder 4
Dead Load	362	287	287	362
Known Vehicle (Normal Lane)	173	147	86	46
Known Vehicle (Max. Eccentricity)	183	142	80	40
0.85 HN Posting Load	300	311	260	185
0.85 HO Rating Load	450	432	332	241

3.2.2 Girder Shear

The shear force in each girder was also found using the grillage analysis. The results are presented in Table 3.2. All results are represented in kN.

Table 3.2 Results of grillage analysis for shear (kN) in the girders.

Load	Girder 1	Girder 2	Girder 3	Girder 4
Dead Load	111	94	94	111
Known Vehicle (Normal Lane)	68	66	23	5
Known Vehicle (Max. Eccentricity)	80	57	19	4
0.85 HN Posting Load	105	126	109	37
0.85 HO Rating Load	172	179	127	50

3.2.3 Deck Capacity

The capacity of the deck was not assessed as part of this investigation. The Deck Capacity Factor for this bridge taken from the TNZ Structural Inventory is 1.05, which indicates that the deck has sufficient capacity to resist the loads applied to it. The deck does not show deterioration of the kind that would affect loading capacity.

3.3 Assessment of Superstructure Capacity

As discussed in section 3.2 of this report, the drawings available for this bridge were not sufficient to determine the bending and shear capacity of the girders. Therefore an assumption was made that the bending capacity of the girders was limiting the capacity of this bridge, and the capacity of the girders was then back-calculated from the Class which had been obtained from the TNZ Structural Inventory. In these calculations a value of 1.3 was used for the impact factor and the dead load factor.

The factored capacity (ϕM) of the girders from these calculations was 1130 kNm for the middle girders and 1200 kNm for the edge girders. Using these strengths the posting evaluation for this bridge was calculated to be 100%.

These calculations for the Tuakopai Bridge can be compared with the capacities and classes of the two bridges most similar to it, i.e. Rakaia and Waitangi Washout bridges. These two bridges have capacities of 1020 kNm and 1320 kNm, and Classes of 76% and 61% respectively.

4. Health Monitoring Programme

The programme of Health Monitoring on the Tuakopai Bridge involved two components:

- Short-term health monitoring of the ambient heavy vehicle traffic for a period of approximately 1.5 days.
- Testing using a heavy vehicle of known mass and dimensions (i.e. the known vehicle) to provide a comparison with the health monitoring data.

This section presents the details and results of the Health Monitoring programme on the Tuakopai Bridge.

4.1 Instrumentation

The instrumentation installed on the bridge included four Demountable Strain Gauge transducers and four Deflection transducers installed on the main girders at midspan of the structure, and the positions of this instrumentation are illustrated in Figure 4.1. The demountable strain gauge transducers measured the longitudinal bending strain in the soffit of the girders, and the deflection transducers recorded the vertical deflection at midspan.

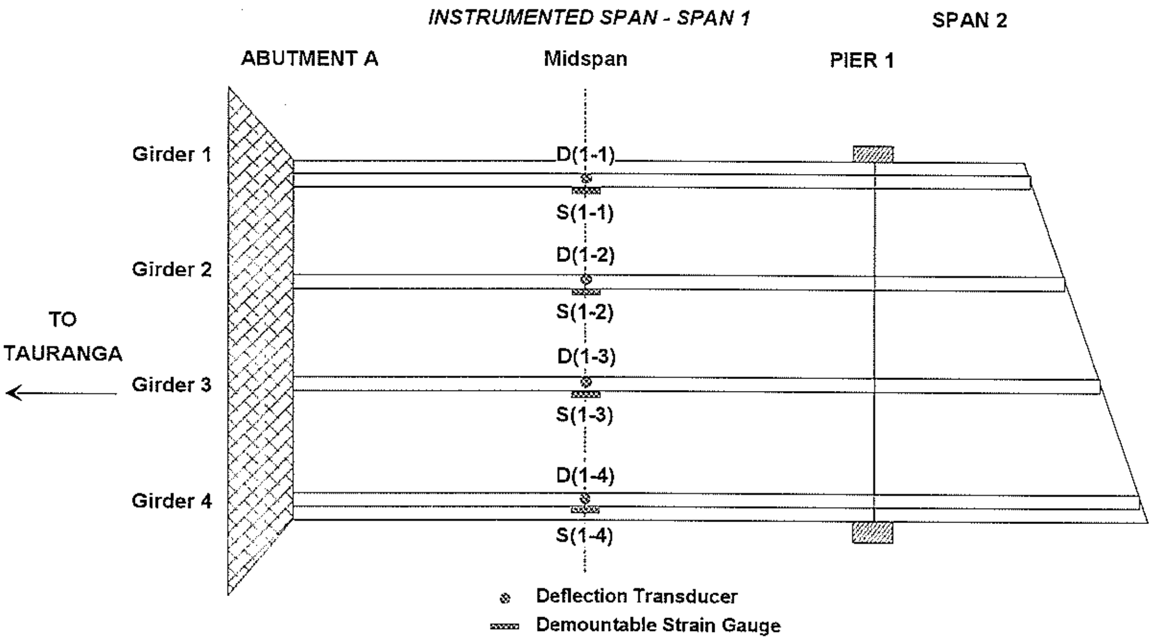


Figure 4.1 Instrumentation plan for Tuakopai Bridge.
S - Demountable Strain Gauge D - Deflection transducer

The following sign conventions apply to the results from these transducers:

- Strains: positive values for tension; negative for compressive strains;
- Deflections: positive values for downward, negative for upward deflections.

The demountable strain gauges (gauge length 230 mm) measure strain at a point 20 mm below the soffit of the girders. The data presented in this report has been adjusted to represent the strain in the soffit of the girders.

4.2 Procedure

The Health Monitoring of the structure began on Thursday 1 October, and continued until Saturday 3 October, 1998, giving a total monitoring period of approximately 35 hours. During the monitoring period, the response of the bridge to approximately 860 heavy vehicles was recorded, excluding the passage of the known vehicle.

In order to provide a control for all the data gathered during the entire monitoring period, the behaviour of the bridge in response to a known load (i.e. a heavy vehicle of known mass and dimension) was measured. This component of the Health Monitoring programme was conducted on Friday 2 October, 1998, using a known heavy vehicle, supplied by TD Haulage Ltd, Tauranga (shown on the bridge in Figure 4.2). It was a seven-axled heavy vehicle of known mass (gross 44.8 tonnes) and dimensions. The axle weights and configuration are illustrated in Figure 4.3.

Figure 4.2 The known vehicle used for behavioural testing, on the Tuakopai Bridge.

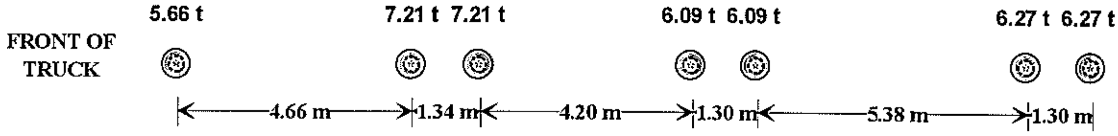


Figure 4.3 Axle mass and configuration of the known vehicle.

The testing with the known vehicle was conducted by recording the response of the bridge to the vehicle as it passed over the bridge at different speeds. The tests were conducted with the vehicle travelling in both directions (to and from Tauranga), ranging from a crawl (20 km/h) to 80 km/h, in increments of 10 km/h. The lateral position of the known vehicle was in its normal lane. Testing was completed by slowing the traffic in each direction or in some cases stopping it for a few minutes at a time. This ensured minimal traffic interruptions and also allowed the continuous monitoring of ambient heavy vehicles between the test runs with the known vehicle.

4.3 Short-Term Health Monitoring Results

4.3.1 Girder Response

A typical strain response versus time was graphed (as waveforms in Figure 4.4) for the midspan bending strains recorded during the Health Monitoring for the passage of a typical heavy vehicle travelling from Tauranga at 7.30pm, on Friday 2 October.

Figure 4.5 presents the midspan girder deflections for the same event. These results indicate that the strains are highest in the second and third girders, while the deflections are highest in Girders 1 and 2 for this event.

Scatter diagrams representing the extreme values recorded during the passage of each heavy vehicle are presented in Figure 4.6 for the midspan strain transducers and in Figure 4.7 for the deflection transducers. These plots give an indication of the heavy vehicle characteristics including the distribution of mass and number of vehicles. The gap in the data on Friday morning is caused by monitor downtime, rather than an absence of traffic.

4.3.2 Extrapolated Data

The data from the scatter diagrams can also be plotted on a histogram that incorporates a cumulative distribution. An example of the histogram from the scatter diagram is presented for transducer D(4-1) in Figure 4.8. The histogram illustrates two separate sections or populations of data. This is characteristic of traffic travelling in opposite directions on different sides of the bridge, or of different populations of vehicles. By separating the data into directions, the data relevant to each transducer can be plotted and a more accurate indication of the traffic can be determined.

Figure 4.4 Midspan bending strains versus time for typical heavy vehicle recorded at 7.30pm, 2 October 1998 (vehicle travelling towards Tauranga).

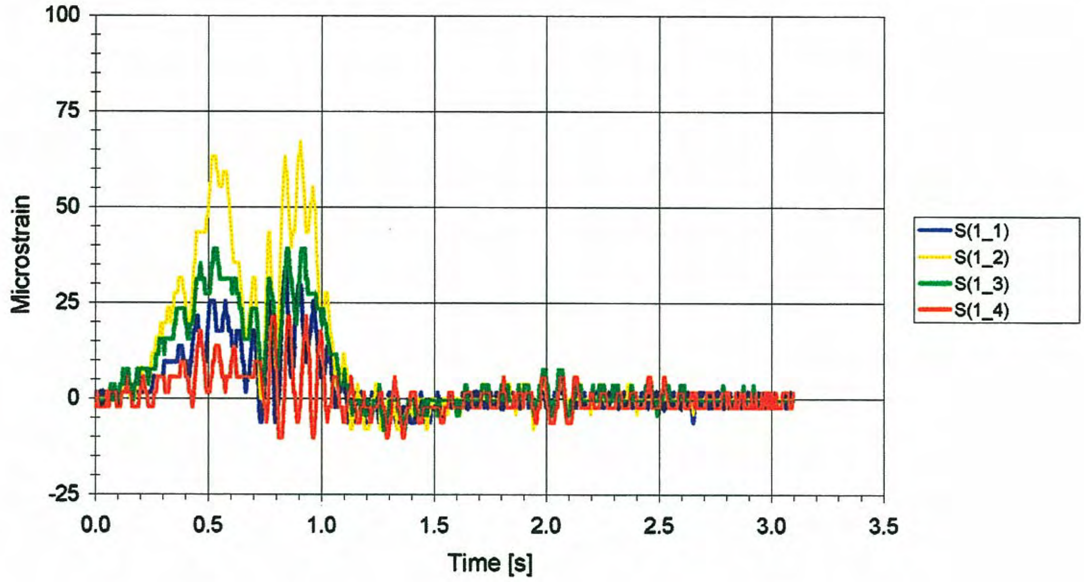


Figure 4.5 Midspan girder deflections versus time for a typical heavy vehicle, recorded at 7.30pm, 2 October 1998, travelling to Tauranga.

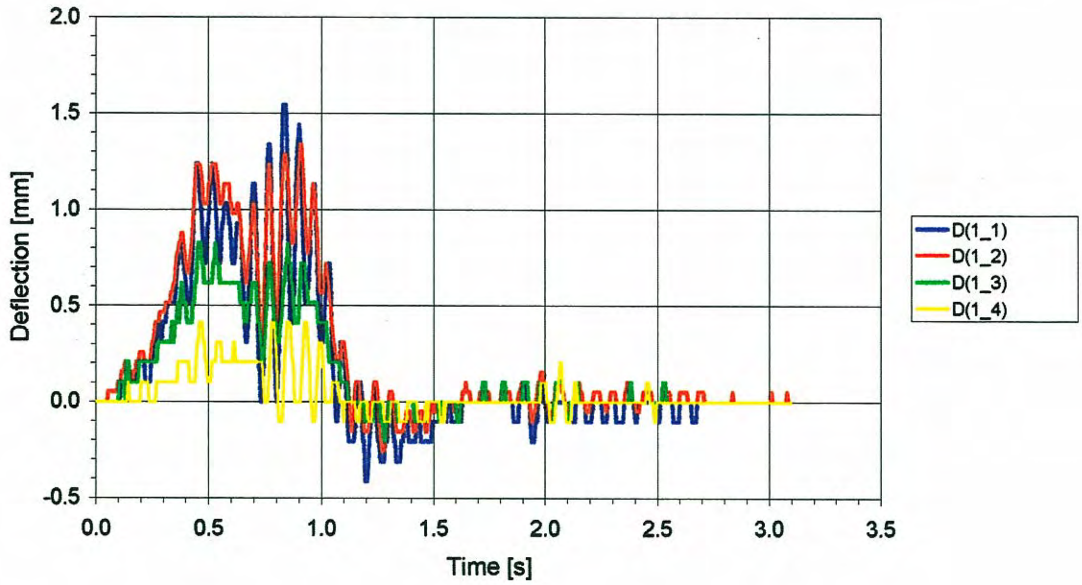


Figure 4.6 Scatter diagram of maximum responses for strain transducers.

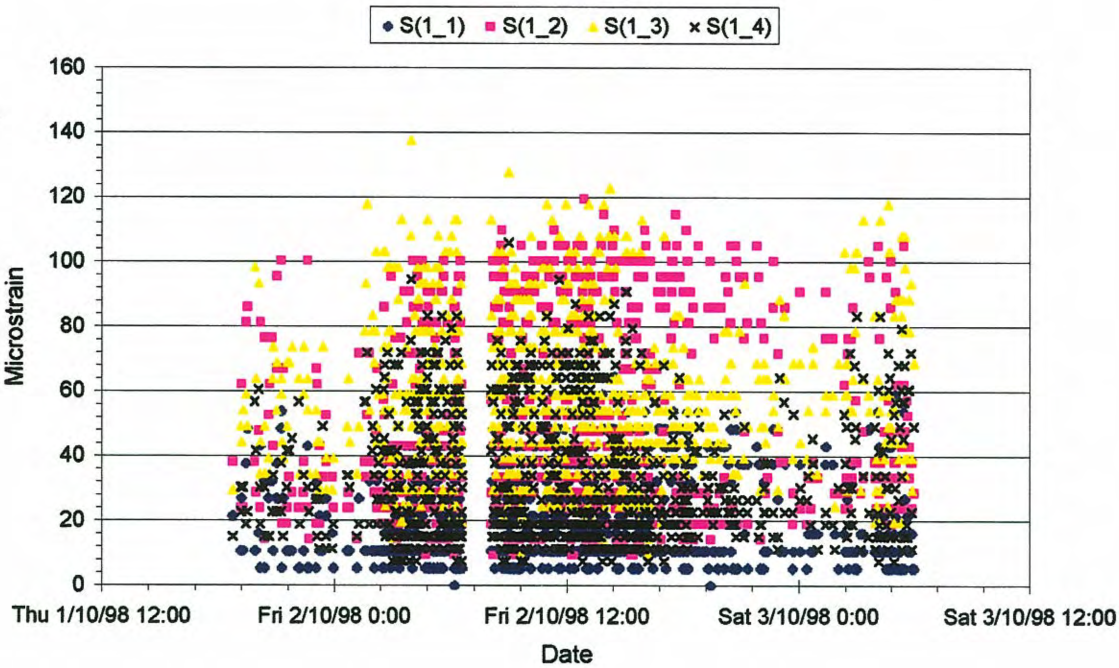
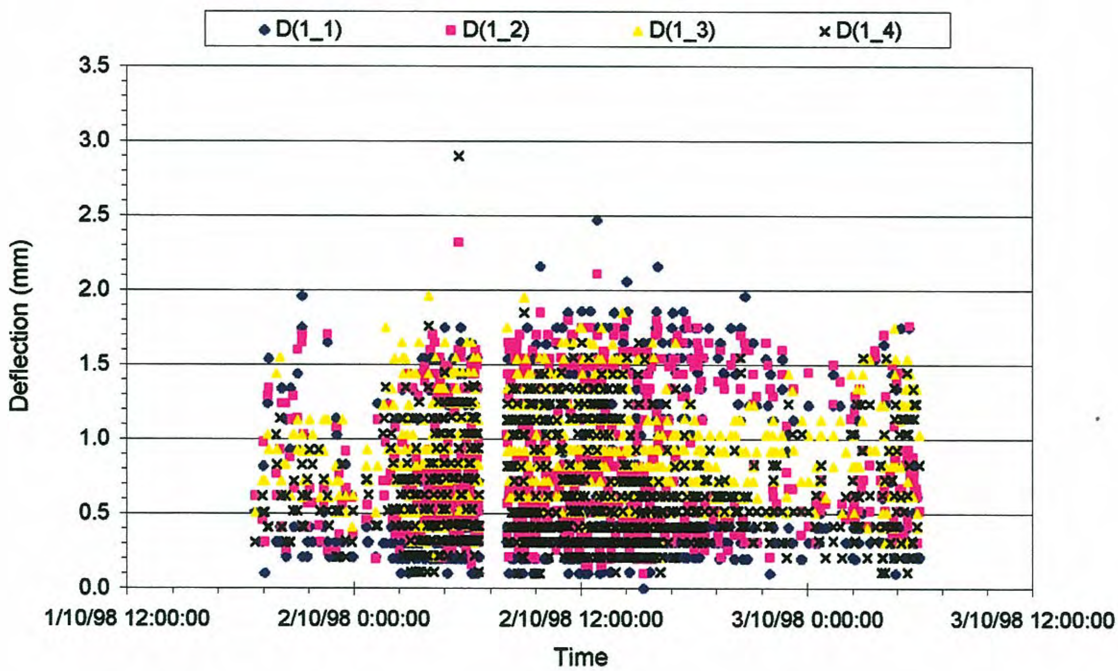


Figure 4.7 Scatter diagram of maximum responses for deflection transducers.



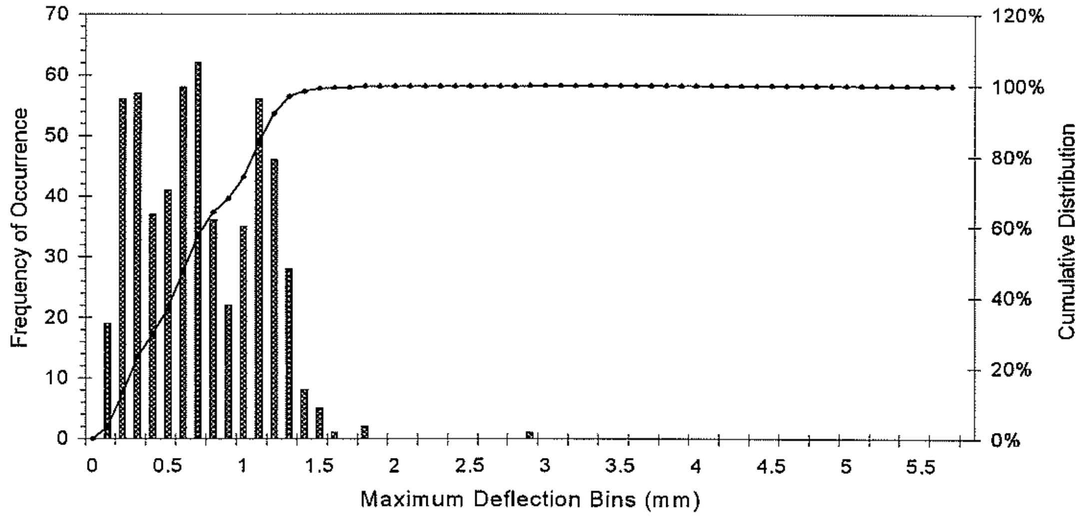


Figure 4.8 Histogram and cumulative distribution function for transducer D(1-4).

The cumulative distribution function can then be plotted on a probability scale known as an "inverse normal scale". The inverse normal plot for each of the transducers measuring midspan bending strain is presented in Figure 4.9.

On this graph the vertical scale represents the number of standard deviations that each point is away from the mean. The horizontal scale is the maximum strain recorded for each event. The point at which a data plot crosses the horizontal axis represents the average (mean) strain. A straight line represents a normally distributed sample of data. This plot shows some significant variation in results for the strain transducers between girders on this bridge.

Horizontal lines representing the expected position of the 95% confidence limit for the data for 1 day, 1 month, 1 year, and 100 years have been plotted. Extrapolating the recorded data allows estimates of strain for these longer return intervals. The strain extrapolated for the 95% confidence limit for 100 years represents the ultimate traffic load effect for the Fitness for Purpose Evaluation as outlined in section 2 of this report.

Figure 4.10 shows the inverse normal plots for all the deflection transducers. These plots have been influenced by a few isolated events which caused higher than typical deflections. These events are also evident on the scatter plot in Figure 4.7.

The maximum results along with the extrapolated results for all transducers are presented in Table 4.1. The maximum recorded strain was 140 $\mu\varepsilon$ in Girder 3 and the maximum deflection was 2.9 mm in Girder 4.

Figure 4.9 Inverse normal plot for strain transducers installed on the Span 1 girders at the midspan.

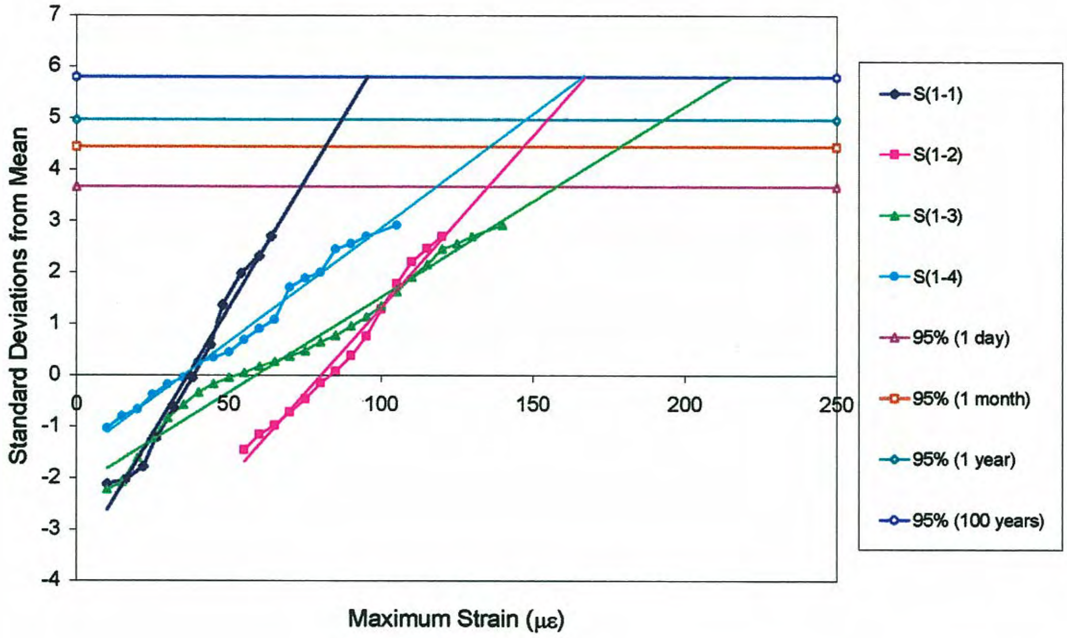


Figure 4.10 Inverse normal plot for deflection transducers.

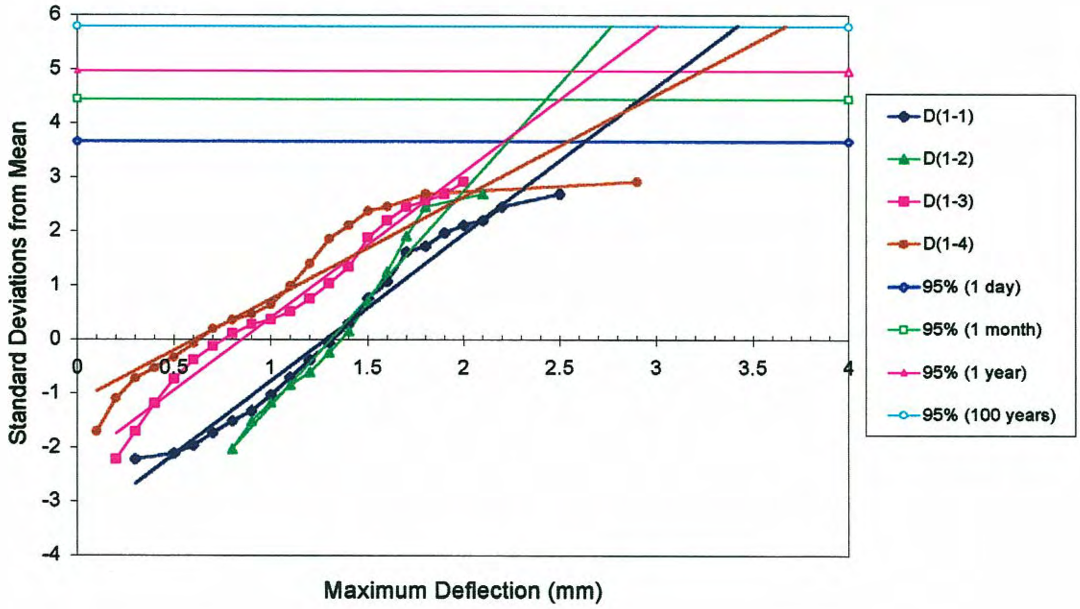


Table 4.1 Summary of extrapolated data obtained from inverse normal distributions.

Transducer	Maximum Recorded Value (Health Monitoring)	Extrapolated Value (95% confidence limit) for 1 Year	Extrapolated Value (95% confidence limit) for 100 years
	Strain (με)		
S(1-1)	65	90	95
S(1-2)	120	155	170
S(1-3)	140	190	215
S(1-4)	105	150	170
	Deflection (mm)		
D(1-1)	2.5	3.1	3.4
D(1-2)	2.1	2.6	2.8
D(1-3)	2.0	2.7	3.0
D(1-4)	2.9	3.2	3.7

4.4 Known Vehicle Testing

The maximum strains and deflections recorded for each transducer during the testing with the known vehicle are presented in Table 4.2. The maximum strain recorded was 80 με in Girders 2 and 3, and the maximum deflection was 1.5 mm in Girder 1.

Table 4.2 Maximum responses (strains (με) and deflections(mm)) for known vehicle testing.

Transducer	Maximum Response
S(1-1)	45με
S(1-2)	80με
S(1-3)	80με
S(1-4)	60με
D(1-1)	1.5mm
D(1-2)	1.4mm
D(1-3)	1.3mm
S(CG-2)	1.1mm

Figure 4.11 Distribution of strain for known vehicle (directions to and from Tauranga as indicated).

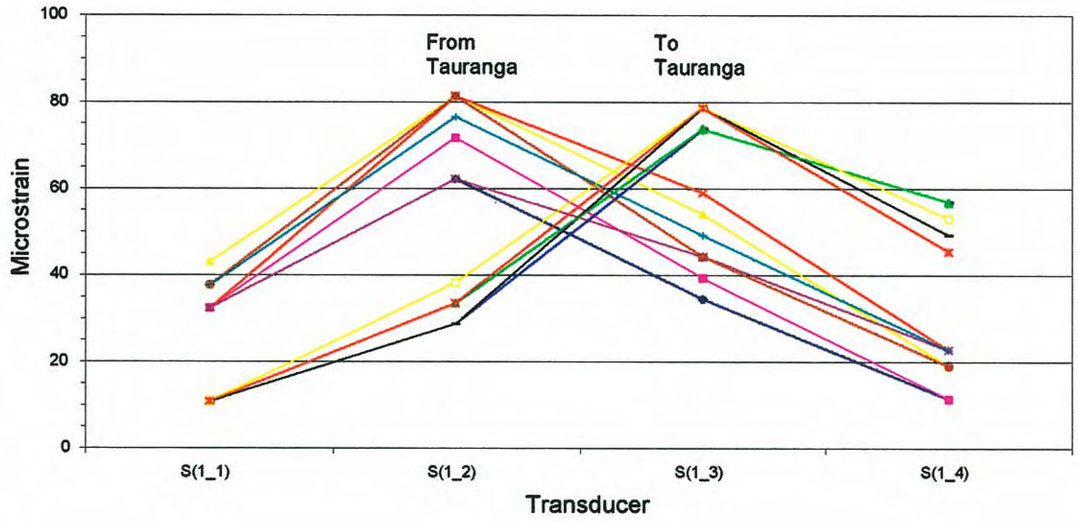
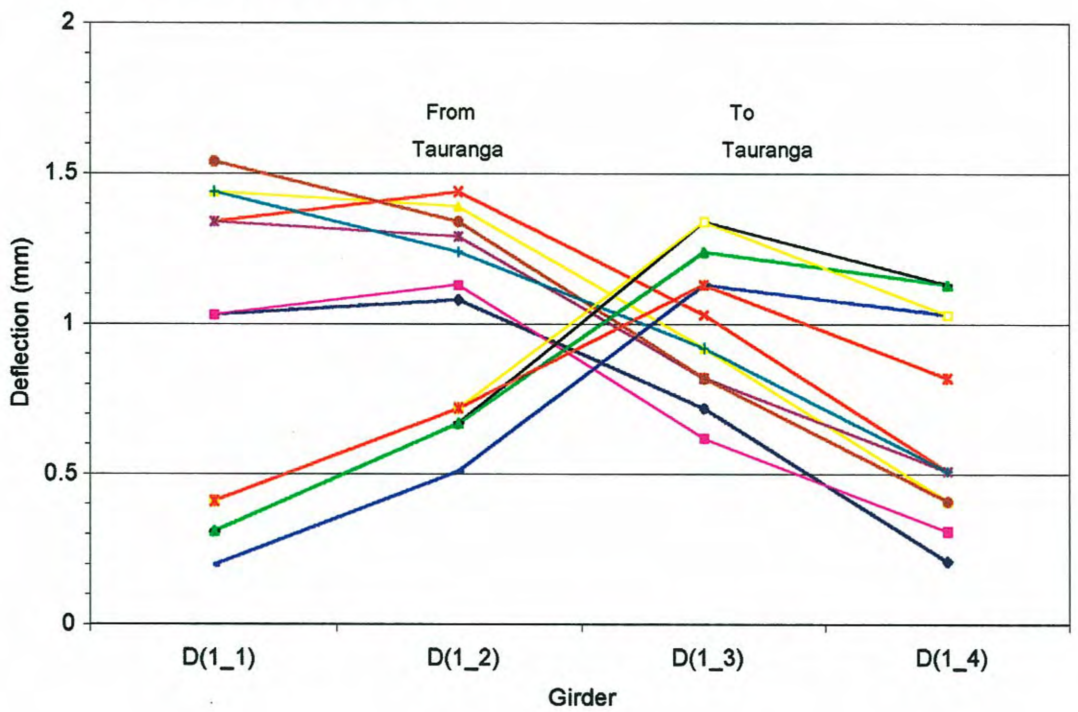


Figure 4.12 Distribution of deflection for known vehicle (directions to and from Tauranga as indicated).



4.4.1 Distribution

The distribution of strain across the four girders is presented in Figure 4.11 and the distribution of deflection is shown in Figure 4.12. These distributions are based on the results with the known vehicle driving at a range of speeds in the normal lane position. The strain and deflection distributions show differences, and typically there is more deflection compared with strain in the outer girders. This is particularly the case for Girder 1.

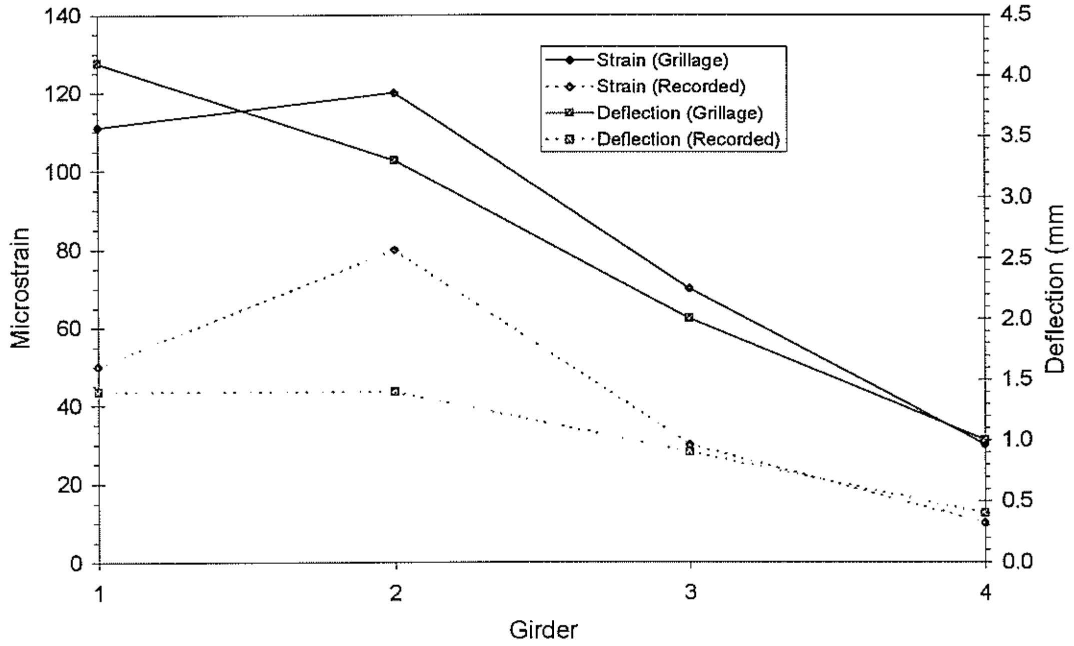


Figure 4.13 Comparison of recorded and grillage results for known vehicle

Figure 4.13 presents a comparison of the known vehicle results from the Health Monitoring procedure and the results from the grillage model. This comparison shows that the recorded strains and deflections from the Health Monitoring are much lower than those predicted from the grillage analysis. The difference in the shape of the distribution shows that the actual behaviour of the edge girders is stiffer than that assumed in the grillage model, while the overall difference in the magnitude of the strains and deflections could be related to a higher actual concrete strength or some continuity with the abutments.

4.4.2 Dynamic Increment & Natural Frequency

The impact factor is used by the Bridge Manual to indicate the increase in the effect of a vehicle on a structure as the speed increases. The impact factor or dynamic increment (AUSTROADS 1992) was calculated using the following equation:

$$DI = \frac{\varepsilon_{dynamic} - \varepsilon_{static}}{\varepsilon_{static}} \qquad \text{(Equation 7)}$$

The response of the crawl test was used for the static result in the calculation of dynamic increment. The data are plotted for the three midspan transducers which are most influenced by the vehicles travelling towards Tauranga. Figure 4.14 presents the dynamic increment data for known vehicle travelling from Tauranga. The dynamic effects on this bridge are high, with the maximum recorded dynamic increment around 50% while the highest average value recorded was 35%.

The natural frequency of the structure calculated from the free vibration response of the structure after the vehicle has driven off the bridge is 12 Hz.

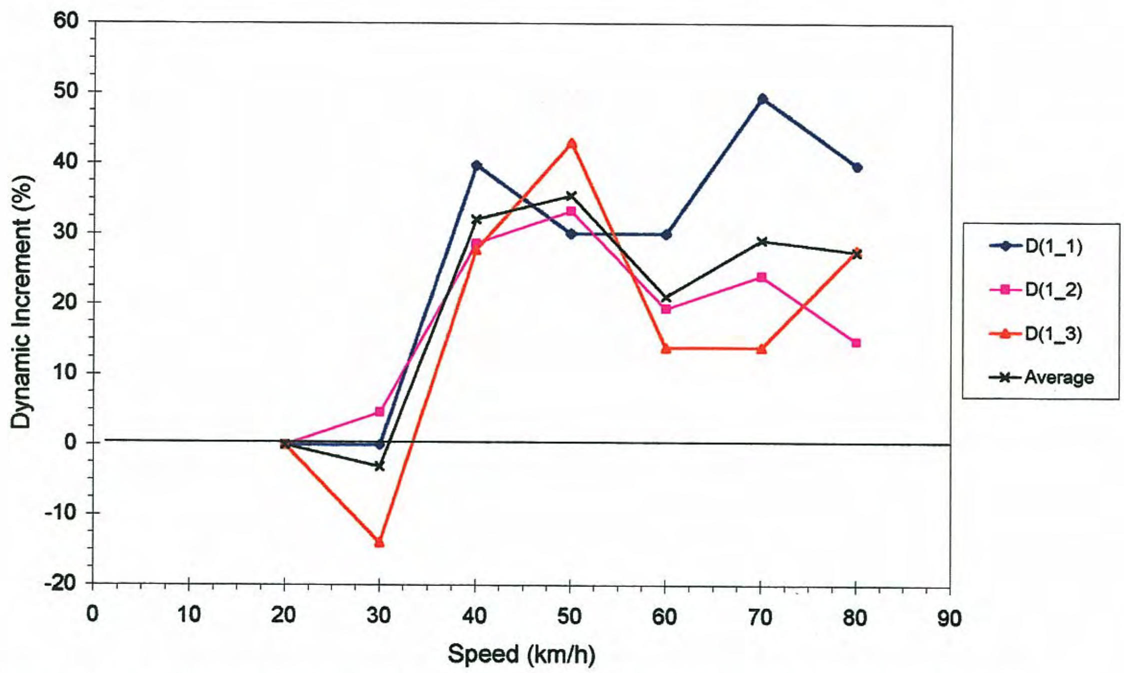


Figure 4.14 Dynamic increment versus speed for the known vehicle travelling from Tauranga.

4.5 Summary

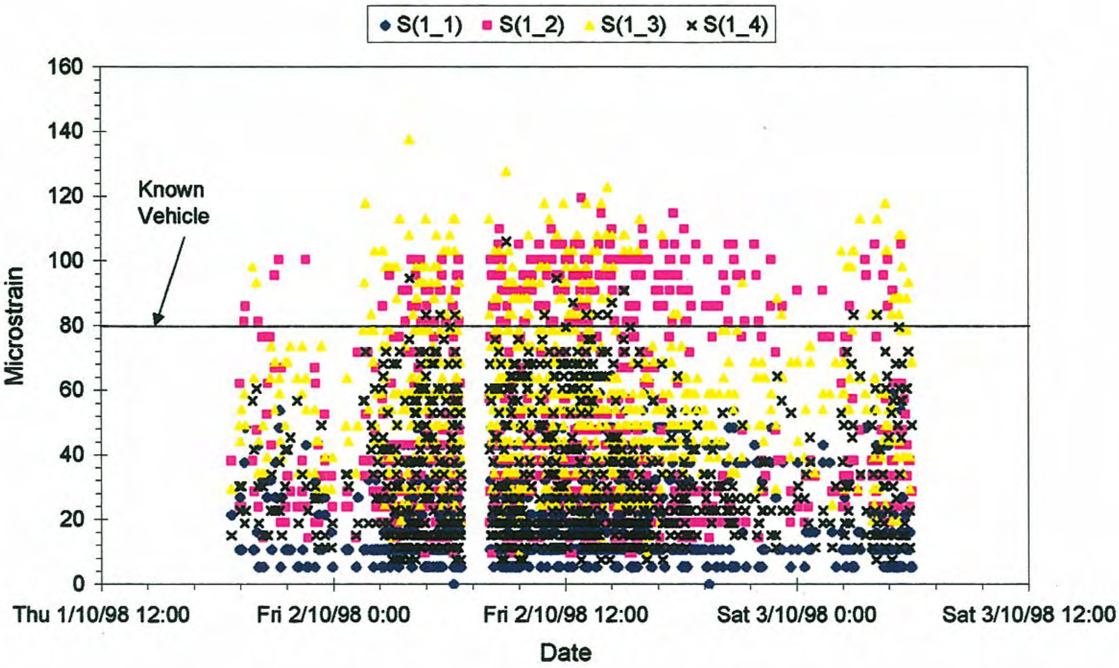
A summary of the data recorded for the Health Monitoring and the testing with the known vehicle is presented in Table 4.3. Comparison of the results from the known vehicle with the maximum values from the Health Monitoring procedure shows evidence of overloading on this route. This is also confirmed in Figure 4.15 which compares the maximum strains recorded for each event during the Health Monitoring with the maximum strain recorded in Girder 3 from the known vehicle. The known vehicle, used on this bridge, induced effects around 85% of the 0.85 HN vehicle. The ambient heavy traffic is inducing effects that range from 1.45 to 1.75 times that of the known heavy vehicle, depending on the girder. This indicates that the heavy vehicle traffic on this route is exceeding the 0.85 HN posting load by up to 50% (based on the effects caused by the known vehicle).

A comparison of results of health monitoring and grillage analyses for this bridge found that the actual strains and deflections were much lower than those predicted by the grillage analysis.

Table 4.3 Summary of health monitoring data.

Transducer	Maximum Recorded Value (Known Vehicle)	Maximum Recorded Value (Health Monitoring)	Extrapolated Value (95% confidence limit) for 1 Year	Extrapolated Value (95% confidence limit) for 100 years
	Strain ($\mu\varepsilon$)			
S(1-1)	45	65	90	95
S(1-2)	80	120	155	170
S(1-3)	80	140	190	215
S(1-4)	60	105	150	170
	Deflection (mm)			
D(1-1)	1.5	2.5	3.1	3.4
D(1-2)	1.4	2.1	2.6	2.8
D(1-3)	1.3	2.0	2.7	3.0
D(1-4)	1.1	2.9	3.2	3.7

Figure 4.15 Scatter plot of strains, compared with strain imposed by known vehicle.



5. Fitness for Purpose Evaluation

Because the drawings for this bridge were an incomplete set, the bending and shear strength of the girders could not be calculated for it. Therefore the Fitness for Purpose for the Tuakopai Bridge could not be assessed using the methodology defined for this project in section 2 of this report. Instead the Fitness for Purpose of this bridge has been assessed by comparing the actual performance of the structure with theoretical behaviour, and with other bridges with similar characteristics.

5.1 Multiple Presence

The Tuakopai 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). The probability of this occurring on one instrumented span at the time of monitoring is small, and therefore it is expected that a multiple presence event would not have occurred during the monitoring period.

To account for multiple presence events, a number of approaches are available. One is to simulate a multiple presence event by summing the 95% in 100 year event for both lanes. This is consistent with the Bridge Manual and has been used in this report. The method may be conservative because it assumes that a maximum event occurs in each lane at the same time.

An approach based on Turkstra's Rule (Turkstra & Madsen 1980) may be more appropriate. This rule suggests that an extreme event should be combined only with an average event. In applying the Health Monitoring procedure this means that a maximum event in one lane should be combined with an average event in the other lane. This approach to multiple presence will be confirmed using the long-term monitoring of the Atiamuri Bridge over the Waikato River, another bridge which is also part of this project.

Figure 5.1 summarises an assessment of the multiple presence effects for midspan bending strain. The diagram is based on the health monitoring data using the method that is consistent with the Bridge Manual. The diagram shows a transverse distribution of strain for each direction and the sum of these two distributions for both the 95% in 1 year serviceability limit state and the 95% in 100 year ultimate limit state. The maximum strains for multiple presence is 321 $\mu\varepsilon$.

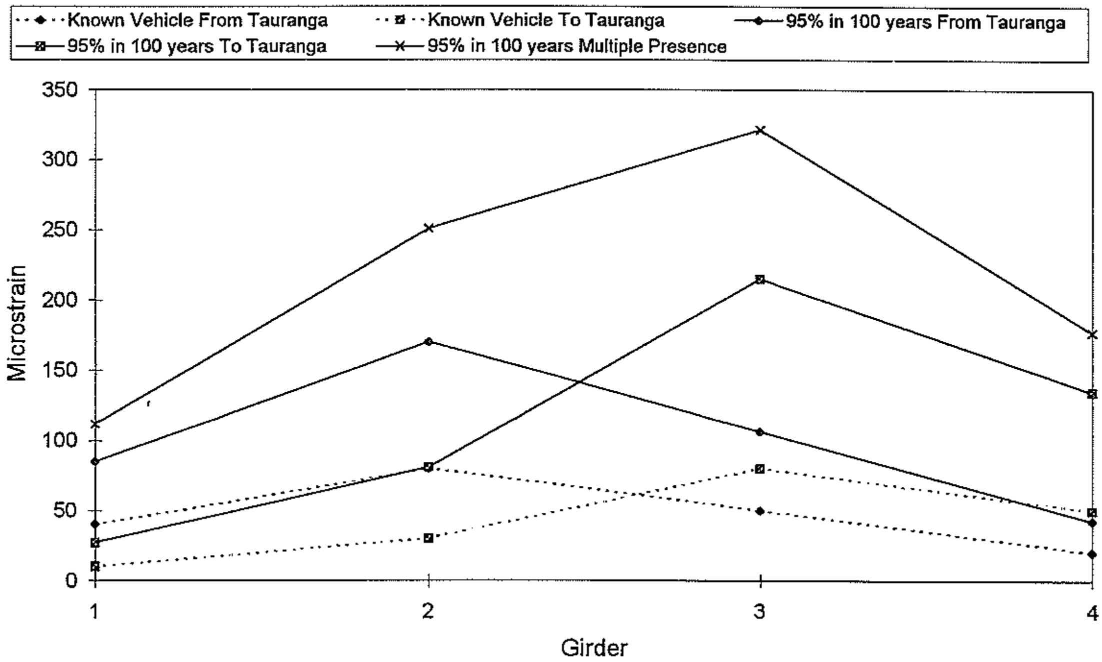


Figure 5.1 Summary of multiple presence assessment based on the Bridge Manual method for 95% in 1 year, and in 100 years.

5.2 Summary of Health Monitoring & Analysis Programme

The programme of Health Monitoring and theoretical assessment on the Tuakopai Bridge found that:

- The girders on this bridge should have a bending strength of approximately 1200 kNm. The assumption was made that midspan bending was the critical failure mode for the bridge.
- The Health Monitoring results show evidence of significant overloading on this bridge, with some of the ambient traffic inducing responses that are up to 50% higher than the known vehicle. The known vehicle is equivalent to around 85% of the 0.85 HN vehicle on this bridge.
- The dynamic effects are high, and an impact factor of around 35% is appropriate for this bridge.
- The actual strains and deflections induced by heavy vehicles on this route are much lower (approximately 50%) than the strains and deflections predicted by the grillage analysis. The maximum strain recorded was 140 $\mu\varepsilon$ and the maximum deflection recorded was 2.9 mm.

In summary, overloading occurs on the Tuakopai Bridge but the structural response is lower than expected probably because of end restraint of the main members at the abutments.

5.3 Comparison with Similar Bridges

As noted in section 3.2 of this report, two bridges with similar structural characteristics to the Tuakopai Bridge have also been monitored as part of this project. These bridges are the Rakaia Bridge and the Waitangi Washout Bridge (Infratech 2000a, b). They have similar spans and construction, with the Rakaia Bridge having four girders, and the Waitangi Washout Bridge having three girders.

Table 5.1 compares the characteristics and performance of these three bridges. The table lists details such as the span, Class from the TNZ Structural Inventory, other details on the structure, and results from the Health Monitoring programme for each bridge. The information shows that the Tuakopai Bridge has similar geometry to the Rakaia Bridge.

The higher Class obtained from the Inventory indicates that the Tuakopai Bridge either has more reinforcement or the end fixity of the girders has been accounted for in the calculations used to determine the bridge Class. The recorded strains in the Tuakopai Bridge are much lower compared with those for the Rakaia and Waitangi Washout bridges.

Based on the information in this table and the results of the Health Monitoring programme, the Fitness for Purpose Evaluation for the Tuakopai Bridge should be similar to or higher than that for the Rakaia Bridge. This is assuming that the Tuakopai Bridge has similar reinforcement to the Rakaia Bridge.

Table 5.1 Comparison of three bridges having similar characteristics, for estimating Fitness for Purpose of Tuakopai Bridge.

Item	Tuakopai	Rakaia	Waitangi Washout
Span (m)	12.2	12.2	12.2
Class (SI) (%)	87	76	61
Deck Capacity Factor (SI)	1.05	0.93	1.0
No. of Girders	4	4	3
Slab Thickness (mm)	200	180	220
Girder Depth (from slab soffit) (mm)	560	530	730
Girder Width (mm)	355	355	380
Bending Reinforcement	Unknown	*12x 28mm bars	*12x 28mm bars
Max. Strain (HM) ($\mu\varepsilon$)	140	195	175
Extrapolated Value 95% Confidence Limit for 100 years	215	250	200
Extrapolated Value 95% Confidence Limit for 100 years Multiple Presence	321	415	370
Max. Strain (Known Vehicle) ($\mu\varepsilon$)	80	129	105
Max. Deflection (HM) (mm)	2.9	-	2.0
Max. Deflection (Known Vehicle) (mm)	1.5	-	1.2
Impact (from test results)	35	30	30
Ultimate Live Load Capacity Strain ($\mu\varepsilon$)	Not Calculated	567	575
Fitness for Purpose Evaluation	Not Calculated	137	155

* A total of 12x 28mm bars in each beam/girder.
HM Health Monitoring
SI TNZ Structural Inventory 1999

6. Conclusions

This report presents the details and results of the Health Monitoring programme applied to the Tuakopai Bridge.

Theoretical Analysis
As the existing drawings for this bridge were incomplete, it has been assessed by comparing its performance with other bridges. The bridge has a Class of 87% according to the 1999 TNZ Structural Inventory, and a Deck Classification Factor of 1.05.

Health Monitoring Results
The results for the Health Monitoring programme of the Tuakopai Bridge were compared with the Rakaia and Waitangi Washout bridges that have similar structural characteristics. The investigation found that:

- The girders on this bridge should have a bending strength of approximately 1200 kNm. The assumption was made that midspan bending was the critical failure mode for the bridge.
- The health monitoring results show evidence of significant overloading on this bridge, with some of the ambient heavy traffic inducing responses that were up to 75% higher than for the known vehicle. The known vehicle is equivalent to around 85% of the 0.85 HN vehicle on this bridge.
- The dynamic effects are high, and an impact factor of around 35% is appropriate for this bridge.
- The actual strains and deflections induced by heavy vehicles on this route are much lower (approximately 50%) than the strains and deflections predicted by the grillage analysis. The maximum strain recorded during Health Monitoring was 140 $\mu\varepsilon$, and the maximum deflection recorded was 2.9 mm.

Overloading occurs on the Tuakopai Bridge but the structural response is lower than expected, probably because of end restraint of the main girders.

Fitness for Purpose Evaluation
The comparison of the performance of this bridge with the Rakaia Bridge found that the Tuakopai Bridge would have a Fitness for Purpose Evaluation similar to or higher than that for the Rakaia Bridge.

The Fitness for Purpose Evaluation for the Rakaia Bridge was 137%, which means the bridge has adequate strength capacity to resist the effects of the heavy traffic it has to withstand.

7. Recommendations

Recommendations for the Tuakopai Bridge are:

- Posting of the bridge is not necessary;
- The apparent overloading on this route should be investigated further.
- Methodology for using Health Monitoring results in the comparative manner used for this bridge should be further developed.

8. References

Andersen, R.P., Roberts, W.S., Heywood, R.J., Heldt, T.J. (Infratech) 2000a. Health Monitoring of superstructures of New Zealand road bridges: Rakaia Bridge, Canterbury. Infratech Systems & Services Pty, Ltd, Brisbane. *Transfund New Zealand Research Report No. 167.* 48pp.

Andersen, R.P., Roberts, W.S., Heywood, R.J., Heldt, T.J. (Infratech) 2000b. Health Monitoring of superstructures of New Zealand road bridges: Waitangi Washout Bridge, Hawke's Bay. Infratech Systems & Services Pty Ltd, Brisbane. *Transfund New Zealand Research Report No. 171.* 47pp.

AUSTROADS 1992. AUSTROADS Bridge Design Code. AUSTROADS Inc., Sydney.

Transit New Zealand (TNZ) 1994. *Bridge Manual.* Transit New Zealand, Wellington, New Zealand.

Transit New Zealand (TNZ) 1995. *Overweight Permit Manual.* 1st edition. Transit New Zealand, Wellington, New Zealand.

Transit New Zealand (TNZ) 1999. *Structural Inventory.* Database, Transit New Zealand, Wellington, New Zealand.

Turkstra, C.J., Madsen, H.O. 1980. Load combinations in codified structural design. *Journal of the Structural Division, ASCE, 106 (ST12):* 2527 – 2543.