Humes Pipeline Systems recently completed a detailed redesign of their precast concrete box culvert range, with the aim of optimising the designs while maintaining compliance to the New Zealand building code. The redesign project involved innovative engineering in conjunction with experimental testing to validate the performance of the modified culvert designs, leading to highly efficient designs being developed.

The fatigue loading requirements of the New Zealand Standards was identified as a key area of potential savings. A special study was completed investigating the effect of fatigue loading on box culverts. A series of full scale box culverts were manufactured and subjected to a series of repetitive loadings, simulating the impact loads from passing vehicles. The results from the experimental programme highlighted a number of issues in the design procedures used in the New Zealand Standards when determining the fatigue capacities of structures.

This paper summarise the experimental redevelopment project completed on the Humes precast concrete box culverts and discusses our findings with regards to ultimate loading and fatigue performance.

**BACKGROUND**

Precast concrete box culverts are often used as sub-surface drainage systems or accessways. The rectangular shape of the box culverts make them efficient for both applications. Due to their applications, box culverts are typically shallow buried with little overburden.

When a box culvert crosses a road network it is often required to also act as a highway bridge, given that it is not typically feasible to bury culverts below the effects of vehicle loads. As a result, concrete box culverts are required to be designed using the requirements of the Transit New Zealand Bridge Manual, TNZBM [T1] and the New Zealand Concrete Code, NZS 3101 [N1]. Internationally, many countries have recognised the unique demands on box culverts and have developed specific Standards for their design and manufacture.

In 2009 Humes commissioned Holmes Solutions to undertake a full detailed review of their box culvert product range with the intention of increasing the efficiency in the designs. This paper highlights the work that was completed in the review and provides an insight into the areas of potential saving that were identified, particular with respect to fatigue induced loading combinations.

**PRODUCT RE-ENGINEERING**

Re-engineering of existing products has been shown to be a cost effective means of increasing product performance or reducing product costs with relatively low risk. It allows companies to improve their competitive advantages without the risks associated with developing and launching new products into the market.

Humes Pipeline Systems commissioned Holmes Solutions to undertake the re-engineering of their existing precast concrete box culverts product range. The primary goal for the project was to increase the efficiency of the current designs of the entire box culvert range, thereby providing an increased competitive advantage in the marketplace. Furthermore, Humes wanted any changes implemented from the project be directly transferable into the current manufacturing environment with minimal disruption to production.

Holmes Solutions developed a product re-engineering framework for this project that allowed the desired outcomes to be obtained with minimal risk to manufacturing efficiencies. The process included a detailed technical review of the product and the associated design requirements, a review of new and emerging technologies, and an optimisation procedure for the use of materials. Integral with the process was the inclusion of experimental testing to verify that the modified product maintained compliance with the required Design Standards [T1, N1]. The use of a
comprehensive experimental verification process was critical for the project as it allowed for considerable innovation in the design process. The final outcome of the process was the generation of stepwise improvements in the assessed products whilst maintaining the current manufacturing efficiencies.

STAGED PROJECT

The re-engineering of the Humes precast concrete box culverts was completed in a series of stages, allowing changes to be finalised for one stage prior to addressing other areas of potential saving.

The first stage focused on optimising the ultimate load capacity of the box culverts. Previously completed International research had shown that box culverts with considerably less flexural reinforcement than required by the New Zealand Standards can still achieve suitable strengths [S2].

The second stage of the project focused on optimising the fatigue resistance of the box culverts. In New Zealand, fatigue is often the governing load case for box culverts and therefore governs the required flexural steel volumes. This is not typically the case internationally [M1].

The third stage of the project will focus on the shear resistance of the sections, with the aim of optimising the performance against the requirements of the design codes.

EXPERIMENTAL PRODUCT VERIFICATION

A critical aspect of the product re-engineering methodology adopted for this project was the validation of design changes using experimental testing.

AS/NZS 1170.0 [A1] has allowances for experimental testing to validate the performance of a system. It is intended that these requirements outdate any testing verification procedures documented in the New Zealand materials Standards, such as NZS 3101 [N1]. Any products using experimental testing to validate the performance should utilise testing programmes that comply with the requirements of this Standard.

Appendix A in AS/NZS 1170 provides guidance on the completion of special studies to “establish information or methods for design not given in this standard, or to define formation or methods used, or where more accuracy is considered necessary”. A similar allowance for special studies is provided in the Transit New Zealand Bridge Manual. Any testing undertaken for the special study of AS/NZS 1170 is required to comply with the requirements of Appendix B of the standard.

Appendix B in AS/NZS 1170 defines two forms of product verification testing: Proof Testing of a structure or assembly, and Prototype Testing of a representative sample of a population.

Guidance is provided as to the requirements of the testing programme for both forms of product verification. However, when completing the development of a new product it is not typically feasible to undertake Prototype Testing, as the units are unlikely to have been produced in production quantities.

Detailed research programmes in New Zealand, such as University research programmes, have typically used experimental testing as a means to validate and calibrate analytical models that have been derived to predict the behaviour of building element. This form of testing does not comply with the requirements of Appendix B of AS/NZS 1170.

It is internationally accepted practice that experimental testing be used as a means of calibrating analytical model, provided the model adequately describes the behaviour of the test specimen, predicts the failure mode, and is used to determine the point of failure (the failure load or displacement) of the test specimen. Experimental testing of this nature has been used in the development of the material design Standards in New Zealand and internationally.

Any experimental testing programmes using this approach are required to meet strict criteria;

- The results from the testing must be used to calibrate a sound theoretical model used to predict the failure mechanism and failure point in the test specimen.
- The testing specimen must match the boundary conditions imposed in a real structure, and the test apparatus can neither help nor hindering the performance of the test specimen.
- The loading regime imposed should accurately match the imposed actions, in scale, timing, and sequence, that is imposed in the real structure.
- The testing programme should be peer reviewed by experienced parties, or be able to be replicated by an independent third party testing agency.
- The test reports must meet the reporting criteria imposed in AS/NZS 1170, include the evaluation and interpretation of the data.
CONCRETE BOX CULVERTS

The Humes precast concrete box culverts vary in span length from 1500 mm to 4500 mm, and rise from 1500 mm to 4000 mm. The typical length (or lay length) of the units is 1550 mm. The thickness of the side walls and slabs varies depending on span length and applied loading requirements for the individual culverts. Non-standard box culverts are manufactured with span lengths up to 6000 mm on request.

Box culverts are typically identified by their rise, span, and joint length dimensions (i.e. 2.0 m x 4.5 m x 1.55 m).

Precast concrete box culverts are typically reinforced with deformed reinforcing steel in both the longitudinal and transverse directions. Cover concrete requirements to the reinforcement are defined by appropriate exposure classification class for the structure.

Figure 1 Standard Precast Concrete Box Culvert

Precast concrete box culverts are typically used as sub-surface drainage systems or access pathways. The rectangular shape of the box culverts make them highly efficient for these applications, however due to these applications they are often required to be buried at shallow depths with little overburden.

The Transit New Zealand Bridge Manual [T1] defines the loads and load combinations required for bridge structures in New Zealand. For concrete bridge structures, the TNZBM requires all designs to be completed to the requirements of the New Zealand Concrete Structures Standard, NZS 3101 [N1].

Precast concrete box culverts have limited mention in either the TNZBM or NZS 3101, however it is generally accepted that the requirements of the TNZBM are conservative for box culvert structures, particularly when compared to the specific requirements for culverts adopted by other countries.

TRANSIT NEW ZEALAND BRIDGE MANUAL

All bridge structures in New Zealand are required to be designed using the loads and various load combinations detailed in Chapter 3 of the Transit New Zealand Bridge Manual.

The primary traffic loading is defined as HN-HO-72 loading, and is required to be used for the design of all members from deck slabs to main members and foundations.

Guidance is provided for the size, positioning, and location of the various loading profiles. Furthermore a series of load combinations are provided to combine the loading profiles from the various loading effects. A full description of the TNZBM loading requirements can be found elsewhere [T1].

The normal wheel loadings (HN) are based on an axle width of 1800 mm, and the overload conditions (HO) use a nominal axle width of 2100 mm. All box culvert sections manufactured by Humes have a unit length of 1550 mm and as such each culvert section can only be subjected to a single wheel loading from an applied axle load.

Box culverts are typically classified as Importance Level 2 structures and are therefore required to have an annual probability of exceedence for the ultimate limit states loads of 1/1000. The design working life of a culvert is required to be 100 years.

Serviceability Loads

The serviceability limit state (SLS) load is defined as the load at which a structure becomes unfit for its intended use through deformation, vibratory response, degradation, or other operational inadequacy.

The load combinations for serviceability loads in the TNZBM have an allowance for dynamic impact loading and an additional requirement for increased dead loads due to closed up stationary vehicles. Given the short span lengths of all box culvert structures (6 m or less) it is unlikely that these structures will be subjected to this form of simultaneous loading.

Ultimate Loads

The ultimate limit state load is defined as the load at which the strength or ductility capacity of the
structure is exceeded, or when it cannot maintain equilibrium and becomes unstable.

The nominal Ultimate Load Capacities to be applied to a box culvert structure are detailed in the TNZBM, with the unfactored HO loading being equal to 240 kN per axle.

**Fatigue Loads**

The TNZBM provides little guidance with regards to fatigue loading of bridge structures. No standard fatigue load spectrum is defined for New Zealand traffic conditions. However, TNZBM does allow the use of the standard fatigue spectrum from BS 5400 [B1] when designing a bridge structure, but warns that the obtained results are likely to be highly conservative.

Alternatively TNZBM recommends that for structures where fatigue details significantly influence the design, an appropriate spectrum can be developed, taking into account of the current and likely future traffic volumes and sizes.

The design of a reinforced concrete box culvert section is often governed by the fatigue requirements. This is primarily due to a mismatch in methodology between the TNZBM, defining the loads, and the concrete design standard, defining the sectional strength requirements.

**Special Study**

Section 2.7 of the TNZBM allows the use of Special Studies when using a structural form or method of construction that is not adequately covered by the acceptable standard or design criteria. Guidance is provided as to what information must be included in the Special Study report.

Holmes Solutions implemented a Special Study on the Humes precast concrete box culvert structures to generate the product improvements whilst ensuring the resulting designs remained compliant with the Standard. This included the development of an alternative loading spectrum for the fatigue resistance of the box culvert sections.

**ULTIMATE LOAD CAPACITY**

Stage 1 of the project involved refining the ultimate load carrying capacity of the various box culvert structures.

**DESIGN LOADING**

All design loads and load combinations used in determining the ultimate load carrying capacity of the Humes precast concrete box culverts were determined in direct accordance with the TNZBM.

**PRODUCT RE-ENGINEERING**

Product re-engineering under ultimate load conditions primarily focused on improving the efficiency of the designs under the imposed loads. The re-engineering process was used to generate significant performance enhancements and product improvements through better use of existing materials and detailed structural assessments.

The results achieved in the re-engineering process yielded considerable savings over existing design solutions. The changes developed to the designs could be implemented immediately by Humes with minimal manufacturing difficulty.

It was observed that additional improvements in the designs could be achieved if the fatigue loading requirements of the box culverts were revised. This work was completed as Stage 2 of the project, and is reported in a subsequent section.

**EXPERIMENTAL TESTING**

An experimental testing programme was developed by Holmes Solutions to verify the performance of the modified box culvert designs against the requirements of the TNZBM and NZS 3101. The testing programme satisfied the intent of AS/NZS 1170, and the special study requirements of the TNZBM.

A series of three full scale box culverts were manufactured to the revised designs. The specimens were manufactured by the Humes Christchurch Plant, using conventional manufacturing techniques and processes. Material samples were taken of all reinforcement and concrete used in the test specimen prior to manufacture.

The testing programme was developed to investigate the behaviour of the test specimen when loaded on the top surface, simulating vehicle wheel loading. The results of the testing were used to verify the revised model used in the design of the test specimen. At the completion of the primary testing programme, a further series of tests was completed on the bases of the previously tested units to verify the performance of these elements.
The test specimens were 2.0 x 2.5 x 1.55 m precast concrete box culverts. The designs of the test specimen had been refined during the product re-engineering phase. All box culvert specimens were designed with a maximum over burden allowance of 200 mm.

Test Setup

The test specimens were tested under worse case boundary conditions to ensure the obtained results represented a lower bound solution to the products performance. Previous researchers have shown that testing of concrete box culverts can be adequately modelled without the inclusion of lateral side pressure induced by the surrounding soil [A3, V1]. As such all testing was completed with the inclusion of wheel loading on the top surface only.

All simulated vehicle loads complied with the loaded dimensions required in the TNZBM, namely a contact area of 900 x 600 mm defined for overload conditions (HO loading).

Load applied to the test specimen and the deformations at various locations on the top surface of the test specimen were continuously recorded throughout the testing programme.

All test specimens were subjected to worse case bending loads, with the wheel loading positioning the centre span of the top slabs. Specimen BC1 and BC3 were tested with the wheel load located centrally in a transverse direction, to allow the degree of lateral load spread to be observed. Loading on specimen BC2 was shifted to the lateral edge of the test specimen to simulate loading on an edge of the culvert section.

Loading Protocol

All simulated vehicle loading was applied in a pseudo-static loading rate at increasing loading steps. Once the target loading step was achieved, the load was held to allow a detailed inspection of the test specimen. Any damage to the concrete unit was documented.

The loading applied to the test specimen was increased in a stepwise manner until the specimen failed. Failure was defined as a significant reduction in the load carrying capacity. The steps used for the load increases were based on the key loading criteria defined by TNZBM.

Given that the span length of each culvert section was only 1.55 m, each culvert section was only capable of withstanding one wheel from any axle load combination. As such, the key wheel weights used in the testing were:

- Maximum Legal Wheel: 65 kN
- Maximum Legal Overload Wheel: 80 kN
- HN Wheel Load Combination (SLS-4): 156 kN
- HO Wheel Load Combination (ULS-4): 232 kN

After the achievement of the maximum HO loading combination, the loads were increased until the specimen failed.

Test Results and Observations

The test units were cured in-situ for a minimum of 28 days prior to testing. On the day of testing all materials used in the specimen were tested to determine their material properties.

The strengths obtained for the reinforcing steel and concrete used in the test specimen are shown below.

<table>
<thead>
<tr>
<th>Specimen I.D</th>
<th>$f_c$ (MPa)</th>
<th>$f_y$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC1</td>
<td>43</td>
<td>545</td>
</tr>
<tr>
<td>BC2</td>
<td>45</td>
<td>550</td>
</tr>
<tr>
<td>BC3</td>
<td>45</td>
<td>555</td>
</tr>
</tbody>
</table>

The following test observations are based on general observations across all test specimens. Specific comments on individual test specimen are noted accordingly.
All test specimens resisted the maximum legal and overload wheel loading with minimal observed visual cracking to the concrete elements.

As the loading was increased to the maximum required Serviceability load (HN), a number of the existing cracks increased in length. The maximum crack width was documented as 0.15 mm, located on the underside of the top slab surface immediately under the applied load.

Upon reaching the serviceability load value of 156 kN (HN load combination), the load was removed from the test specimens with all previously documented cracks observed to close. It was determined that the serviceability cracks would not pose a durability issue for the culverts across their required 100 year design life.

Loading was reapplied up to the specimen, up to the ULS design load of 232 kN. All test specimens withstood the design load with no obvious signs of distress. The slope on the recorded Load verse Deflection graph remained linear up to and surpassing the ULS design load, indicating that the specimen was remaining nominally elastic.

Loading was continued on specimen BC1 up to a maximum load value of 498 kN. Specimen BC3 achieved maximum load value of 492 kN. Upon completion of the testing, specimens BC1 and BC3 had formed significant plastic hinges in the centre of the top slab (immediately below the point of load application), and in the top of the side walls (immediately below the haunch to the top slab). Both test specimens maintained a high degree of load carrying capacity at the completion of the testing.

Test specimen BC2 reached failure at 440 kN, due to Punching Shear around the applied loading point. The failure surface is detailed in Figure 6.

All three test specimen achieved actual design strengths that exceeded the TNZBM requirements by over 200%. Upon completion of the ultimate load testing, the box culverts were inverted and test loads applied to the base slabs.

![Figure 3 Load vs Deflection results for BC1](image)

![Figure 4 Crack pattern BC1 at SLS Loading](image)

![Figure 5 Failure of BC1 at 215% ULS Loading](image)

![Figure 6 Failure of BC2 at 190% ULS load](image)
FATIGUE LOAD CAPACITY

Stage 2 of this re-engineering project involved refining the design of the Humes precast box culverts against the fatigue loading requirements of the TNZBM. The results obtained from stage 1 of the review indicated that the design strengths of the sections was often governed by the fatigue requirements rather than the ultimate load carrying capacity section.

DESIGN LOADING

The TNZBM provides little direct guidance on suitable loading profiles for fatigue loading combinations. As such, the fatigue design is typically completed using serviceability limit state (SLS) design loads. This will result in overly conservative design solutions.

TNZBM allows the use of the fatigue loading spectrum from the British Standard, BS 5400 [B1], but indicates that the obtained results may be very conservative.

A detailed review was completed of the BS 5400 fatigue loading spectrum by Holmes Solutions. The spectrum requirements detailed in BS 5400 is heavily influenced by high traffic volumes and very large allowable vehicle axle loads. It was considered inappropriate to use a similar loading spectrum for box culverts in New Zealand.

TNZBM allows the use of an appropriately developed loading spectrum for applications where the fatigue details significantly influence the design of the structure. Holmes Solutions completed a Special Study into the fatigue resistance of box culverts and developed an appropriate fatigue loading spectrum for use with the Humes Box Culverts.

The Australian Bridge Design Standard, AS 5100 [A4], provides guidance on the fatigue requirements for bridge structures. A number of reviews have been completed on this standard by New Zealand authors [C1, K1]. In summary this standard recommends a design fatigue load equal to 70% of the A160 axle loads with dynamic load allowances, approximately equivalent to 160 kN. Furthermore AS 5100 requires the structures to be designed to withstand the following number of loading cycles;

\[(\text{current no of heavy vehicles per day}) \times 4 \times 10^4 \times RF\]

RF is defined as the Route Factor for the particular road in question (0.5 for rural roads and 0.7 for urban freeways).

The New Zealand Land Transport Agency places restrictions on the maximum allowable vehicle on the New Zealand roading network. The requirements were updated in 2010, allowing an increase in the legal overweight axle load to 124 kN (with dynamic impact factor). This is significantly lower than the 160 kN axle weight allowance of the AS 5100 standard.

The New Zealand Land Transport Agency also provides Average Annual Daily Traffic (AADT) information for various roading locations in New Zealand. This information was used, in conjunction with the maximum legal overload axle weight to develop a fatigue loading spectrum for the New Zealand roading network.

INCOMPATIBILITY OF LOADS AND DESIGN

A critical aspect of the fatigue loading requirements for bridge structures is the inconsistence between the TNZBM and NZS 3101 with regards to performance under fatigue requirements. TNZBM does not provide specific fatigue loading requirements and as such the fatigue loads default to the conventional SLS load combinations. These load combinations are considerably larger than the maximum legal overweight allowance on New Zealand roads.

The New Zealand Concrete Structures Standard, NZS 3101, is referenced in the TNZBM for use when designing concrete structures. NZS 3101 limits the allowable stress fluctuations in reinforcing steel to prevent fatigue failure of the reinforcing steel. The limitations are based on the ACI requirements and are designed to ensure an infinite fatigue life of the structure. This is incompatible with the fatigue loads based on SLS loads imposed in TNZBM, which are significantly greater than the maximum loads likely to be sustained by the bridge structure across its design life.

It is recommended that the allowable stress fluctuations detailed in NZS 3101 be used with realistic fatigue loads to achieve economic and cost effective design solutions.

INTERNATIONAL RESEARCH FINDINGS

Significant international research has been completed into the fatigue resistance of concrete box culvert structures. Most recently a series of research projects have been completed in the United States of America, comparing the experimental behaviour of the culverts to the requirements of AASHTO LRFD Standard Specification [M1].

The research projects completed experimental testing on 2 full scale box culvert structures. The
structures had span lengths of 3600 mm and 2100 mm respectively. Each culvert was subjected to 5 million loading cycles to 65 kN, 85 kN and finally 123 kN load limits. At the completion of the load cycles the units were taken to failure.

The results of the research indicated that the culverts were unaffected by fatigue loading and that the final ultimate capacity of the test specimen achieved was similar to the ultimate strength of identical section that had not been subjected to the fatigue loading. The results also indicated that infinite fatigue life for the structures is achieved after 1 million load cycles.

Similar findings have been presented by other researchers [V1].

PRODUCT RE-ENGINEERING

Product re-engineering for the fatigue load cases focused on improving the efficiency of the designs under imposed fatigue loads. The allowable reinforcing bar stresses were limited in accordance with the requirements of NZS 3101. However, the imposed fatigue loading was determined from a newly derived fatigue loading spectrum for the New Zealand roading network.

The reduction in the imposed loading associated with the development of the New Zealand fatigue loading spectrum resulted in a significant reduction in the required volume of reinforcement for the fatigue load combinations.

For the majority of culvert designs the fatigue load combination was no longer the governing design case.

EXPERIMENTAL TESTING

An experimental testing programme was developed by Holmes Solutions to verify the performance of the modified box culvert designs when subjected to fatigue load combinations. All testing was completed to the intent of AS/NZS 1170, and the special study requirements of the TNZBM.

Two full scale box culverts were manufactured to the revised design for zero over burden situations. Both fatigue test specimens were 2.0 x 4.5 x 1.55 m precast concrete box culverts, manufactured by the Humes Christchurch factory using conventional manufacturing techniques. Material samples were taken of all reinforcement and concrete used in the test specimen prior to manufacture.

The testing programme was developed to investigate the behaviour of the test specimen when loaded on the top surface, simulating a traversing vehicle wheel load. This was achieved by a series of three hydraulic actuators spaced along the span of the culvert, each applying a loading profile in sequence. The spacing of the actuators was altered to approximate the loading profile generated by a moving wheel across the structure.

At the completion of the fatigue testing programme, both test specimens were subjected to increasing loads until failure, to determine if the fatigue loading had resulted in any strength reduction of the box culverts. The loading arrangement for the ultimate testing was identical to that used for Specimens BC1 and BC3.

Test Setup

The test specimens were tested under worse case boundary conditions to ensure the obtained results represented a lower bound solution to the products performance, namely without the inclusion of lateral side pressure induced by the surrounding soil. The box culverts were located on a sand bed to ensure realistic pressures on the bottom surface.
All simulated vehicle loadings complied with the loaded dimensions required in the TNZBM, namely a contact area of 500 mm x 200 mm defined for normal loading conditions (HN loading).

Each test specimen was fitted with a series of strain gauges on the longitudinal and transverse reinforcing steel. A continuous electronic record was recorded for all of the strain gauges, the applied loads, and the associated deformations of the culvert throughout the testing programme.

**Loading Protocol**

All simulated vehicle loading was applied at a dynamic loading rate of approximately 1 Hz. This was the maximum rate possible of the test equipment given the flexibility of the box culvert and support frame. Testing was completed by applying and then removing the load from each hydraulic actuator in sequence to simulate a vehicle traversing across the top surface of the culverts. Testing was stopped periodically to document any damage to the test specimens. Given the span length of each culvert section is only 1.55 m, each culvert section was only subjected to a single wheel load from any axle load combination. As such, the fatigue wheel weight used in the testing was 90 kN, simulating an axle load of 180 kN.

Testing was continued for 1.5 million load cycles, exceeding the infinite fatigue life of the structures by 500,000 cycles.

At the completion of the fatigue loading cycles, each test specimen was tested to destruction by applying an increasing load to the centre of the top slab, in an identical test arrangement to that used on the ultimate load tests of Specimen BC1 and BC3.

**Test Results and Observations**

The test units were cured in-situ for a minimum of 28 days prior to testing. On the day of testing all materials used in the specimen were tested to determine their material properties, as shown below.

<table>
<thead>
<tr>
<th>Specimen I.D</th>
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<th>$f_y$ (MPa)</th>
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<tbody>
<tr>
<td>BC4</td>
<td>47</td>
<td>545</td>
</tr>
<tr>
<td>BC5</td>
<td>46</td>
<td>550</td>
</tr>
</tbody>
</table>

The following test observations are based on general observations across all test specimen. Specific comments on individual test specimen are noted accordingly.

Specimen BC4 and BC5 showed minor cracking to the underside of the deck slab during application of the repeat fatigue loading. The majority of the recorded cracks stabilised in length and width within the first 250,000 loading cycles. The maximum recorded crack width was 0.3 mm. Minor cracking was observed on the outside of the wall elements, near the junction with the deck slab. All of the cracks in the test specimen were observed to close completely upon removal of the applied loading and were therefore not considered to unduly affect the durability of the structure.

A direct measure of the steel strains was obtained across the testing programme by the strain gauges located on the longitudinal and transverse reinforcement in the deck slab and walls. In no circumstances did the steel strain fluctuate greater than the 150 MPa limit imposed by NZS 3101. There was no noticeable variation in the recorded steel strains under the imposed loading across the applied 1.5 million loading cycles in either test article.

The vertical deformation of the deck slab and lateral movement of the side walls stayed consistent across the fatigue testing programme. At the completion of the 1.5 million load cycle neither test specimen showed any visual signs of stress. All previously observed cracks in the concrete sections closed upon removal of the load.

Immediately following the fatigue testing, Specimens BC4 and BC5 were subjected to ultimate load testing as described in the previous section. BC4 obtained an ultimate load capacity equal to 185% of the required ULS load prior to failing in a ductile manner. Failure occurred due to the formation of plastic hinges in the centre of the deck slab and at the top of the side walls, as shown in Figure 11. Specimen BC5 obtained an ultimate strength equal to 192% of ULS loading before failing in an identical manner to BC4.

The ultimate strength obtained by BC4 and BC5 was comparable to the previously recorded strengths of specimen BC1-BC3, indicating that the specimens had maintained their full load carrying capacity despite being subjected to 1.5 million load cycles of repetitive fatigue loading.
CONCLUSIONS

A detailed re-engineering project was completed on the entire Humes range of precast concrete box culverts. All design changes recommended by the project were validated with comprehensive experimental testing. The results of the project include:

- Significant advancements can be generated in the ultimate load capacity of Box Culvert structures.
- The fatigue loading requirements of the Transit New Zealand Bridge Manual are incompatible with the fatigue stress limitations of NZS 3101
- A special study was completed to develop a fatigue loading spectrum for the New Zealand roading network.
- A series of box culvert structures were manufactured to the new designs, and subjected to extensive testing under fatigue and ultimate load conditions. All modified structures exceeded the requirements of the New Zealand Standards.
- The re-engineering process used on suite of the Humes box culverts was highly successful and resulted in considerable advancement in their box culvert designs.

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[B1] BS 5400, "Steel, Concrete, and composite Bridges", British Standard, 1999


[S2] Smeltzer, Benz "Research Suggests Conservative Design of Concrete Box Culverts", Environmental Science and Engineering, May 2004

[T1] Transit New Zealand Bridge Manual (2nd Ed)