STRUCTURAL DYNAMICS OF MODULAR BRIDGE EXPANSION JOINTS RESULTING IN ENVIRONMENTAL NOISE EMISSIONS AND FATIGUE

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A thesis submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy (By Publication)

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of the requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work is acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Eric John Ancich

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I also acknowledge the contributions of the co-authors of the various papers set out in Appendices A-N.

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PUBLICATIONS

The following technical papers have been published based on the work in this thesis:

Journal Publications:

1. Ancich E.J., Chirgwin G.J. and Brown S.C. (2006). Dynamic Anomalies in a Modular Bridge Expansion Joint, *Journal of Bridge Engineering*, Vol. 11, No. 5, 541-554.

2. Ancich E.J. and Brown S.C. (2004). Engineering Methods of Noise Control for Modular Bridge Expansion Joints, *Acoustics Australia*, Vol. 32, No. 3, 101-107.

Conference Papers:

3. Ancich E.J. and Brown S.C. (2009). Premature Fatigue Failure in a Horizontally Curved Steel Trough Girder Bridge, *Proc. International Association for Bridge & Structural Engineering (IABSE) Symposium,* Bangkok, Thailand.

4. Ancich E.J., Chirgwin G.J., Brown S.C. & Madrio H. (2009). Fatigue Implications of Growth in Heavy Vehicle Loads and Numbers on Steel Bridges, *Proc. International Association for Bridge & Structural Engineering (IABSE) Symposium,* Bangkok, Thailand.

5. Ancich E.J., Chirgwin G.J., Brown S.C. & Madrio H. (2009). Fatigue Sensitive Cope Details in Steel Bridges and Implications from Growth in Heavy Vehicle Loads and Numbers, *Proc. 7th Austroads Bridge Conference*, Auckland, New Zealand.

6. Ancich E.J. (2007). Dynamic Design of Modular Bridge Expansion Joints by the Finite Element Method, *Proc. International Association for Bridge & Structural Engineering (IABSE) Symposium,* Weimar, Germany.

7. Ancich E.J., Forster G. and Bhavnagri V. (2006). Modular Bridge Expansion Joint Specifications and Load Testing, *Proc. 6th Austroads Bridge Conference*, Perth, Western Australia, Australia.

8. Ancich E.J. and Bradford P. (2006). Modular Bridge Expansion Joint Dynamics, *Proc. 6th World Congress on Joints, Bearings, and Seismic Systems for Concrete Structures*, Halifax, Nova Scotia, Canada.

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10. Ancich E.J. and Bhavnagri V. (2006). Fatigue Comparison of Modular Bridge Expansion Joints Using Multiple Bridge Design Code Approaches, *Proc. 6th World Congress on Joints, Bearings, and Seismic Systems for Concrete Structures*, Halifax, Nova Scotia, Canada.

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12. Ancich E.J. and Brown S.C. (2004). Modular Bridge Joints – Reduction of noise emissions by use of Helmholtz Absorber, *Proc. 5th Austroads Bridge Conference*, Hobart, Tasmania, Australia.

13. Ancich E.J., Brown S.C. and Chirgwin G.J. (2004). Modular Deck Joints – Investigations into structural behaviour and some implications for new joints, *Proc. 5th Austroads Bridge Conference*, Hobart, Tasmania, Australia.

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14. Ancich E.J. (2000). A Study of the Environmental Noise Generation & Propagation Mechanisms of Modular Bridge Expansion Joints, *RTA Environmental Technology Report No. 000203*, Roads & Traffic Authority of NSW, Sydney, NSW, Australia.

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Appendix B

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Appendix D

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Appendix E

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Appendix I

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Appendix J

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Appendix K

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Appendix L

Ancich E.J., Chirgwin G.J., Brown S.C. & Madrio H. (2009). Fatigue Sensitive Cope Details in Steel Bridges and Implications from Growth in Heavy Vehicle Loads and Numbers, *Proc. 7th Austroads Bridge Conference*, Auckland, New Zealand.

Appendix M

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Notations

f_{lim}	Stress at limit state for fatigue
f^*_{u}	Computed Stress for ultimate design load
f_t	Tyre pulse frequency (Hz)
f_p	Wheel/beam pass frequency (Hz)
V	Vehicle speed (m/s)
G	Spacing between centre beams (m)
L_p	Sound Pressure Level (dB)
L_{eq}	Equivalent Continuous Sound Pressure Level (dB)
L_t	Tyre patch length (m)
b	Width of the centre beam top flange (m)
ϖ	Forcing radian frequency (rads/s)
ω_n	Natural radian frequency (rads/s)
m_B	Effective mass of the centre beam
m_V	Effective mass of the vehicle
$P(t)$	Unit vehicle (pulse) excitation with a maximum value of 1
P	Sound pressure (Pa)
P_{ref}	Reference pressure (20μPa)
x_0	Co-ordinate of the first beam node
Δt_T	Tyre pulse duration
N	Number of centre beams
f^*_{f}	Computed stress for fatigue design load
Φ_{f}	Capacity reduction factor
H	Longitudinal live load
W_{x}	Axle load
W_{xu}	Factored axle load for strength design
W_{xf}	Factored axle load for fatigue design
χ	Dynamic amplification factor (DAF)
γ_{u}	Strength limit state factor
γ_{f}	Fatigue limit state factor
β	Distribution factor
f_{lim}	Fatigue stress range limit

f_{TH}	Fatigue threshold limit
$J_{s,max}$	Maximum joint opening at serviceability limit state
$J_{s,min}$	Minimum joint opening at serviceability limit state
J_f	Joint opening at fatigue limit state
ε_{dyn}	Strain range due to the vehicle travelling at designated speed (peak-to-peak)
ε_{stat}	Strain range due to vehicle travelling at crawl (slow roll) speed (zero-to-peak)
δ_{dyn}	Maximum displacement due to the vehicle travelling at designated speed
δ_{stat}	Maximum displacement due to the vehicle travelling at crawl (slow roll) speed
DAF	Dynamic amplification factor
MBEJ	Modular bridge expansion joint
OEM	Original equipment manufacturer
RTA	Roads & Traffic Authority of NSW (Australia)

ABSTRACT

Whilst the use of expansion joints is common practice in bridge construction, modular bridge expansion joints are designed to accommodate large longitudinal expansion and contraction movements of bridge superstructures. In addition to supporting wheel loads, a properly designed modular joint will prevent rain water and road debris from entering into the underlying superstructure and substructure. Modular bridge expansion joints (MBEJs) are widely used throughout the world for the provision of controlled pavement continuity during seismic, thermal expansion, contraction and long-term creep and shrinkage movements of bridge superstructures and are considered to be the most modern design of waterproof bridge expansion joint currently available. Modular bridge expansion joints are subjected to more load cycles than other superstructure elements, but the load types, magnitudes and fatigue-stress ranges that are applied to these joints are not well defined. MBEJs are generally described as single or multiple support bar designs. In the single support bar design, the support bar (beam parallel to the direction of traffic or notionally parallel in the case of the swivel joist variant) supports all the centre beams (beams transverse to the direction of traffic) using individual sliding yoke connections (for the swivel joist variant, the yoke connection is characterised as a one-sided stirrup and swivels rather than slides). In the multiple support bar design, multiple support bars individually support each centre beam using a welded connection.

Environmental noise complaints from home owners near bridges with modular expansion joints led to an engineering investigation into the noise production mechanism. It was generally known that an environmental noise nuisance occurred as motor vehicle wheels passed over the joint but the mechanism for the generation of the noise nuisance has only recently been described. Observation suggested that the noise generation mechanism involved possibly both parts of the bridge structure and the joint itself as it was unlikely that there was sufficient acoustic power in the simple tyre impact to explain the persistence of the noise in the surrounding environment.

Engineering measurements were undertaken at two bridges and subsequent analysis led to the understanding that dominant frequency components in the sound pressure field inside the void below the joint were due to excitation of structural modes of the joint and/or acoustic modes of the void. This initial acoustic investigation was subsequently overtaken by observations of fatigue induced cracking in centre beams and the welded support bar connection. A literature search revealed little to describe the structural dynamics behaviour of MBEJs but showed that there was an accepted belief amongst academic researchers dating from around 1973 that the loading was dynamic. In spite of this knowledge, some Codes-of-Practice and designers still use a static or quasi-static design with little consideration of the dynamic behaviour, either in the analysis or the detailing. In an almost universal approach to the design of modular bridge expansion joints, the various national bridge design codes do not envisage that the embedded joint may be lightly damped and could vibrate as a result of traffic excitation. These codes only consider an amplification of the static load to cover sub-optimal installation impact, poor road approach and the dynamic component of load. The codes do not consider the possibility of free vibration after the passage of a vehicle axle.

Codes also ignore the possibilities of vibration transmission and response reinforcement through either following axles or loading of subsequent components by a single axle. What the codes normally consider is that any dynamic loading of the expansion joint is most likely to result from a sudden impact of the type produced by a moving vehicle '*dropping*' onto the joint due to a difference in height between the expansion joint and the approach pavement.

In climates where snow ploughs are required for winter maintenance, the expansion joint is always installed below the surrounding pavement to prevent possible damage from snow plough blades. In some European states (viz. Germany), all bridge expansion joints are installed some 3-5mm below the surrounding pavement to allow for possible wear of the asphaltic concrete. In other cases, height mismatches may occur due to sub-optimal installation.

However, in the case of dynamic design, there are some major exceptions with Standards Australia (2004) noting that for modular deck joints "…*the dynamic load allowance shall be determined from specialist studies, taking account of the dynamic characteristics of the joint*…" It is understood that the work reported in Appendices B-E was instrumental in the Standards Australia committee decisions. Whilst this Code recognizes the dynamic behavior of MBEJs, there is no guidance given to the designer on the interpretation of the specialist study data. AASHTO (2004), Austrian Guideline RVS 15.45 (1999) and German Specification TL/TP-FÜ 92 (1992) are major advancements as infinite fatigue cycles are now specified and braking forces considered but there is an incomplete recognition of the possibility of reinforcement due to in-phase (or notionally in-phase) excitation or the coupled centre beam resonance phenomenon described in Chapter 3.

This thesis investigates the mechanism for noise generation and propagation through the use of structural dynamics to explain both the noise generation and the significant occurrence of fatigue failures world-wide. The successful fatigue proofing of an operational modular joint is reported together with the introduction of an elliptical loading model to more fully explain the observed fatigue failure modes in the multiple support bar design.