Modular Deck Joints – Investigations into structural behaviour and some implications for new joints

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Eric has over 20 years experience in acoustics, vibration and for the last three years he has directed the structural dynamics studies of four RTA road bridges to determine the mechanism causing the premature fatigue induced failure of modular expansion joints. It is considered that this work has identified a major defect in the quasi-static load case assumption used universally in bridge design codes.

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For the last 20 years, Steve has practiced the field of noise and vibration. He has a particular talent in experimental modal analysis and is noted for his innovative and cost-effective solutions to complex dynamic problems.

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Gordon has 31 years experience in roads and bridges, and for the last 10 years has been managing technical policy in the bridge and structural fields.

SYNOPSIS

Environmental noise complaints from homeowners near bridges with modular expansion joints (MBEJ) led to an engineering investigation into the noise production mechanism. The investigation identified modal vibration frequencies in the MBEJ coupling with acoustic resonances in the chamber cast into the bridge abutment below the MBEJ. This initial acoustic investigation was soon overtaken by observations of fatigue induced cracking in structural beams transverse to the direction of traffic. These beams are, in the English-speaking world, universally referred to as centre beams. However, in Europe the use of *lamella* to describe these beams is equally common. A literature search revealed little to describe the structural dynamics behaviour of MBEJ's 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 almost all designers use a static or quasi-static design with little consideration of the dynamic behaviour, either in the analysis or the detailing.

Principally, this paper identifies the natural modes of vibration of the single support bar design MBEJ installed into Sydney's Anzac Bridge and the welded multiple support bar design MBEJ installed into the southern abutment of the southbound carriageway of the bridge over the south channel of the Manning River (Taree By-pass). Secondly, the paper will report the dynamic amplification factors (DAF) obtained after extensive static and dynamic strain gauge measurements of both MBEJ's.

1 INTRODUCTION

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 rainwater and road debris from entering into the underlying superstructure and substructure. 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 [Dexter *et al* (1)].

A literature search revealed little to describe the structural dynamics behaviour of MBEJ's but showed that there was an accepted belief amongst academic researchers from around 1973 that the loading was dynamic [Tschemmernegg (2)]. Subsequently, Tschemmernegg (3) noted that "…*Although everybody knows that expansion joints of bridges are the heaviest dynamic-loaded components of bridges, the design calculations, if any, were of a static nature. The results are a lot of well-known problems of detail with high costs for repair, interruption of traffic, etc…*"

2 DESCRIPTION OF MODULAR BRIDGE EXPANSION JOINTS

Modular bridge expansion joints 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) supports all the centre beams (beams transverse to the direction of traffic). In the *multiple* support bar design, multiple support bars individually support each centre beam. **Figures 1 & 2** show typical single support bar and welded multiple support bar MBEJ's respectively.

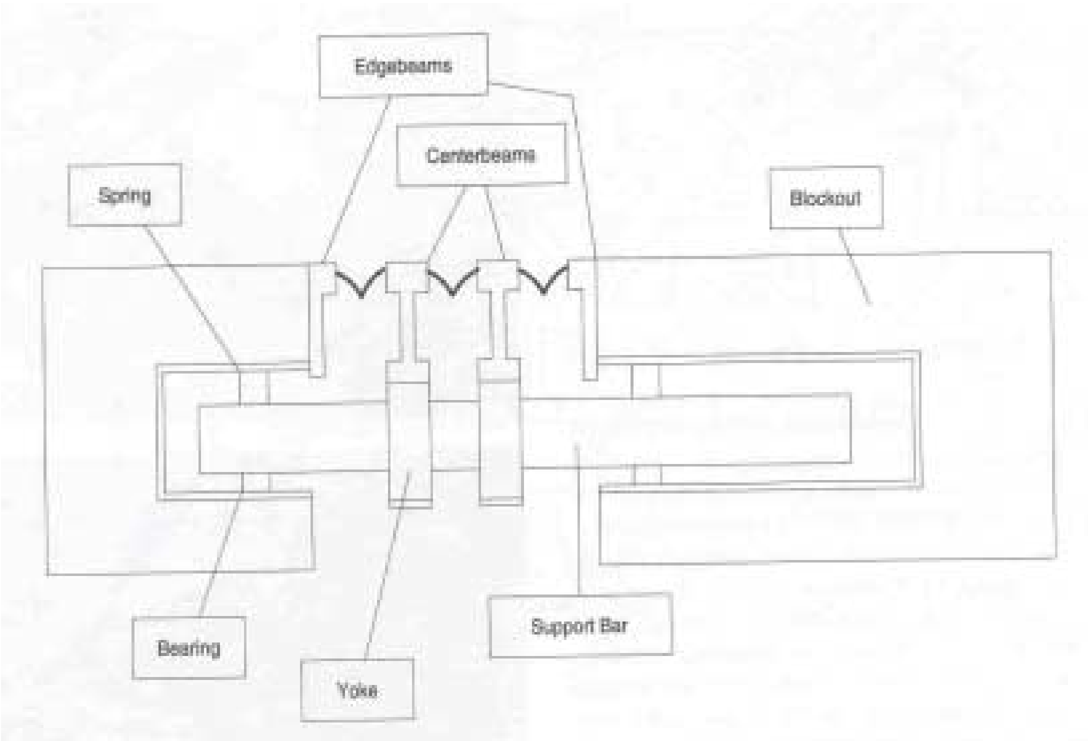


Figure 1: Typical Single Support Bar Design MBEJ

The MBEJ installed into the Western abutment of Anzac Bridge is, in fact, a hybrid design having pairs of support bars in series across the full width of the joint. Each pair of support bars is attached to alternate groups of four centre beams [i.e. Centre beams 1, 3, 5 & 7 are attached to support bar #1 (and the other odd numbered support bars) and centre beams 2, 4, 6 & 8 attached to support bar #2 (and the other even numbered support bars)]. The support bar pairs are spaced at 2.25m centres across the full width of the bridge resulting in a total of 24 support bars (2 x 12).

The MBEJ installed into the southern abutment of the southbound carriageway of the bridge over the south channel of the Manning River (Taree By-pass) is a typical multiple support bar design as shown in **Figure 2**. MBEJ's typically employ mechanisms to maintain equidistant centre beam spacing over the full range of joint movement. Equidistant devices include elastomeric springs and mechanical linkages such as pantographs or the so-called "*lazy tong*". The MBEJ installed into the Western Abutment of Anzac Bridge employs a mechanical linkage system and the Taree By-pass MBEJ utilises elastomeric control springs.

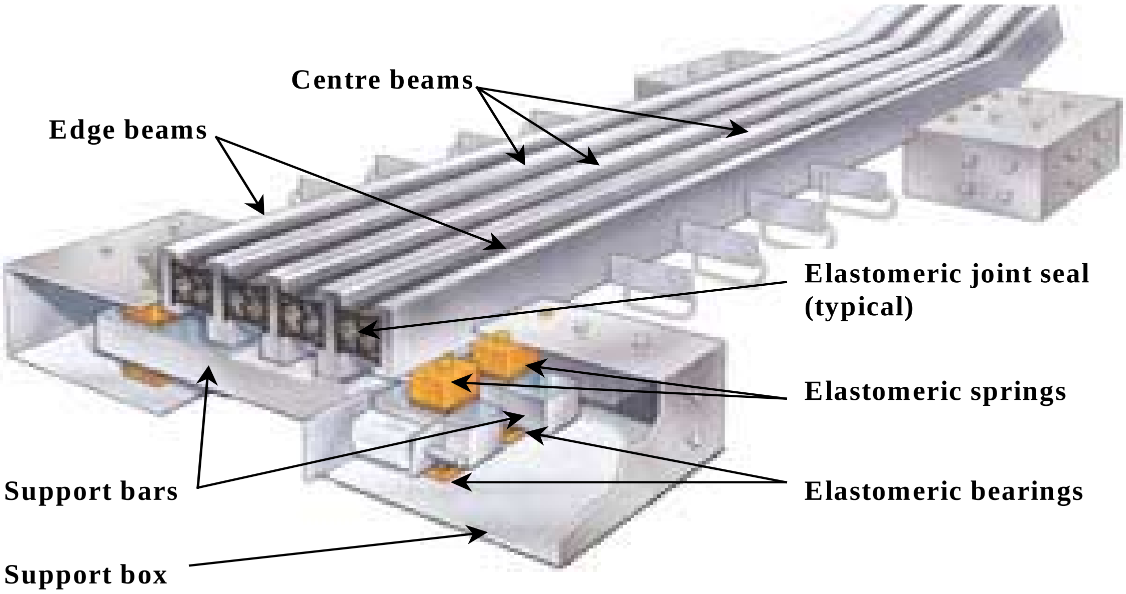


Figure 2: Typical Multiple Support Bar Design MBEJ

3 STRUCTURAL DYNAMICS STUDIES

3.1 Initial Noise Investigation

There was anecdotal evidence from environmental noise nuisance complaints received by the Roads & Traffic Authority of NSW (RTA) that the sound produced by the impact of a motor vehicle tyre with modular bridge expansion joints was audible up to 500 metres from a bridge in a semi-rural environment. This observation suggested that the noise generation mechanism involved possibly both parts of the bridge structure and the joint itself as it is unlikely that there is sufficient acoustic power in the simple tyre impact to explain the persistence of the noise in the surrounding environment [Ancich & Brown (4)].

The analysis of simple vibration measurements of the 9-seal MBEJ installed into the Anzac Bridge [Ancich *et al* (5)] revealed that most of the traffic-induced vibration was at a frequency of 71 Hz. An FFT spectrum is shown as **Figure 3**.

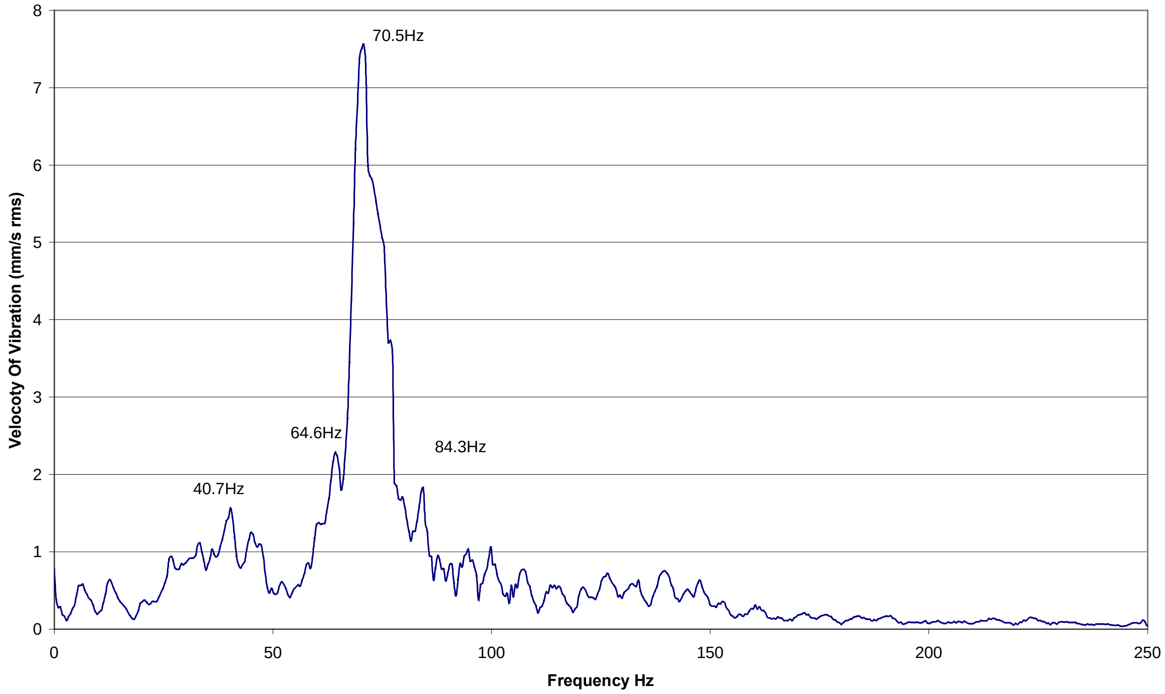


Figure 3: Centre Beam Vibration Spectrum – Anzac Bridge

A preliminary analytical study failed to identify the vibrational mode responsible for this frequency and an experimental modal analysis study was subsequently undertaken. The modal analysis study revealed that the 71 Hz frequency was predominantly due to a quasi-rigid body mode where the MBEJ was essentially bouncing on its bearing supports in combination with some support bar and centre beam vertical bending. It was deduced that at least 90% of the MBEJ mass was mobilised at this frequency.

Classical first and second order centre beam vertical bending modes were found at 85 Hz, 91 Hz and 97 Hz. Due to access restrictions, horizontal modal data could not be acquired in sufficient detail to identify horizontal bending or torsional modes. It should be noted that Ostermann (6) also shows an analytically determined vertical mode at 87 Hz that exhibits elements of the quasi-rigid body (bounce/bending) mode.

It is also interesting to note that experimental modal analysis results [Ancich *et al* (5)] indicated that the support bars and centre beams were acting dynamically as if simply supported. This observation is somewhat counter-intuitive.

Roeder (7) postulated that the dynamic response of MBEJ's is complicated because hundreds of modes of vibration may contribute to the response. The present data do not support that view.

To the contrary, the predominant dynamic response responsible for peak dynamic strains is attributed to the participation of the first three or four vertical modes. Horizontal bending and torsional modes were not identified due to experimental limitations.

However, the presence of the quasi-rigid body (bounce/bending) mode at 71 Hz was unexpected. Although this mode was implied by Köster (8), it does not appear to have been previously reported.
It is noted that modal analysis measurements at Taree also revealed the presence of this quasi-rigid body (bounce/bending) mode. In all cases measured, the "bounce/bending" mode occurred at lower frequencies than the respective centre beam fundamental (vertical) bending modes. The experimental modal analysis results revealed that all the Anzac modes were very lightly damped (<2% of critical) and consequently likely to contribute to free un-damped vibration of structural members of the MBEJ.

Under some operating conditions, lightly damped single support bar systems may experience dynamic amplification of loads up to 5 times the nominal static load. It is considered that this dynamic response is a direct result of the phenomenon of coupled centre beam resonance [Ancich *et al* (9)].

The modal analysis data were subsequently used to optimise the placement of strain gauges as part of the fatigue life assessment of the Anzac and Taree MBEJ's. Details of the methodology employed in the strain gauge testing are given in Ancich *et al* (9).

4 STATIC & DYNAMIC STRAIN MEASUREMENT

Figure 4 represents a plan view diagram of the eastbound kerbside lane of Anzac Bridge and shows the six strain gauge locations (SG1 to SG6) and **Figure 5** represents a plan view diagram of the southbound kerbside lane of the Taree By-pass Bridge and shows the six strain gauge locations (SG1 to SG6). All gauges were of a linear type and orientated in the anticipated principal stress direction (i.e. parallel to the long axis of the respective structural members).

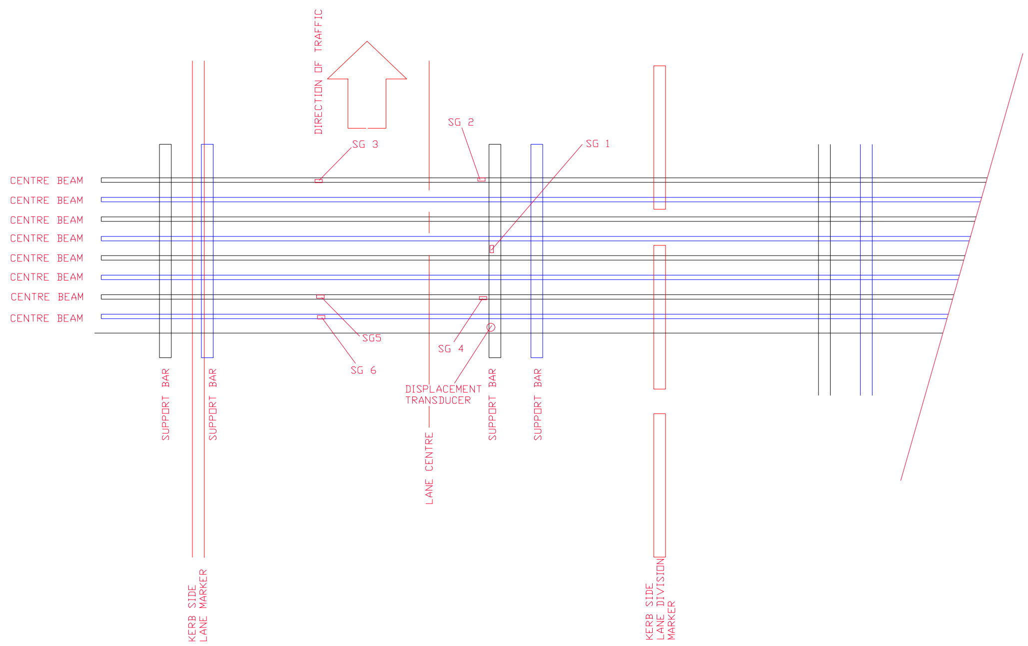


Figure 4: Anzac Eastbound Carriageway - Strain Gauge Locations (SG1 to SG6)

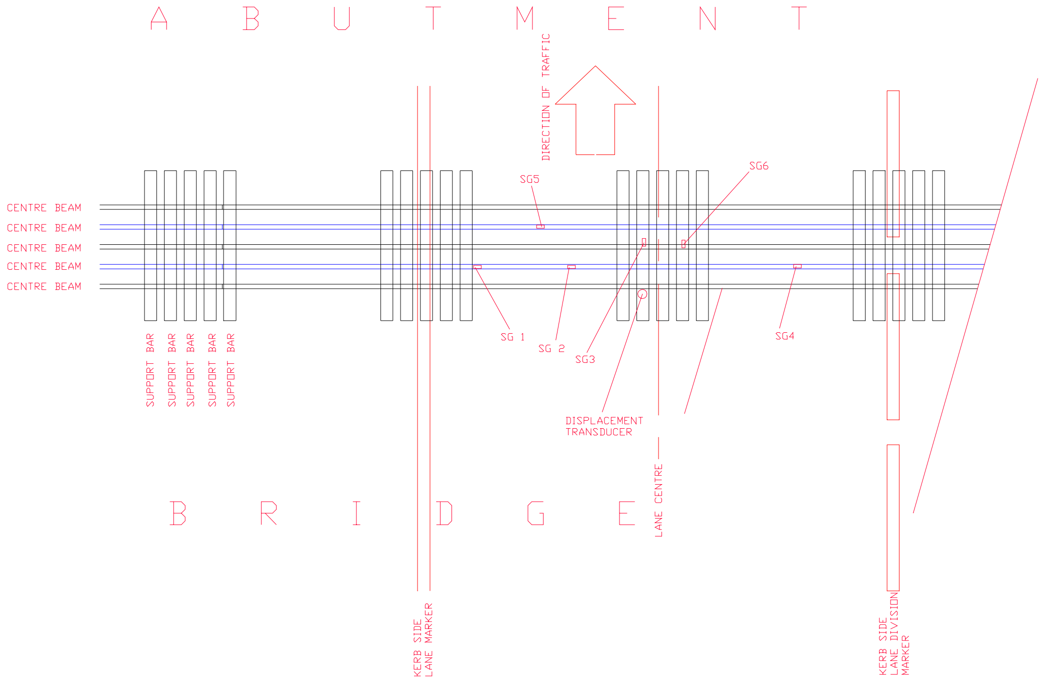
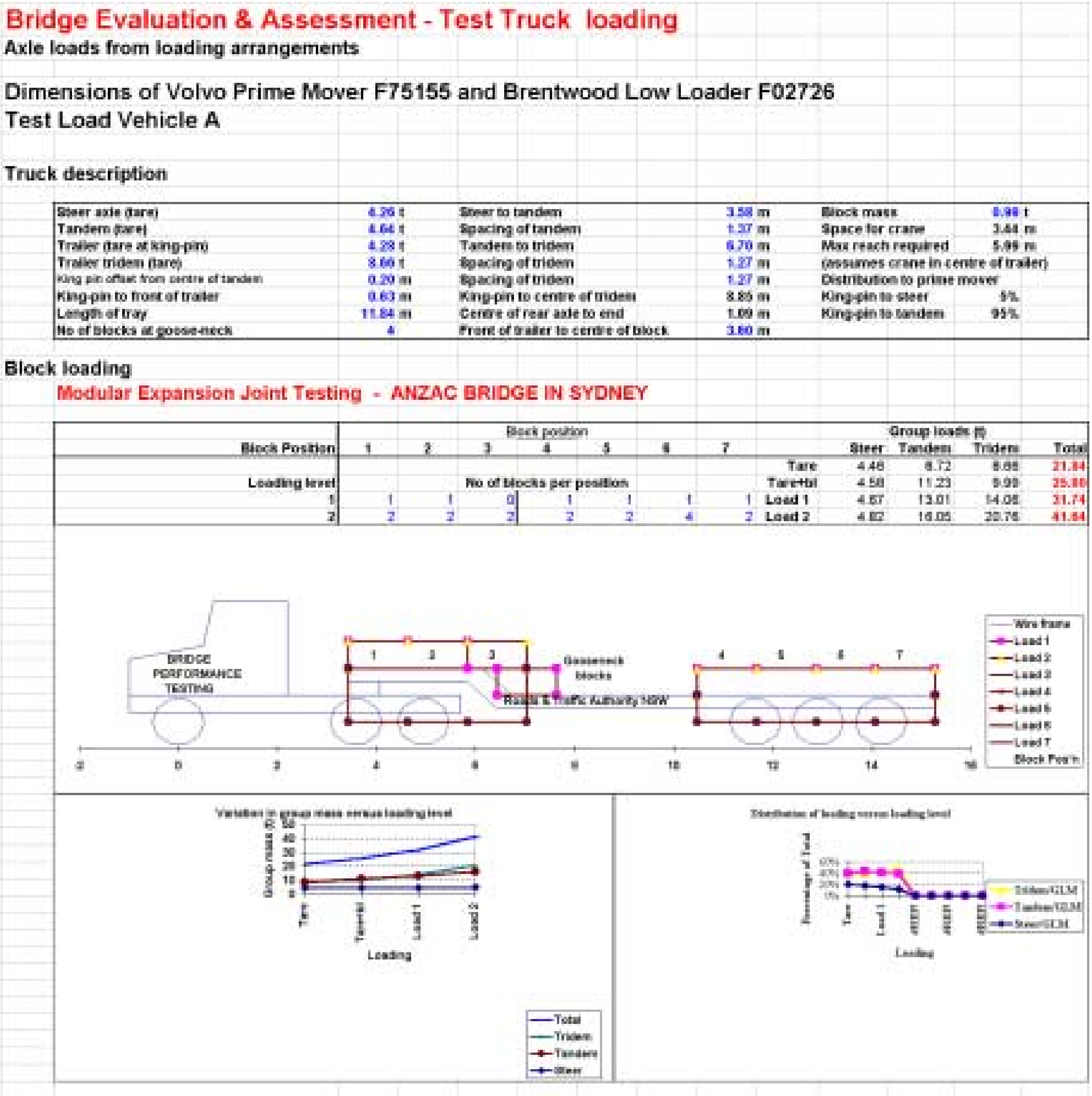


Figure 5: Taree Southbound Carriageway - Strain Gauge Locations (SG1 to SG6)



Bridge Evaluation & Assessment - Test Truck loading
Axle loads from loading arrangements

Dimensions of Volvo Prime Mover F75155 and Brentwood Low Loader F02726
Test Load Vehicle A

Truck description

Steer axle (tare)	4.26 t	Steer to tandem	3.58 m	Block mass	0.98 t
Tandem (tare)	4.64 t	Spacing of tandem	1.37 m	Space for crane	3.44 m
Trailer (tare at king-pin)	4.28 t	Tandem to tridem	6.70 m	Max reach required	5.09 m
Trailer tridem (tare)	8.66 t	Spacing of tridem	1.27 m	(assumes crane in centre of trailer)	
King pin offset from centre of tandem	0.20 m	Spacing of tridem	1.27 m	Distribution to prime mover	
King-pin to front of trailer	0.63 m	King-pin to centre of tridem	8.85 m	King-pin to steer	5%
Length of tray	11.84 m	Centre of rear axle to end	1.09 m	King-pin to tandem	95%
No of blocks at goose-neck	4	Front of trailer to centre of block	3.80 m		

Block loading
Modular Expansion Joint Testing - ANZAC BRIDGE IN SYDNEY

	Block position								Group loads (t)			
Block Position	1	2	3	4	5	6	7		Steer	Tandem	Tridem	Total
								Tare	4.46	8.72	8.66	21.84
Loading level			No of blocks per position					Tare+bl	4.58	11.23	9.99	25.80
1	1	1	0	1	1	1	1	Load 1	4.67	13.01	14.06	31.74
2	2	2	2	2	2	4	2	Load 2	4.82	16.05	20.76	41.64

Figure 6: Test Truck Load Profile used in Dynamic Testing at Anzac & Taree

Figure 6 shows the test vehicle loading arrangement used for both series of tests. The test truck was loaded to the maximum legal axle load for Australia and had a gross vehicle mass (GVM) of 42 tonnes.

Figures 7 & 8 present a schematic elevation diagram of each modular expansion joint in relation to the nominal kerbside lane position and nominal test truck wheel positions. In order to approximate true static strains and displacements, the truck was traversed over the joints at less than 3-km/hr producing negligible dynamic response of the truck or structure. All static and dynamic strains and displacements were recorded during this test.

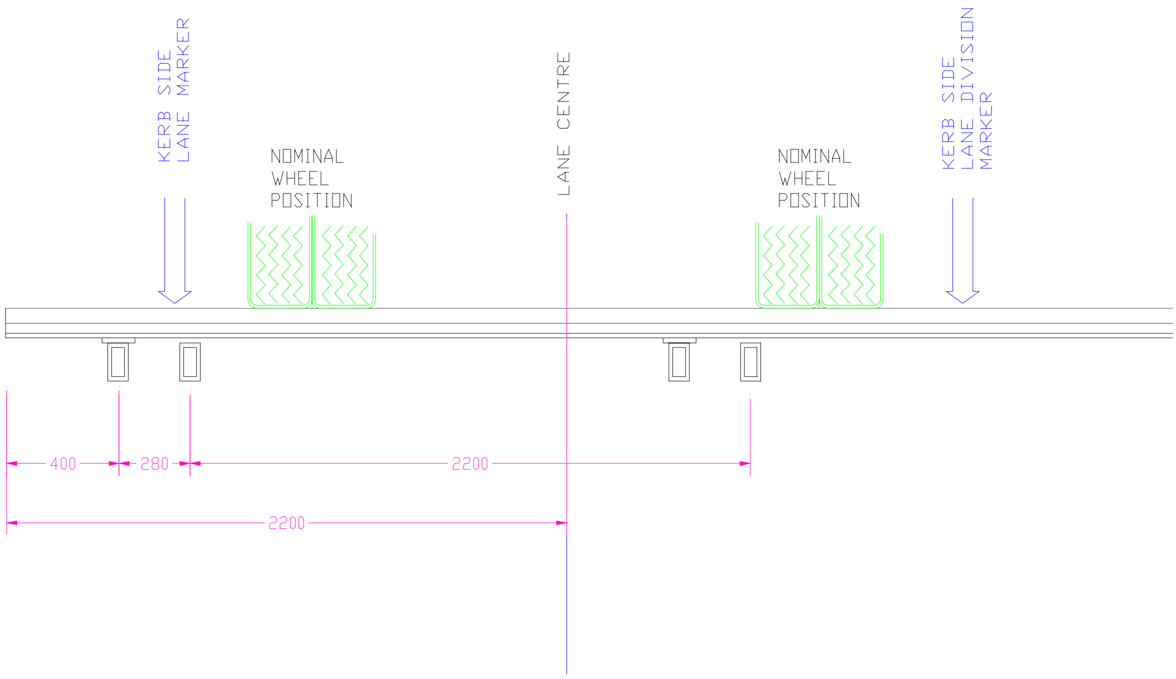


Figure 7: Elevation of MBEJ and Nominal Test Truck Position (Anzac)

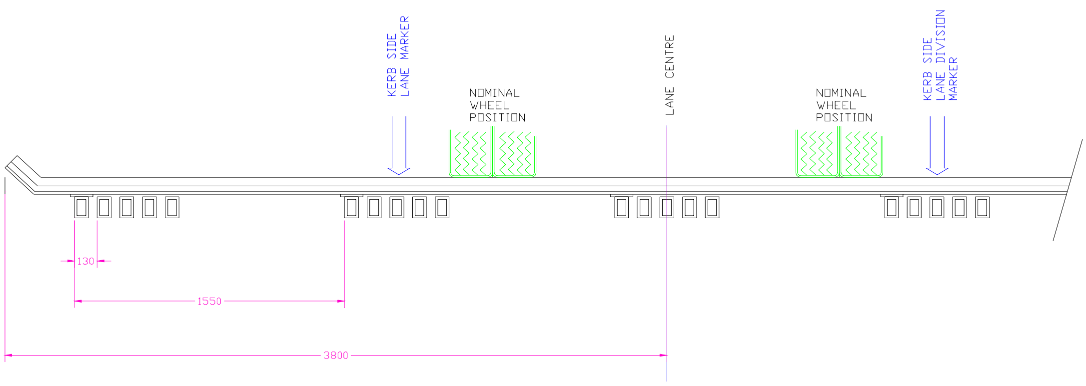


Figure 8: Elevation of MBEJ and Nominal Test Truck Position (Taree)

Following as closely as possible to the same line as the slow roll test, the truck was traversed at several speeds in the target speed range of 45-km/hr to 70-km/hr (Anzac) and 39-km/hr to 105-km/hr (Taree) with the actual truck pass-by speeds measured using a radar speed gun. The reproducible accuracy of the vehicle speed measurement is considered to be at least ± 2-km/hr.

Table 1 presents the target pass-by speeds as well as the measured (actual) pass-by speeds.

Table 1 Target & Actual Test Truck Pass-by Speeds

Run Number	Anzac		Taree	
	Target	Actual	Target	Actual
1	40 km/hr	47 km/hr	39 km/hr	39 km/hr
2	50 km/hr	50km/hr	57km/hr	57 km/hr
3	60 km/hr	53 km/hr	73 km/hr	70 km/hr
4	60 km/hr	61 km/hr	78 km/hr	82 km/hr
5	65 km/hr	63 km/hr	97 km/hr	98 km/hr
6	70 km/hr	68 km/hr	105 km/hr	104 km/hr

Further analysis included the extraction of the maximum and minimum strain and displacements resulting from the passage of the six individual test truck axles. These data were used to calculate dynamic amplification factors for each strain and displacement signal.

The positive dynamic amplification factor was calculated as follows:

$$\textbf{Dynamic Amplification Factor (Positive)} = \frac{\text{Max. Dynamic Strain (same sense as static strain)}}{\text{Maximum Static Strain}}$$

The negative dynamic amplification factor was calculated as follows:

$$\textbf{Dynamic Amplification Factor (Negative)} = \frac{\text{Max. Dynamic Strain (opposite sense to static strain)}}{\text{Minimum Static Strain}}$$

The total dynamic amplification factor was calculated as follows:

$$\textbf{Dynamic Amplification Factor (Total)} = \frac{\text{Max.} + \text{ve Dynamic Strain} - \text{Max.} - \text{ve Dynamic Strain}}{\text{Maximum Static Strain}}$$

5 STRAIN MEASUREMENT RESULTS

Tables 2 & 3 present summaries of the resulting maximum strains, stresses and dynamic amplification factors for each bridge test.

Table 2: Summary of Resulting Strains, Stresses and Dynamic Amplification Factors (Anzac)

Test Truck Pass-by Speed	Transducer Location	Strain and Stress								
		Strain (με)			Stress (MPa)			Dynamic Amplification Factors		
		Max Tensile	Max Compressive	Peak to Peak	Max Tensile	Max Compressive	Peak to Peak	Max Tensile	Max Compressive	Peak to Peak
Slow Roll	Support Bar	100	-1	101	20	0	20	0.0	0.0	0.0
	Centre Beam	154	-101	153	31	-20	31	0.0	0.0	0.0
47 km/hr	Support Bar	185	-30	215	37	-6	43	1.8	-0.4	2.2
	Centre Beam	167	-157	179	33	-31	36	1.9	-0.4	2.1
50 km/hr	Support Bar	226	-66	293	45	-13	59	2.3	-0.9	3.2
	Centre Beam	203	-113	234	41	-23	47	1.5	-0.3	1.8
53 km/hr	Support Bar	213	-54	268	43	-11	54	2.1	-0.6	2.7
	Centre Beam	136	-132	165	27	-26	33	2.0	-0.5	2.5
61 km/hr	Support Bar	270	-116	386	54	-23	77	2.7	-1.7	4.5
	Centre Beam	233	-141	308	47	-28	62	2.1	-0.6	2.6
63 km/hr	Support Bar	256	-114	370	51	-23	74	2.7	-1.9	4.6
	Centre Beam	225	-148	307	45	-30	61	1.9	-0.7	2.5
68 km/hr	Support Bar	218	-104	311	44	-21	62	2.4	-1.5	3.9
	Centre Beam	215	-137	280	43	-27	56	1.6	-0.7	2.2
Maximum	All	270	-157	386	54	-31	77	2.7	-1.9	4.6

Table 3: Summary of Resulting Strains, Stresses and Dynamic Amplification Factors (Taree)

Test Truck Pass-by Speed	Transducer Location	Strain and Stress								
		Strain (με)			Stress (MPa)			Dynamic Amplification Factors		
		Max Tensile	Max Compressive	Peak to Peak	Max Tensile	Max Compressive	Peak to Peak	Max Tensile	Max Compressive	Peak to Peak
Slow Roll	Support Bar	85	0	85	17	0	17	0.0	0.0	0.0
	Centre Beam	161	0	161	32	0	32	0.0	0.0	0.0
39 km/hr	Support Bar	97	-10	104	19	-2	21	1.5	-0.3	1.8
	Centre Beam	183	-9	192	37	-2	38	1.3	-0.1	1.4
57 km/hr	Support Bar	121	-21	139	24	-4	28	1.7	-0.3	1.9
	Centre Beam	185	-23	199	37	-5	40	1.3	-0.3	1.6
70 km/hr	Support Bar	133	-25	153	27	-5	31	1.9	-0.5	2.3
	Centre Beam	186	-33	202	37	-7	40	1.3	-0.5	2.1
80 km/hr	Support Bar	151	-43	177	30	-9	35	2.2	-0.6	2.6
	Centre Beam	203	-45	239	41	-9	48	1.8	-0.6	2.5
98 km/hr	Support Bar	177	-49	226	35	-10	45	2.3	-0.8	3.1
	Centre Beam	233	-56	265	47	-11	53	1.6	-0.7	2.7
104 km/hr	Support Bar	165	-54	219	33	-11	44	2.3	-0.9	3.1
	Centre Beam	219	-46	255	44	-9	51	1.6	-0.6	2.6
Maximum	All	233	-56	265	47	-11	53	2.3	-0.9	3.1

The following amplification factors are deduced from this investigation:

- The maximum beam stress total dynamic amplification factors measured were 4.6 (Anzac) and 3.1 (Taree).
- The maximum beam stress positive dynamic amplification factors were 2.7 (Anzac) and 2.3 (Taree).
- The maximum beam stress negative dynamic amplification factors were 1.9 (Anzac) and 0.9 (Taree).

These dynamic amplification factors are clearly well in excess of existing bridge codes. From a fatigue analysis perspective, the dynamic response of a structure may lead to higher than expected strain levels due to dynamic amplification.

Test Truck Slow Roll

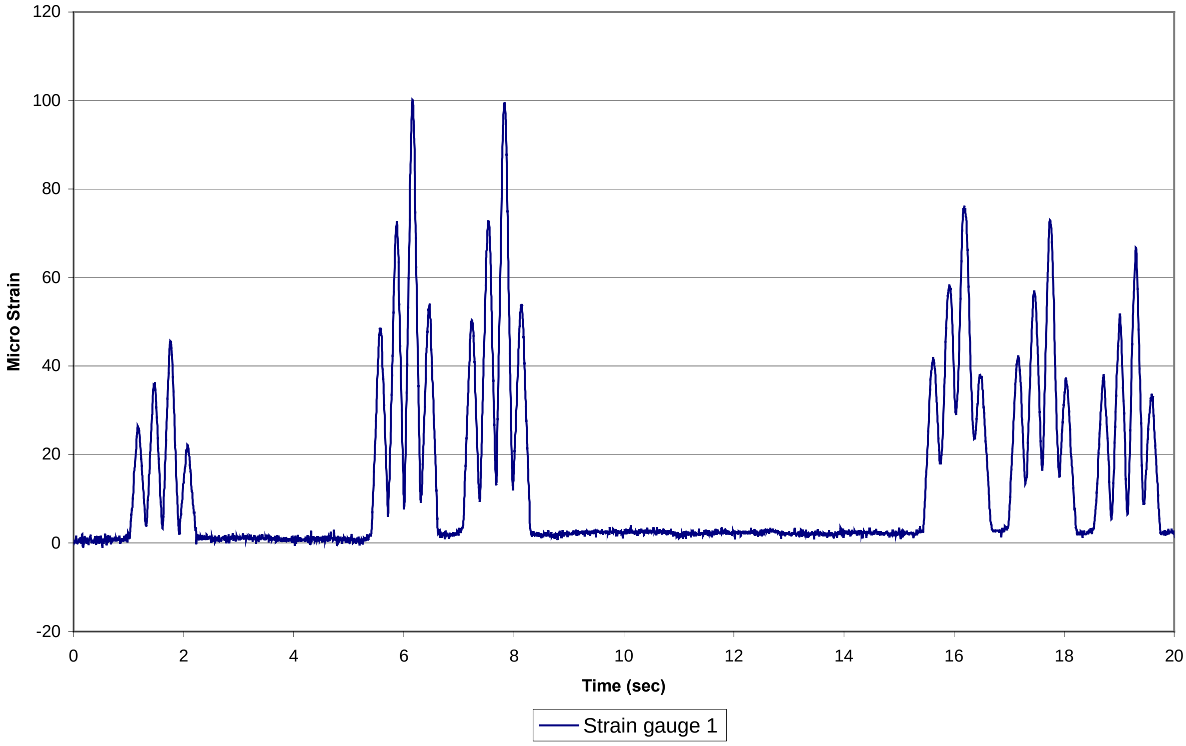


Figure 9: Quasi-static response due to test vehicle pass-by (Anzac)

Figure 9 shows the quasi-static response of a strain gauge (SG1) located in the middle of an Anzac support bar and the impact of each of the test vehicle's six axles with each of the centre beams connected to this support bar is clearly evident.

The dynamic behaviour of the Anzac Bridge MBEJ may be considered as two independent structures (i.e. one structure with one set of odd numbered centre beams with associated support bars, and a second structure with one set of even numbered centre beams and support bars). The coupled nature of the "*odd*" and "*even*" structures is further demonstrated in **Figure 10**.

The dynamic response here is demonstrated by the impact of the tandem axles of the prime mover and the tri-axles of the trailer where the vibration is in phase and virtually continuous. An independent centre beam structure responding to a single impulse would, of course, be expected to display an initial maximum amplitude followed by an exponential decay.

The build-up in centre beam response may be attributed to the phase relationship of each wheel to centre beam impact. This phenomenon is described as coupled centre beam resonance [Ancich *et al* (8)].

A simple comparison between **Figures 9 & 10** shows that the quasi-static slow roll produced 100 με (Peak-Peak) and the 61-km/hr pass-by produced 385 με (Peak-Peak). This comparison indicates a dynamic amplification factor (DAF) of, at least, 3.85 times static.

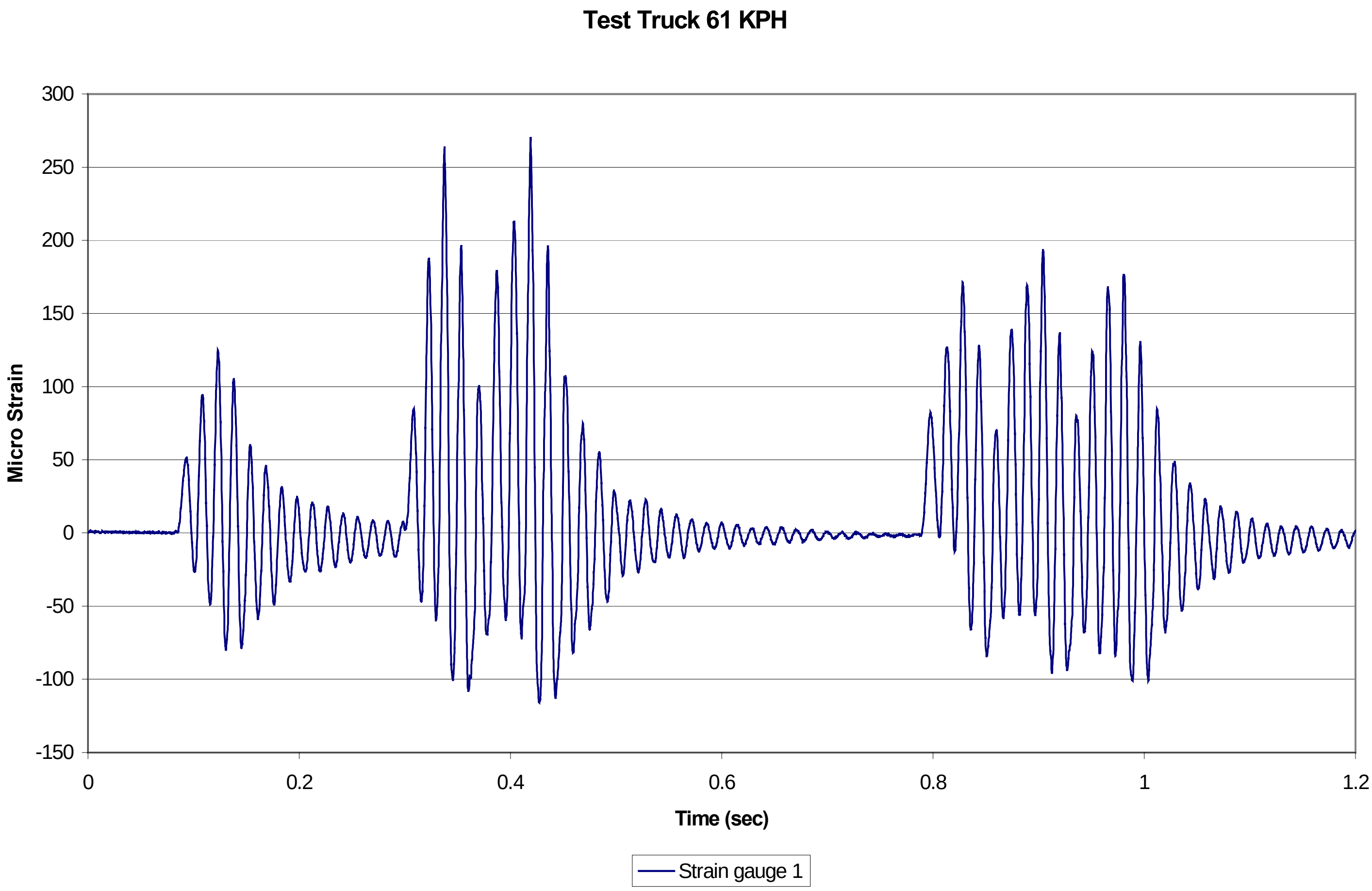


Figure 10: Dynamic response induced by heavy vehicle pass-by (Anzac)

Furthermore, not only are the peak dynamic strains at least 3.85 times the quasi-static but further observation of **Figure 10** shows that the steer and tandem axles of the prime mover produced at least 16 cycles of vibration (per vehicle passage) where the dynamic strain equalled or exceeded the quasi-static strain of 100 με (Peak-Peak).

Similarly, the tri-axle group of the trailer produced at least 14 cycles of vibration (per vehicle passage) where the dynamic strain equalled or exceeded the quasi-static strain of 100 με (Peak-Peak). The simple addition of these events shows that each heavy vehicle passage, of the load configuration of the test vehicle, produced around 30 vibration cycles where the dynamic strain equalled or exceeded the quasi-static strain of 100 με (Peak-Peak).

6 CONCLUSION

Structural dynamics studies were performed on a single support bar design MBEJ installed in the western abutment of Anzac Bridge and a multiple support bar design MBEJ installed into the southern abutment of the southbound carriageway of the bridge over the south channel of the Manning River (Taree By-pass). The studies showed that for these joints:

- The response of MBEJ's, responsible for peak strains, is predominantly dynamic.
- Depending on the components of construction, configuration and loading, MBEJ's may exhibit a non-linear dynamic response.
- The DAF cannot be adequately prescribed in a Code-of-Practice.
- Notionally in-phase or partially in-phase excitation is common. Notionally out-of-phase excitation is less common.

- The DAF for single support bar design MBEJ's (and variants thereof) is damping dependent and has a lower limit of 2.5 and an upper limit exceeding 5.
- The DAF for multiple support bar design MBEJ's is also damping dependent (but to a lesser extent) and has a lower limit of 2 and an upper limit exceeding 3.
- However, for any joint (both single & multiple support bar designs) the DAF achieved in service will depend on a number of factors including, joint configuration, number of exciting axles and the extent to which the manufacturer is able to incorporate damping into the design.
- Dynamic Finite Element Models must be used in design. The calibration must be to real loads operating at speeds that will give rise to notionally in-phase excitation.
- Steel components should be designed for infinite fatigue cycles.
- It is easier to estimate the extreme values of dynamic load response than to estimate the weighted mean value of dynamic load response. Hence, design should be done using extreme values coupled with CAFL properties of steel.

The widely held assumption of quasi-static behaviour for single and multiple support bar design MBEJ's (and variants thereof) is not sustainable and both bridge designers and modular joint suppliers must think in terms of a fully dynamic system.

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