Forth Estuary Transport Authority
Forth Road Bridge

Main Tower Link Arrangements Assessment for 2010 BSALL

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This report has been prepared in accordance with procedure OP/P03 of W A Fairhurst & Partners' Quality Assurance System.

CONTENTS

1 INTRODUCTION

Assessments of the main tower link arrangements have previously shown that elements of the links are overstressed under the application of the recommended 2005 BSALL loading. In order to prioritise essential maintenance and upgrading works FETA requested that W.A. Fairhurst & Partners review the assessment of the link arrangements for a lower level of 2010 BSALL derived from a reduced return period.

The review was to determine the lowest levels of stress indices associated with a 2010 BSALL which can be safely accepted thereby limiting the extent of any upgrading required to the brackets in the short term. On this basis we have also considered what further reductions to the recommended 2010 BSALL loading which may be acceptable in the short term.

This report details the findings of the re-assessment, the reductions in the 2010 BSALL which we believe can be accepted in the short term and the extent of upgrading works required for this reduced level of 2010 BSALL.

2 ASSESSMENT FOR 2010 BSALL WITH A 10 YEAR RETURN PERIOD

The main tower link arrangements have been re-assessed for the 2010 BSALL derived from a return period of 1 in 10 years and the calculated stress indices are tabulated in tables 1 and 2 Appendix A. The reduction in return period to 1 in 10 years from 1 in 120 years for the recommended loading reduces the total carriageway loading by approximately 8%. For comparison the overstress indices due to load combinations comprising full design HA loading are also provided.

As reported previously the levels of stress are lower in the side span link arrangement in comparison to the main span. The operational load combinations which produce overstress indices and the elements affected are as follows.

Main Span Link Arrangement,

- Dead and Wind – The welds connecting the bracket to the tower only.
- Dead, BSALL and BSFLL – The welds connecting the bracket to the tower and the main plates of the bracket itself. The main plates were less highly stressed than the welds.
- Dead, BSALL, BSFLL and Wind 50mph – The welds connecting the bracket to the tower and the main plates of the bracket itself. All overstress indices were increased from the dead and live case above but the main plates were still less highly stressed than the welds.

Side Span Link Arrangement,

- Dead, BSALL and BSFLL – The welds connecting the bracket to the tower and the main plates of the bracket itself. The main plates were less highly stressed than the welds.
- Dead, BSALL, BSFLL and Wind 50mph – The welds connecting the bracket to the tower and the main plates of the bracket itself. The levels of stress are less than for the dead, BSALL and BSFLL combination.

3 CONSIDERATION OF FURTHER REDUCTIONS TO THE RECOMMENDED 2010 BSALL

3.1 Identification of Potential Reductions

An initial review of the BSALL derivation was undertaken to identify aspects where, for a particular element on the bridge, the recommended loading could be reduced. The following where identified for consideration;

- The adopted lane factors for lanes coincident with the critical lane (Lane 1).
- The application of an ultimate limit state load factor to the BSALL loading and the likelihood of this factored loading occurring.
- The application of the BSALL loading in the assessment which is applied in conjunction with a KEL.

3.2 Lane Factors

The recommended BSALL is formed of both the critical lane 1 loading and lane factors for the application of coincident loading in adjacent lanes and carriageways. In the assessment of the links the critical loadcases are based on both lanes of a single carriageway being loaded i.e. lanes 1 and 2. The basis of the recommended lane factors for lanes 1 and 2 is summarised below.

- The lane 1 factor is taken as 1.0 times the highest calculated lane loading.
- The lane 2 factor represents the lane adjacent to the lane 1. Calculations for lane 2 are undertaken on the same statistical basis as lane 1. These loadings are then compared to those for lane 1. On this basis the 2010 BSALL lane 2 is a maximum of 0.48 times the lane 1 loading. However we normally recommend that the factor for lane 2 be set as 0.67 as detailed in the current design codes. The reason for this recommendation is that the increased factor will cover loading scenarios which may not have been predicted by the BSALL analysis. where does 0.67 come from.

The use of an increased factor of 0.67 for the lane 2 loading is intended to allow for scenarios, which may occur but are not reflected in the sampled traffic data. However it is possible to use the calculated lane factor of say 0.48 and still have a margin of safety on the total carriageway loading. The reasoning behind this is as follows. The calculated lane factor is based on lane 2 load being calculated on the same statistical basis as lane 1. That is both lanes individually have a 5% probability of occurrence in the return period. When these loadings are combined to form a carriageway loading the actual probability will be reduced significantly below 5%.

* surely the same argument could be held for the lane 1 loading

Based on the above comments the reduction in lane factor could be adopted whilst still giving a margin for scenarios not reflected in the sampled data, albeit a margin reduced by 14%. ?

3.3 Application of an Ultimate Limit State Live Load Factor

The derivation of the BSALL loading is based on actual traffic data and the application of statistical techniques to achieve a loading which has a 5% probability of occurrence in 120 years. This loading is referred to as the characteristic loading. The normal practice is to calculate a nominal loading which is compatible with the design codes by dividing the characteristic loading by 1.2.

The assessment of the links is undertaken at the ultimate limit state in accordance with the standards. For load combinations involving dead plus BSALL this involves applying a factor of 1.5 to the nominal BSALL loading and in doing so we greatly reduce the probability that the BSALL loading will actually be realised. We understand that in the derivation of the full HA loading detailed in BD 37 the ultimate limit state loading would occur once in every 200,000 years. This fact is noted in design guides where the ultimate limit state loading represents extremely improbable occurrences. For a reduced return period of 10 years this figure will be substantially reduced. However the application of a factor of 1.5 still significantly lowers the probability that the derived loading will be realised from that assumed in the original derivation.

The load combinations involving BSALL and wind use a factor of 1.25 on the BSALL loading. A reduction in the probability from that assumed in the original derivation will still be made although the magnitude will not be as great as for cases with no wind load.

The issue is then whether it would be safe to use the characteristic loading for the assessment of the link brackets. This requires consideration of the potential mode of failure of the bracket if the characteristic loading was exceeded, the consequences of a failure and if necessary the measures which could be put in place to monitor the bracket for signs of failure.

For the link brackets the overstresses are due to yielding of the welds and yielding of the plates under combined stresses due to shear and bending. Our buckling analysis has shown that the bracket will not buckle under the recommended BSALL. Therefore should an extreme loading be realised during the short term then in the case of the bracket local buckling is likely to occur with stresses re-distributing until equilibrium is achieved. Failure would most likely occur in a controlled manner as opposed to a sudden failure due to say buckling. In relation to the welds re distribution of stresses is more difficult to achieve. Therefore to reduce the risk of a failure of the welds strengthening of the welds would be a prudent option in the short term.

More significantly we should consider the fact that whilst the characteristic loading is being used to assess the level of stress the capacity of the elements also assumes factors on material strength. For the bracket plates the yield stress is reduced by 1.155 and for the welds the capacity is reduced by 1.32.

On the above basis we are of the opinion that the characteristic BSALL loading could be adopted for short term assessment of the links. However we would recommend that routine inspections of the link brackets are carried out to monitor for signs of distortion caused by yielding which would indicate that the loading had been achieved.

3.4 Adjustment for KEL Effects

The BSALL loading applied in the assessment includes a KEL in each lane based on that stated in BD 37 but applied with the recommended lane factors.

The inclusion of the KEL is a conservative approach as the derivation of the BSALL has not allowed for any adjustment to take account of simultaneous application with the KEL. The reason being that the non linear nature of the Forth Road Bridge makes the adjustment for the KEL very difficult. As the KEL is only a small proportion of the total loading we considered it reasonable to apply the KEL with the BSALL.

However for particular elements it is possible to consider simplistic methods of adjustment to determine the approximate magnitude by which the BSALL would be reduced to take account of the KEL. These calculations indicate that the BSALL loading would decrease by approximately 3.6%. If we then assume that half of a typical UDL is transferred to the link arrangements this could result in a 2% reduction in the load in the links.

Due to the small percentage change caused by allowance for the KEL in the assessment the implications on the link brackets have not been considered further.

4 EFFECTS OF A REDUCED 2010 BSALL ON THE LINK ARRANGEMENTS

The greatest effect on the total loading in terms of reduction is from the adjustment of the lane factors and use of the characteristic loading to represent the Ultimate Limit State.

These effects have been incorporated and the reduced 2010 BSALL loading applied to the computer models of the bridge. The effect on the calculated stress indices is shown in Tables 1 and 2 Appendix A for the main span and side span respectively.

The tables show that the reductions in the BSALL loading significantly reduce the stress indices in the plates to levels marginally above 1.00 for both critical operational load cases. The location where the stress index exceeds 1.00 is limited to section D which is immediately inside the face of the tower. The levels of overstress being limited to 1.03 under load combination of dead, BSALL and BSFLL increasing to 1.06 under load combination of dead, BSALL, BSFLL and 50mph wind.

Significant levels of overstress remain in the welds albeit at reduced level from those calculated for the recommended BSALL with the 1 in 10 year return period. Strengthening of the welds is discussed later in this report.

5 EFFECTS OF A REDUCED 2010 BSALL ON THE END POST

Under load combinations representing the operational loading of the bridge the end posts of the stiffening truss are overstressed under the dead and BSALL.

The stiffening truss assessment reports a ULS overstress index for the end post of 1.24. This calculated overstress ignores local moments arising due to the fixity of the joints in the truss in accordance with the assessment standard as the joints in the truss are assumed to rotate at the ultimate limit state and redistribute these stresses. However if we choose to adopt the characteristic loading for the assessment we consider it prudent to include the stresses due to moments which increases the overstress index to 1.39.

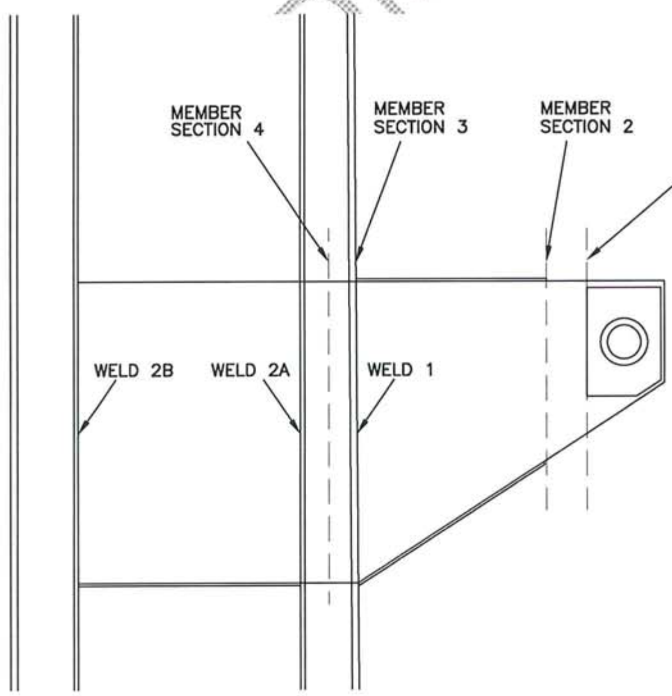
Based on the reduced loading the reduction in force in the end post will result in the overstress being reducing to approximately 1.13. This overstress and is due to local buckling of the plates making up the box section which forms the end post. Failure of the end post if extreme loading is realised would likely involve local buckling of the critical plates. The end posts could be monitored visually for any signs of this scenario having occurred. A total failure of the end post is unlikely as for this to occur the section will yield and allow redistribution of the stresses due to moments. This is the philosophy applied for ultimate limit state checks of the truss members. Redistribution of moments reduces the overstress index to 0.95.

6 STRENGTHENING OF THE WELDS AT THE LINK BRACKET

Under the reduced BSALL loading the welds connecting the bracket to the tower have significant levels of overstress. As a minimum we would recommend that these welds are strengthened to the level of the reduced BSALL loading. There would not appear to be any merit in attempting to strengthen beyond this level as the capacity of the plates would then control the rating of the links. In addition strengthening to higher levels of loading will require significant increases in weld sizes which are more problematic to form and have greater potential to create distortions in the elements being welded.

Based on the reduced BSALL loading the weld sizes required for the bracket to the tower would be as follows, note that these sizes ignore any existing weld. For weld 1 weld sizes have been given for a single sided weld and a double sided weld as access may restrict the welding which can be undertaken. The location of the welds are indicated in the sketch below.

Weld Location	Proposed Weld Type	Single Sided Weld Size		Double Sided Weld Size	
		Main Span	Side Span	Main Span	Side Span
1	Fillet Weld	28 mm	25 mm	14 mm	12 mm
2A / 2B	Fillet Weld	N/A	N/A	8	8 mm



Location of Welds 1, 2A and 2B

APPENDIX A – TABLES

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Table 1 – Main Span Link Arrangement Stress Indices

				Link Member						Bracket Welds					Bracket Section 2 La 0.305 m Md 0.53 MNm Vd 3.033 MN		Bracket Section 3 1.143 m 2.255 MNm 5.321 MN 0.718 MNm		Bracket Section 1 0.1524 m 0.357 MNm 2.62 MN		Bracket Section 4 1.143 m 1.736 MNm 5.321 MN	
Load Case	Load in end link arrangement (MN) *(member type 28 in Lusas Model)*	Load in single link arm (MN)	Element Capacity expressed as equivalent single link member force (MN)	Link Member	Link Member Welds	Link Pins top	Link Pins Bottom	Link Fork Coupling	Link Pin Slab	Bracket Weld 1 outer weld	Bracket weld 2A (Outer stiffener)	Bracket weld 2B (inner cell stiffener)	Bracket weld longitudinal (web to flange)	Bracket weld cheek plate	Moment shear interaction (V>0.5Vd)	Final OI Value	Moment shear interaction (V>0.5Vd)	Final OI Value	Moment shear interaction (V>0.5Vd)	Final OI Value	Moment shear interaction (V>0.5Vd)	Final OI Value
				2.693	*2.107*	*2.458*	*2.484*	*2.256*	*2.479*	0.984	0	0.81	6.38	4.353								
Maximum Capacity of Plates in Bracket	**3.03**	1.515		0.56	0.72	0.62	0.61	0.67	0.61	**1.54**	0.00	**1.87**	0.24	0.35	No	0.87	No	0.77	Yes	0.80	No	1.00
Permanent Loading																						
Dead	**0.8706**	0.4353		0.16	0.21	0.18	0.18	0.19	0.18	0.44	0.00	0.54	0.07	0.10	No	0.25	No	0.22	No	0.19	No	0.29
Dead + Wind	**2.6**	1.3		0.48	0.62	0.53	0.52	0.58	0.52	**1.32**	0.00	**1.60**	0.20	0.30	No	0.75	No	0.66	No	0.55	No	0.86
Operational Load Cases with Characteristic 2010 BSALL based on a 1 in 10 year return period and adjusted Lane Factors																						
Dead + BSALL + BSFLL	**3.124**	1.562		0.58	0.74	0.64	0.63	0.69	0.63	**1.59**	0.00	**1.93**	0.24	0.36	Yes	0.93	No	0.79	Yes	0.86	No	**1.03**
Dead + BSALL + BSFLL + 50mph Wind	**3.207**	1.6035		0.60	0.76	0.65	0.65	0.71	0.65	**1.63**	0.00	**1.98**	0.25	0.37	Yes	0.98	No	0.81	Yes	0.91	No	**1.06**
Operational Load Cases with recommended 2010 BSALL based on a 1 in 10 year return period																						
Dead + BSALL + BSFLL	**3.892**	1.946		0.72	0.92	0.79	0.78	0.86	0.78	**1.98**	0.00	**2.40**	0.31	0.45	Yes	**1.40**	No	0.99	Yes	**1.32**	No	**1.28**
Dead + BSALL + BSFLL + 50mph Wind	**3.505**	1.7525		0.65	0.83	0.71	0.71	0.78	0.71	**1.78**	0.00	**2.16**	0.27	0.40	Yes	**1.16**	No	0.89	Yes	**1.09**	No	**1.15**
Full Design Loading																						
Dead + HA + Ftway	**6.51**	3.255		**1.21**	**1.54**	**1.32**	**1.31**	**1.44**	**1.31**	**3.31**	0.00	**4.02**	0.51	0.75	Yes	**3.02**	Yes	**1.80**	Yes	**2.87**	Yes	**2.43**
Dead + HA + Ftway + Wind (78mph)	**5.51**	2.755		**1.02**	**1.31**	**1.12**	**1.11**	**1.22**	**1.11**	**2.80**	0.00	**3.40**	0.43	0.63	Yes	**2.40**	Yes	**1.42**	Yes	**2.28**	Yes	**1.90**

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Table 2 – Side Span Link Arrangement Stress Indices

Load Case	Load in end link arrangement (MN) *(member type 28 in Lusas Model)*	Load in single link arm (MN)	Element Capacity expressed as equivalent single link member force (MN)	Link Member: Link Member	Link Member: Link Member Welds	Link Member: Link Pins top	Link Member: Link Pins Bottom	Link Member: Link Fork Coupling	Link Member: Link Pin Slab	Bracket Welds: Bracket Weld 1 outer weld	Bracket Welds: Bracket weld 2A (outer stiffener)	Bracket Welds: Bracket weld 2B (inner cell stiffener)	Bracket Welds: Bracket weld longitudinal (web to flange)	Bracket Welds: Bracket weld cheek plate	Bracket Section 2 (La 0.305 m, Md 0.687 MNm, Vd 3.381 MN, Mf): Moment shear interaction (V>0.5Vd)	Bracket Section 2: Final OI Value	Bracket Section 3 (0.863 m, 2.354 MNm, 5.321 MN, 0.749 MNM): Moment shear interaction (V>0.5Vd)	Bracket Section 3: Final OI Value	Bracket Section 1 (0.1524 m, 0.463 MNm, 2.848 MN): Moment shear interaction (V>0.5Vd)	Bracket Section 1: Final OI Value	Bracket Section 4 (0.864 m, 1.736 MNm, 5.321 MN): Moment shear interaction (V>0.5Vd)	Bracket Section 4: Final OI Value
				2.693	*2.107*	*2.458*	*2.484*	*2.256*	*2.479*	**1.126**	**0**	**1.075**	**6.38**	**4.353**								
Maximum Capacity of Welds in Bracket	**2.145**	1.0725		0.40	0.51	0.44	0.43	0.48	0.43	0.95	0.00	1.00	0.17	0.25	No	0.48	No	0.39	No	0.35	No	0.53
Permanent Loading																						
Dead	**0.788**	0.394		0.15	0.19	0.16	0.16	0.17	0.16	0.35	0.00	0.37	0.06	0.09	No	0.17	No	0.14	No	0.13	No	0.20
Dead + Wind	**1.112**	0.556		0.21	0.26	0.23	0.22	0.25	0.22	0.49	0.00	0.52	0.09	0.13	No	0.25	No	0.20	No	0.18	No	0.28
Operational Load Cases with Characteristic 2010 BSALL based on a 1 in 10 year return period and adjusted Lane Factors																						
Dead + BSALL + BSFLL	**2.769**	1.3845		0.51	0.66	0.56	0.56	0.61	0.56	**1.23**	0.00	**1.29**	0.22	0.32	No	0.61	No	0.51	No	0.46	No	0.69
Dead + BSALL + BSFLL + 50mph Wind	**2.862**	1.431		0.53	0.68	0.58	0.58	0.63	0.58	**1.27**	0.00	**1.33**	0.22	0.33	No	0.63	No	0.52	Yes	0.48	No	0.71
Operational Load Cases with recommended 2010 BSALL based on a 1 in 10 year return period																						
Dead + BSALL + BSFLL	**3.458**	1.729		0.64	0.82	0.70	0.70	0.77	0.70	**1.54**	0.00	**1.61**	0.27	0.40	Yes	0.79	No	0.63	Yes	0.78	No	0.86
Dead + BSALL + BSFLL + 50mph Wind	**3.132**	1.566		0.58	0.74	0.64	0.63	0.69	0.63	**1.39**	0.00	**1.46**	0.25	0.36	No	0.69	No	0.57	Yes	0.62	No	0.78
Full Design Loading																						
Dead + HA + Ftway	**5.76**	2.88		**1.07**	**1.37**	**1.17**	**1.16**	**1.28**	**1.16**	**2.56**	0.00	**2.68**	0.45	0.66	Yes	**1.98**	Yes	**1.11**	Yes	**1.97**	No	**1.43**
Dead + HA + Ftway + Wind (78mph)	**5.129**	2.5645		0.95	**1.22**	**1.04**	**1.03**	**1.14**	**1.03**	**2.28**	0.00	**2.39**	0.40	0.59	Yes	**1.65**	No	0.94	Yes	**1.65**	No	**1.28**

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