FORTH ESTUARY TRANSPORT AUTHORITY

FORTH ROAD BRIDGE

ASSESSMENT OF CONNECTIONS BETWEEN STIFFENING TRUSS AND MAIN AND SIDE TOWERS

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1. INTRODUCTION

W. A. Fairhurst & Partners were appointed by the Forth Estuary Transport Authority to undertake a supplementary assessment of elements connecting the suspended structure of the Forth Road Bridge to the main and side towers.

The need for the supplementary assessment arose due to the initial findings of the main report on the stiffening truss which identified potential high stresses in the link elements and in particular their connections. This report details the further analysis undertaken and the associated results and supplements W. A. Fairhurst & Partners' Report titled; Stiffening Truss Assessment Report dated March 2008.

1. CONNECTIONS

2.1 Introduction

The connections between the stiffening trusses and the towers are comprised of four discrete arrangements. At the side towers the truss ends are supported by rockers and lateral bearings. At the main towers the truss ends are connected by lateral thrust bearings, to transmit the lateral loadings, and truss end links supporting the vertical loads.

2.2 Connection between Stiffening Truss and Main Towers

The links connecting the main towers to the ends of the stiffening trusses are formed from mild steel H sections. The link embers are connected to the bottom chord of the truss and to cantilevered support brackets from the main towers. These connections are formed with pins made from high tensile steel. Details of the links are shown in Figure 1.

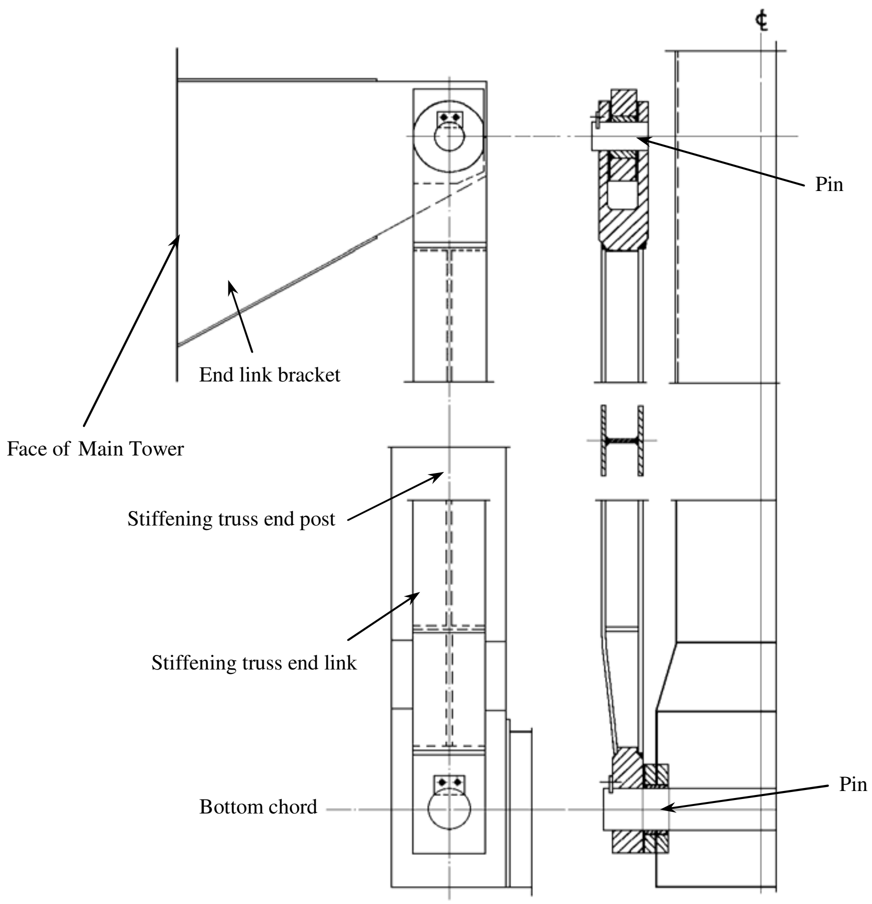

Figure 1 – Stiffening Truss End Link

The link members are not designed to resist lateral forces. These forces are transferred to the main towers by the lateral thrust members. Sliding bearings which form part of the arrangement restrain the lateral loads but allow the trusses to move longitudinally in the axis of the bridge. Both the side span and main span stiffening trusses are connected using this detail. This arrangement is shown on Figure 2.

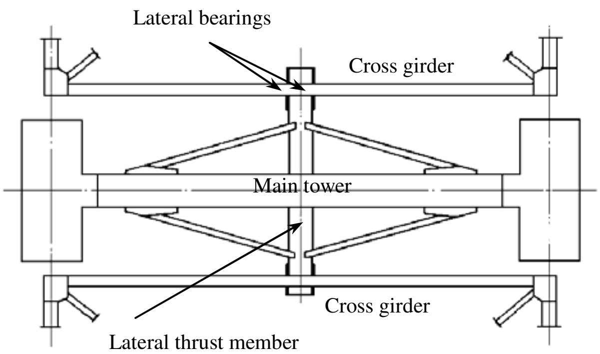

Figure 2 – Arrangement of Lateral Bearings at Main Towers

2.3 Connection between Stiffening Truss and Side Towers

Each stiffening truss is supported at the side towers by rockers, each of which consists of mild steel H steel section connected to the top chord of the stiffening truss and fixed to the concrete of the side tower. The connection of the rocker to the side tower and to the truss is made by post tensioned screwed rods. The rocker arrangement is shown in Figure 3.

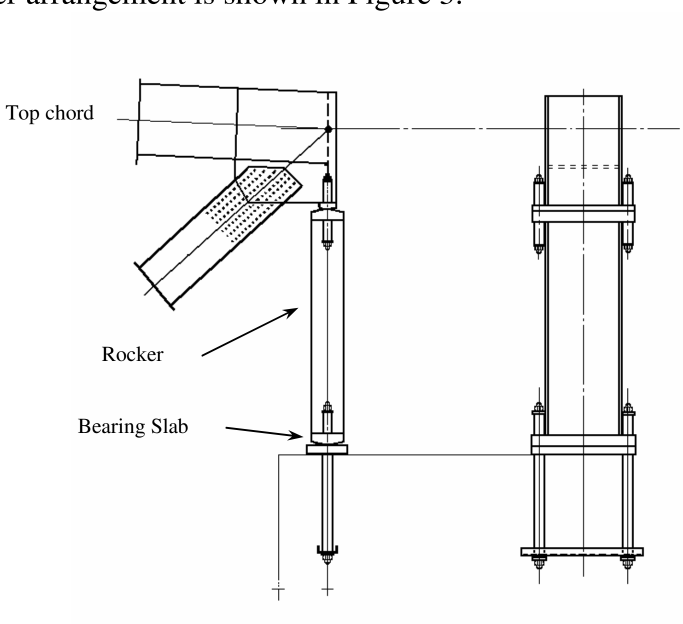

Figure 3 – Arrangement of Rockers at Side Towers

The rockers as with the links at the main towers are designed to support vertical loads only. Lateral loads are transmitted to the side towers via the lateral bearings which are cast in to the concrete wall of the side tower. Three 64.5mm diameter post tensioned bars clamp the end of the lateral bracing members to the bearing, the frictional force developed supporting the self weight of the lateral members. Longitudinal loads are transferred to the side tower through the post tension bars or by bearing through the pivot block depending on the direction of the load. The arrangement is detailed in Figure 4 below.

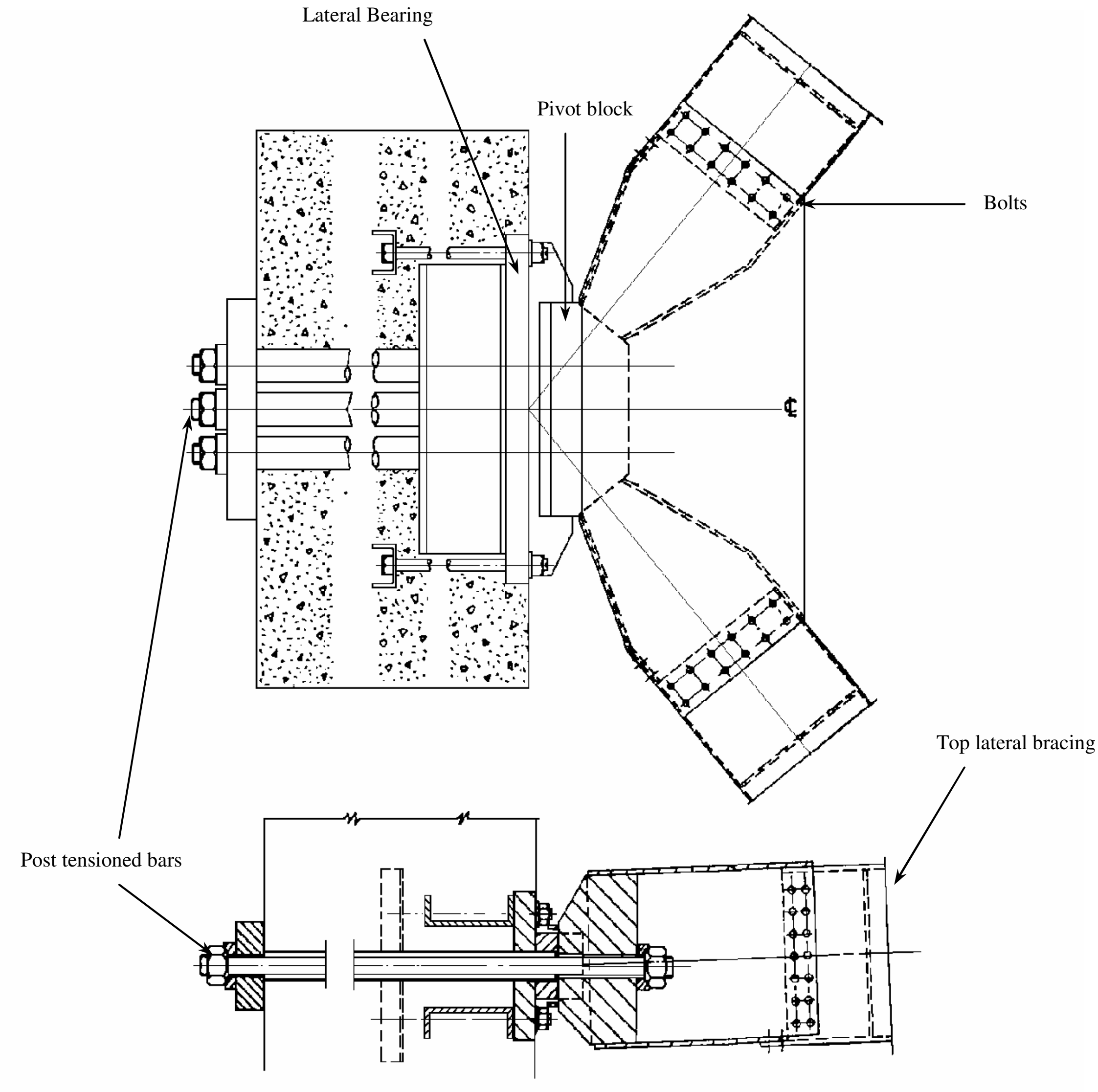

Figure 4 – Arrangement of Lateral Bearings at Side Towers

3. ANALYSIS

The analysis of the elements was undertaken using finite element computer models. Loadings and global displacement were obtained from global models of the bridge while local developed models were used to analyse local stress distributions. A nonlinear contact analysis was performed to establish the contact stresses in the rocker bearing slabs at the side towers. A linear buckling analysis was also undertaken to determine the maximum load that can be supported by the end link brackets at the main towers prior to structural instability. Numerous load combinations were considered in the assessment, however in the following sections only the critical load combinations have been reported.

4. ASSESSMENT

4.1 General

All the elements in the connections were assessed according to BD 56/96. Loading scenarios are as detailed in Section 5.0 of the Stiffening Truss Assessment Report dated March 2008. Bridge Specific Assessment Live Loading (BSALL) is based on the report by W. A. Fairhurst & Partners titled Bridge Specific Assessment Live Loading dated June 2006.

4.2 Lateral Thrust Members at Main Towers

A summary of lateral thrust members overstress indices is shown in Table 1 below.

The critical combinations for lateral thrust members were:

Dead + Wind – maximum wind loading applied to the main span and relieving wind loading applied to the remaining spans, wind loading considered transverse to stiffening truss.

Dead + Wind + Live – maximum wind loading with coexisting live loading applied to the main span, the remaining spans were loaded with wind load calculated for locations that have a relieving effect on the element under consideration.

Element	Loadcase	Limit State	Overstress Indices
Lateral thrust member	Dead + Wind	ULS	0.816
	Dead + Wind + Live	ULS	0.638
Lateral bracing element	Dead + Wind	ULS	0.908
	Dead + Wind + Live	ULS	0.403

Table 1 – Summary of Lateral Thrust Member Overstress Indices

The assessment found no overstressed elements in lateral thrust arrangement. The maximum overstress index was 0.816 for the lateral thrust member and 0.908 for the lateral bracing. These occurred under a load combination that incorporated wind loading. The lateral thrust members are not subjected to vertical loading from the stiffening truss and as a result live loading has little effect on these elements.

4.3 Stiffening Truss End links

A summary of the critical overstress indices for the stiffening truss end links at the main towers is provided in Table 2.

The critical load combinations for the links were:

Dead + Wind – maximum wind loading applied to the main span and relieving wind loading applied to the remaining spans, wind loading considered at 50 degrees to stiffening truss to produce greatest longitudinal loads.

Dead + Wind + Live – maximum wind loading with coexisting live loading applied to the one side span , the remaining spans were loaded with wind load calculated for locations that have a relieving effect on the element under consideration.

Dead + Live (BSALL) – HA or BSALL applied to the single carriageway over 40 bays from one tower and the opposite carriageway loaded for the remainder of the loaded length from the opposite tower.

Link element	Loadcase	Limit State	Overstress Indices
Main members	Dead	ULS	0.139
	Dead + Wind	ULS	0.216
	Dead + Wind + Live	ULS	0.698
	Dead + Live	ULS	0.767
	Dead + BSALL	ULS	0.607
Pin joints	Dead	ULS	0.159
	Dead + Wind	ULS	0.247
	Dead + Wind + Live	ULS	0.800
	Dead + Live	ULS	0.878
	Dead + BSALL	ULS	0.695
Welds	Dead	ULS	0.150
	Dead + Wind	ULS	0.233
	Dead + Wind + Live	ULS	0.754
	Dead + Live	ULS	0.828
	Dead + BSALL	ULS	0.655

Table 2 – Summary of Links Overstress Indices

No overstress indices exceeding 1.00 occurred in the link members or their immediate connections. The maximum overstress index was 0.767 in main members for the load combination including HA. When analysed using BSALL in place of HA loading, this reduced the overstress index to 0.607. Slightly higher overstress indices were found to exist in the pin joints and butt welds between the link coupling and fabricated section. For combinations including dead and live load, they were 0.878 and 0.828 for pin joints and welds respectively. When analysed using BSALL in place of HA loading the reductions of the overstress indices were approximately 21%.

4.4 End Link Brackets at Main Towers.

The capacity of the end link brackets was based on the results of a linear buckling analysis as required by BD56/96 due to the configuration of the member. A summary of the critical overstress indices for the brackets is presented in Table 3 below. The critical load combinations for the brackets were:

Dead + Wind – maximum wind loading applied to the main span and relieving wind loading applied to the remaining spans, wind loading considered at 50 degrees to the stiffening truss to produce greatest longitudinal loads.

Dead + Wind + Live – maximum wind loading with coexisting live loading applied to the main span over 200m , the remaining spans were loaded with wind load calculated for locations that have a relieving effect on the element under consideration.

Dead + Live (BSALL) – HA or BSALL applied to the single carriageway over 40 bays from one tower and the opposite carriageway was loaded for the remainder of the loaded length from the opposite tower.

Bracket element	Loadcase	Limit State	Overstress Indices
Main members	Dead	ULS	0.256
	Dead + Wind	ULS	0.399
	Dead + Wind + Live	ULS	1.289
	Dead + Live	ULS	1.416
	Dead + BSALL	ULS	1.120
Welds	Dead	ULS	0.365
	Dead + Wind	ULS	0.569
	Dead + Wind + Live	ULS	1.838
	Dead + Live	ULS	2.020
	Dead + BSALL	ULS	1.597

Table 3 – Summary of End Link Brackets Overstress Indices

Although the link members do not have overstress indices greater than 1.0 the end link brackets connecting the links to the main towers have. The critical load combination is Dead + Live with the live load HA loading. This gave an overstress index 1.416. Replacing HA loading with BSALL has the effect to reduce the overstress index to 1.12.

For welds the highest overstress indices were derived for the same load combinations as for the main members. These were found to be 2.020 for load combination including Dead + Live based on HA loading, reducing to 1.597 when HA was replaced by BSALL. It should be noted that welds had also overstress index exceeding 1.0 under the load combination of dead, live and wind.

4.5 Rockers at Side Towers

A summary of the critical overstress indices for rockers is provided in Table 4. The critical load combinations for the rockers were:

Dead + Wind – maximum wind loading applied to the one side span and relieving wind loading applied to the remaining spans, wind loading considered at 50 degrees to the stiffening truss to produce greatest longitudinal loads.

Dead + Wind + Live – maximum wind loading with coexisting live loading applied to the one side span , the remaining spans were loaded with wind load calculated for locations that have a relieving effect on the element under consideration.

Dead + Live – HA or BSALL applied to one side span carriageway over a full length.

Rocker bearing	Loadcase	Limit State	Overstress Indices
Main members	Dead + Wind	ULS	0.203
	Dead + Wind + Live	ULS	0.940
	Dead + Live	ULS	1.310
	Dead + BSALL	ULS	1.043

Table 4 – Summary of Rockers Overstress Indices

Rockers were found to have overstress indices greater than 1.0 only for one load combination. The maximum calculated overstress index was 1.310 which occurred under Dead + HA loading. Substituting BSALL the overstress index was reduced by approximately 20%. For load combination incorporating dead, live (HA) and wind load the overstress index was 0.94. Contact stresses in the bearing slabs were found to be less than the design capacity of the material.

4.6 Lateral Bearings at Side Towers

A summary of the critical overstress indices is shown in Table 5. The critical load combinations for the lateral bearings at side towers were:

Dead + Wind – maximum wind loading applied to one side span and relieving wind loading applied to the remaining spans, wind loading considered at 50 degrees to the stiffening truss to produce greatest longitudinal loads.

Dead + Wind + Live – maximum wind loading with coexisting live loading applied to the one side span , the remaining spans were loaded with wind load calculated for locations that have a relieving effect on the element under consideration.

Dead + Wind (reduced 50mph) + BSALL – maximum wind loading with coexisting live loading applied to the one side span, the remaining spans were loaded with wind load calculated for locations that have a relieving effect on the element under consideration.

Dead + Live – HA applied to one side span carriageway over a full length.

Lateral bearing element	Loadcase	Limit State	Overstress Indices
Lateral bearing elements	Dead + Wind	ULS	0.785
	Dead + Wind + Live	ULS	0.626
	Dead + Live	ULS	0.231
	Dead + Wind + BSALL	ULS	0.338
Bolts	Dead + Wind	ULS	0.446
	Dead + Wind + Live	ULS	0.364
	Dead + Live	ULS	0.276
	Dead + Wind + BSALL	ULS	0.199
Bars	Dead + Wind	ULS	1.930
		SLS	1.022
	Dead + Wind + Live	ULS	1.772
		SLS	1.090
	Dead + Live	ULS	0.795
		SLS	0.388
	Dead + Wind + BSALL	ULS	0.926
		SLS	0.526

Table 5 – Summary of Lateral Bearings Overstress Indices

The overstress indices were found to be less than 1.0 for all elements considered with the exception of the post tensioned bars clamping the bearings to the side towers. Under a combination of Dead + Wind + Live (HA) load the index was 1.772. Using BSALL and reduced wind loads (50mph) in the analysis the overstressed index dropped to 0. 926. Furthermore the combination of Dead + Wind results in high longitudinal forces which exceed the clamping force provided by the post tensioned bars. The post tensioned bars are contained in oversized ducts and are not considered to act in shear. The loss of the clamping force removes the vertical support to the end of the lateral bracing which in turn induces high moments and torques into these members as they cantilever from the top chords of the stiffening truss. The overstress index for the lateral bracing members when considering the loss of clamping force could rise to 2.24 from 1.74.

5. CONCLUSIONS

This report presents the findings of the analysis and assessment of the connections between the stiffening truss and both the main and side towers of the bridge. All the elements considered have been assessed according to BD 56/96.

The findings of the assessment are the following elements have overstress indices greater that 1.0:

- End brackets, supporting the links at the main towers.
- Rocker members supporting the truss at the side towers.
- Post tensioned bars at the side tower lateral bearings.

In relation to the end brackets the maximum overstress index is 2.02. This overstress index relates to the load combination of Dead + Live (HA). When BSALL is substituted for HA the overstress index reduces to 1.597. The BSALL used to calculate this load is based on traffic data obtained in 2005. As traffic increases and in particular heavy goods vehicle numbers and weight increases the BSALL will increase. Thus the overstress index will increase.

At the side towers the rockers were found to have overstress indices greater than 1.0. The maximum overstress in the members is 1.31 which occurs under a load combination of Dead + Live (HA) Loading. When BSALL is substituted the overstress index reduces to 1.043.

In relation to the lateral support only the post tensioned bars clamping the lateral bracing to the side towers have overstress indices greater than 1.0. This value is 1.93 and is induced by a combination of Dead + Wind (longitudinal wind). The longitudinal forces produced under this load combination overcome the clamping force and as a result the vertical support provided to the lateral bracing is not effective. The removal of this support increases the overstress index of the lateral bracing members at this location to 2.24.

In summary each of the truss end connections, with the exception of the lateral thrust members at the main towers, have elements which have overstress indices greater than 1.0. We are not aware of any visual indication that these elements are showing signs of distress. However these elements are critical to the safe operation of the bridge and we consider that remedial works should be undertaken at the earliest opportunity.