Forth Road Bridge

Review of Failure Mode and Effect Analysis

Forth Estuary Transport Authority

August 2012

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Table of contents

1. Introduction

Since 2008 Atkins has been engaged by the Forth Estuary Transport Authority (FETA) to review the condition of the main bridge deck roller shutter joints which have become excessively worn and subject to increasing maintenance by FETA. Atkins were requested to advise on the viability of delaying the replacement of the joints until the replacement Forth Road Crossing was in place, currently due in 2016. By delaying the joint replacement traffic can be diverted onto the new crossing and therefore traffic disruption and negative effects on the local economy could be mitigated.

To assess the viability of delaying the replacement of the joints a Failure Mode and Effect Analysis (FMEA) was undertaken and the results of this are the subject of an Atkins report titled 'Extending the Life of the Main expansion Joints' (reference 5057541/011). The analysis concluded that the joints could be retained but recommended that certain 'failsafe' measures were put in place, more frequent and rigorous inspections of the joints were undertaken, with the inspections assisted by improved and safer access under the bridge deck. All these measures have taken place, but the report also recommended that periodic reviews were undertaken to ensure that original assumptions were correct and to assess the rate of deterioration of the joints.

This report will cover the results of a meeting held between FETA and Atkins held on 21st March 2012 where the results of inspections of the main bridge deck roller shutter expansion joints were discussed. It was also agreed that the FMEA should be reviewed following progress made and the results of inspections.

2. Inspections Undertaken

To date two whole roller shutter joint plate trains have been lifted out to allow close inspection. The first inspection was undertaken just before the original FMEA process in January 2009. The findings of this inspection can be found in Atkins report 'Extending the Life of the Main Expansion Joints', reference 5075541/011 and were used to develop the FMEA. The recommendations of this report included improving the safety and extent of the maintenance access walkways under the suspended spans of the bridge, increasing the frequency of inspections (made possible by the improved walkways), installing failsafe measures on identified critical components and the periodic lifting out of sample joint plate trains to allow a close and detailed inspection of all areas of the joint.

The second inspection was undertaken in October 2011. The findings of this inspection as well as other work undertaken on the bridge joints are discussed in Atkins report 'Update on Extending the Life of the Main Bridge Deck Expansion Joints', reference 5088418/996. This joint was selected as it was thought to be one that had deteriorated more than others, based on the current routine inspections. Nothing unexpected was found apart from debris that had been trapped beneath one of the feet of the plate train. This is thought to have caused the increased wear in the pin from extra resistance to movement of the plate train and the increased and uneven gap between two plates in the train. It is noted that the current inspection regime picked up the increased wear in this joint

3. Lifting Out of Plate Trains

3.1 General

Although two plate trains have been lifted out, the original FMEA report recommended the systematic lifting out of most of the plate trains over a rolling programme of say 3 years. This has not happened, mainly because of the need to install temporary carriageway closures and the benefit that would be obtained from the inspection.

3.2 Carriageway Closures

The lifting out of a plate train requires a full carriageway closure. This is because there is insufficient width in a two lane carriageway for room to allow lifting equipment to be positioned and used without an unnecessary safety risk to the travelling public and workforce on site. To undertake a carriageway closure, all the traffic needs to be diverted onto the other carriageway so this operates with traffic running two ways. FETA have established procedures to do this in an effective manner both in terms of putting the traffic management in place and also the advance publicity required to forewarn the travelling public and to enable them to make other plans.

Public sensitivity to carriageway closures is increasing as such closures cause significant traffic congestion even at periods when traffic flows are at their lowest (Saturday night / Sunday morning). It has also been necessary to have more frequent closures for other maintenance reasons such as the recent replacement to hanger bolts.

The closure of a carriageway for repairs also gives a public perception that the bridge is 'falling down' and is in worse condition than it actually is. Closures therefore need to be carefully considered and if they are necessary full advantage should be made and as much inspection and maintenance should be done as possible.

3.3 Need to Lift Out Plate Trains

As any closure of a carriageway has a negative impact on the public, the need to lift out the plate trains as frequently as originally recommended needs to be constantly reviewed. Currently all the joints are routinely inspected from carriageway level and from the inspection platform below. The second plate lifted out was chosen as inspections did pick up increased wear in this joint over the others. The need to lift out plate trains was discussed at the meeting in March 2012 and the following advantages and disadvantages were identified.

The advantages of lifting out a plate train can be summarised as follows:

- If a carriageway is to be closed for other works, then the opportunity of lifting out a plate train should be considered. The public will see more work being undertaken and may understand more readily that the closure was necessary. However, a closure requires resources which may be being used on other works;
- Lifting out plate trains enables the workforce to be trained / practised in such an operation which could be useful in an emergency. There is a constant risk that a joint could suddenly fail and to minimise the impact to the public repairs would be necessary as quickly as possible;
- Although access to the joints is now much improved, the design of the joints means that some components are still not visible. In particular this includes the pins in the plate train hinges which have excessive wear. The only way to effectively inspect theses components is to lift out a plate train;
- While a plate train has been lifted out advantage has been made to undertake some maintenance work that would otherwise be difficult to do. For example, at the last inspection, the tongue and shuttle plate support blocks had formed lips around the edge which were ground off. In addition the joint can be cleaned of debris which although can be done from underneath water sprays up through the joint which could alarm a driver. It has been noted that more and larger items of debris fall through the joint because of the larger gaps between plates which have formed because of wear;
- Not finding any change in the condition is, in itself, a positive outcome from inspection as it provides assurance as to the current condition.

There are also disadvantages with lifting out a plate train which could be summarised as follows:

- Lifting out a plate train requires a carriageway closure as discussed above:
- The plate trains are badly worn and there is a risk that a train may not settle back into the joint correctly or it may take some time to achieve this. This could lead to delays in reopening the carriageway, or in the worst case, may result in extensive repairs being required which could take some days;
- If plate trains are not lifted out, and a failure occurred, there would inevitably be a period when a carriageway or lane may need to be closed for some time. This would lead to adverse publicity with

a reduction in public confidence and questions could be asked on what was done to prevent to prevent failure.

The second inspection did not reveal anything unexpected and given the risks and traffic disruption in doing the work the need to undertake further inspections was considered. However, in summary, it was agreed that advantages outweigh the disadvantages and further inspections should be periodically undertaken. To minimise the number of carriageway closures the lifting out of plate trains should be co-ordinated with other planned works subject to resources.

4. Review of Failure Mode and Effect Analysis

The FMEA process is detailed in the original report 'Extending the Life of the Main Deck Expansion Joints' The report includes the results of the analysis in tabular form and these have been taken from the report and inserted below with the results of an additional review.

In summary the review broadly agrees with the original results although as less plate trains have been lifted out than originally recommended then the risk of detection has increased with some items. In addition, where some components were identified as at risk from corrosion, from the inspections that have been done to date it has shown that such corrosion is limited.

FMEA scoring tables, component diagram and recommended action table reproduced from report 'Extending the life of the Main Deck Expansion Joints' have been included in Appendix A for reference.

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Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Original Assessment									Recommended Action (see Appendix A)	Resulting Assessment from original report						Resulting Assessment as a result of Action Undertaken						Comments
					Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Detection	Detection	RPN	Ranking (based on RPN)		Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN	
1	1	Shuttle Plate horizontal thrust block-attached to plate.	Loss of horizontal restraint of plate train.	Plate train becomes free and could fall into joint.	6	10	10	Weld failure from fatigue.	6	6 monthly inspections	8	480	4	1, 2, 4, 5, 6, 7	5	5	5	6	5	150	5	5	5	6	6*	180	Plate trains lifted out less often than originally proposed
2	1	"	"	"	6	10	10	Overloading of thrust block on shuttle plate (where wear between the feet and the track beams cause extra resistance).	5	6 monthly inspections	9	450	5	1, 2, 5, 6, 7	5	5	5	5	7	175	5	5	5	5	8*	200	Plate trains lifted out less often than originally proposed
3	1	"	"	"	6	10	10	General corrosion.	2	6 monthly inspections	7	140	34	1, 2, 5, 6, 7	5	5	5	2	5	50	5	5	5	2	5	50	Inspections show no major corrosion (loss of section)
4	17	Shuttle Plate horizontal thrust block-attached to support.	Loss of horizontal restraint of plate train.	Plate train becomes free and could fall into joint.	6	10	10	Weld failure from fatigue.	5	6 monthly inspections	8	400	8	1, 2, 5, 6, 7	5	5	5	5	5	125	5	5	5	6	6	180	Plate trains lifted out less often than originally proposed
5	17	"	"	"	6	10	10	Overloading of thrust block attached to support (where wear between the feet and the track beams cause extra resistance).	5	6 monthly inspections	8	400	8	1, 2, 5, 6, 7	5	5	5	5	6	150	5	5	5	5	8*	200	Plate trains lifted out less often than originally proposed
6	17	"	"	"	6	10	10	General corrosion.	2	6 monthly inspections	6	120	35	1, 2, 5, 6, 7	5	5	5	2	5	50	5	5	5	2	5	50	Inspections show no major corrosion

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7	17	"	"	"	6	10	10	Impact loading due to lack of fit	3		8	240	21	1, 2, 5, 6, 7	5	5	5	3	6	90	5	6	5	3	6	90	Shuttle plates dropping through wear causing increasing step with central pedestal.
8	18	Support under shuttle plate horizontal thrust block.	"	"	6	10	10	Overloading of thrust block support (where wear between the feet and the track beams cause extra resistance). Local failure of the top flange/cracking around block within supporting steelwork.	2	6 monthly inspections	8	160	31	1, 2, 5, 6, 7	5	5	5	2	6	60	5	5	5	2	7	70	Plate trains lifted out less often than originally proposed
9	2	Vertical bearing to Shuttle Plates- attached to plates.	Loss of vertical restraint of plate train.	Shuttle plate can rotate upwards about opposite bearing and protrude into carriageway.	5	7	7	Weld failure from fatigue.	6	6 monthly inspections	8	336	11	1, 2, 5, 6, 7	5	7	7	6	5	210	5	7	7	6	6	252	Plate trains lifted out less often than originally proposed
10	2	"	"	"	5	7	7	Overloading of bearing block.	5	6 monthly inspections	7	245	20	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken other than inspections
11	2	"	"	"	5	7	7	General corrosion.	2	6 monthly inspections	6	84	42	None	-	-	-	-	-	-	-	-	-	-	-	-	Inspections show no major corrosion

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12	19	Vertical bearing to Shuttle Plates-attached to supports.	Loss of vertical restraint of plate train.	Shuttle plate can rotate upwards about opposite bearing and protrude into carriageway.	5	5	5	Weld failure from fatigue.	6	6 monthly inspections	8	240	21	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken other than inspections
13	19	"	"	"	5	5	5	Overloading of bearing block support beam top flange causing local failure of the top flange/cracking around block within supporting steelwork.	6	6 monthly inspections	8	240	21	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken other than inspections
14	19	"	Wear of bearing block.	Poor vertical carriageway profile/step in carriageway.	2	3	3	Wear due to cyclic movement.	9	6 monthly inspections	3	81	46	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken other than inspections
15	3	Shuttle Plate Holding Down Pins.	Loss of vertical restraint to plate train.	Plate train becomes free and can be dislodged, and could fall into joint.	6	10	10	Overloading of pin (where wear between the feet and the slide track beams cause increased dynamic movement).	4	6 monthly inspections	6	240	21	1, 3 (use high grade bolts in place of pins), 5, 7	5	7	7	3	5	105	5	7	7	3	5	105	Pins replaced.

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16	3	"	"	"	6	10	10	General corrosion.	2	6 monthly inspections	2	40	55	1, 3 (use high grade bolts in place of pins), 5, 7	5	7	7	2	2	28	5	7	7	2	2	28	Pins replaced
17	4	Spring around Holding Down Pin to shuttle plate.	Loss of vertical restraint of plate train.	Plate train becomes free and can be dislodged.	5	10	10	Overloading of spring (where wear between the feet and the track beams cause increased dynamic movement).	6	6 monthly inspections	5	300	14	1, 3, 5, 7	5	7	7	3	4	84	5	7	7	3	4	84	Spring replaced
18	4	"	"	"	5	10	10	General corrosion.	4	6 monthly inspections	2	80	47	1, 3, 5, 7	5	7	7	2	2	28	5	7	7	2	2	28	Spring replaced
19	20	Tongue Plate Holding Down Pins.	Loss of vertical restraint to plate train.	Tongue plate becomes free and can be dislodged, and could fall into joint.	6	10	10	Overloading of pin (where wear between the feet and the slide track beams cause increased dynamic movement).	4	6 monthly inspections	6	**240**	21	1, 3 (use high grade bolts in place of pins), 5	5	7	7	2	5	**70**	5	7	7	2	5	**70**	Pins replaced
20	20	"	"	"	6	10	10	General corrosion.	2	6 monthly inspections	3	**60**	51	1, 3 (use high grade bolts in place of pins), 5	5	7	7	2	2	**28**	5	7	7	2	2	**28**	Pins replaced

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21	21	Spring around holding down pin to tongue plate.	Loss of vertical restraint to tongue plate.	Plate becomes free and can be dislodged.	5	10	10	Overloading of spring(where wear between the feet and the track beams cause increased dynamic movement).	6	6 monthly inspections	5	**300**	14	1, 3 (use high grade bolts in place of pins), 5	5	7	7	3	4	84	5	7	7	3	4	84	Springs replaced
22	21	"	"	"	5	10	10	General corrosion	2	6 monthly inspections	3	**60**	51	1, 3, 5	5	5	5	2	2	20	5	5	5	2	2	20	Springs replaced
23	5	Shuttle plate / plate train.	Uneven vertical profile of running surface.	Potential for "cat1" surface profile defect due to poor vertical profile.	2	2	2	Wear of joint components.	10	6 monthly inspections	2	**40**	55	None	-	-	-	-	-	-	-	-	-	-	-	-	Shuttle plates dropping through wear causing increasing step with central pedestal.
24	5	"	Loss of textured running surface.	Lack of skid resistance for vehicles.	2	5	4	Tyre wear to joint surface.	9	6 monthly inspections	2	**72**	48	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
25	5	"	Failure of plates.	Plate train becomes free and could fall into joint.	8	10	10	Impact loading increased due to lack of fit.	2	6 monthly inspections	8	160	31	1, 2, 5, 6, 7	5	5	5	2	5	50	5	5	5	2	5	50	Wear is increasing
26	5	"	"	"	8	10	10	Excessive corrosion.	2	6 monthly inspections	2	40	55	1, 2, 5, 6, 7	5	5	5	2	1	10	5	5	5	2	1	10	Inspections show no major corrosion

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27	6	Tongue Plate.	Excessive wear of plate thickness.	Plate ends further back giving poor vertical alignment.	3	4	4	Increased vehicle impact effects.	10	6 monthly inspections	3	120	35	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken but wear also creates a sharp edge to the edge of the plate.
28	6	"	Loss of textured running surface.	Lack of skid resistance for vehicles.	3	4	4	Tyre wear to joint surface.	9	6 monthly inspections	2	72	48	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
29	6	"	Failure of plates.	Tongue plate would fall into joint.	7	10	10	Tyre wear to joint surface.	2	6 monthly inspections	8	160	31	1, 2	5	5	5	2	3	30	5	5	5	2	4	40	Plate trains lifted out less often than originally proposed
30	6	"	"	"	7	10	10	Corrosion.	2	6 monthly inspections	2	40	55	1, 2	5	5	5	2	1	10	5	5	5	2	1	10	Inspections show no major corrosion
31	7	Feet supporting plate train.	Failure of connection between feet and plates.	Collapse of plate train or plate train falls into joint.	6	9	9	Weld failure from fatigue.	5	6 monthly inspections	8	360	10	1, 2, 4, 5, 6	5	5	5	5	7	175	5	5	5	5	7	175	Inspections show no weld cracking but plate trains lifted out less often than originally proposed.
32	7	"	"	"	6	9	9	Impact loading due to lack of fit.	6	6 monthly inspections	8	432	7	1, 2, 5, 6	5	5	5	6	7	210	5	5	5	6	7	210	Can be detected without lifting trains.

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33	10	Hinge between plates in plate train.	Failure of hinge pins.	Plate train becomes free and could fall into joint.	8	10	10	Fatigue failure of pin.	6	6 monthly inspections	10	600	2	1, 2, 5, 6	5	5	5	6	7	210	5	5	5	6	8	240	Plate trains lifted out less often than originally proposed
34	10	"	"	"	8	10	10	Impact loading due to lack of fit.	7	6 monthly inspections	10	700	1	1, 2, 5, 6	5	5	5	7	7	245	5	5	5	7	8	280	Plate trains lifted out less often than originally proposed
35	10	"	"	"	8	10	10	Excessive wear in pin.	5	6 monthly inspections	9	450	5	1, 2, 5, 6	5	5	5	5	7	175	5	5	5	5	8	200	Plate trains lifted out less often than originally proposed
36	10	"	"	"	8	10	10	Overloading of pin (where wear between the feet and the track beams cause extra resistance).	6	6 monthly inspections	10	600	2	1, 2, 5, 6	5	5	5	6	7	210	5	5	5	6	8	240	Plate trains lifted out less often than originally proposed
37	9	End keeper plate to hinge pins.	Plate becomes unattached.	Hinge pin 'works out' from bushing causing plates to come apart.	8	10	10	Weld failure from fatigue.	3	6 monthly inspections	4	120	35	1, 2, 3, 5	5	5	5	3	2	30	5	5	5	3	3	45	Plate trains lifted out less often than originally proposed
38	9	“	Wear through	“	8	10	10	Wear through	10	6 monthly inspections	3	300	14	1, 2, 3, 5	5	5	5	4	2	40	5	5	5	4	3	60	Plate trains lifted out less often than originally proposed

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39	8	Hinge pin bearing area.	Bearing areas crack and fail.	Hinge separates and overloads other components. Plate train could become free and fall into joint.	3	3	3	Impact loading due to lack of fit.	9	6 monthly inspections	4	108	40	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
40	8	"	Bearing areas worn excessively.	Plate train seizes due to excessive plan rotation and overloads other components. Plate train could become free and fall into joint.	3	3	3	Excessive wear in bushing.	10	6 monthly inspections	2	60	51	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken. Wear through bushing into hinge block noted during the plate lift out in October 2011. Excessive wear detected.
41	11	Foot to underside of end plate of plate train.	Loss of connection between foot and plate.	End plate drops onto track beam and support is lost to tongue plate.	4	5	5	Weld failure from fatigue.	4	6 monthly inspections	6	120	35	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
42	12	Pedestal between moving parts of joint.	Loss of surfacing material.	"Cat1" defect. Poor vertical alignment causing damage to joint and / or vehicles.	2	3	3	Lack of bond of surfacing material to steel pedestal.	9	6 monthly inspections	2	54	54	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken, although surfacing repairs have been undertaken.

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43	13	Horizontal/vertical restraint blocks to tongue plates-attached to support.	Restraint becomes detached from support beams.	Loss of horizontal/vertical restraint to tongue plates.	7	10	10	Weld failure from fatigue.	4	6 monthly inspections	8	320	12	1, 2, 4, 5, 6	5	5	5	4	7	140	5	5	5	4	7	140	Inspections show no weld cracking but plate trains lifted out less often than originally proposed. Can be inspected from underneath.
44	13	"	"	"	7	10	10	Overloading of horizontal restraint (where wear between the feet and the track beams cause extra resistance).	3	6 monthly inspections	8	240	21	1, 2, 5, 6	5	5	5	3	7	105	5	5	5	3	7	105	Plate trains lifted out less often than originally proposed. Can be inspected from underneath
45	13	"	"	"	7	10	10	Impact loading due to lack of fit.	4	6 monthly inspections	8	320	12	1, 2, 4, 5, 6	5	5	5	4	7	140	5	5	5	4	7	140	Plate trains lifted out less often than originally proposed. Can be inspected from underneath
46	13	"	"	"	7	10	10	General corrosion.	2	6 monthly inspections	6	120	35	1, 2, 5, 6	5	5	5	2	5	50	5	5	5	2	5	50	Plate trains lifted out less often than originally proposed. Can be inspected from underneath

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					Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Detection	Detection	RPN	Ranking (based on RPN)		Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN	
47	23	Support to horizontal/vertical restraint blocks to tongue plates.	"	"	7	8	8	Overloading of supporting steelwork (where wear between the feet and the track beams cause extra resistance).	3	6 monthly inspections	7	168	29	1, 2, 5, 6	5	5	5	3	6	90	5	5	5	3	6	90	Plate trains lifted out less often than originally proposed. Can be inspected from underneath
48	23	Support to horizontal/vertical restraint blocks to tongue plates.	"	"	7	8	8	General corrosion.	3	6 monthly inspections	7	168	29	1, 2, 5, 6	5	5	5	3	6	90	5	5	5	3	6	90	Plate trains lifted out less often than originally proposed. Can be inspected from underneath
49	22	Horizontal/vertical restraint blocks to tongue plates- attached to tongue plate.	Restraint becomes detached from tongue plate.	Loss of horizontal/vertical restraint to tongue plates.	7	8	8	Weld failure from fatigue.	4	6 monthly inspections	8	256	18	1, 2, 4, 5, 6	5	5	5	4	7	140	5	5	5	4	7	140	Plate trains lifted out less often than originally proposed. Can be inspected from underneath
50	22	"	"	"	7	8	8	Overloading of horizontal or vertical restraint (where wear between the feet and the track beams cause extra resistance).	5	6 monthly inspections	7	280	17	1, 2, 5, 6	5	5	5	5	6	150	5	5	5	5	6	150	Plate trains lifted out less often than originally proposed. Can be inspected from underneath

Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Original Assessment									Recommended Action (see Appendix A)	Resulting Assessment from original report						Resulting Assessment as a result of Action Undertaken						Comments
					Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Detection	Detection	RPN	Ranking (based on RPN)		Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN	
51	22	"	"	"	7	8	8	Impact loading due to lack of fit.	4	6 monthly inspections	7	224	27	1, 2, 5, 6	5	5	5	4	6	120	5	5	5	4	6	120	Plate trains lifted out less often than originally proposed. Can be inspected from underneath
52	14	Backing plate at rear edge of tongue plate.	Loss of horizontal restraint of plate train.	Tongue plate becomes free and could fall into joint.	5	4	5	Weld failure from fatigue.	5	6 monthly inspections	10	250	19	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
53	14	"	Wear of top edge of plate.	Damage to vehicle tyres.	3	4	4	Excessive wear.	8	6 monthly inspections	3	96	41	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
54	15	Track Beams.	Excessive wear in top surface of top flange.	Increased resistance to movement of joint causing potential overload to other components (e.g. hinge pins and restraints).	7	6	7	Excessive wear.	7	6 monthly inspections	4	196	28	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
55	15	"	Failure of top flange by rotation.	Loss of support to plate train causing excessive wear in plate train.	7	6	7	Excessive wear.	3	6 monthly inspections	4	84	42	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken

Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Original Assessment									Recommended Action (see Appendix A)	Resulting Assessment from original report						Resulting Assessment as a result of Action Undertaken						Comments
					Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Detection	Detection	RPN	Ranking (based on RPN)		Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN	
56	15	"	Failure of top flange by deflection	Loss of support to plate train causing excessive wear in plate train	7	6	7	Excessive wear.	3	6 monthly inspections	4	84	42	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
57	15	"	"	"	7	6	7	Impact loading due to lack of fit.	3	6 monthly inspections	4	84	42	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
58	16	Slide track flange splice plate.	Failure of splice plate connection.	Loss of support to plate train causing excessive deflection and wear in plate train.	4	4	4	Fatigue failure of bolt due to increased impact loading as a result of lack of fit. Wear of counter sunk bolt head.	4	6 monthly inspections	4	64	50	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
59	24	Lateral restraint blocks to underside of plate train	Loss of blocks	Plate train can ‘crab’ causing it to bind	2	2	2	Excessive corrosion	2	6 monthly inspections	3	12	60	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
60	24	“	“	“	2	2	2	Weld failure from fatigue or impact.	4	6 monthly inspections	4	32	59	None	-	-	-	-	-	-	-	-	-	-	-	-	No specific action taken
61	5	Shuttle plate / plate train.	Locking of joint by debris becoming trapped beneath train feet or between plate elements (causing ‘crabbing’ of units).	“	-	-	-	Plate train binds causing uneven loading and wear leading to failure of train or accelerated wear under feet.	-	-	-	-	-	None	-	-	-	-	-	-	-	-	-	-	-	-	New failure mode not previously recorded.

5. Further Recommendations

The inspections have been on-going and, to date, although no failures have occurred it is apparent that wear in the joints is increasing. Although inspections have noted this wear there needs to be an objective measurement to determine the rate of increasing wear. This could be advantageous for three reasons:

1. There is a risk that small incremental changes over time may not be noticed;
2. A change in rate of wear may give warning of imminent failure of a component and therefore early action could be taken;
3. Taking measurements could reduce the need to lift out plate trains as frequently as originally recommended (if no increase in wear is measured).

Measurements could be undertaken at the same time as routine inspections, although they will extend the time it takes to undertake the overall inspection. It is recommended that measurements are taken at least once every six months or more frequently if the inspector considers a particular joint seems to be deteriorating faster than others or normal. All measurements should be recorded. Areas of most wear are in the plate train hinges and in the support blocks to the shuttle and tongue plates.

Wear in the plate train hinges can be measured by placing a tapered wedge between plates and measuring the gap. This is already being done to some extent. The measurements would record that increasing wear is / is not happening in either the pins, and / or the pin holes. The distance a wedge can be put through a gap can be sensitive to small changes in the width of the gap. The gaps in the plate trains vary with the natural movement of the joint so some judgment will be needed from the inspector to assess when the gap is at its maximum.

Wear in the support blocks under the tongue and shuttle plates can be measured by taking the distance between the underside of the plate and the top surface of the respective support beam. The measurements would record loss of thickness in the support block itself and the restraint the block seats in. This measurement can also be undertaken from underneath the joint. The measurement highlights the vertical step between the top of the tongue plates and the central pedestal. A significant step increases wheel impact loads on the tongue plates and also could become a hazard to vehicles, particularly motorcycles.

Another measurement that could be taken is the distance between the underside of a plate in the train and the top of the track beam. The feet of the plates are wearing into the track beam and this is likely to be most significant at the shuttle plate feet. There is probably little long term benefit in doing this.

All the joints are becoming increasingly worn and there needs to be consideration as to how bad a joint needs to be before the risk of failure becomes too great and action is needed. To determine a trigger point would be impossible since the joints are already worn far beyond their design limits and therefore this will need to come down to the judgment of the inspector. Required action may be either a temporary closure of a lane or carriageway while more detailed investigation and repairs take place or it may be necessary to replace the joint. Spares could be held for a few components but generally a new part would not fit successfully into a badly worn joint. However a contingency plan should be put in place so that if an emergency happens there is the minimum delay to effect repairs.

A Contingency Plan should include method statements for closing lanes / carriageways, method statements for removing and replacing various parts, a list of suppliers of parts, materials and plant and an assessment of the likely timescales for returning failed joint back into service.

6. Summary

The Atkins report 'Extending the Life of the Main Expansion Joints' provided a Failure Mode and Evaluation Analysis on considering if the roller shutter joints in the main deck of the bridge could remain in service until they could be replaced once the second Forth Road crossing was in place. The report concluded that, although the joints are badly worn, they could remain in place with certain mitigation measures. These measures were the installation of 'failsafe' measures, improved access under the deck and more frequent and rigorous inspections of the joints. The inspection regime was to include the systematic lifting out of plate trains. To date all the measures have taken place except the rolling programme of lifting out plate trains. To lift out plate trains requires the closure of a carriageway which causes traffic disruption and negative publicity. There are advantages in lifting in plate trains; these include inspecting components that are otherwise hidden, training and practice for the workforce in undertaking the work in case of an emergency and the opportunity to undertake minor maintenance work.

A review of the FMEA concludes that most of the original assumptions remain valid, although some detection risks have increased without the systematic removal of plate trains. To mitigate this it is recommended that inspections should record measurements indicating wear that would show the rate of deterioration and may show early signs of imminent failure. In addition it is also recommended that a contingency plan is developed which can be put in place should failure occur.

Appendix A

FMEA scoring tables, component diagram and recommended action table reproduced from report ‘Extending the life of the Main Deck Expansion Joints’

A.1 FMEA Scoring Tables

A.1.1 Economic Severity Scoring Table

Economic severity has been defined as the period of closure that would be necessary to undertake sufficient repairs to enable traffic to safely cross over the joint.

Score	Description
10	Complete bridge closure or construction of temporary bridge over joint.
9	Greater than 1 month unplanned full carriageway closure.
8	Greater than 1 week unplanned full carriageway closure.
7	Greater than 1 month planned full carriageway closure.
6	Greater than 1 week planned full carriageway closure.
5	Less than 1 week unplanned full carriageway closure.
4	Less than 1 week planned full carriageway closure.
3	Planned full weekend carriageway closure.
2	Non-emergency overnight carriageway closure.
1	No effect.

The above assumes that single lane closures are not acceptable for safety reasons.

A.1.2 Public Perception Severity Scoring Table

Public perception has been defined as what effect failure of the joints would have on the travelling public. Delays are considered to be covered by economic severity.

Personal injury as a result of an accident is difficult to predict with any degree of certainty. The likely scale of an incident has been used as an indication of the degree of personal injury which could be sustained.

Score	Description	Criteria – Vehicles	Criteria – Injury
10	Catastrophic / Certain	Severe damage to multiple vehicles	Death or Severe injury- permanent disablement, unable to work.
9		Severe damage to a single vehicle. Vehicle would be insurance write off	Severe injury, requiring a long period off work.
8	Major / Probable	Major damage to a single vehicle, probably insurance write-off.	Moderate, requiring hospital treatment and more than three days off work.
7		Major damage to a single vehicle but repairable.	Moderate requiring over three days off work.
6	Moderate / Possible	Moderately damaged, immobilised vehicles, but relatively easily repairable.	Minor, requiring hospital treatment.
5		Damaged, such as dents or broken lights, but driveable vehicle	Minor, requiring on site medical treatment.
4	Minor / Unlikely	Tyre replacement or minor bodywork damage.	Minor, requiring GP self referral.
3		Very minor damage, such as scratched paintwork.	Minor, not requiring medical treatment.
2		Insignificant damage to vehicle.	Negligible.
1	Negligible / Remote	None.	None.

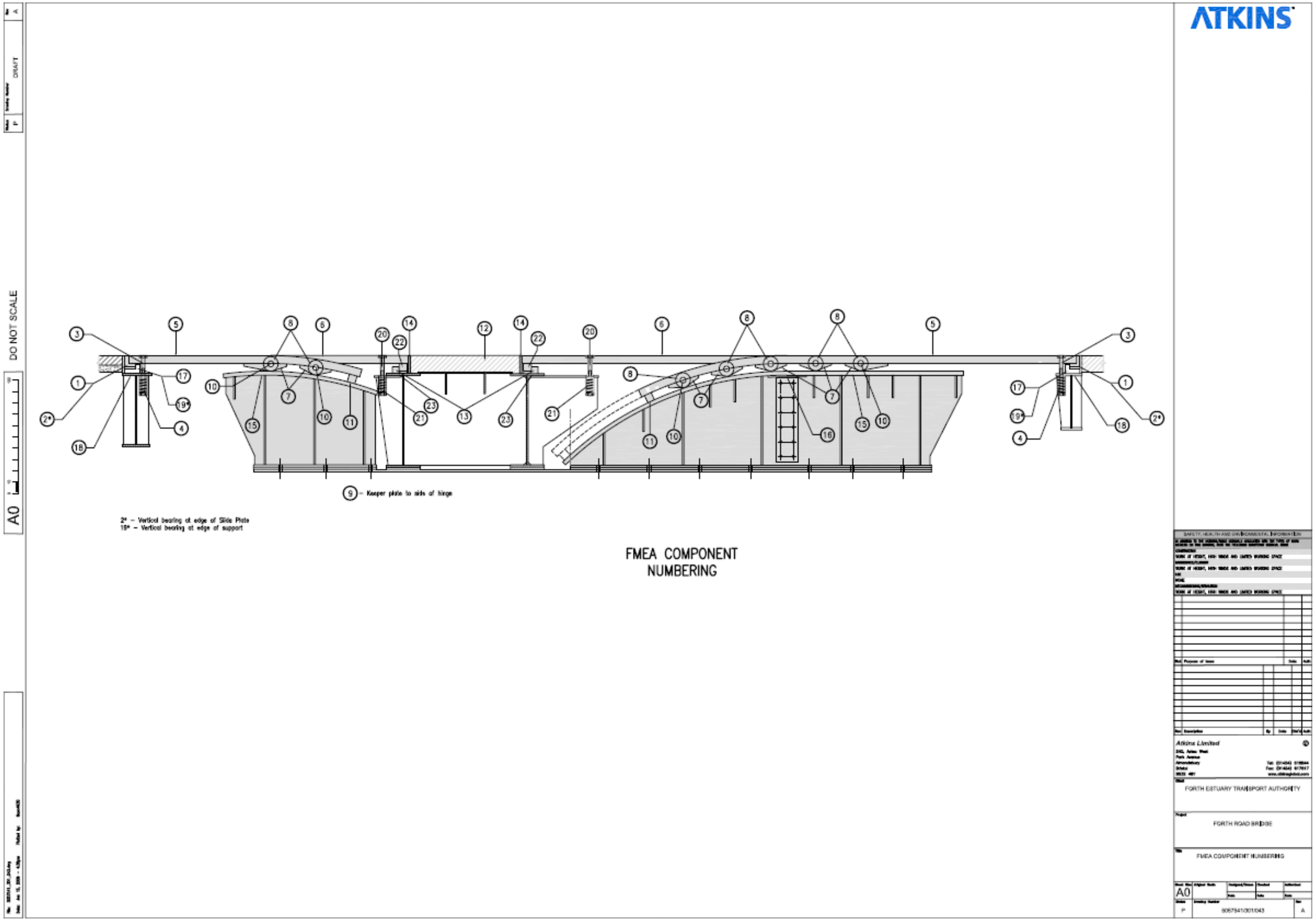
A.1.3 Occurrence Scoring Table

Score	Description
10	Certain
9	
8	Probable
7	
6	Possible
5	
4	Remote
3	
2	Improbable
1	

A.1.4 Detection Scoring Table

Score	Description	Criteria	Example
10	**Almost impossible** to detect before the impact of the effect is realised.	Requires dismantling and testing to detect defect.	Cracking in hinge pins.
9	**Very remote chance** defect is detected before the impact of the effect is realised.		
8	**Remote chance** defect is detected before the impact of the effect is realised.	Difficult to access and difficult to detect.	Cracking to horizontal restraint to shuttle plate.
7	**Very unlikely** to be detected before the impact of the effect is realised.		Corrosion leading to significant loss of section to bearing shelf.
6	**Unlikely** to be detected before the impact of the effect is realised.	Access to within touching distance. Defect not progressive in nature (sudden failure).	Failure of holding down pins.
5	**Likely** to be detected before the impact of the effect is realised.	Easy access to within touching distance. Defect progressive but not detectable without testing.	Fatigue cracking in welding to bearing block.
4	**Moderately Likely** to be detected before the impact of the effect is realised.	Easy access to within touching distance. Defect progressive and detectable visually.	Distortion of top flange of slide tracks.
3	**Highly likely** to be detected before the impact of the effect is realised.	Easy access to within touching distance. Defect detectable using "telltale" etc. (objective criteria).	
2	**Almost certain** to be detected before the impact of the effect is realised.	Defect detectable by visual inspection from a distance.	
1	**Certain** to be detected before the impact of the effect is realised.	Defect clearly detectable by visual inspection from a distance.	

A.1.3 Sketch of Components Identified in FMEA Spreadsheet



A.1.4 Description of Actions to Reduce RPN

Recommended Action	Description	Comment	Target Completion Date
1	Lift out plate train and tongue plate for close examination.	Close inspection reduces occurrence and detection scores.	August 2009
2	Improved access walkways under bridge deck.	Allows inspection of all areas of joint to reduce detection score.	August 2009
3	Replace component.	Replacing component increases reliability and therefore reduces occurrence score.	August 2009
4	Test welds.	Detailed inspection to check for welds reduces occurrence and detection scores.	August 2009
5	End stop blocks on track beams	Blocks limit distance plate train could fall into joint to reduce public perception severity score.	August 2009
6	Straps fixed to underside of plate train (in a longitudinal direction)	Straps limit distance plate train could fall into joint to reduce public perception severity score.	August 2009
7	Additional restraint to the underside of shuttle plates to prevent plates falling off support beam.	Straps fixed to underside of shuttle plates to support beam to limit distance plate could move away from the support beam therefore ensuring support remains.	August 2009

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