Forth Estuary Transport Authority

Forth Road Bridge
Extending the Life of the Main Expansion Joints ~~Roller Shutter Joints~~

Revision C

January 2009

Forth Estuary Transport Authority

Reducing the Risk of Failure and Extending the Life of the Main Expansion Joints ~~Roller Shutter Joints~~

January 2009

Notice

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Contents

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Executive Summary

The roller shutter joints in the Forth Road Bridge are located at the main towers~~under the main supports~~ of ~~the suspended span of~~ the bridge. Following increasing maintenance work and the findings of routine inspections it is apparent that the joints have reached the end of their working life. With increasing wear in the joints there is a co-existent risk of failure of a component of the joints. Such a failure would be a significant safety risk to the travelling public, and could also lead to closures of carriageways with no advance notice. Such closures of carriageways would inevitably lead to traffic congestion and would affect the local economy of the region.

Tenders were invited from c~~C~~ontractors to extensively refurbish / replace the roller shutter joints and also to improve access under the bridge deck to give better facilities for future inspection and maintenance. Tenders were returned in September 2008 but the tender recommended was approximately £5 million above the pre-tender estimate. Additionally, since the return of the tenders, the Scottish GovernmentExecutive has announced that a new Forth Replacement ~~oad~~ Crossing will be in place in~~by~~ 2016.

FETA requested Atkins to consider what the risks would be if the life of the joints was extended to 2016 and what measures could be taken to reduce any such risks to the public until the new Crossing was open and the full joint replacement works were carried out~~completed~~. This report identifies these risks and what measures could be taken to mitigate such risks considering the site constraints and possible modes and consequences of failure.

~~Measures discounted because of the potential for traffic congestion were closure of the bridge or erecting the temporary bridge that is proposed for the main contract works over the joints~~(not sure why we would have to put these up for discounting). Other measures also included partial repairs or manufacturing spare components that could be readily installed should the need arise. These options were discounted because of the likely incompatibility between new and worn parts. *Note: but what about replacing link pins (if they are not bent) shuttle and tongue plate holding down pins –with bolts, and springs*

The recommended actions are to increase the prevention and detection controls of the joints to detect for signs of impending failure. To assist in the prevention of failure it is also recommended that the frequency of inspections is increased and access to the joints is improved. Mitigation measures to reduce the effects of failure include installing restraining straps under the plate trains that would catch the plates, and also adding blocks *(blocks rather than a thin plate fuse?)* to the track beams to prevent the plate train sliding down into the joint if a hinge fails. These mitigation measures would only be in place until the joints are replaced in 2016.

The inspection and control strategy must be reviewed at least annually to ensure levels of risk are appropriate and acceptable. Wear levels on the joints should also be assessed annually to ensure they are not accelerating. *Can add removal and inspection of all 48 plate trains over the 8 year period* Should a review indicate unacceptable risk levels of failure, full replacement prior to opening of the new Forth crossing would be necessary.

This is the difficult one…. we have to say clearly at this point what the recommendations are that the joints can be kkept going but with the provisos and in addition we have to say that the risk of full replacement is high medium or low. Obviously at the moment it is not high or we would be replacing the joints so thwe risk has to be low or low to medium and that risk will be reassessed each year . Now, we can say that the risk level may change and is unlikely to / will not decrease but it is probably not possible to predict that from here

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1. Introduction

Atkins has been requested by the Forth Estuary Transport Authority (FETA) to consider the risks and consequences of a failure of the roller shutter joints in the Forth Road Bridge. This is to extend to identifying any measures that could be undertaken to potentially extend the life of the joints. This is in response to an announcement of the construction of a new Forth road crossing programmed to be completed by 2016. The risks and consequences and any subsequent safeguarding measures would need to be considered until after the new crossing has been opened. Once in place, the new crossing would allow work to be undertaken on the joints without the need for extensive temporary works and minimal ~~less potential for~~ traffic disruption and therefore ensuring best value.

2. Scope of Report

The roller shutter joints are the main carriageway deck movement joints located at both main towers~~supports~~ and both carriageways of the suspended section of the bridge. After covering recent background, this report will identify the risks and consequences of failure of any component of the joints. This will be achieved by using a Failure Mode and Effect Analysis (FMEA) which will highlight which parts of the joints are most at risk. This report will then continue to discuss what strategies could be undertaken to mitigate and prevent a failure and then, finally, provide recommendations on what actions to take.

3. Background

In 2007 Atkins was commissioned by the Forth Estuary Transport Authority (FETA) to investigate options for either the repair or replacement of all the bridge deck movement joints in the Forth Road Bridge. This was in response to increasing maintenance work on the joints and the findings of inspections which revealed areas of heavy wear. A final report (ref 5032119.125.002 Rev B 'Options Report for Bridge Deck Joints') was presented in November 2007. The report concluded that the joints have reached the end of their useful working life and all should be replaced or extensively refurbished to ensure satisfactory long term performance. In addition an improvement to general access for inspection and maintenance of the main roller shutter joints under the bridge deck was recommended.

As a consequence Atkins prepared tender documentation for the work to the joints and for the improved access. This work would need long term access to the joints from the carriageway which would have required carriageway and full bridge closures. Such closures would have severe detrimental effects on traffic flows over the bridge and, as a consequence, significant economic effects in the region. To minimise these effects, the proposed works included for the construction of temporary bridging over the roller shutter joints. The temporary bridging would allow continued traffic flow (except for heavy goods vehicles) whilst works progressed on the joints underneath.

Tenders for the Works were sent to Contractors expressing an interest in the work on 7th July 2008, and these were returned on 12th September 2008 (including a two week extension). The pre-tender estimate, prepared by Atkins, was for approximately £8.7m. Following an analysis of the tender submissions the tender recommended for acceptance was from Balfour Beatty for a sum of £13,753,932.86, approximately £5m above the estimate. The main difference between the estimate and the returned tender was in preliminary items and the temporary bridging. These items proved difficult to evaluate because of the unique nature and high contractual risk of the works.

Following the announcement by the Scottish GovernmentExecutive in December 2008 that a new Forth crossing would be in place by 2016, FETA requested that Atkins look into the consequences of retaining the joints until the new crossing is in place. This should take the form of assessing the possible modes and risks of failure, and what measures could be taken to extend the life of the joints.

4. Failure Mode and Effect Analysis

4.1 Description of the Roller Shutter Joints

Each separate roller shutter joint in the bridge comprises a series of six individual units. Each unit has effectively two movement joints, one for each (side and main) span. Each individual joint unit comprises an shuttle (also known as a bridge or anchor) plate which is articulated on the deck side and effectively spans over the physical movement gap of the deck itself. On the opposite side to the deck, the shuttle plate is connected to a series of link plates by hinges to form a train. The shuttle and link plates slide, via discrete feet, over the curved top flanges of track beams as the deck moves. The pier side of the joint supports a tongue plate. This tongue plate is also supported on top of the link plate train to form a level running surface for traffic. An as-built drawing showing the typical layout of the joint is included in Appendix A.

4.2 Failure Mode and Effect Analysis

4.2.1 Replace Components

In identifying possible modes of failure and the consequential effects use has been made of a Failure Mode and Effect Analysis (FMEA) process which is commonly used in the manufacturing industry. A FMEA is a systematic method aimed at identifying and preventing product and process problems before they occur. The objective of a FMEA is to identify possible modes of failure, evaluate the risk of failure and to provide recommended actions for control measures that should be put in place to reduce the risk of failure. A FMEA usually uses historic product or process data to assess risks of failure. This is not easily available for the roller shutter joints therefore the assessment of risks is to some extent based on engineering judgement, previous inspections and maintenance experience. The roller shutter joints are virtually original to the construction of the Bridge back in 1964. Records show that they have had one major overhaul in 1975, although there is evidence that other repair work has been undertaken. Experiences with other such joints on similar bridges suggest a working life of between 20 and 30 years before major intervention is necessary. The joints on the bridge are therefore probably overdue for major works. The results of the FMEA have been included in Appendix B of this report.

4.2.2 Components and Types of Failure

For the application of the FMEA process to the roller shutter joints, each individual component of the joints has been considered and what the potential mode, effect and cause of failure of that component would be. The components have been listed in a FMEA spreadsheet and cross referenced to a drawing and photographs of the joint (see Appendix B). Generally most components can potentially fail in a number of ways and these include:

(i) Weld failure from fatigue or corrosion;

(ii) Excessive wear;

(iii) Excessive corrosion;

(iv) By overloading, from either increased traffic loading from the original design or from wear of other components;

(v) Fatigue or fracture;

(vi) Seizure.

To enable identification of which component has the highest failure risk factor a Risk Priority Number (RPN) is determined. The RPN is derived from three criteria: severity, occurrence and detection, with each based on a 10 point scale. Descriptions for each point are provided in Appendix B.

4.2.3 Severity of Failure

In deriving descriptions for severity for the joints two forms of severity were considered, these being economic severity and public perception severity. The economic severity is defined as the estimated time period that a carriageway on the bridge would need to be closed to make repairs should a failure of a joint unit occur. The temporary closure of a carriageway or individual traffic lanes would inevitably lead to traffic congestion. Traffic flows currently regularly exceed the theoretical capacity of the carriageway. For a closure of a carriageway, road user delay costs are estimated to be in the order of £650,000 per day. The period of closure could be affected by external influences such as poor weather and availability of resources. Traffic delays from such closures would also inevitably lead to bad publicity and criticism. Some types of failure could be relatively minor or foreseeable in the short term and repairs could be planned for in advance allowing advance publicity and this has also been reflected in the scoring criteria.

The public perception severity is defined as how the travelling public would be affected if a joint failed in terms of personal injury or accident damage to vehicles. Some types of failure, such as loss of the plate train, would leave large gaps in the carriageway giving a high potential for a serious vehicle accident and personal injury. It should be noted that no comparison should be made between economic severity, personal injury and vehicle damage of the same score.

4.2.4 Occurrence of Failure

Descriptions for occurrence simply range from a score of 10 if the probability of the cause of failure of a component is considered to be certain, down to 1 for a near impossibility. A full list is provided in Appendix B. Ideally this should be based on past data, such as 1 in 100,000 fail, but in the case of the joints the occurrence is considered to be likely to increase with increasing age and wear so in determining a score some form of judgement is necessary.

4.2.5 Detection of Failure

Descriptions for detection are based on the probability of a potential failure of a component being detected before the impact of the effect of failure is realised. For the roller shutter joints the means of detection are currently based on routine six monthly close inspections and daily walkover inspections. Even with the current inspection regime an impending failure may go unnoticed. For example, fatigue cracking in a hidden component such as a hinge pin would not be readily observed. Failures could also be sudden with little or no advance warning, but corrosion of a visible component, say the track beams would be. A further consideration would be the ease of access to the relevant part of the joint as the current access walkways do not enable all parts of the joints to be reached.

4.3 Identification of Areas of High Risk

The scoring for the severity, occurrence and detection are multiplied together to determine the RPN. The higher the RPN the higher the risk, and therefore, by ranking the scores guidance is provided on where to focus the most attention to reduce the overall risk.

The scoring for the FMEA is first based on the current condition of the joint units. Each component was scored and six areas of high risk were identified. Areas of high risk have been defined as those with a RPN in excess of 200 (250?). In summary these are:

(i) The shuttle plate horizontal thrust block that is attached to the plates themselves (component 1);

(ii) The shuttle plate horizontal thrust block that is attached to the support (component 17);

(iii) The vertical bearing to the shuttle plate that is attached to the plates themselves (component 2);

(iv) The vertical bearing to the shuttle plate that is attached to the support (component 19);

(v) The feet supporting the plate train on the track beams (component 7);

(vi) The hinges between the plate trains (component 10);

Generally the main reason the above components have a high RPN is because of the high severity score, although the plate train feet and hinges also have high detection scores.

4.4 Minimising the Risk of Failure

Following the FMEA process consideration should be given to see what could be done to reduce the risk of failure. Reducing the risk can be seen as what could be done to prevent the failure in the first place, or what could be done to mitigate the effects of a failure should it occur. Prevention strategies include works such as replacing high risk components before they fail and enhancing current inspection and monitoring regimes to predict the on-set of failure. Mitigation strategies include installing safeguarding measures or having components in stock so that they can be quickly installed should a failure occur. However, there are a number of constraints and issues that need to be considered, and these are discussed in Section 5 below.

5. Constraints / Issues

5.1 Access

Part of the main joint replacement works contract was to provide improved access around the bridge joint underneath the deck. Although the joint can be reached under the existing arrangements not all parts can be easily inspected or repaired. With increasing wear and risk of failure, the lack of good access would remain a constraint and safety risk in a potentially harsh environment. The current six monthly inspection regime involves temporarily ~~improving~~ ?access using scaffolding which is difficult ~~and potentially dangerous~~ to erect. Permanent improvements to access could be made as originally proposed to improve access and to reduce the safety risk of erecting temporary scaffolding.

5.2 Weather

If emergency repairs become necessary then these could happen with little or no notice, at any time of the year. If poor weather conditions prevail at the time repairs are needed this could lead to further delays and an increased safety risk to the workforce. Repairs would most likely require the use of cranes which would be susceptible to even moderate wind speeds.

5.3 Availability of Resources

Most of the components of the joints are unique to the joint and replacements would require special manufacture. *However, pins, springs and etc which are identified as having high RPN's are not* This manufacturing process may take some time, allowing for locating a supplier, the procurement process, and the manufacture and delivery of the part. In addition, repair or replacement may require specialist equipment and trades, both of which also may not be immediately available *not in the case of pins, springs and etc*. –*FETA can do*

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5.4 Traffic Management

As with the proposed main contract works, when determining risk reduction measures, the need for traffic management should also be considered. Traffic management that requires closures of carriageways leads to congestion, user delay costs, negativepoor publicity and an increased safety risk to the workforce. Closures of carriageways require liaison with other roadshighway authorities to avoid clashing works.

5.5 Funding

Any risk reduction measure would lead to additional work in terms of inspection regimes, repairs or other remedial measures. Such work in itself would lead to additional costs both in terms of the cost of the work itself and, if traffic management is required, road user delay costs. These costs would not be large but wouldlargely be in addition to the cost of the main remedial works as there would be no duplication of works. The provision of a permanent access system at a cost of £***** had also been included as a requirement and cost in the tender for replacement of the joints and therefore is not an additional cost of delaying the work.

5.6 Procurement of Main Works

Should it be necessary to replace the joints time needs to be allowed for the tender process, engagement of a Contractor, mobilisation, manufacture and the actual works themselves. In addition, because of winter weather and traffic demand on the bridge, the works can only be effectively done at certain times of the year which is mainly late spring and early autumn. This could mean that the time period between deciding the joints must be replaced because of failure to having a new joint installed could be up to 18 months.(is this not a bit pessimistic given we have tender documents)

5.7 Timing of the Replacement Crossing Opening Political Pressure to Retain Existing Joints Until 2016

If the existing joints are retained until after the opening of the Forth Replacement Crossingsecond road crossing then there are significant potential cost savings in the temporary bridging and deck strengthening as each carriageway can be closed in turn without significant disruption to traffic.traffic can be easily diverted elsewhere. Although the mini bridging solution minimised traffic disruption it is acknowledged that the ramps by their geometry would lead to some reduction in flow and some increase in congestion and the restriction on use by heavy goods vehicles would cause some additional congestion on the diversion routesI If the work is delayed until the new bridge is opened these two issues lose relevance.t is also possible that there would be less overall traffic congestion in the area. Based on the tender returns for the joint replacement the actual works cost is saving is in the order of around £6m. Although there are additional costs in retaining the joints (see 5.5 above) these would be a fraction of the less than £6m cost as the majority of the work would be carried out in house by FETA staff and there could be pressure to pursue this

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~~potential saving. This pressure could increase, particularly if the opening of the new crossing is only a year or two away.~~ The FMEA has been used to evaluate the risk of failure of joint components which could result in accidents occurring and that analysis has been used to design mitigating measures to reduce that risk to acceptable levels.

The FMEA has also been used to evaluate the risk of serviceability failures of joint components which would not cause an issue for public safety but may lead to some disruption whilst repairs are carried out. These failures have a lower risk priority number which means that even if they occurred there is a low impact on the travelling public.

There is a further risk that there could be an unforeseen serviceability failure of a joint before 2016 as a result of further wear of the joints. This type of failure would likely lead to disruption to traffic . This risk is difficult to quantify but is likely to be within the medium (medium to low??) . The inspection and monitoring regime proposed will offset part of that risk that a future, as yet unforeseen, serviceability failure will occur.

There is also an external risk that ~~The risks are that a joint could ultimately fail before 2016 so that no saving is made and that the failure caused an accident. There is also a risk~~ that the opening of the new crossing is delayed ~~as work on the crossing is still in its early stages.~~and the service life of the joints has to be extended. Depending on the extent of the delay a review of the decision to extend the service life of the joints would have to be further reviewed.

5.8 Reviewing Decisions

If the recommendation that the life of the joints can be extended is accepted by the Authority then that recommendation should be ~~decision is made to retain the joints, that decision~~ should be reviewed at regular intervals to ensure that it remains the right decision. As previously discussed, the joints have reached the end of their working life and the risk of failure can only increase with time. The FMEA spreadsheet should be considered a live document that should be subject to periodic review. If RPN increase to unacceptable levels and options to mitigate the risk have been exhausted then a decision to retain the joints should be changed.

6. Options for Reducing the Risk of Failure

6.1 General

Options for reducing the risk of failure involve either those that prevent such a failure, or, if failure cannot be prevented, those that mitigate a failure. The choice of method to reduce a RPN should be considered carefully. A RPN for a cause of failure of a component could be reduced by reducing the detection score (by say increasing the frequency of inspections) but the severity or occurrence remains the same. The effect of this is not actually reducing the result of an accident which could be serious such as a fatality~~deat~~h. Prevention of failure is preferable to mitigation, but short of replacing a whole joint it is unlikely that full prevention of all components can be achieved. It is likely, therefore, that a combination of options achieves the best way of reducing the RPN.

Methods of preventing failure include the following:

i Replace components identified as being high risk;

ii Implement enhanced inspection and testing regimes to identify likely ~~impending~~ areas of failure;

iii Improving access to the joints;

Methods of mitigating failure include the following:

i Undertaking modifications to reduce the effect of failure;

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ii Installing monitoring devices;

iii Stock spare parts, including a whole joint, in stock so in the event of failure repairs can be undertaken quickly;

iv Install a temporary bridge over a failed joint or undertake the necessary strengthening so that a temporary bridge could be installed with the minimum of delay;

v Keep suitable Contractors and Plant on stand-by for quick repair mobilisation.

6.2 Preventing failure

6.2.1 Replace Components

Some of the components could be relatively easily replaced and this would reduce the risk of failure. Such components would include the shuttle and tongue plate holding down bolts and the associated springs. However, the scope for replacing the high RPN components identified in section 4.3 is limited. The joints are heavily worn and parts have bedded together which will be disturbed if replacement is undertaken. For example the hinge feet have been identified as high risk, but they have worn into the supporting track beams. *Is it not the welding to the hinge feet that is the high risk and could we not reweld while each train is out during inspection* Similarly the two sides of the thrust blocks in both the shuttle and tongue plates have worn together. Repairs may introduce articulation problems resulting in poor operation and damage to other parts of the joint such as the hinge pins. Alternatively repairs would be so extensive, it would be practically and financially better to replace the whole joint. Any replaced components would need to be discarded when the whole joint is replaced so there would be no cost saving to the main replacement works.

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6.2.2 Enhanced Inspection Regime

Currently the joints are subject to a detailed six monthly inspection and a daily walkover. In addition to this, FETA have also lifted out a few plate trains and tongue plates for a closer examination of parts that are not normally visible during the six monthly inspections. The inspections would note areas of increasing wear and corrosion that may give warning of imminent failure. Fatigue failure would be difficult to see until failure had happened.

If the inspection regime is enhanced then any potential failure may be spotted earlier and the appropriate action can be planned for. An enhanced regime can be in two forms. One is to decrease the inspection interval so that the joints are looked at closely more frequently and the other is to periodically and systematically lift out plate trains and tongue plates. Lifting out plates allows for a close examination and also enables some testing to be undertaken such as dye penetration testing of welds to check for cracking. Detailed measurements can be taken such as wear on hinge fit and the slack in the hinges between plates. There is a risk of lifting plates out in that they may not settle back into the original position satisfactorily, the joint may get damaged, or changes in weather may prevent the use of a crane to return the plates.

Enhancing inspection regimes will have cost and resource implications. If the inspection team is undertaking more inspections then this distracts them from other important work elsewhere on the bridge. – No The testing work would require specialist skills.

6.2.3 Improving Access to the Joints

Currently when a six monthly inspection of the joints is undertaken the existing access walkways under the bridge deck are extended by temporary scaffolding.

This scaffolding is installed and removed each time. The scaffolding work is ~~potentially hazardous~~ difficult aas it is carried out in ~~in~~ a harsh and restricted environment. Part of the proposed works for the whole replacement of the joints involves improving the existing permanent access. If the improved access is installed earlier then inspections can be undertaken more safely, more thoroughly and quicker.

6.3 Mitigating failure

6.3.1 Undertake Modifications to the Joint

The effects of failure could be reduced by undertaking modifications to the joints. One of the modes of failure seen on other bridge with a similar type of joint is failure of the link plate hinges causing the plates to drop into the joint and leaving a large gap in the carriageway. One measure to prevent such a gap forming would be to install a form of flexible strap, chain or cable attached to the underside of the plates that would effectively ‘catch’ the plate train should a hinge fail. Flexibility of the straps is necessary to allow normal working of the joint. Should a hinge joint fail then emergency repairs and carriageway / lane closures would be necessary as the retaining straps should not be relied upon to hold the plates, but they ~~may~~ *would be designed to* prevent catastrophic collapse.

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An alternative, or additional means of preventing the plate train falling completely into the structure of the joint is to install *blocks* *see previous comments would the block act as a fuse?* on top of the track beam top flanges just beyond the end of the trailing plate of the plate train. If a hinge fails the train would only slide down the track beam as far as the block reducing the size of a gap in the carriageway. A reduction in the gap size could reduce the effects of an accident. The position of the block would need to be considered carefully to allow free movement of the joint in normal use, but also to minimise the gap in the event of failure. The blocks could be bolted to the track beam flange so that they could be moved with changes in joint position with changing seasons of the year.

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6.3.2 Installing Monitoring Devices

To supplement inspections, some form of monitoring or tell tale device could be installed where changes could be recorded. This would help to reduce the subjectivity of inspections. An increase in wear in the plate hinge joints would manifest in an increased gap between the plates. The difficulty with installing a monitoring device is that the joints are constantly moving with the constant variations in traffic, wind and temperature loading. Slack is currently evident in most link plate hinges and when the joint gap changes the slack is taken up before the plates themselves move. Any form of monitoring device would also need to be designed so as to avoid interfering with the normal working of the joint.

Generally there two standard types of readily available tell tales. The first is the ‘Avonguard’ acrylic type which would be too rigid to work across the plate gap and the current slack in the hinges is too large to allow this system to be used. The second standard way is to measure the distance between two studs, one fixed either side of the gap, with a “demec” gauge or callipers. The difficulty with this method is that the distance between the plates would be virtually impossible to measure with the constant moving of the joint.

Consideration has been given to devising some form of bespoke monitoring device as an alternative to a standard method. One method is to fix a flexible strap across the gap between and underneath the plates. If the gap increases the strap would break giving an inspector clear evidence that a change has taken place. With this method an inspector does not need to get close to the joint to check if strap failure has occurred. However a suitable material for the strap that would be flexible and break has not been identified. A second method is to fix one end of a rigid pointer to the underside of one plate that reaches across the gap to a scale fixed to the underside of a neighbouring plate. The range of movement can then be recorded by an inspector. With this method, however, close access to the underside of the plates would be necessary which is difficult to achieve. In addition the full range of movement may not occur at the time of inspection.

6.3.3 Stock Spare Parts

During routine inspections, and especially when plates are lifted out, some parts could be replaced. These include the holding down pins and associated springs to the tongue and shuttle plates. With traffic management in place these parts are relatively easy and low cost to replace.

Whole replacement joint units could be fabricated to the original design to allow prompt replacement of any failed unit. The new unit would have much higher tolerances than the existing surrounding worn trains and consequently would not be as capable of 'flexing' to accommodate the uneven slide tracks and seatings. In addition, the new units would not be worn and so would not bed into the same profile of the adjacent trains leading to an uneven vertical profile. The original design used six different widths of train units which prevent units being interchanged. A view could be taken on the most likely units to fail to limit the number of spare units, but this may prove incorrect.

As well as spare parts spare plates could be held in stores that could be used to bridge gaps in a joint left by a failed joint, such as a plate train. There would be difficulty in fixing a plate down securely enough to allow traffic to pass over the failed joint and also allow the bridge deck to move.

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6.3.4 Install Temporary Bridging

As discussed in section 5.6 above it may take up to 18 months *pessimistic?* to procure a replacement joint should one fail completely. The decision could be taken to install temporary bridging before a joint unit fails. As proposed in the original main works contract a temporary bridge could be installed over the joint to allow a carriageway to be reopened. Before a temporary bridge could be installed it is necessary to undertake some strengthening of the bridge deck to accommodate the temporary bridge loads. This could be done in advance so that if a temporary bridge is needed it can be installed relatively quickly. Arrangements to procure a temporary bridge could also be done in advance.

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Four temporary bridges in total would be necessary. It is expected that the temporary bridges themselves would cause some congestion and would be more susceptible to icing and high winds than the rest of the bridge. A temporary bridge itself would have a high maintenance requirement and would need to be in place for some years as opposed to about 8 weeks in the proposed main joint contract. This is likely to cause problems with accommodating the movement of the suspension bridge, due to temperature and other loads.

Maintenance and inspection of the temporary structures would be required. As with the main contract proposals, strengthening of the deck is likely to be necessary to take the loads from the temporary bridges.

I don't think the following is practical and it is neither included or excluded from the Recommendation.

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6.3.5 Keep Specialist Contractors and Plant on Stand-By

Repairing or replacing a joint would require specialist trades and equipment. To reduce the time for procurement arrangements could be made with such trades and plant suppliers in advance so that they could be called upon in an emergency. A review of what specialists and equipment that may be needed would need to be undertaken. This could include a review of in-house maintenance team to identify any skills shortfalls or gaps, for example welders, or inspectors.

6.4 Actions

The FMEA process requires specific action to be taken to reduce the RPN for each component and failure mode to an acceptable level. The action required for each is a combination of the options described in Section 6 above and these have been added to the FMEA spreadsheet included in Appendix B. With the actions identified the RPN is then recalculated, using the same severity, occurrence and detection criteria, to confirm that the end risk is acceptable. As previously mentioned, the FMEA spreadsheet should be regarded as a live document and a periodic review, say annually, is needed to ensure the identification, risk and actions remain appropriate.

7. Recommendations

It is preferred that the roller shutter joints are replaced ~~refurbished~~ as soon as practicable. The joints are at the end of their useful life and wear is evident that could lead to failure and a safety risk to the road user. Failure of a joint will necessitate the closure of a lane or carriageway while repairs are undertaken. Such repairs may take some time as specialist labour and materials would be necessary. However, it is evident that deferring full replacement until the new forth crossing is constructed has considerable benefits in both road user delays and contract costs ~~(if temporary viaducts are deleted)~~. It is recommended therefore, at this stage, that the joints are retained with additional preventative and mitigating actions.

The FMEA process has identified components at highest risk and what actions are required and this is summarised in the FMEA spreadsheet. Measures to prevent failure are recommended and it is advised that inspections are undertaken more frequently, say every three months, and a plate train and tongue plate is lifted from a joint unit also at three monthly intervals. To allow the increased number of inspections to be undertaken with greater safety and better access it is recommended that the existing permanent access is improved along the lines proposed for the original joint replacement contract. Other preventative measures include repair or replacement of parts of the joint units. Undertaking a limited level of repair to the joints would be difficult and may upset the existing load path through the components of the joints leading to a failure anyway. The only recommended repair is to replace the tongue and shuttle plate holding down pins and associated springs.

Measures to mitigate the effects of failure are also recommended and these are to install restraining straps underneath the plate trains and restraining blocks(*see previous comments*) on the track beams. The restraining blocks and straps will prevent the plate trains from sliding completely into the joint in the event of failure, but some limited sliding would still occur. This can ~~should~~ be considered a ~~limited~~ 'fail safe' system but is limited as it would not allow the joints to continue in use after a failure until repairs are made.

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~~Erection of temporary bridging is not recommended as an action at this stage since this involves high cost and introduces additional hazards to the bridge user. The temporary bridges would also likely cause additional congestion in themselves~~ Why would we even consider this in such detail?? –it is really only causing confusion. Monitoring devices have been considered, but these are considered to be unnecessary if the recommended increased inspection regime is put in place.

The final recommendation is that the FMEA process is reviewed annually to ensure the appropriate actions are in place and increasing wear on the joints is not causing an unacceptable increase in risk. It should be borne in mind that the review may conclude that full replacement of the joints before 2016 is the only option.

8. Summary

The main expansion joints roller shutter joints are considered to be at the end of their useful working life as evidenced by general wear. There is a risk of failure of one or more of the components of the joint resulting in a major safety hazard to the bridge users. As a result, a tender was let for the extensive refurbishment of the joints and to improve general access for future maintenance and inspection. However, since the letting of the tender, but before award, the Scottish GovernmentExecutive have announced that a second Forth Replacementroad crossing will be in place by 2016.

~~To reduce the inevitable congestion that replacement of the joints would cause it has been suggested that the replacement is delayed until after the new crossing is in place~~. With an ~~alternative crossing the need to install temporary bridging over the joints while they are replaced could also be removed giving a cost saving.~~ *Neither of these are correct*

To consider the safety risk of retaining the joints a FMEA has been undertaken to identify areas of highest risk and the prevention and mitigation actions that could be taken to reduce such risks. None of the actions would ~~eliminate the safety risk,~~! *Why have we done the FMEA?* and all would require funding in themselves. *How does that compare to spending £6 m* The prevention actions recommended are to increase the frequency of inspections, to closely examine joint units by lifting out the plates, and to replace tongue and shuttle plate holding down pins and springs. The mitigation actions recommended are to improve access under the bridge deck for inspections and repair, and to install restraining straps and blocks to the plate trains.

The FMEA spreadsheet produced should be reviewed annually to confirm that there is no significant change in risk and that the actions recommended remain appropriate.

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Appendix A

Details of existing roller shutter joint.

Appendix B

FMEA Results Spreadsheet, with Component Identification Drawing and Photographs and Scoring Criteria.

B.1 FMEA Scoring Tables

B.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.

B.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.

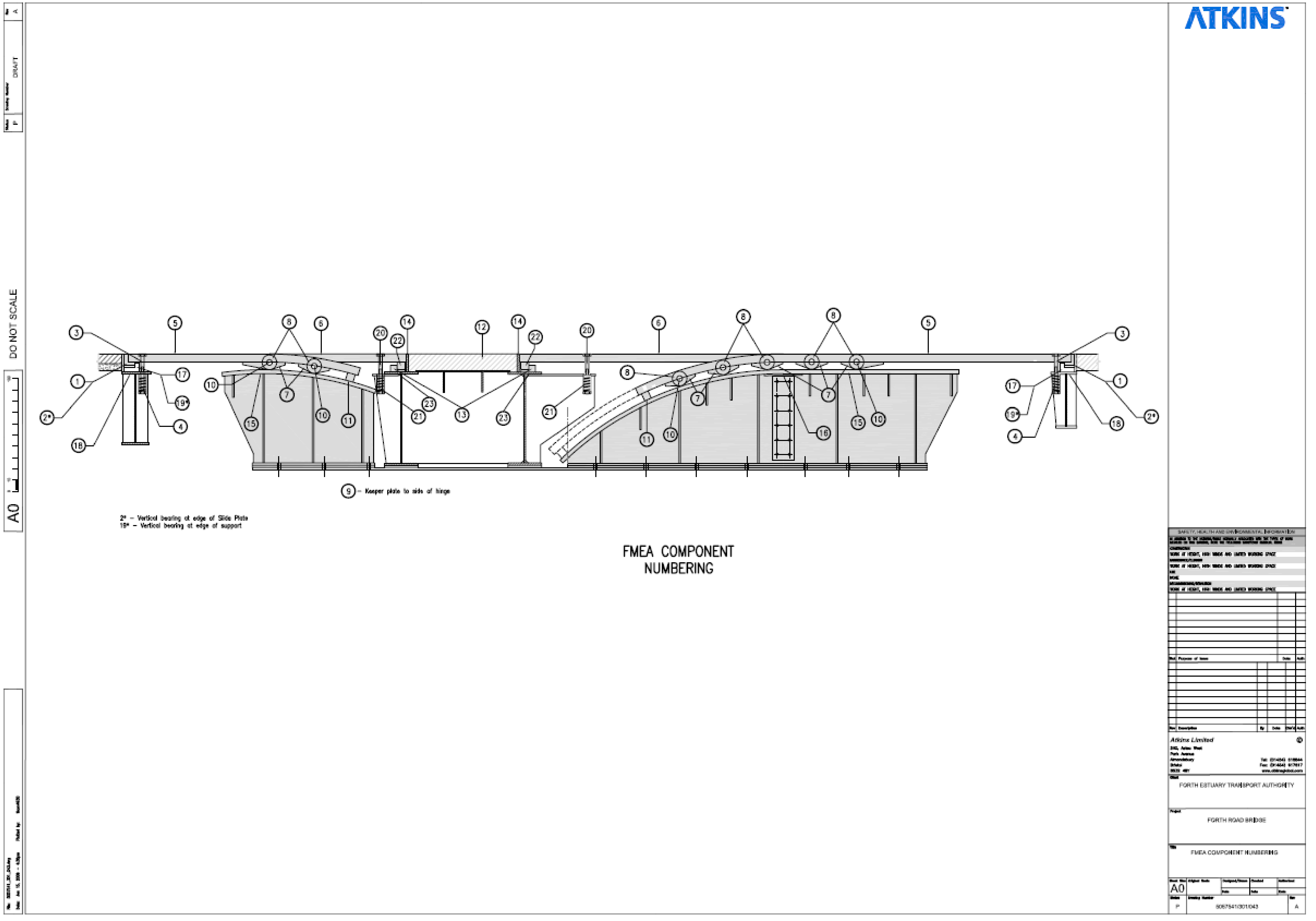
B.1.3 Occurrence Scoring Table

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

B.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			
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	**Highly 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		Easy access to within touching distance. Defect progressive but not detectable without testing.	Fatigue cracking in welding to bearing block.
4	**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	**Most 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.	

B.2 FMEA Component Drawing



B.3 FMEA Assessment

																	Resulting Assessment					
Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Prevention	Current Controls, Detection	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	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.				Weld failure from fatigue.														
2	1	"	"	"				Overloading of thrust block on shuttle plate (where wear between the feet and the track beams cause extra resistance).														
3	1	"	"	"				General corrosion.														
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.				Weld failure from fatigue.														
5	17	"	"	"				Overloading of thrust block attached to support (where wear between the feet and the track beams cause extra resistance).														
6	17	"	"	"				General corrosion.														
6a	17	"	"	"				Impact loading due to lack of fit.														

																	Resulting Assessment					
Line	**Component No**	**Component and Function**	**Potential Failure Mode**	**Potential Effect of Failure**	**Economic Severity**	**Public Perception Severity**	**Overall Severity**	**Potential Causes of Failure**	**Occurrence**	**Current Controls, Prevention**	**Current Controls, Detection**	**Detection**	**RPN**	**Recommended Action**	**Responsibility and Target Completion Date**	**Action Taken**	**Economic Severity**	**Public Perception Severity**	**Overall Severity**	**Occurrence**	**Detection**	**RPN**
7	18	"	"	"				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.														
8	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.				Weld failure from fatigue.														
9	2	"	"	"				Overloading of bearing block.														
10	2	"	"	"				General corrosion.														
11	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.				Weld failure from fatigue.														
12	19	"	"	"				Overloading of bearing block support beam top flange causing local failure of the top flange/cracking around block within supporting steelwork.														
13	19	"	Wear of bearing block.	Poor vertical carriageway profile/step in carriageway.				Wear due to cyclic movement.														

Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Prevention	Current Controls, Detection	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
14	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.				Overloading of pin (where wear between the feet and the slide track beams cause increased dynamic movement).														
15	3	"	"	"				General corrosion.														
16	4	Spring around Holding Down Pin to shuttle plate.	Loss of vertical restraint of plate train.	Plate train becomes free and can be dislodged.				Overloading of spring(where wear between the feet and the track beams cause increased dynamic movement).														
17	4	"	"	"				General corrosion.														
18	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.				Overloading of pin (where wear between the feet and the slide track beams cause increased dynamic movement).														
19	20	"	"	"				General corrosion.														
20	21	Spring around holding down pin to tongue plate.	Loss of vertical restraint to tongue plate.	Plate becomes free and can be dislodged.				Overloading of spring(where wear between the feet and the track beams cause increased dynamic movement).														

Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Prevention	Current Controls, Detection	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
21	21	"	"	"				General corrosion														
22	5	Shuttle plate / plate train.	Uneven vertical profile of running surface.	Potential for "cat1" surface profile defect due to poor vertical profile.				Wear of joint components.														
23	5	"	Loss of textured running surface.	Lack of skid resistance for vehicles.				Tyre wear to joint surface.														
24	5	"	Failure of plates.	Plate train becomes free and could fall into joint.				Impact loading increased due to lack of fit.														
25	5	"	"	"				Excessive corrosion.														
26	6	Tongue Plate.	Excessive wear of plate thickness.	Plate ends further back giving poor vertical alignment.				Increased vehicle impact effects.														
27	6	"	Loss of textured running surface.	Lack of skid resistance for vehicles.				Tyre wear to joint surface.														
28	6	"	Failure of plates.	Tongue plate would fall into joint.				Tyre wear to joint surface.														
29	6	"	"	"				Corrosion.														
30	7	Feet supporting plate train.	Failure of connection between feet and plates.	Collapse of plate train or plate train falls into joint.				Weld failure from fatigue.														
31	7	"	"	"				Impact loading due to lack of fit.														
32	10	Hinge between plates in plate train.	Failure of hinge pins.	Plate train becomes free and could fall into joint.				Fatigue failure of pin.														

Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Prevention	Current Controls, Detection	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
33	10	"	"	"				Impact loading due to lack of fit.														
34	10	"	"	"				Excessive wear in pin.														
35	10	"	"	"				Overloading of pin (where wear between the feet and the track beams cause extra resistance).														
36	9	End keeper plate to hinge pins.	Plate becomes unattached.	Hinge pin 'works out' from bushing causing plates to come apart.				Weld failure from fatigue.														
36 a	9	"	Wear through.	"				Wear through.														
37	8	Hinge pin bush.	Bush cracks and fails.	Hinge separates and overloads other components. Plate train could become free and fall into joint.				Impact loading due to lack of fit.														
38	8	"	Bush wears excessively.	Plate train seizes due to excessive plan rotation and overloads other components. Plate train could become free and fall into joint.				Excessive wear in bushing.														
39	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.				Weld failure from fatigue.														
40	12	Pedestal between moving parts of joint.	Loss of surfacing material.	"Cat1" defect. Poor vertical alignment causing damage to joint and / or vehicles.				Lack of bond of surfacing material to steel pedestal.														

Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Prevention	Current Controls, Detection	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
41	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.				Weld failure from fatigue.														
42	13	"	"	"				Overloading of horizontal restraint (where wear between the feet and the track beams cause extra resistance).														
43	13	"	"	"				Impact loading due to lack of fit.														
44	13	"	"	"				General corrosion.														
45	23	Support to horizontal/vertical restraint blocks to tongue plates.	"	"				Overloading of supporting steelwork (where wear between the feet and the track beams cause extra resistance).														
46	23	Support to horizontal/vertical restraint blocks to tongue plates.	"	"				General corrosion.														
47	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.				Weld failure from fatigue.														
48	22	"	"	"				Overloading of horizontal or vertical restraint (where wear between the feet and the track beams cause extra resistance).														
49	22	"	"	"				Impact loading due to lack of fit.														

Line	Component No	Component and Function	Potential Failure Mode	Potential Effect of Failure	Economic Severity	Public Perception Severity	Overall Severity	Potential Causes of Failure	Occurrence	Current Controls, Prevention	Current Controls, Detection	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
50	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.				Weld failure from fatigue.														
51	14	"	Wear of top edge of plate.	Damage to vehicle tyres.				Excessive wear.														
52	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).				Excessive wear.														
53	15	"	Failure of top flange by rotation.	Loss of support to plate train causing excessive wear in plate train.				Excessive wear.														
54	15	"	Failure of top flange by deflection	Loss of support to plate train causing excessive wear in plate train				Excessive wear.														
55	15	"	"	"				Impact loading due to lack of fit.														
56	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.				Fatigue failure of bolt due to increased impact loading as a result of lack of fit. Wear of counter sunk bolt head.														
57	24	Lateral restraint blocks to underside of plate train	Loss of blocks	Plate train can 'crab' causing it to bind				Excessive corrosion.														
58		"	"	"				Weld failure from fatigue or impact														

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