Forth Estuary Transport Authority

Forth Road Bridge
Extending the Life of the Main Expansion Joints

Revision E

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Forth Estuary Transport Authority

Reducing the Risk of Failure and Extending the Life of the Main Expansion Joints

February 2009

Notice

This report was produced by Atkins Limited for FETA for the specific purpose of reducing the risk of failure and extending the life of the main expansion joints

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Executive Summary

This report considers the risk and measures that could be undertaken to reduce the risk, of extending the life of the main roller shutter expansion joints in the Forth Road Bridge. These are the joints that are located at the main towers of the suspended span of the bridge. Following increasing maintenance work and the findings of routine inspections it is apparent that the joints are excessively worn and have reached the end of their working life. The increasing wear means that there is a risk of failure of a component of the joints, the effect of which would be a significant safety risk to the travelling public and possibly emergency carriageway closures 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 contractors 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. In addition the works would have included temporary bridging over the joints to allow works to progress while keeping the carriageway open to traffic. 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, but before the award of a contract, the Scottish Government has announced that the Forth Replacement Crossing will be in place in 2016.

FETA requested Atkins to consider what the risk of a joint failure would be if the life of the joints was extended to 2016. With a replacement crossing the temporary bridging originally envisaged would no longer be necessary, leading to savings (over £6m) in contract works costs and a reduction in the works programme. To evaluate the risk of failure of a component in a joint unit a Failure Mode Evaluation Analysis (FMEA) was undertaken. This considered the effects of failure of each component under three criteria: these being severity, occurrence and detection. Severity is defined as the consequence of failure should it occur, i.e. traffic accident and / or carriageway closure. Occurrence is defined as the probability or frequency of the failure occurring and detection is defined as the probability of the failure being detected before the impact of the effect is realised. The three criteria are multiplied together to produce a Risk Priority Number (RPN). The higher the RPN the higher the risk of failure, or the effects of failure, a component would have. The basis of the scoring under each criterion was engineering judgment, past inspection and maintenance experience, and the condition of a sample joint unit dismantled by lifting out the tongue plate and plate trains. This process identified a number of components with an unacceptably high risk and therefore, requiring action in the form of prevention and mitigation measures to maintain current levels of operation and safety.

Preventative measures recommended are to double the frequency of inspections from the current six monthly programme to three monthly. To enable such inspections to be undertaken at the more frequent intervals, and to enable close access to all parts of the joints, it is recommended that the improvements to the access walkways under the bridge deck proposed in the original works contract are implemented. In addition, all the joint units should be systematically partially dismantled by lifting out the plate trains and tongue plates and closely examined and components tested. Whilst the plates are lifted out it is also recommended that all the tongue and shuttle plate holding down pins and springs are replaced with holding down bolts and springs to improve reliability. Other repairs to the joints should be limited to replacing the keeper plates at the end of the outer hinge pins in the plate trains.

Mitigation measures recommended are to install restraining straps to the underside of the plate trains and stop end blocks on the track beams. These measures should limit the extent a plate train could slide into a joint in the event of hinge failure in the train or failure of the anchored support of the shuttle plates. Further restraining straps are recommended to prevent the shuttle plate dropping from the anchored end of the support beam. These mitigation measures would only be in place until the joints are replaced.

The total cost of the preventative and mitigation measures is estimated to be approximately £150,000 to £200,000 using FETA in-house resource. In addition, the improvements to the access walkways are estimated to be approximately £500,000, but this work was planned in the original contract so is considered to be cost neutral. The combined cost of these is considerably less than the cost of the temporary bridging.

This report recommends that the life of the joints can be extended, but only if the above prevention and mitigation measures are put in place to ensure the risk of failure is maintained at acceptable levels. In addition the FMEA should be reviewed at least annually to ensure the conclusions remain applicable and actions remain effective.

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1. Introduction

Atkins has been requested by the Forth Estuary Transport Authority (FETA) to consider the risks and consequences of delaying the replacement of the roller shutter joints in the Forth Road Bridge. This is in response to an announcement by the Scottish Government that a new road crossing of the Forth (the Forth Replacement Crossing) will be in place by 2016. Delaying the replacement of the joints until after 2016 allows traffic to be diverted onto the new crossing and therefore the potential for traffic disruption, with the consequent economic effects in the region, will be reduced. In addition there is potential for savings in the costs of replacing the joints by avoiding the need to install mitigation measures to reduce traffic congestion, such as temporary bridging over the joints. However, the existing joints are extensively worn, and are at the end of their service life, and there is the risk that part of a joint could fail before 2016. Although the risk of failure is low, the failure could result in a serious accident and closure of a carriageway on the bridge.

2. Scope of Report

The roller shutter joints are the main carriageway deck movement joints located at both main towers and on both carriageways of the suspended section of the bridge. This report will cover recent background events and 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 provide recommendations on what actions to take.

3. Background

In 2007 Atkins was commissioned by 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 service life and all should be replaced 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. Installation of the new joints would have required long term access to the joints from the carriageway under 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 issued to pre-qualified 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 analyses of the tenders, the submission recommended for acceptance was for a sum of £13.8m, 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. Based on the returned tenders, the cost of the temporary bridging is over £6m.

After the return of the tenders, but before award of a contract, the Scottish Government announced on 10th December 2008 that a new Forth Replacement Crossing would be in place by 2016. In response FETA requested that Atkins investigate the consequences of retaining the joints until the new crossing is in place. This investigation 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 movement joint comprises a 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 other 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 Objective

To assess the level of risk, and to identify possible modes of failure and the consequential effects, use has been made of a Failure Mode and Effect Analysis (FMEA) process. This process is commonly used in the manufacturing industries. 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 to an acceptable level. A FMEA usually uses historic product or process data to assess risks of failure. This is not available for the roller shutter joints therefore the assessment of risk 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 overdue for major works. The results of the FMEA have been included in Appendix A 2.1 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. The potential mode, effect and cause of failure of each of those components has been identified. The components have been listed in a FMEA spreadsheet and cross referenced to a drawing and photographs of the joint (see Appendices A 2.1 and A 2.2). 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 between moving parts.

To enable identification of which component has the highest failure risk factor a Risk Priority Number (RPN) is determined. The highest risk components will have the highest RPN. The RPN is derived from three criteria: severity, occurrence and detection, with each based on a 10 point scale (with 10 being the worst case for each). Descriptions for each point are provided in Appendices A 1.1, 1.2, 1.3 and 1.4. A high RPN does not necessarily mean that a component has a high probability of failure. The component could have a relatively low risk but the effect of the failure is severe or the possibility of detection prior to failure is low.

The failure of an individual component may not lead to a failure of the joint in itself, but may lead to a 'domino effect' (or failure tree) by overstressing other components which could then lead to joint failure.

To assist in determining a score for each of the three criteria, and to provide a benchmark, a plate train, tongue and anchor plate was lifted from one joint unit over the weekend of 16/17th January 2009. In addition advice was taken from FETA using their past inspection and maintenance experience of how the joints have performed.

4.2.3 Severity Criteria

In deriving descriptions for the severity criteria 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 emergency repairs should a failure occur. The longer the time a carriageway is closed, the higher the severity score. 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 carriageways. 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 carriageway closures would also inevitably lead to negative 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. The more the public is considered to be affected, the higher the score. 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 Criteria

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. 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 engineering judgement is necessary.

4.2.5 Detection Criteria

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. Less detectable failures will have a higher score. For the roller shutter joints the means of detection are currently based on routine six monthly close inspections and daily carriageway inspections. Even with the current inspection regime an impending failure may go undetected. 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, whereas corrosion of a visible component, say the track beams, would occur over a period of time and therefore the warning signs would be expected to be detected in advance of failure. 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 FMEA is first based on the current condition of the joint units and the current methods of preventing and detecting failure. The scoring was undertaken by three independent teams, considering each individual component in turn. In considering each component the effect and consequence of the failure was also considered (failure tree). For example, the failure of a hinge pin in itself would not produce a high RPN, but such a failure would lead to overstressing of other hinges and failure of the plate train. Using three teams helped to ensure that all potential risks and failure mechanisms were identified. Once scored, the teams met at a workshop to share information and to discuss any disparity between scores. As each team was independent there was still some disparity between scores at the end of the workshop so to identify areas of high risk the average of the three sets of scores were taken (rounded up where appropriate to the nearest whole number) and then multiplied together to get the overall RPN.

The higher the RPN result, the higher the risk of failure or the effects of failure a component could have. Areas of high risk that require action have been identified as those with an average RPN of greater than 250. However there were some borderline scores and it was agreed at the workshop that action should be considered for these also. In addition to considering areas with a high RPN, a chart has been created to map the severity, occurrence and detection scores to ensure that any other areas which may need action are identified. For example a component with high severity and occurrence scores may have a low RPN because the detection score was low. The chart mapping the RPN results is attached in Appendix A 4.1. The x-axis of the chart represents severity; the y-axis represents occurrence, and the size of the bubbles represent detection. A large bubble in the top right of the chart would indicate a particularly high risk and conversely a small bubble in the bottom left of the chart represents a low risk. The mapping of the results not only shows those areas with a high RPN, but also highlights a few other areas for consideration. Items that will require action have been indicated on the FMEA spreadsheet.

Further analysis was undertaken by preparing a Pareto diagram and this is attached in Appendix 4.3. This showed that 50% of the risk can be attributed to 25% of the components. This demonstrated that certain components have more influence on the risk of failure than others. By focussing on these components, rather than others, the overall risk can be reduced more effectively.

Eight components were identified as being of high risk and requiring action. In summary, and these are:

(i) The failure of a hinge pin (in the plate train) from fatigue, overloading or excessive wear (component 10);

(ii) The failure of a shuttle plate horizontal thrust block (the part attached to the underside of the plate) from weld fatigue or overloading (component 1);

(iii) The failure of a shuttle plate horizontal thrust block (the part attached to the supporting beam) from weld fatigue or overloading (component 17);

(iv) The failure of a foot supporting the plate train from weld fatigue or overloading (component 7);

(v) The failure of a restraint block to a tongue plate (the part attached to the supporting beam) from weld fatigue or overloading (component 13);

(vi) The failure of a vertical bearing to a shuttle plate (the part attached to the underside of the plate) from weld fatigue (component 2);

(vii) The failure of a shuttle plate holding down pin from overloading (component 3);

(viii) The failure of a spring around a holding down pin to the tongue or shuttle plate from overloading (components 4 and 21).

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

The FMEA process identifies the areas where action should be considered to reduce the risk of failure. Once actions have been identified and put in place the same areas are scored again, using the same criteria, to demonstrate that the actions reduce the risk to an acceptable level. Measures to reduce the risk of failure fall into one of two categories. The first is ways to prevent the failure occurring in the first place, and the second is ways to mitigate the effects of a failure should it occur. Prevention strategies include works such as replacing or repairing 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

The original joint replacement contract included provision of improved permanent access around the joints underneath the deck. Although the joints can be reached under the existing arrangements not all parts can be easily inspected or repaired. The current six monthly inspection regime involves erecting temporary access scaffolding. With increasing wear and risk of failure the lack of good access would remain a constraint and an increased safety risk in a potentially harsh environment. Permanent improvements to access could be made as originally proposed to improve inspections and to reduce the safety risk of erecting temporary scaffolding.

5.2 Weather

Emergency repairs could become necessary 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 at even moderate wind speeds.

5.3 Availability of Components and Resources

Some parts of the joints, such as the plate holding down pins and associated springs, can be readily obtained and FETA currently do retain a stock of such parts. However, many components are unique to the joint, such as the plate trains and track beams, and would need to be specially manufactured if replacements were necessary. Obtaining such replacements may take some time allowing for the procurement process, the manufacture, delivery, and installation of the part. It should be noted that the risk of these other components being required is relatively low.

Installation of replacement components may require the use of specialist equipment and labour skills. For example, the lifting out of the plate trains requires the use of cranes. Such equipment or skills may not be readily available. However, the current FETA maintenance team have developed many skills and knowledge of the joints and this has proved invaluable in maintaining the joints. It is important that such skills are maintained.

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, negative publicity and an increased safety risk to the workforce and potentially the travelling public. Closures of carriageways require liaison with other road authorities to avoid clashing with other highway works (such as the Kincardine Bridge), although if the closure is an emergency then such a clash would be unavoidable.

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 work itself and, if traffic management is required, road user delay costs. The cost of the risk reduction measures would not be large, but would be in addition to the cost of the main joint replacement works as there would be no duplication of works. In addition to the reduction measures there would be cost associated with providing an improved permanent access system, as noted in 5.1 above. However, as this was a requirement of the original joint replacement works it is therefore not an additional cost.

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 between late spring and early autumn. This could mean that the time period between deciding the joints must be replaced to having a new joint installed could be between 15 and 18 months.

5.7 Costs of Temporary Bridging

If the existing joints are retained until after the opening of the Forth Replacement Crossing then there are significant potential cost savings from the temporary bridging and deck strengthening. This is because, with an alternative diversion route available, each carriageway can be closed in turn without significant disruption to traffic. The temporary bridging solution was devised to minimise traffic disruption, but there would have been a reduction in traffic flow capacity because of their geometry, restriction on use by heavy goods vehicles and a 30mph speed restriction. Based on the tender returns for the joint replacement this saving would be over £6m. In addition, with no temporary bridging, there would be a shorter works period and less contract risk to a contractor, which although not quantifiable, would add to the savings. Although there are additional costs in retaining the joints (see 5.5 above) these would be significantly less than the temporary bridging costs.

5.8 Reviewing Decisions and Risk of Retaining Joints

If the decision is made to retain the existing joints, then this 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 process has been used to evaluate the level of risk of failure of all the components of the joints. Using the results of the analysis appropriate measures can be incorporated to reduce the level of risk to an acceptable level. There is a risk that there are unforeseen factors or that increasing wear could still lead to a failure of a component and for this reason the FMEA spreadsheet should be considered a live document that is subject to periodic review. This should keep the level of risk of failure to a low level, however if any RPN increases to an unacceptable level and options to mitigate the risk have been exhausted, then a decision to retain the joints should be reviewed.

There is an external risk that the opening of the Forth Replacement Crossing is delayed and that the service life of the joints needs to be extended further still. If such an extension occurs then this should lead to a further review of the FMEA process.

6. Actions for Reducing the Risk of Failure

6.1 General

Actions 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 action to reduce a RPN should be considered carefully. The RPN for a component could be lowered 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 potentially serious, such as a fatality. Prevention of failure is preferable to mitigation, but short of replacing a whole joint, it is unlikely that full prevention from failure of all components can be achieved. It is likely, therefore, that a combination of actions 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 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;

ii Installing monitoring devices;

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

iv Install temporary bridging;

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 their failure. Such components would be the shuttle and tongue plate holding down pins and the associated springs, and also the keeper plates retaining the hinge pins in the plate trains. However, the scope for replacing some of 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 two halves of the horizontal and vertical support blocks to the shuttle and tongue plates have worn down against each other.

Repairs may potentially 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 make practical and financial sense 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.

If the plate holding down pins and springs are to be replaced then the opportunity could be taken to improve the design of the pins. The springs around the pins have been known to fracture releasing the tension in the pins so that the collets retaining the springs and pins can fall out leaving the pin to also fall out. If the pins were replaced with modified bolt arrangements then the plate, although loose, would remain held down. If the pins are to be replaced then such a modification would have negligible cost.

The cost of replacing all the 144 pins and associated springs is estimated to be £20,000 to £25,000. This assumes the replacements are done at the same time as when the plates are lifted out for inspection. To replace all the keeper plates is estimated to be £2,000 to £3,000, again if the work is done at the same time as when the plates are lifted out. This work is within the capabilities of the FETA maintenance team and the cost estimates have assumed they would undertake the work.

6.2.2 Refurbish Plate Train Hinges

The hinges in the plate train lifted out over the weekend of the 17 / 18th January 2009 were found to be excessively worn; particularly the ones nearest the shuttle plate in the main deck span side. It is strongly suspected that the hinges in other joint units have worn in a similar way. The excessive wear is in the hinge bushing / hole rather than the pin itself where the bushing has partially worn away and the hinge hole has elongated into an oval shape causing the pin to rotate on plan by an angle of about 15 degrees. The wear in the hinge hole means that the gap between the plates in the train has also increased, although not to an unacceptable width from a road user point of view. Consideration has been given to re-boring the hinge holes and replacing the bushings and pins with those of a larger diameter. The re-boring would need to be done accurately as any misalignment would cause rapid wear back to the current situation. The re-boring would also need to be done at the same a time as when a plate train has been lifted out under a carriageway closure. This would mean that the work would need to be done at night (refer to 6.2.3 below). This work would be difficult to do within a carriageway closure period as time is required for setting up equipment on site or transporting the plates to and from fabricators.

6.2.3 Enhanced Inspection Regime

Currently the joints are subject to a detailed six monthly inspection and a daily carriageway inspection. In addition to this, FETA have also lifted out some plate trains and tongue plates for a closer examination of parts that are not normally visible during the six monthly inspections. The inspections have noted areas of increasing wear and corrosion that may give warning of imminent failure. Early signs of fatigue would be difficult to detect until actual 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. Each joint unit is wearing at different rates and in different ways therefore all units should be examined. 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.

Lifting out plate trains requires a carriageway closure, but from past experience gained this can be achieved on a Friday night to early Saturday morning and / or Saturday night to early Sunday morning without causing significant traffic disruption. If the work is undertaken on a rolling programme over, say 3 years, then eight units could be inspected over the weekends of May and June when daylight hours are at their longest. As discussed in section 5.4 this would need liaison with other highway authorities. Rolling the inspections over three years allows efficient use of resources, forward programming and a measure of continued wear in the joints.

Enhancing inspection regimes will have cost and resource implications as such work would have to be done more often. The inspection work and most of the testing is within the capabilities of the FETA maintenance team, but some may require specialist skills, such as ultra-sonic testing of hinge pins for fatigue cracking.

6.2.4 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. The scaffolding is installed and removed each time. This scaffolding work is difficult as it is carried out 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 in a reduced time.

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. Such modifications should focus on those areas with a high RPN identified in 4.3 above and include providing additional or alternative methods of restraining components. The modifications should consider the normal working of the joint and not prevent the lifting out of plates for detailed inspection. Three forms of restraint have been identified and these are:

(i) Fixing stop end blocks on the track beams (action 5 on FMEA spreadsheet);

(ii) Fixing straps along the underside of each plate train (action 6 on FMEA spreadsheet);

(iii) Providing additional restraint to the anchored ends of the shuttle plates (action 7 on FMEA spreadsheet).

Conceptual sketches of the modifications have been shown in Appendix B.

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Stop End Blocks on the Track Beams (Action 5)

A possible consequential effect of failure of the shuttle and tongue plate thrust blocks, the hinge pins, the feet supporting the plate trains and the shuttle and tongue plate holding down pins and springs is that the plate train could fall into the joint. A means of preventing this is to install stop end blocks 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 stop end block reducing the size of an open gap in the carriageway. A reduction in the gap size could reduce the effects of an accident. As a guide the maximum transverse gap in a carriageway that is permitted in a bridge expansion joint is 65mm (ref BD33/94 'Expansion Joints for Use in Highway Bridge Decks), although this is a serviceability requirement and in an emergency a wider gap may be tolerated. The position of the stop end 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 carriageway in the event of failure.

The stop end blocks could be bolted to the track beam flange so that they could be manually moved with changes in general joint position with changing seasons of the year. However, such changes are weather and vehicle loading dependent and would be difficult to predict in advance. If the joint closed so the end of the plate train pushed against the stop end block then the plate train could buckle upwards overstressing the hinge joints and the shuttle plate holding down pins. The stop end blocks could be designed to fail if the movement of the bridge deck pushes the plate train against them, but be strong enough to support the weight of the plate train if a hinge joint fails, i.e. incorporating a form of 'fuse'. However, loss of the stop end block means that if a plate train fails before the stop end block is replaced then there would be nothing to catch the plate train. An alternative to designing the stop end block to fail is to put a spring between the stop block and trailing edge of the plate train. The spring would compress if movement of the bridge pushed the plate train against it but the spring would be stiff enough to support the plate train if it failed. With the spring supporting a failed plate the resultant gap created in the carriageway can be limited and therefore the effects of an accident can be minimised. A detailed design of the stop end block would need to be developed but a guide to the cost would be around £25,000.

Fixing Straps Along the Underside of Each late Train (Action 6)

An additional method to Action 5 to prevent a plate train falling into a joint is to install a form of flexible restraining strap, chain or cable attached to the underside of the plates. This 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 restraining straps should not be relied upon to hold the plates, but they would be designed to prevent immediate catastrophic collapse. Fixing can be achieved by either welding on threaded studs or drilling and tapping into the plates to allow bolts to be screwed in. The bolts or studs could then anchor the ends of the straps. A detailed design of restraining strap needs to be developed but it is estimated that installation of the straps would cost in the order of £40,000.

Providing Additional Restraint to the Anchored Ends of the Shuttle Plates (Action 7)

Failure of the holding down pins / springs and / or horizontal restraint blocks of the shuttle and tongue plates could lead to the plates (and consequently the plate train) becoming dislodged and dropping into the joint gap. The tongue plates could also fail in a similar way but the ability of these plates to fall into the joint is limited by projections (that retain the holding down pins) from their support beam. Similar projections were considered for the shuttle plates but these would have reduced the expansion gap of the joint. Two methods have been considered to provide further restraint.

The first method is to tie neighbouring plates together with steel straps fixed (transversely) to the underside of the plates. Fixing of the straps can be achieved by a similar method to the straps for action 6. The straps would need to allow for differential movement between neighbouring plates and this can be accommodated by elongating the holes in the straps that take the bolts / studs. Care would be needed with this option to prevent clashing with the restraining cables fixed along the plate train (action 6).

The second method is to restrict the ability of the plates to move by using further restraining cables. With this, there is a potential situation where the end of the plate is left hanging just from the cables. As the movement of the anchored ends of the shuttle plates is limited this can be prevented by keeping the cables short and with minimum slack so that the plates cannot move away from the support beam. As with the other actions, a detailed design needs to be developed but a guide to the cost would be approximately £5,000.

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 as 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 plate train hinges (particularly in the hinges nearest the shuttle plate) 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.

One form of monitoring device is the tell tale and generally there are two standard types of readily available. 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 type of tell tale is one manufactured by Bill Harvey Associates Ltd. This is more flexible, but the tell tale is designed to measure small movements and would not be suitable for the joints. An alternative method 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 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 yet break under the right load 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 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. A third method is to insert steel or hardwood wedges in the gap between plate trains and measure the thickness of the wedge that fits between the plates. If the angle of the wedge is kept acute then accurate measurements can be achieved. Hardwood wedges would be less likely to damage the plates than steel, but would probably have a very limited life so a stock of them would be needed.

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 track beams. 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 carriageway profile and rocking of plates. The original design used six different types of train units which prevent units being easily 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. In view of the drawbacks, the option of retaining spare joint units has been discounted.

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. For this reason the use of spare plates has been discounted.

6.3.4 Install Temporary Bridging

The risk of an accident associated with a joint failure could be eliminated by installing the temporary bridging over the joints as envisaged in the original joint replacement contract. However, this has a high installation cost and on-going inspection and maintenance costs. Whilst in place heavy goods vehicles would need to be prevented from using the temporary bridges and there would be a 30mph speed restriction in place. The temporary bridges would also be more susceptible to high winds and ice. In addition, local strengthening of the existing bridge deck to accommodate the temporary bridge loading is necessary. For these reasons this option is discounted.

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. In practice, however, such arrangements rarely work well as it is inefficient and impracticable for Contractors to have specialist staff on stand-by. The existing Bridge Maintenance Team has managed to maintain the joints beyond their service life and has developed extensive experience in the performance and behaviour of the joints. The option of retaining specialist contractors on stand-by is therefore not considered to have any merit and has been discounted. However, it would be important that the skills and capability of the FETA team are maintained to ensure continuity in the up keep of the joints.

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. For all the components that require risk reduction, a combination of the actions described in Section 6 above is necessary, and these have been added to the FMEA spreadsheet included in Appendix A. 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, at least annually, is needed to ensure the identification, risk and actions remain appropriate.

7. Recommendations

The joints are at the end of their service 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 more likely a 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 Forth Replacement Crossing is constructed has considerable benefits in both road user delays and contract costs. These benefits include avoiding the need for temporary bridging over the joints, and consequent works period, and also reduced congestion as there will be a better diversion route for traffic. This is especially true for heavy goods vehicles as they would not have been able to use the temporary bridges. 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 the actions that are required and this is summarised in the FMEA spreadsheet. Measures to prevent failure are recommended and it is advised that the existing inspections are undertaken more frequently, say every three months. In addition it is also recommended that plate trains and tongue plates are lifted from a joint for inspection purposes. Based on recent experience on undertaking this work it is thought that two joint units of a pair of plate trains and tongue plates (one unit being a train and tongue plate from the main span and the neighbouring plates from the side span) could be lifted in one weekend. This means that all the joint units could be examined over 12 consecutive weekends, but if resources prevent this, then inspections should be done first on the joint units directly under vehicle wheel tracks. 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 as part of the original joint replacement contract.

Other preventative measures include repair or replacement of parts of the joint units. Undertaking repairs to the joints would be difficult and may upset the existing load path through the components of the joints leading to a failure anyway. Such repairs include re-boring and bushing the plate train hinges, filling the gouging by the feet of the track beams and the hinge feet themselves. For this reason such repairs are not recommended. Some replacement of parts could be undertaken without disturbing the load path of a joint unit and these are the holding down pins and associated springs, and also the keeper plates to the hinge pins. The holding down pins should be replaced with a modified bolt arrangement that is less likely to fall out if the spring fails. The holding down pins and keeper plates can easily be replaced while the plate trains and tongue plates are lifted out of a joint.

Measures to mitigate the effects of failure are also recommended. These involve installation of restraining straps longitudinally underneath the plate trains and providing links between the shuttle plates and support beams. In addition stop end blocks should be fitted on all the track beams. The lateral restraint straps fixed between the underside of the shuttle plates are considered to be less effective than the straps between the support beam and shuttle plate. It is recommended that the restraining straps are fitted between all the plates in the plate trains. The stop end blocks should incorporate a spring that would compress if the joint closed but would support a plate train if a hinge failed. This is preferred to a stop end block that has a fused link that would fail if the joint closed because the stop would be lost and therefore the potential support to the plate train would also be lost. The stop end blocks should be designed to be able to be adjustable in position on the track beams for fine tuning, allowing minimum movement of a failed plate train and maximum movement for the joint. The combination of both restraining stop end 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. While this is considered to be a ‘fail safe’ system which would hold the components in place, the joints would require remedial work prior to their use for traffic after any deployment of the ‘fail safe’ measures.

Monitoring devices have also been considered. These are considered to be unnecessary if the recommended prevention and mitigation measures are put in place. However, the wedge device to measure the gap between plates in a plate train could be used to check for increasing wear in the hinges. This may prove difficult in practice with a constantly moving joint but the cost of the wedges would be low and could be trialled to assess effectiveness.

Options not recommended include erection of temporary bridging, stocking spare joint units because new units would not fit with neighbouring old units, and keeping specialist contractors on stand-by as skills and knowledge is available with the in-house maintenance team.

The final recommendation is that the FMEA process is reviewed annually to ensure the appropriate actions are in place and increasing wear on, and loss of reliability of, 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 replacement of the main expansion joints would have ensured continued predictability and reliability for the foreseeable future. The joints are probably the oldest (unmodified) of their type still in service and it is the past good maintenance and inspection regime that has ensured their continued use. However, the main expansion joints are considered to be at the end of their service 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 Government have announced that a Forth Replacement Crossing will be in place by 2016.

With a Forth Replacement Crossing in place the joints could be replaced with much less traffic congestion and consequent economic effects in the region. The original joint replacement contract allowed the use of temporary bridges over the joints while they are being replaced. However, with reduced traffic flows the joint replacement could be undertaken during carriageway closures and therefore reducing the works period and saving the cost of the temporary bridging. Based on the tender prices for the original contract the cost of the temporary bridging, including existing bridge deck strengthening is in excess of £6m. Extending the life of the joints even further beyond the end of their design life does mean there is an increasing risk of failure of a joint component which could result in traffic accidents and carriageway closures.

To evaluate the risk of failure of a component in a joint unit a Failure Mode Evaluation Analysis (FMEA) was undertaken. This process considers the effects of failure of each component of the joint under three criteria; these being severity, occurrence, and detection. Severity is defined as the consequence of failure should it occur, i.e. traffic accident and / or carriageway closure. Occurrence is defined as the probability or frequency of the failure occurring and detection is defined as the probability of the failure being detected before the impact of the effect is realised. The three criteria are multiplied together to produce a Risk Priority Number (RPN). The higher the RPN, the higher the risk of failure or the effects of failure, a component would have. This process identified a number of components with an unacceptably high risk and therefore requires action to maintain current levels of operation and safety.

It is recommended that the life of the existing joints can be extended, but this is only on the basis that there are additional preventative and mitigation measures installed. Recommended preventative measures include reducing the period between existing inspections from six to three months. In addition, all the plate trains and tongue plates should be lifted out over a number of months to check for wear and fatigue. To allow for the additional inspections to be undertaken safely and more thoroughly it is recommended that an improved permanent access is installed, as was proposed in the original joint replacement contract. Recommended mitigation measures are to install stop end blocks on the track beams and restraining straps to the underside of the plate trains to prevent plate trains falling into the joint. In addition further restraining straps are recommended between the shuttle plate and support beam to prevent the shuttle plates falling into the joint. To assist in the inspections, means of monitoring increasing wear were considered. The only monitoring measure that is recommended is to use hardwood or steel wedges between the plates to measure the gap and hence increasing wear.

The additional preventative and mitigation measures involve some additional cost. These are expected to be in the region of £150,000 to £250,000. Of this, the mitigation measures of installing stop end blocks and restraint cables would cost approximately £70,000. In addition the cost of improving the permanent access around the joints under the deck is approximately £500,000, but as this was planned for in the original joint replacement work this is considered to be cost neutral. The total cost of the measures is therefore significantly less than the cost of temporary bridging therefore there are cost savings to be made. Traffic delay costs savings have not been included, but are significant.

Through the FMEA process it can be demonstrated that incorporating the above measures will reduce the level of risk to an acceptable level. However, as the joints are continuing to wear and inspections may highlight new areas of concern the FMEA process should be reviewed annually to ensure the measures remain appropriate and comprehensive.

Appendix A

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

ATKINS

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.

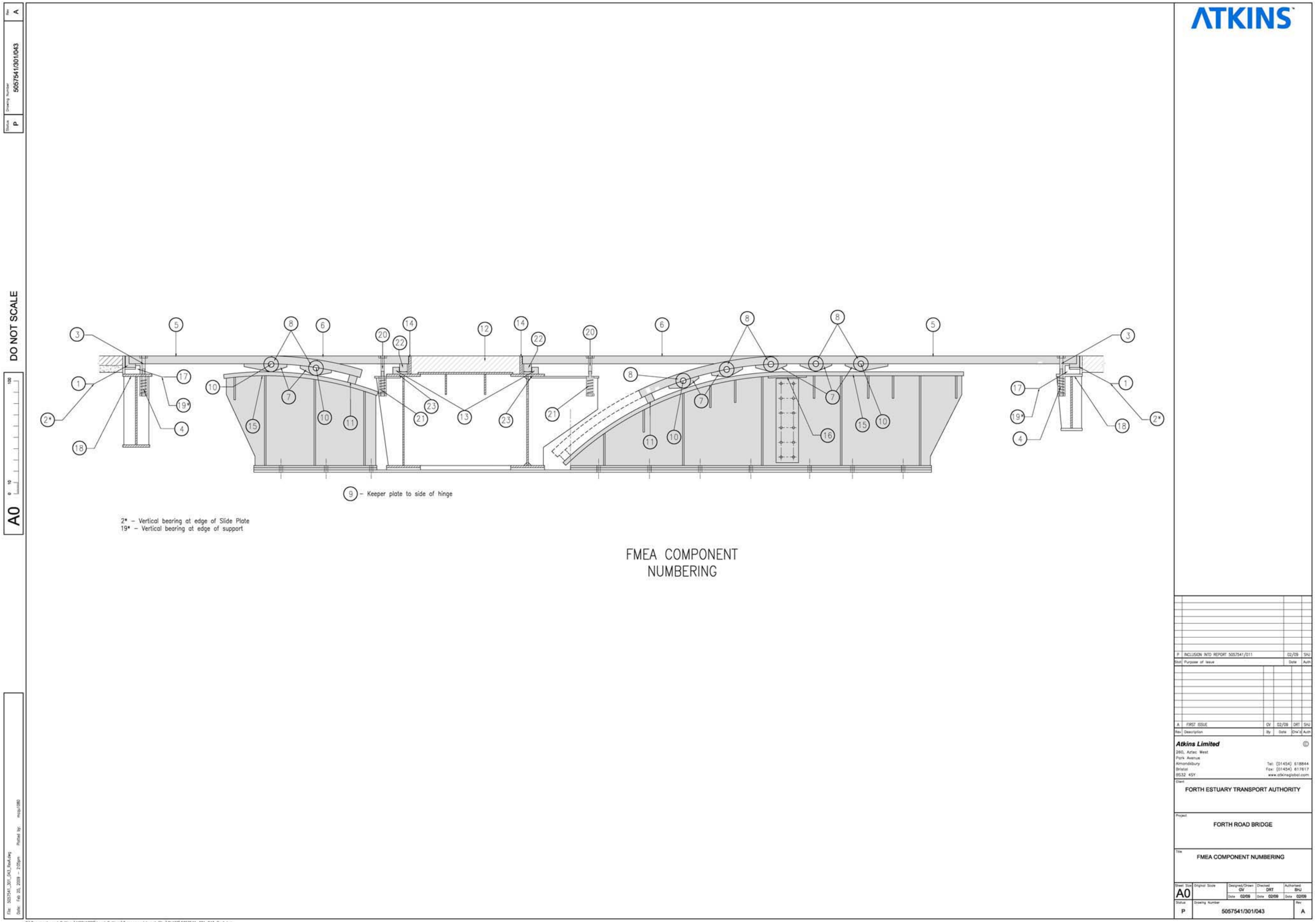
A.1.3 Occurrence Scoring Table

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

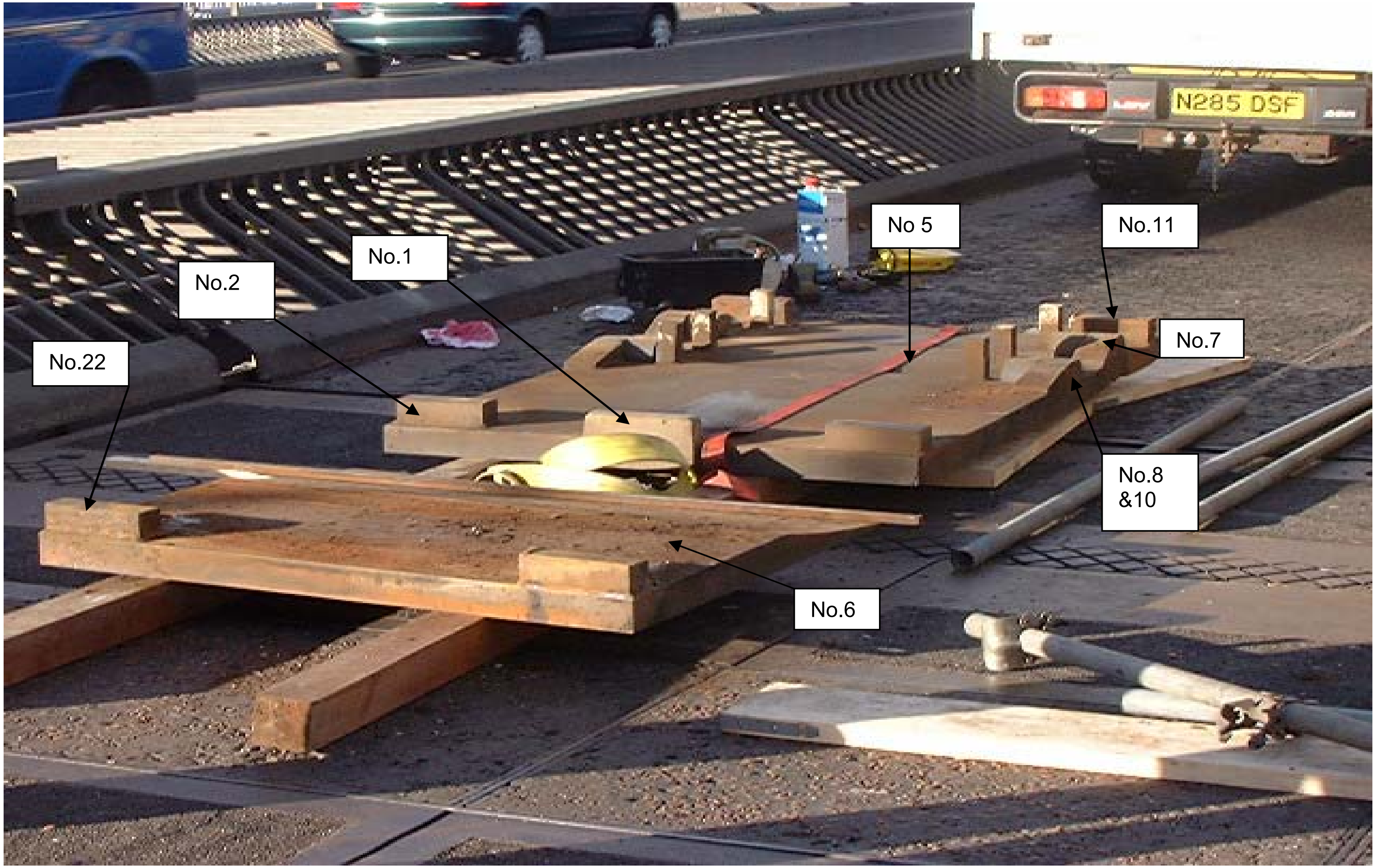
A.1.4 Detection Scoring Table

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.	

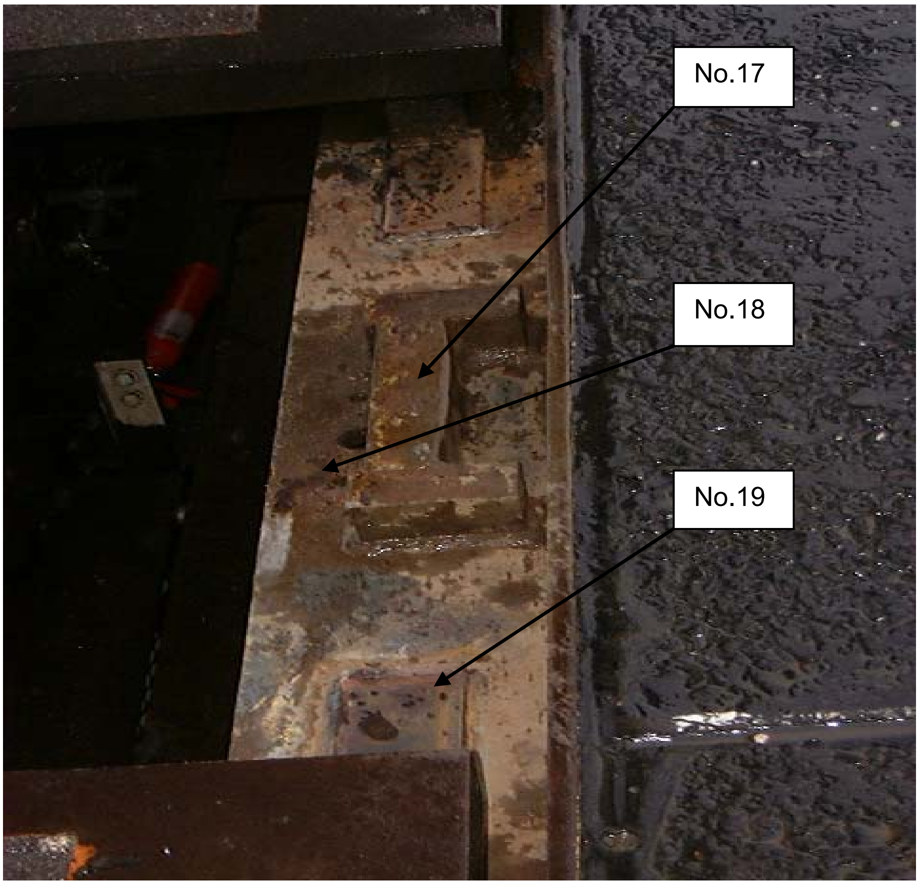
A.2.1 Sketch of Components Identified in FMEA Spreadsheet



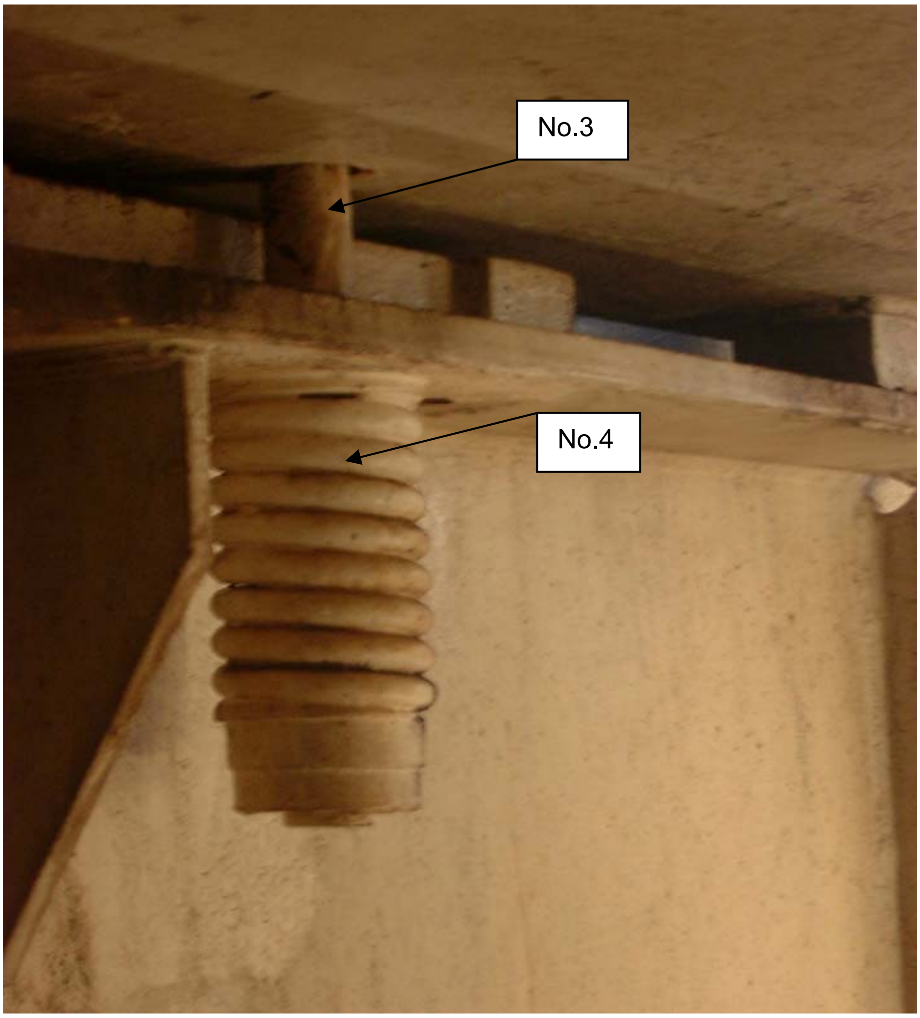
A.2.2 Photographs of Components in FMEA Spreadsheet.



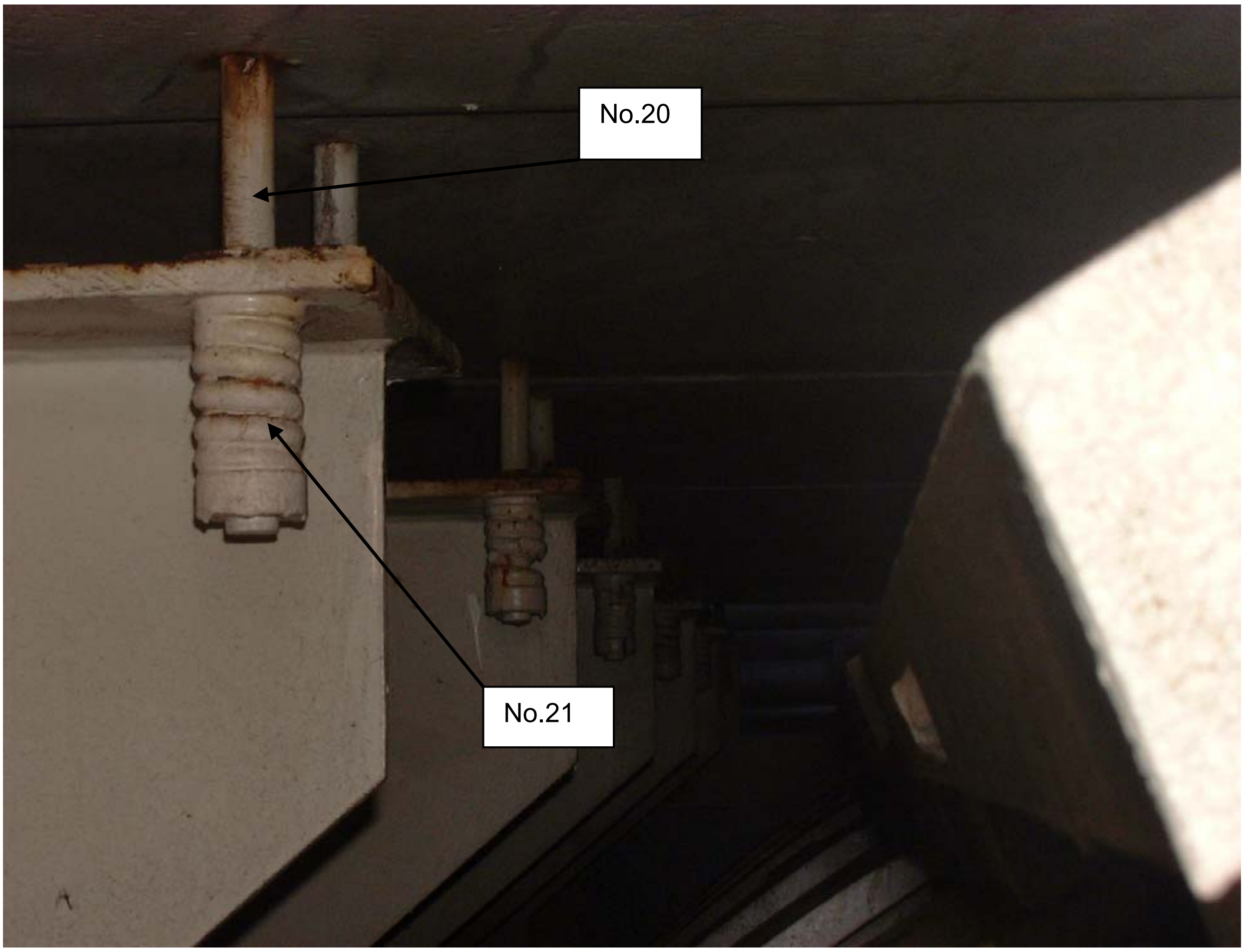
Photograph 1 - View of Underside of Lifted out Plate Train and Tongue Plate



Photograph 2 – View of Top of Shuttle Plate Support Beam

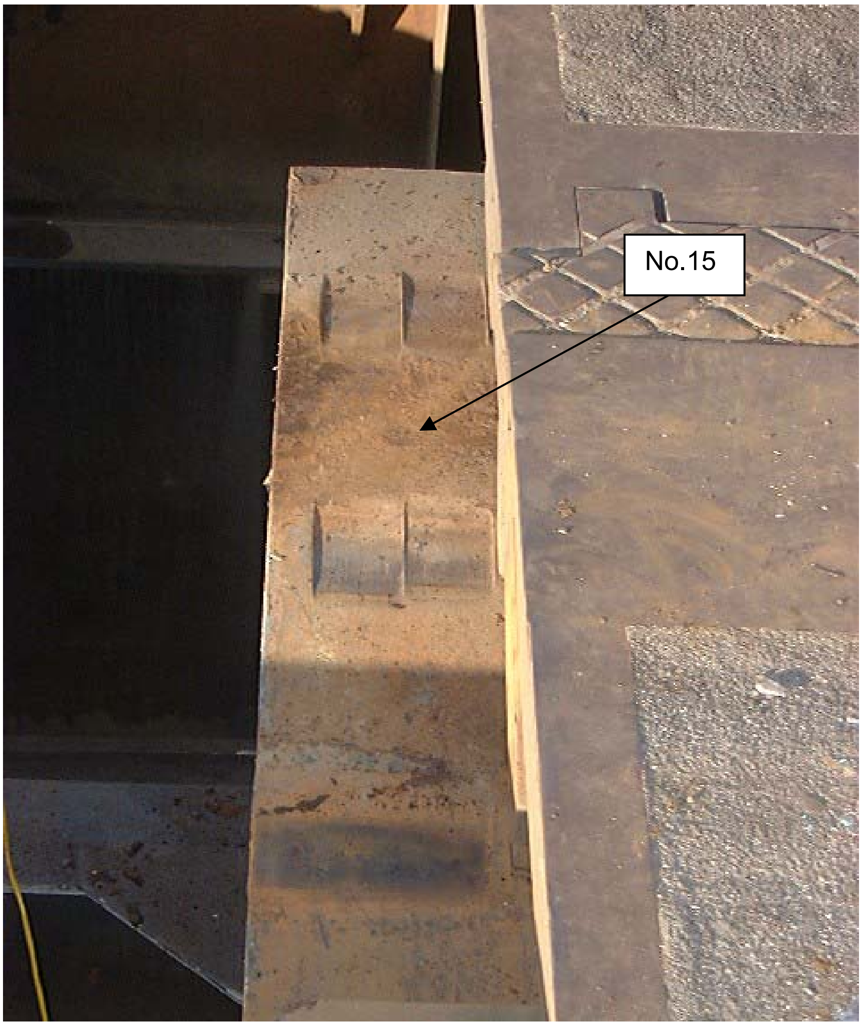


Photograph 3 – View of a Shuttle Plate Holding Down Pin and Spring

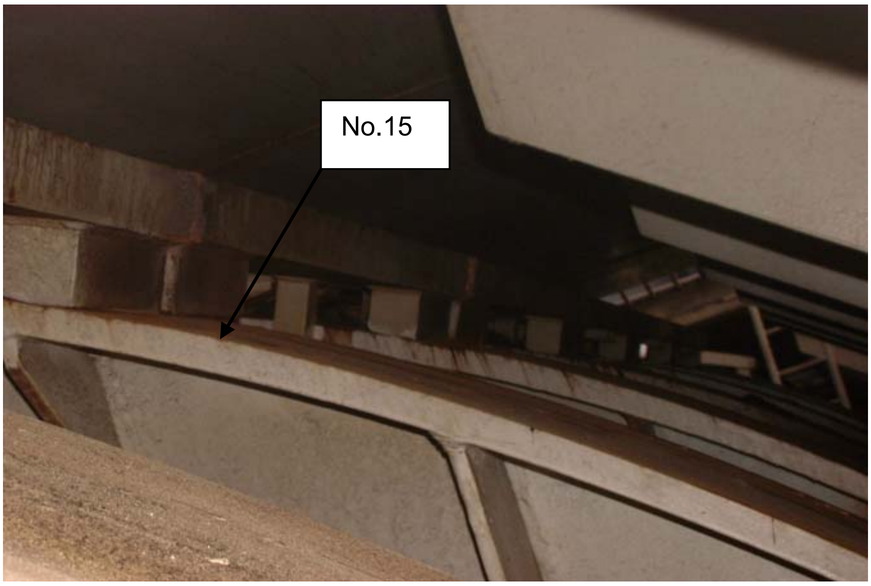


Photograph 4 – View of a Tongue Plate Holding Down Pin and Spring.

Photograph 5 – View of Tongue Plate Restraint Block



Photograph 6 – View of Top of a Track Beam



Photograph 7 – Side View of a Track Beam

A.3.1 FMEA 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	Ranking (based on RPN)	Recommended Action (see separate table after this spreadsheet)	Responsibility and Target Completion Date	Resulting Assessment					
																	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	None	6 monthly inspections	8	480	4	1, 2, 4, 5, 6, 7	FETA	5	5	5	6	5	150
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	None	6 monthly inspections	9	450	5	1, 2, 5, 6, 7	FETA	5	5	5	5	7	175
3	1	"	"	"	6	10	10	General corrosion.	2	None	6 monthly inspections	7	140	34	1, 2, 5, 6, 7	FETA	5	5	5	2	5	50
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	None	6 monthly inspections	8	400	8	1, 2, 5, 6, 7	FETA	5	5	5	5	5	125
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	None	6 monthly inspections	8	400	8	1, 2, 5, 6, 7	FETA	5	5	5	5	6	150
6	17	"	"	"	6	10	10	General corrosion.	2	None	6 monthly inspections	6	120	35	1, 2, 5, 6, 7	FETA	5	5	5	2	5	50
7	17	"	"	"	6	10	10	Impact loading due to lack of fit	3			8	240	21	1, 2, 5, 6, 7	FETA	5	5	5	3	6	90
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	None	6 monthly inspections	8	160	31	1, 2, 5, 6, 7	FETA	5	5	5	2	6	60

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	Ranking (based on RPN)	Recommended Action (see separate table after this spreadsheet)	Responsibility and Target Completion Date	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
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	None	6 monthly inspections	8	336	11	1, 2, 5, 6, 7	FETA	5	7	7	6	5	210
10	2	"	"	"	5	7	7	Overloading of bearing block.	5	None	6 monthly inspections	7	245	20	None	N/A	-	-	-	-	-	-
11	2	"	"	"	5	7	7	General corrosion.	2	None	6 monthly inspections	6	84	42	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	8	240	21	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	8	240	21	None	N/A	-	-	-	-	-	-
14	19	"	Wear of bearing block.	Poor vertical carriageway profile/step in carriageway.	2	3	3	Wear due to cyclic movement.	9	None	6 monthly inspections	3	81	46	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	6	240	21	1, 3 (use high grade bolts in place of pins), 5, 7	FETA	5	7	7	3	5	105
16	3	"	"	"	6	10	10	General corrosion.	2	None	6 monthly inspections	2	40	55	1, 3 (use high grade bolts in place of pins), 5, 7	FETA	5	7	7	2	2	28

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	Ranking (based on RPN)	Recommended Action (see separate table after this spreadsheet)	Responsibility and Target Completion Date	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
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	None	6 monthly inspections	5	300	14	1, 3, 5, 7	FETA	5	7	7	3	4	84
18	4	"	"	"	5	10	10	General corrosion.	4	None	6 monthly inspections	2	80	47	1, 3, 5, 7	FETA	5	7	7	2	2	28
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	None	6 monthly inspections	6	240	21	1, 3 (use high grade bolts in place of pins), 5	FETA	5	7	7	2	5	70
20	20	"	"	"	6	10	10	General corrosion.	2	None	6 monthly inspections	3	60	51	1, 3 (use high grade bolts in place of pins), 5	FETA	5	7	7	2	2	28
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	None	6 monthly inspections	5	300	14	1, 3 (use high grade bolts in place of pins), 5	FETA	5	7	7	3	4	84
22	21	"	"	"	5	10	10	General corrosion	2	None	6 monthly inspections	3	60	51	1, 3, 5	FETA	5	5	5	2	2	20
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	None	6 monthly inspections	2	40	55	None	N/A	-	-	-	-	-	-
24	5	"	Loss of textured running surface.	Lack of skid resistance for vehicles.	2	5	4	Tyre wear to joint surface.	9	None	6 monthly inspections	2	72	48	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	8	160	31	1, 2, 5, 6, 7	FETA	5	5	5	2	5	50
26	5	"	"	"	8	10	10	Excessive corrosion.	2	None	6 monthly inspections	2	40	55	1, 2, 5, 6, 7	FETA	5	5	5	2	1	10

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	Ranking (based on RPN)	Recommended Action (see separate table after this spreadsheet)	Responsibility and Target Completion Date	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
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	None	6 monthly inspections	3	120	35	None	N/A	-	-	-	-	-	-
28	6	"	Loss of textured running surface.	Lack of skid resistance for vehicles.	3	4	4	Tyre wear to joint surface.	9	None	6 monthly inspections	2	72	48	None	N/A	-	-	-	-	-	-
29	6	"	Failure of plates.	Tongue plate would fall into joint.	7	10	10	Tyre wear to joint surface.	2	None	6 monthly inspections	8	160	31	1, 2	FETA	5	5	5	2	3	30
30	6	"	"	"	7	10	10	Corrosion.	2	None	6 monthly inspections	2	40	55	1, 2	FETA	5	5	5	2	1	10
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	None	6 monthly inspections	8	360	10	1, 2, 4, 5, 6	FETA	5	5	5	5	7	175
32	7	"	"	"	6	9	9	Impact loading due to lack of fit.	6	None	6 monthly inspections	8	432	7	1, 2, 5, 6	FETA	5	5	5	6	7	210
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	None	6 monthly inspections	10	600	2	1, 2, 5, 6	FETA	5	5	5	6	7	210
34	10	"	"	"	8	10	10	Impact loading due to lack of fit.	7	None	6 monthly inspections	10	700	1	1, 2, 5, 6	FETA	5	5	5	7	7	245
35	10	"	"	"	8	10	10	Excessive wear in pin.	5	None	6 monthly inspections	9	450	5	1, 2, 5, 6	FETA	5	5	5	5	7	175
36	10	"	"	"	8	10	10	Overloading of pin (where wear between the feet and the track beams cause extra resistance).	6	None	6 monthly inspections	10	600	2	1, 2, 5, 6	FETA	5	5	5	6	7	210
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	None	6 monthly inspections	4	120	35	1, 2, 3, 5	FETA	5	5	5	3	2	30
38	9	“	Wear through	“	8	10	10	Wear through	10	None	6 monthly inspections	3	300	14	1, 2, 3, 5	FETA	5	5	5	4	2	40

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	Ranking (based on RPN)	Recommended Action (see separate table after this spreadsheet)	Responsibility and Target Completion Date	Resulting Assessment					
																	Economic Severity	Public Perception Severity	Overall Severity	Occurrence	Detection	RPN
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	None	6 monthly inspections	4	108	40	None	N/A	-	-	-	-	-	-
40	8	"	Bearing areas wears 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	None	6 monthly inspections	2	60	51	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	6	120	35	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	2	54	54	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	8	320	12	1, 2, 4, 5, 6	FETA	5	5	5	4	7	140
44	13	"	"	"	7	10	10	Overloading of horizontal restraint (where wear between the feet and the track beams cause extra resistance).	3	None	6 monthly inspections	8	240	21	1, 2, 5, 6	FETA	5	5	5	3	7	105
45	13	"	"	"	7	10	10	Impact loading due to lack of fit.	4	None	6 monthly inspections	8	320	12	1, 2, 4, 5, 6	FETA	5	5	5	4	7	140
46	13	"	"	"	7	10	10	General corrosion.	2	None	6 monthly inspections	6	120	35	1, 2, 5, 6	FETA	5	5	5	2	5	50

																	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**	**Ranking (based on RPN)**	**Recommended Action (see separate table after this spreadsheet)**	**Responsibility and Target Completion Date**	**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	None	6 monthly inspections	7	168	29	1, 2, 5, 6	FETA	5	5	5	3	6	90
48	23	Support to horizontal/vertical restraint blocks to tongue plates.	"	"	7	8	8	General corrosion.	3	None	6 monthly inspections	7	168	29	1, 2, 5, 6	FETA	5	5	5	3	6	90
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	None	6 monthly inspections	8	256	18	1, 2, 4, 5, 6	FETA	5	5	5	4	7	140
50	22	"	"	"	7	8	8	Overloading of horizontal or vertical restraint (where wear between the feet and the track beams cause extra resistance).	5	None	6 monthly inspections	7	280	17	1, 2, 5, 6	FETA	5	5	5	5	6	150
51	22	"	"	"	7	8	8	Impact loading due to lack of fit.	4	None	6 monthly inspections	7	224	27	1, 2, 5, 6	FETA	5	5	5	4	6	120
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	None	6 monthly inspections	10	250	19	None	N/A	-	-	-	-	-	-
53	14	"	Wear of top edge of plate.	Damage to vehicle tyres.	3	4	4	Excessive wear.	8	None	6 monthly inspections	3	96	41	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	4	196	28	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	4	84	42	None	N/A	-	-	-	-	-	-

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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	Ranking (based on RPN)	Recommended Action (see separate table after this spreadsheet)	Responsibility and Target Completion Date	Resulting Assessment 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	None	6 monthly inspections	4	84	42	None	N/A	-	-	-	-	-	-
57	15	"	"	"	7	6	7	Impact loading due to lack of fit.	3	None	6 monthly inspections	4	84	42	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	4	64	50	None	N/A	-	-	-	-	-	-
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	None	6 monthly inspections	3	12	60	None	N/A	-	-	-	-	-	-
60	24	“	“	“	2	2	2	Weld failure from fatigue or impact.	4	None	6 monthly inspections	4	32	59	None	N/A	-	-	-	-	-	-

A.3.2 Description of Actions to Reduce RPN

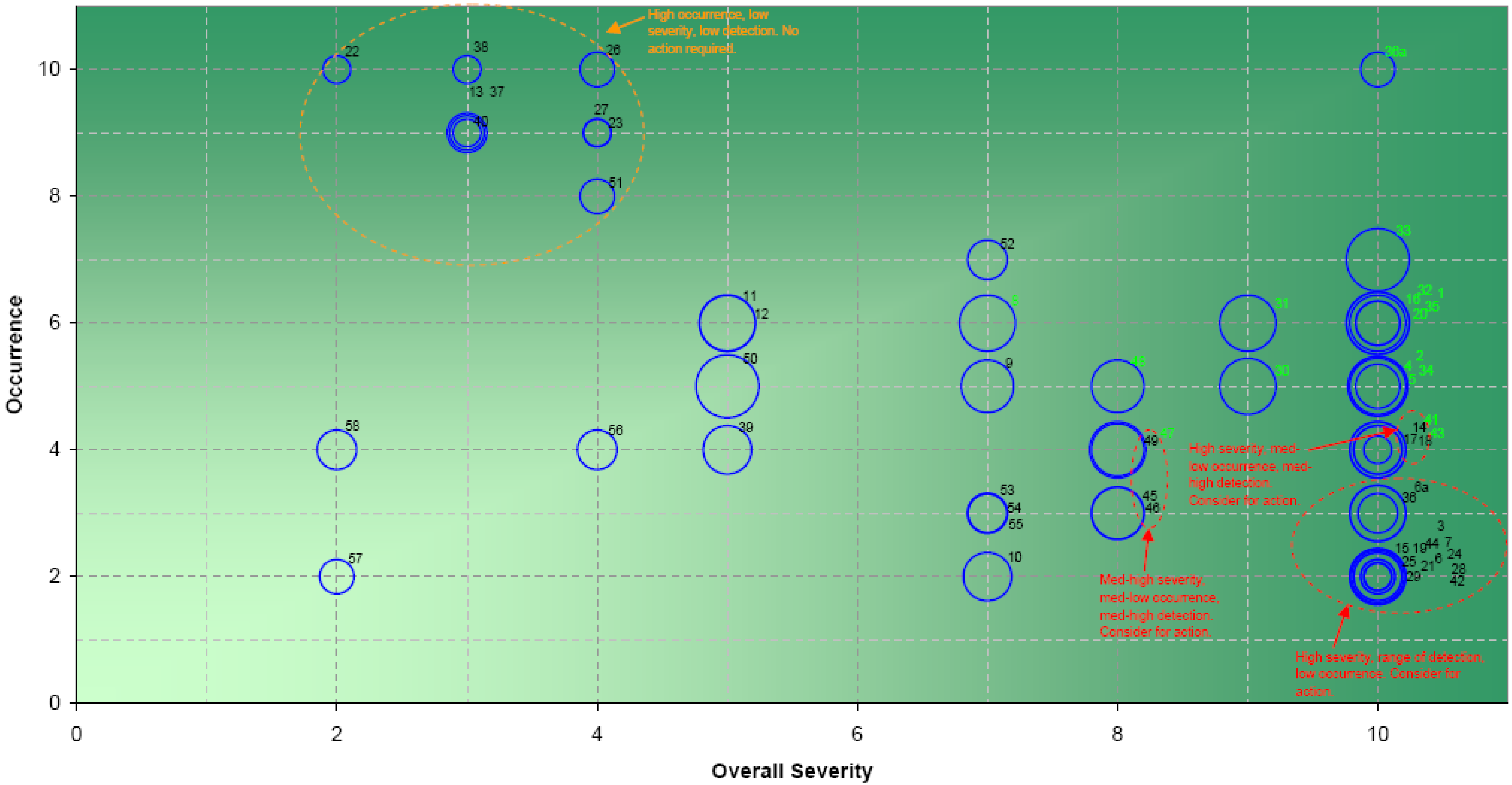
Recommended Action	Description	Comment	Target Completion Date
1	Lift out plate train and tongue plate for close examination.	Close inspection reduces occurrence and detection scores.	August 2009
2	Improved access walkways under bridge deck.	Allows inspection of all areas of joint to reduce detection 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

A.4.1 Bubble Chart for Baseline FMEA Scoring

Key (1):
Bubble size = Detection (large bubble = difficult to detect/high detection score).
Numbers = Line number from FMEA.

Key (2):
Blue bubbles = raw data.
Green = Identified for action by FMEA (RPN>250).
Orange = Trend/pattern - no need for action.
Red = Trend/pattern - need to consider action.

Key (3):
Risk Tolerance is indicated by chart shading. Items which are marked towards the top right (in areas of darker shading) should be considered for action.

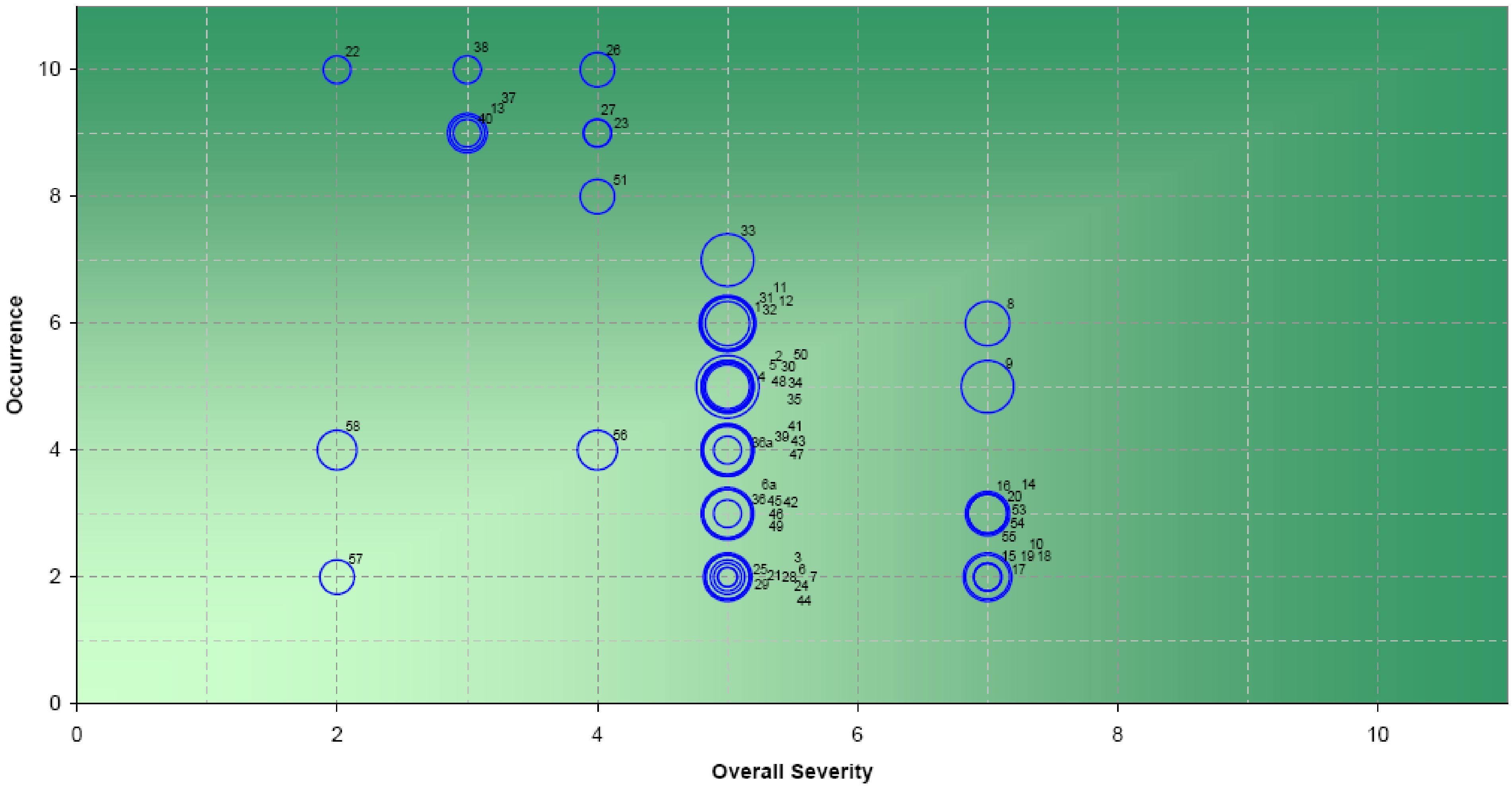


A.4.2 Bubble Chart for Resultant FMEA Scoring

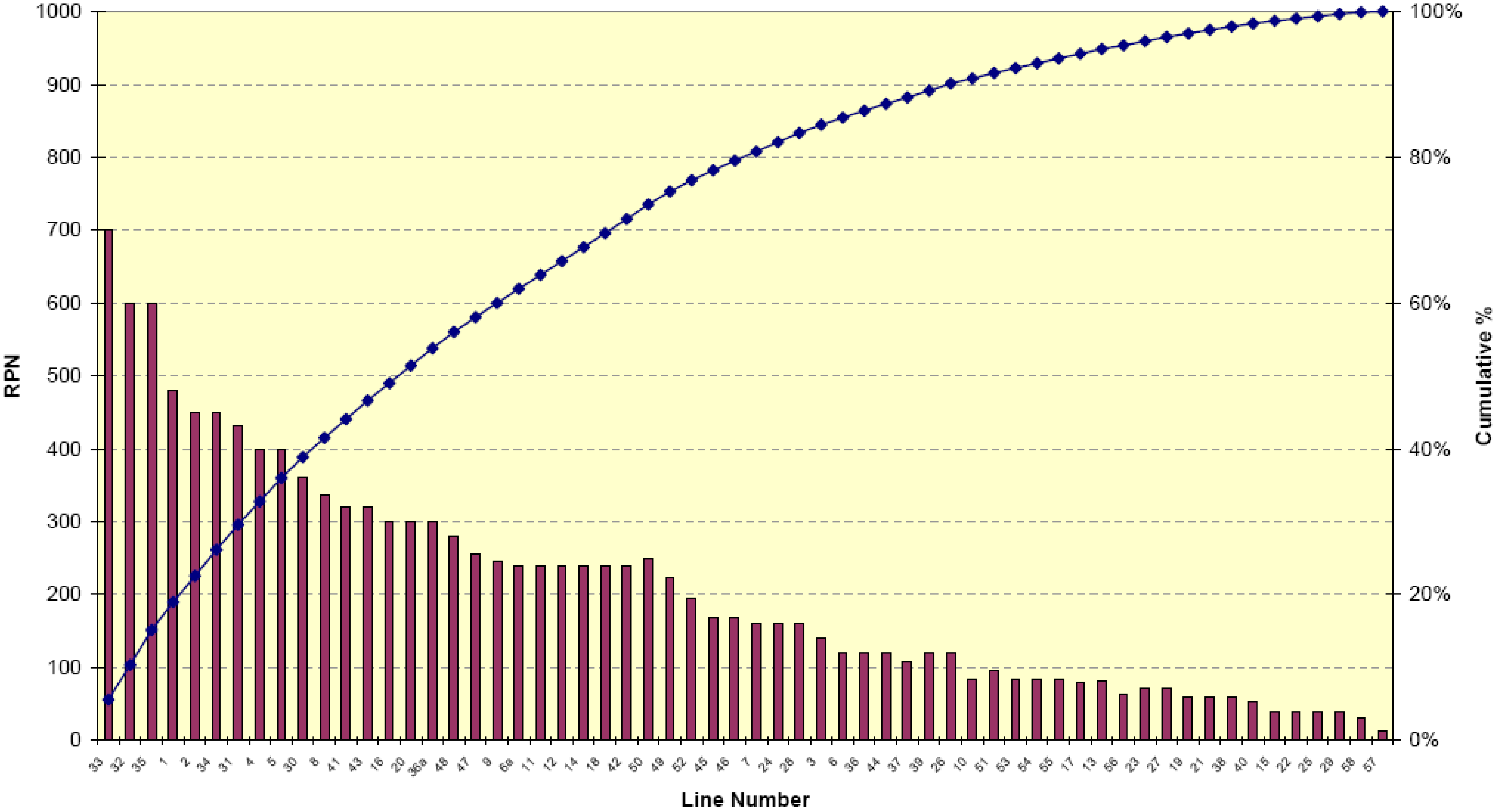
Key (1):
Bubble size = Detection (large bubble = difficult to detect/high detection score).
Numbers = Line number from FMEA.

Key (2):
Blue bubbles = raw data.

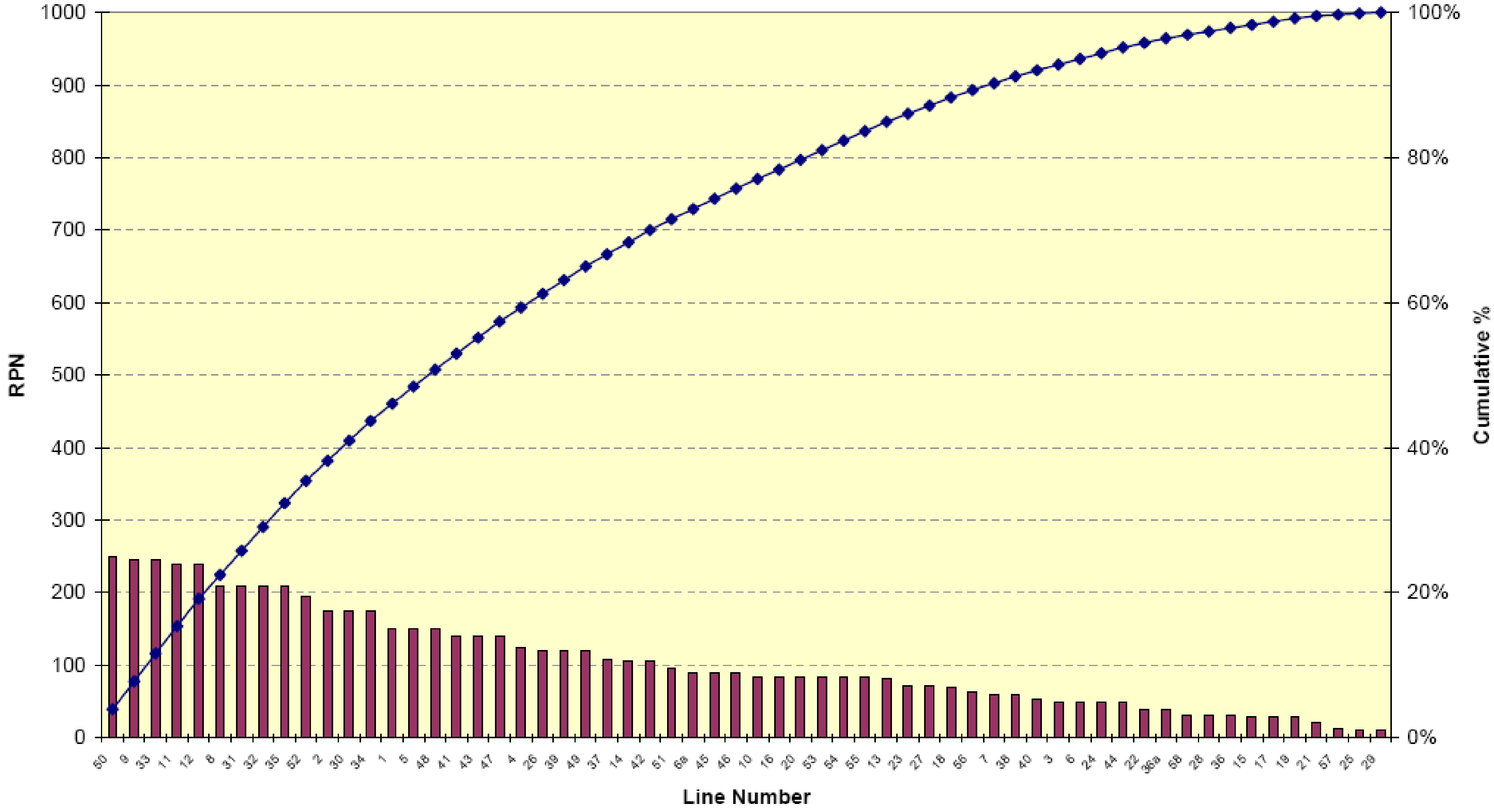
Key (3):
Risk Tolerance is indicated by shading. Items which are marked towards the top right (in darker shading) should be considered for action.



A.4.3 Pareto Chart for Baseline FMEA Scoring

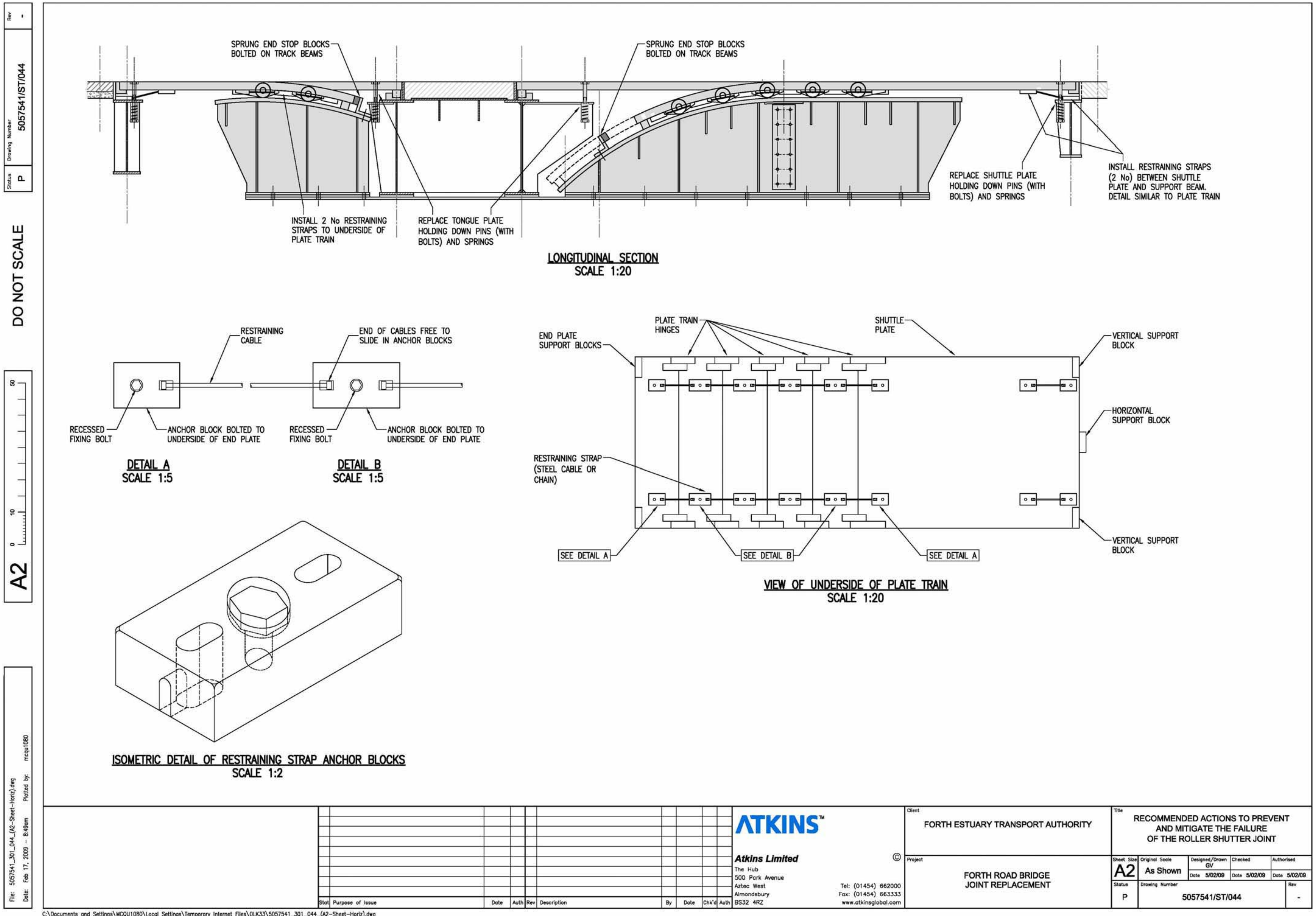


A.4.4 Pareto Chart for Resultant FMEA Scoring



Appendix B

Sketch of Recommended Options.


SPRUNG END STOP BLOCKS BOLTED ON TRACK BEAMS
SPRUNG END STOP BLOCKS BOLTED ON TRACK BEAMS
REPLACE SHUTTLE PLATE HOLDING DOWN PINS (WITH BOLTS) AND SPRINGS
INSTALL RESTRAINING STRAPS (2 No) BETWEEN SHUTTLE PLATE AND SUPPORT BEAM. DETAIL SIMILAR TO PLATE TRAIN
INSTALL 2 No RESTRAINING STRAPS TO UNDERSIDE OF PLATE TRAIN
REPLACE TONGUE PLATE HOLDING DOWN PINS (WITH BOLTS) AND SPRINGS
LONGITUDINAL SECTION
SCALE 1:20
RESTRAINING CABLE
END OF CABLES FREE TO SLIDE IN ANCHOR BLOCKS
RECESSED FIXING BOLT
ANCHOR BLOCK BOLTED TO UNDERSIDE OF END PLATE
RECESSED FIXING BOLT
ANCHOR BLOCK BOLTED TO UNDERSIDE OF END PLATE
DETAIL A
SCALE 1:5
DETAIL B
SCALE 1:5
END PLATE SUPPORT BLOCKS
PLATE TRAIN HINGES
SHUTTLE PLATE
VERTICAL SUPPORT BLOCK
HORIZONTAL SUPPORT BLOCK
RESTRAINING STRAP (STEEL CABLE OR CHAIN)
VERTICAL SUPPORT BLOCK
SEE DETAIL A
SEE DETAIL B
SEE DETAIL A
VIEW OF UNDERSIDE OF PLATE TRAIN
SCALE 1:20
ISOMETRIC DETAIL OF RESTRAINING STRAP ANCHOR BLOCKS
SCALE 1:2
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Status P
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A2
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Checked Date 5/02/09
Authorised Date 5/02/09
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