Forth Estuary Transport Authority

Forth Road Bridge
Options Report for Bridge Deck Joints

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September 2007

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GLOSSARY OF TERMS

Term	***Meaning / Definition***
FETA	Forth Estuary Transport Authority

1 Executive Summary

The Forth Road Bridge is a three span cable suspension bridge with the addition of approach span viaducts on both the north and south sides. To allow for movement in the bridge, expansion joints have been incorporated in both carriageways and also in the foot / cycle paths that flank both sides of the structure.

Three different types of expansion joint have been used in the structure to suit the location and movement range required. At the main towers of the suspended spans the carriageways have roller shutter expansion joints. At the northern end of the north suspended span, and in the southern viaduct approach spans the carriageways have comb joints. At corresponding locations with the roller shutter and comb joints the foot/ cycle paths have a third type of joint comprising a pair of steel plates sliding over each other. All of the joints are basically original to the bridge and have performed in accordance with design requirements. As a result of increasing maintenance work on the joints, and from sample inspections it is apparent that the joints have become badly worn and have generally reached the end of their service life.

This report considers the options available to either repair refurbish or replace each type of expansion joint. Since the original construction of the bridge improvements have been made in the hardness and types of steels, designs have been improved and new designs have been developed. These improvements have been considered in considering the options, along with other factors and constraints such as programme, traffic management, access, resources, procurement, future maintenance and health and safety. The Bridge is a category A listed structure and any major changes will require consent from the local planning authorities. The report includes approximate costs and timescales for the options, but these will need to be refined as detailed design develops.

For the roller shutter joints the recommended option is to completely replace the joint with a new similar type. This takes advantage of improved designs and materials and gains maximum benefit in terms of future performance. A new joint can be pre-fabricated to the tight tolerances this type of joint requires. This option has the least potential for traffic disruption.

Options for the foot / cycle path joint are limited and a full refurbishment of this joint, with a possible replacement of the top sliding plate is recommended. Replacing the top plate enables anti slip surfacing to be incorporated. In addition phosphor bronze wear pads can be inserted to reduce friction and wear.

Finally the comb joints should also be replaced with a new similar joint as repair or refurbishment would practically involve replacement.

2 Introduction

2.1 Requirements of Brief

Atkins have been commissioned by the Forth Estuary Transport Authority (FETA) to investigate options for the repair or replacement of the bridge deck expansion joints in the Forth Road Bridge. The commission is in response to increasing maintenance work on the joints and inspections of the expansion joints by FETA which revealed areas of heavy wear.

2.2 Scope of Report

This feasibility report considers the options available for either the repair and / or replacement of each of the three types of deck expansion joints incorporated into the structure. Options considered for each joint type include minimal repairs, complete refurbishment, or complete replacement with a new similar or alternative type of joint. The report also discusses factors and site constraints which may affect the choice of option. Finally the report provides recommendations for the preferred option for each type of joint.

3 General Description

3.1 Overall Description of Structure

The Forth Road Bridge spans the Firth of Forth to link the towns of North and South Queensferry to the west of Edinburgh. Construction of the bridge was started in 1958 and work was completed with the official opening in 1964. The main structure is a three span suspension bridge with a central span of 1005 metres and side spans of 408 metres. On both approaches to the bridge there are multi-span viaducts, the north side having six spans and an overall length of 257 metres and the south side having 11 spans and an overall length of 438 metres.

The road over the bridge comprises a pair of two lane carriageways, both 7.3 metres wide. The carriageways are flanked by cycle paths 2.74 metres wide and footpaths 1.83 metres wide. The overall width of the structure is 33 metres.

The deck to the main bridge comprises a series of steel trusses spanning transversely, hung from the vertical hangers of the suspension cables. Over the trusses each carriageway and foot / cycle way are separate discrete constructions, which comprise, for the main span, longitudinal steel girders and steel deck plates. The side spans also have longitudinal steel girders and steel deck plates, but with the addition of a reinforced concrete deck slab. The deck on the approach spans comprises a pair of longitudinal steel box girders supporting a series of transversely spanning steel girders. The transverse girders cantilever out from the box girders to support the parapets and verge construction. Over the transverse beams is a reinforced concrete deck slab.

Traffic usage in the first year of opening was over 4 million vehicles and this has grown steadily to over 24 million in 2006.

In 2001 the Bridge gained Category A listed structure status.

3.2 Bridge Deck Expansion Joints

Deck expansion joints allow for the movement of the bridge structure. Movements on a suspension bridge such as the Forth Road Bridge occur as a result of expansion and contraction of the deck and cables from temperature effects and in response to vehicle and wind loading. Such movement occurs in a combination of vertical and horizontal directions as well as in rotation about these axes. In each carriageway, at both main suspension towers, there are two joints to accommodate movement in the main centre span of the bridge and the spans either side. These joints are of the roller shutter type. At the north end of the north suspended side span there are further joints in both carriageways comprising of interlocking combs (or fingers). There are further interlocking comb joints in both carriageways mid way along the south approach viaduct to the main bridge (at pier S3). At each carriageway joint there are also corresponding joints in the both foot / cycle ways. These comprise steel plates that slide over each other.

More detailed descriptions of the joints are contained in the options section of this report.

4 Site Considerations

4.1 Programme

4.1.1 Programme Constraints

In order to minimise the disruption to the road users, the programme for undertaking the works on site needs to consider a number of constraints. The Forth Road Bridge crossing is a strategic route and traffic disruption on the Bridge will affect other roads in the area and also other Firth of Forth crossings. Conversely, works on the other strategic routes in the area will affect the Bridge. The timing of the works therefore needs to be coordinated with planned works on other routes as well as on the Bridge itself. The other routes identified include the M8 and M9 motorways and also the A985 and A977 roads. There are also other factors that will cause additional traffic on the roads, such as large public events (e.g. the Edinburgh Festival) and traffic volumes are generally higher in the summer months.

For safety to the workforce reasons, and to minimise the risk of disruption to the work, it would be preferable to undertake the work in the summer months when the weather is more likely to be suitable. The time periods to undertake each section of work needs to be planned in advance. Allowance will need to be made for unexpected / unforeseen difficulties that may cause time over runs. Some of the work operations are particularly weather sensitive, such as painting and repairs to the deck waterproofing.

In consideration of the above FETA propose that construction work for the joints should be over two phases. The first phase is planned for October 2008 and will involve the south bound carriageway and the second phase is planned for a year later in October 2009 and will involve the north bound carriageway. This will enable work to be complete before the refurbishment work on Kincardine Bridge proposed to start in September 2010.

4.1.2 Programme Risks

The programme for the work will contain a number of risks that may affect the overall timing. Delays will cause prolonged traffic congestion and may affect other planned works. Programme risks should be fully identified and measures taken to manage them throughout the design and construction phases of the work.

Risks identified at this stage include delays caused by poor weather, traffic incidents on the bridge or alternative routes preventing carriageway closures, availability of resources, lead-in times for plant and materials and lack of access or difficulty in dismantling / installing joint components. These can be managed by monitoring weather and traffic conditions, and advance planning of works and resources.

4.2 Traffic Management

Traffic management in the form of full carriageway and lane closures will be necessary to gain access to holding down bolts and top plates of the expansion joints. The length of time required for traffic management will depend on the particular work operation being undertaken, and possibly which part of a joint is being worked on. Traffic usage of the bridge is very high and any traffic management will inevitably cause additional disruption. It is understood that FETA are keen to keep any traffic disruption and consequent delay costs to a minimum.

The last published annual traffic flow data on the bridge is for year 2004. The average weekday traffic flows on the bridge gradually increase from about 33,800 to 36,700

Monday to Friday. At weekends traffic flows are much lower at about 25,500 on Saturdays and 24,500 on Sundays. This compares against a theoretical daily capacity of just under 30,000 vehicles. The number of days the theoretical capacity was exceeded in the year was about 270. Traffic flows vary throughout the year with the highest traffic levels recorded in August and September and the lowest in January and February. Traffic flows are predicted to steadily increase.

There is scope to install a contra-flow on the bridge to allow two-way traffic on one carriageway while the other is closed. FETA have advised that it was observed during resurfacing works in early summer 2007 that the maximum traffic flow in a contra-flow situation was between 1100 and 1200 vehicles per hour per carriageway / lane in either direction. The timing of installing traffic management needs to be carefully considered to reduce the effects on the road network.

Although most of the work on a joint will require a full carriageway closure, the removal of some parts of a joint will only affect one lane of a carriageway. In this case the removed section of a joint will need protecting from errant vehicles and this will need to be achieved by using temporary steel or concrete safety barriers. Temporary steel barriers are usually quicker to install and remove than concrete barriers, but steel barriers need to be anchored into the carriageway, which will cause difficulties.

Work will also be required on the joints in the foot / cycle ways. The Bridge carries part of a national cycle route and a full closure of the path may be necessary. Arrangements will need to be made to divert users onto the path on the other side of the bridge.

The level of disruption that traffic management will cause can be mitigated to some extent by advance publicity. Advice can be given to bridge users on alternative routes or to change their journey time to a quieter time of day.

4.3 Access

Access to the expansion joints is via the carriageway, but it will also be necessary to gain access under the carriageway joints in the main section of the bridge to dismantle some components. This can be achieved by foot via existing access arrangements, but this will need to be extended and improved to enable a workforce to reach all parts. Additional protection may also be necessary to prevent falls from the Bridge.

Vehicle access to the foot / cycle way joints can be achieved by driving along the path. However the maximum vehicle weight the path can safely carry is 3.5 tonnes.

Consideration should be given when working on separate joints in one carriageway concurrently. Once a joint has been removed access for vehicles along the carriageway will be prevented.

4.4 Resources

Resources for the work can be considered in terms of labour, plant and materials. Specialist resources are needed because of the nature of the work and the environment that would be worked in. Such resources may not be readily available and need to be planned for in advance.

Specialist labour would be required, in particular steel fabricators, welders and those trained to use lifting equipment. Labour experienced in undertaking expansion joint work would appreciate the type of work and the need to work to tight tolerances. Plant will include lifting equipment, welding, profiling and cutting equipment on site and in a factory. Use of such plant requires trained personnel. Components are likely to include specialist steels and some parts will need to be specially made.

Planning of finance is also required. Repair and refurbishment of the joints is likely to be very expensive and finance will need to be made available. Such availability may dictate the speed with which the work is done and whether it is spread over more than two years.

4.5 Advance Works

Some work can be undertaken in advance of the main contract for repairs. Advance work can help to ensure that overall the process of repair runs smoothly without delays.

Access to the roller shutter joints can be improved by modifying / extending walkways under the joints so that all bolts and parts can be reached. This has the advantage of enabling a detailed inspection to be undertaken to assess the work required and the overall condition to assess work priorities. Bolts can be checked to ensure they are not seized to make dismantling quicker and easier. Ensuring full access improves overall safety. It is envisaged that improving access will not require the installation of significant traffic management on the carriageways.

FETA have already undertaken what could be considered as trials by partially dismantling some of the components of the joints for inspection. This provides a learning process and helps planning for the right equipment to be available and to assess how long the work will take.

4.6 Procurement

There will be a limited number of Contractors who would be willing and able to undertake this type of work. Working on the bridge is a harsh and risky environment and the type of work is specialist in nature. To ensure the Contractor chosen to do the work can make available the right resources then a long mobilisation period will be required.

Consideration will need to be given to the type of contract and clauses within. Work is likely to be disrupted by poor weather conditions or disruptions on the road network may prevent the installation of traffic management. FETA needs to decide who carries the risk of such disruption. With a reasonable mobilisation period the Contractor could carry the risk of resource availability.

With the specialist nature of the installation works, the procurement process should seek Contractors with previous experience of this type of work. This should enable a Contractor to be appointed who has a good understanding of what is required and reduce the ‘learning curve’ stage of the contract.

4.7 Future Maintenance and Repairs

Every mechanical bridge deck expansion joint will require routine inspection and maintenance. Since the original construction of the bridge there have been improvements in the quality of materials available that can increase the durability of the joint and this should be considered in the options. In addition, more sophisticated fabricating machinery gives the potential for components to be manufactured to tighter tolerances. Even with these improvements future maintenance and repairs will still be necessary.

The existing bridge deck joints have been in place since the opening of the bridge to traffic in 1964. When the bridge was first opened traffic flows in one carriageway were approximately 2.3 million vehicles. This has steadily grown to over 12 million vehicles per carriageway today. If the life of a bridge joint is based on the number of vehicles passing over it, and it is assumed that the joints are at the end of their lives, then each joint has a life of over 300 million vehicles over 43 years. If traffic levels continue to grow and the life of a new / repaired joint is the same as the existing ones in terms of vehicles passing over them, then the life of the new / repaired joints will be a maximum of 20 years. There are some broad assumptions in the figures as no allowance has been made of increased vehicle weights, a maximum physical number of vehicles that can cross the bridge that will limit growth and the effect that removing tolls (if any) will have. However, generally a new / repaired joint can be assumed to have a life, in terms of years, of less than half that of the original joints.

Works on the joints, in particular the roller shutter joints, will require improved access arrangements as discussed above. The improved access will enable future inspections, maintenance and repairs to be easier. In consultation with the manufacturers of the new / repaired joint, a future inspection and maintenance regime can be produced.

4.8 Listed Building Consent

The Forth Road Bridge is a category A listed structure. Any alterations to the structure would require prior Listed Building Consent from both of the local planning authorities, the City of Edinburgh and Fife Councils. The Councils have a statutory duty to determine valid applications within 2 months, although they do not always achieve this. However, minor works which do not affect the character of a structure do not normally require consent and it is recommended that early consultation with the Councils is undertaken to determine if joint replacement does require prior consent.

4.9 Health and Safety

Works on the expansion joints will carry a number of health and safety risks. Full risk assessments will need to be developed for the design and construction phases of the works.

Risks identified at the feasibility stage include the following:

- Installation, maintenance and removal of traffic management;
- Working adjacent to live traffic;
- Adverse weather conditions;
- Working at heights;
- Limited / awkward spaces for working;
- Welding, cutting, drilling and grinding materials;
- Manual handling;
- Use of equipment for heavy lifting;
- Constant movement of bridge (joint gap varying);
- Removing and applying protective coatings;
- Use of cementitious and bituminous materials;
- Asbestos.

5 Carriageway Deck Joints at Main Towers

5.1 Description of Existing Deck Joints

Adjacent to both the main towers of the bridge, each carriageway has two deck movement joints, one for the main centre span, and the other for the side span (making a total of eight joints in all). Each of these joints is of the roller shutter type and they are the original joints to the bridge. This type of joint is able to accommodate the large movements of the deck that occur in a bridge of this type. Information from the 'as built' drawings indicate that the joints were designed to have a movement capacity of +810mm / -920mm (total 1730mm) in the main span and +150 / -260mm (total 410mm) in the side span.

The deck expansion joints comprise a series of units 1232mm wide, giving a total of six units per carriageway. Each unit has effectively two movement joints, one for each (side and main) span. Each individual joint unit comprises an anchor (or bridge) plate which is articulated on one (deck) side of the joint. This plate effectively spans over the structural gap of the joint itself. Attached to the opposite edge of the anchor plate are a series of link plates, all connected together by hinge mechanisms to form a train. The anchor and link plate train slide, via discrete feet, over the top flanges of curved support beams as the structural gap moves. The pier side of the joint supports a tongue plate. This tongue plate is also supported on the link plate train and the end of the deck to form a smooth running surface for traffic. 'As built' drawings of the joint have been included in Appendix A and photographs in Appendix B.

The construction of the joint means that complete water tightness is impossible to achieve and this can lead to corrosion problems and ingress of contaminants. In addition, this type of joint has a reputation of being noisy, particularly when wear becomes advanced in hinges and the mating surfaces between the link plate feet and the surface of the support beams. However, this type of joint is generally of robust construction and has proved to have a good service life on the Forth Road Bridge as well as other large bridges around the world.

5.2 Maintenance History

Roller shutter joints of this type have a typical design life, before major maintenance, of 20 to 30 years. The joints in the Forth Road Bridge are essentially the original ones, which are now over 40 years old, but the joints were subject to a detailed inspection and overhaul in 1975. That inspection was undertaken by specialist bridge joint company, DEMAG Lauchhammer. Generally the joints have proved to perform well and reliably in service, but with general wear, are now becoming an increasing maintenance liability. The 1975 inspection reported that the joint was generally performing well, but evidence of wear was becoming apparent. Defects noted included:

- Two of the tongue plates were cracked;
- Some of the link and anchor plates were loose;
- Play was detected in the hinge joint pins;
- The springs to the holding down bolts for the plates were corroded;
- General wear in the interface between the link plates and the support beam;

- The approach carriageway surfacing was uneven.

Since the 1975 inspection FETA have also undertaken further inspection and maintenance work. This has included:

- Welding 'keeper plates' on the sides of the hinges to prevent the hinge pins from migrating outwards;

- Lifting a joint train and tongue plate to inspect the condition of the sliding surfaces and wear to hinge pins.

5.3 Current Issues

The recent sample inspections by FETA have shown excessive wear in the curved link plate support beams and in the hinges and feet of the link plates. The effect of this wear is that the joint becomes increasingly noisy and play in the mechanisms and wear surfaces causes rapidly increasing damage to the joint. Ultimately the joint will break up with safety implications for the travelling public and / or parts of the joint will seize causing excessive loading on the bridge structure.

In addition to the wear in the joint itself, the traffic surfaces of the steel plates have also become very worn. This has resulted in the wear of the leading edge of the first link plate. In addition, originally the traffic face of the main link plates had grooves cut into them in a diamond pattern to form an anti-skid surface and these have worn away. The steel plates now form a very smooth surface which has a low vehicle skidding resistance, particularly when wet.

5.4 Options for the Joints

5.4.1 Options Considered

Five options for repair or replacement of the joints have been considered and these have been discussed below. In summary the options are:

a) Continue with current maintenance regime;

b) Completely refurbish the existing joint;

c) Completely replace the existing joint with a new roller shutter type joint;

d) Completely replace the existing joint with a supported finger comb type joint;

e) Completely replace the existing joint with an elastomeric type with steel girders.

5.4.2 Continue With Current Maintenance Regime

This option involves keeping the joints as they are and undertaking essential maintenance and repairs as and when necessary to ensure safety and reliability. This means it is to do only reactive or short-term work, and, effectively, it is therefore a 'do-nothing' option.

Reactive work by its nature is unplanned and repairs could be necessary at times inconvenient for resources and at inappropriate times for traffic management. In addition, weather conditions may make working on the bridge too hazardous for safe working. Failure of components of the joint could cause more damage and at worst also cause a major safety hazard to road users. A complete failure of a hinge joint could result in the link plates sliding down into the joint leaving a large gap in the carriageway. Resources for repairs, such as specialist labour, lifting equipment, traffic management operatives and spare parts may not be immediately available leading to unnecessarily prolonged lane or carriageway closures.

Reactive or short term planned work results in repairs being undertaken on an ad-hoc basis. The inherent design of the joint requires that installation and repairs are undertaken to very high tolerances. Experience with repairs on other bridges with similar roller shutter joints has found that even minor discrepancies in levels or alignment can lead to premature failure of components. For example, a difference in top surface level between adjacent support beams can lead to rotation under vehicle load of the link and anchor plates. This has resulted in excessive wear in plate hinge bearings and damage to the link plate feet and running surface.

For repairs, work can be undertaken on a piecemeal basis as each whole joint is built up with six separate units across a carriageway and each individual unit can be dismantled and repaired independently. However, two neighbouring sliding trains share the same curved beam track so repairs on a curved beam affects two units. This makes meeting the necessary tolerances more difficult, as one half of the curved surface needs to be repaired at a time. This means, that for the majority of the repairs, a full carriageway closure will be necessary for the full duration of the repairs. Where the carriageway is not fully closed, the removal of a joint unit will result in a gap in the carriageway which will need to be protected from errant vehicles by temporary safety barriers. During the actual removal or reinstatement of a section of joint a crane will be necessary and the required room for manoeuvrability and size of the crane will mean a full closure of a carriageway.

Since the construction of the Bridge, the roller shutter joint has been installed on a number of large span bridges around the world and also a number of joints on older bridges have also been repaired and refurbished. Further development of the design of the joint has taken place considering the experience gained from joints in use and also from the advancement of specialist steels and other materials. Although the existing joints have had a good service life traffic levels have increased significantly since the Bridge was built and a joint built to the same specification as the original one would not be expected to last as long, say a maximum of 20 years, instead of in excess of 40 years. Retaining the existing joint would not take advantage of improved design and material knowledge and the potential increased service life that would bring.

The extent of traffic management required for this option is difficult to quantify as lane and carriageway closures would not necessarily be planned. Short-term closures, especially as they would become more frequent and the resultant congestion would be subject to criticism from users and therefore would be politically sensitive.

Retaining the existing joint though can lead to short term cost savings and uses a joint that generally has proved to be viable. Some repairs have already been undertaken and retaining the joint maximises the investment already made. However, repairs will become an increasing financial burden as parts will fail at an increasing rate and repairs undertaken on the ad-hoc basis described above may not be long lasting leading to increased overall costs.

The advantages and disadvantages of this option can be summarised in the following table:

Advantages	**Disadvantages**
1. Relatively low short term costs	1. Joint will result in an increasing financial liability as more components wear and fail
2. Retains a proven joint	2. Possible safety risk from failure (increasing with time).
3. Makes use of investment already made in repairs	3. Would be politically unacceptable to close lanes or a whole carriageway to undertake

	emergency repairs.
4. Some spare trains are available for use during the works.	4. Suitable workforce or specialist equipment to undertake repairs at short notice may not be available.
	5. Inherent design short-comings in joint not addressed.
	6. Inherent design requires site repairs to a very tight tolerance level, which may not be achievable, especially on a piecemeal basis.
	7. Weather conditions may not be suitable for emergency repairs.

It is difficult to evaluate the costs of this option as it is dependent on how much work is done and over the time period considered. Traffic management and traffic delay costs will be relatively higher than for other options as works will be done over a number of short periods.

5.4.3 Refurbish Existing Joint

This option also retains the existing joint, but involves a thorough refurbishment of the whole joint construction to effectively return it to an 'as new' condition. Like the previous option this retains a proven joint that reuses the existing support structure, but repairs can be undertaken on a planned basis and possibly take advantage of carriageway closures for other works. With a fully refurbished joint increased reliability can be expected with no further major maintenance for up to 15 years.

The extent of the work in refurbishing joint would depend on its existing condition, but assuming that most components in each section of joint are worn, work would include:

a) A detailed level survey of the existing joint and its support structure. The survey would need to be done to a high level of accuracy. This is necessary to ensure not only that the refurbished components fit back, but also to ensure each part is correct in relative level, in particular the curved support beams to the link plates. The survey would need to be undertaken before and after dismantling the joint.

b) A detailed condition survey of the whole joint. This will enable forward planning of the repair work in terms of time required, ensuring materials are ordered, and specialist labour and equipment is available. In addition repair of the joints can be undertaken on a priority basis to minimise safety and disruption risk. Similar to the level survey the condition of components would need to be done before and after dismantling. After dismantling components can be checked for hidden defects such as deterioration in welds, distortions and microscopic cracking.

c) Repair / refurbishment of each component. For the curved support beams this will likely include refacing or replacing the top curved flange to remove damage. The link plate hinges probably require replacement pins and bushes. The feet under the link plates will require refacing to make good wear. Holding down bolts, springs and washers should be replaced. Finally all components can receive corrosion protection.

As with the previous option, repairs can be undertaken piecemeal, so that traffic management and full carriageway closures can be minimised. Refurbishment of the components is likely to take a number of weeks during which time the affected area of carriageway would need to remain closed. A solution to minimise the closure time would be to fabricate (or use if one is already available) a spare link plate train that can be placed while the original is sent away. At the end of the works the spare could be retained for future emergency use. Use of a spare curved support beam would be difficult as the linked plate train require tight tolerances on the curved beams and the new and spare beams to be exactly the same size.

This option has the advantage over the previous option in that higher standard repairs can be achieved in a factory environment than on site. This is likely to result in a more durable finished product. However as the joint would be repaired in sections great care would need to be taken to ensure all levels are correct across the carriageway to ensure correct overall functioning on completion of the joint. This work will be difficult as one curved slide track supports two link trains.

While components are in the factory there is the option of undertaking design modifications and improvements. These could include using harder wearing steels in the curved support beams, replacing the hinges under the link plates, improving the feet under the link plates and improving the skid resistance of the traffic surfaces. However if extensive modifications are undertaken then this effectively leads to a new joint and consideration needs to be given to this alternative. This option is discussed in section 6.4.4 below.

The advantages and disadvantages of this option can be summarised in the following table:

Advantages	**Disadvantages**
1. No modifications to existing support structure	1. Work will need to be done to a very high standard / tight tolerance to provide longevity.
2. Repairs can be done in stages and usually within one carriageway lane meaning less disruption to traffic. (Assuming spare joint section provided).	2. Does not address design short comings of joint, such as water tightness. New joints of a similar type have been updated.
3. Proven design, known to work.	3. Work will be slow and subject to weather delays.
4. Up to 15 years before next major refurbishment (depending on traffic usage)	4. Possible reduced fatigue life in reused components.
	5. Fabrication tied in with traffic management. Delays in fabrication will extend the duration of carriageway closures.

The costs of this option, assuming the link, tongue and anchor plates are replaced and the top flanges of the curved support beams are replated is in the order of £2.15m, excluding traffic delay costs. Previous experience with a similar type of joint on the Avonmouth Bridge in Bristol is that the full refurbishment of one train of the joint takes up to three weeks, allowing for providing corrosion protection to be applied. Assuming only two trains are worked on at one time, (say two in line at one pair of joints at a pier) this means refurbishment of a pair of joints at a pier could take up to 18 weeks. This could be reduced by increasing the number of units being refurbished at any one time, but this would be subject to the availability of specialist labour and fabrication equipment. With the benefit of experience of the first carriageway, the decision could be made to refurbish the joints at both piers in the other carriageway at the same time with some savings in traffic management and preliminary costs.

5.4.4 Replace with New Roller Shutter Joint

The design of the roller shutter joint was first introduced in the 1930's and the design has since steadily been refined with the benefit of experience and the availability of improved materials. This type of joint appears to have performed well in the Bridge and this option considers replacing the existing joint with a new similar one.

The advantages of a completely new joint are similar to those of a full refurbishment of the existing joint. However, the additional advantage of a new joint is that the whole joint (including curved beam slide tracks) can be fabricated and set up off site to ensure correct functioning and alignment. The new joint can then be dismantled sufficiently for transport and craneage and inserted as a whole unit on site during one carriageway closure. This was how the original joint was constructed when the Bridge was first built.

A completely new joint can incorporate all the current design and material improvements, such as more robust link plate hinges, better water tightness, harder steels and traffic running surfaces. The copyright on the design has expired so in theory any competent fabricator could manufacture the joint, however, it would be advantageous to use an experienced joint manufacturer as they would have a clear understanding of what they are expected to achieve.

The advantages and disadvantages of this option can be summarised in the following table:

Advantages	Disadvantages
1. Minimises overall carriageway closure times.	1. Some modification to existing support structure may be required.
2. Takes into consideration improvements in design since the construction of the original bridge	2. High initial cost.
3. Improved materials will give better durability.	3. Financial investment in repairing existing joint lost.
4. No major refurbishment for up to 20 years depending on traffic usage.	4. Tight fitting tolerances
5. Whole new joint can be fully prepared off site in factory conditions. This means that fabrication is not directly tied in with carriageway closures, so fabrication delays will not extend the duration of the closure.	5. Specialist labour and equipment required.
6. Type of joint known to work	6. Limited number of suppliers
7. Lower noise levels	

The initial cost of a new joint is likely to be relatively high, but probably not significantly higher than refurbishing. In addition some of the investment made in repairing the existing joints would be lost. This needs to be weighed against the increased probability of achieving a durable and reliable joint system a significant reduction in carriageway and lane closures.

For a full replacement of all the roller shutter joints the total cost, including traffic management and preliminaries is in the order of £2.51m (excluding traffic delay costs). The time required on site to replace one pair of joints will be 3 to 4 weeks (plus off site fabrication time). Assume one pair of joints is replaced at a time in a carriageway this will give a total works period on site of up to 8 weeks (plus off site fabrication). For the second carriageway, with the benefit of experience of the first carriageway, the decision could be made to replace both pairs of joints at the same time with some savings in traffic management and preliminary costs.

5.4.5 Replace with Supported Finger Joint

The other carriageway joints on the bridge are of the Comb (finger) joint type. The range of movement required means that the fingers need to be supported to be able to take traffic wheel loading. The range of movement on the main and side spans of the bridge is much larger than on the approach spans. No joint was identified from manufacturers information that can accommodate the extent of movement required therefore no further consideration was given to this type of joint.

5.4.6 Replace with Elastomeric with Metal Runners

An alternative type of joint that was not available during time of the original bridge construction is the elastomeric joint with metal runners. The joint comprises a series of steel transverse beams mechanically linked together in such a way as to allow even movement between each beam. Between each beam there is a seal to provide water tightness. Each transverse beam is supported and able to slide and rotate on a series of longitudinal support joists via an elastomeric bearing. The joints are manufactured in one length, so in the case of the Forth Road Bridge, will cover an entire carriageway width. Details of the joint are contained in Appendix B.

This type of joint is available from three Manufacturers. These are Mageba (called Tensa Modular Type), Ekspan (called WSG type) and Maurer (called Swivel Joist Joints).

Using the information provided in the data sheets supplied by Mageba an approximation of the width of the joint (longitudinally along the bridge deck) can be calculated. A maximum space between the transverse beams of 65mm has been assumed in accordance with the Transport Scotland document BD33/94 (Expansion Joints for Use in Highway Bridge Decks). The total width of the joint, covering both spans, ranges approximately between 6830mm and 9040mm depending on temperature. The width of the existing roller shutter joint similarly ranges between 7333mm and 9477mm. A pair of replacement joints would in theory fit, but very careful consideration needs to be given to accommodating the mechanisms under the joints to avoid them clashing with each other and the deck construction.

Although in theory such a joint would work in this situation it is not recommended. The joint will be working at the upper range of its design capability, which may affect its long term reliability. As a large number of elements are required, the consequent high number of moving parts increases the risk of a failure. However, the joint is designed to be able to have many parts replaced in-situ so repairs can be achieved. The joints are continuous across the carriageway so repairs to seals will need a full closure. The bridge joint supporting structure was not designed for this type of joint so therefore would require modification. This will add to the cost and time required on site to undertake the work.

There is constant movement across the expansion joints because of the sensitivity of the bridge to varying wind and traffic loading and thermal effects. Fixing across this constantly varying gap with this type of joint would be extremely difficult to achieve accurately. In addition there will be safety considerations.

Another feature of a large number of metal runners is that they would have a poor traffic ride quality because a ‘cattle grid’ effect would be created. The poor ride quality would probably produce more traffic noise. A similar joint was fitted on the Tacoma Bridge in the U.S.A. and this brought complaints about noise levels.

The advantages and disadvantages of replacing the existing joints with the elastomeric joint with metal runners can be summarised as follows:

Advantages	Disadvantages
1. Individual components can be replaced while bridge is in service	1. Repair / replacement would require closure on an entire carriageway
2. Generally water tight, with replaceable seals	2. Modification of existing joint support structure required to accommodate different type of joint. Will be time consuming and expensive
3. Replacing whole joint as one unit will increase the likelihood of correct functioning in service.	3. Large number of moving connections increasing potential for failure
	4. Care will be needed in designing the joint so that it fits into the space available (particularly longitudinally).
	5. Movement required is towards the upper limit of the capacity of this type of joint
	6. There is little evidence of successful long term use of joint in this type of bridge structure.
	7. Use of this joint would involve procuring a named product which may prove contractually difficult.
	8. Use of a different type of joint may not achieve Listed Building Consent.

Costs for this option are difficult to evaluate as detailed work would be required to establish what modifications would be required to the existing support structure. As this option is not recommended no work has been done to establish costs. The time period to fit the joint would take a number of months therefore it is thought this type of joint would be uneconomic in terms of traffic management and delay costs.

6 Options Available for Footway Deck Joints

6.1 Description of Existing Deck Joints

The Bridge has combined foot and cycle ways of total 4.65 metres width along both sides of the main deck. This not only provides a route for pedestrians and cyclists but also for light maintenance vehicles. The foot / cycleway deck joints are located adjacent to the main suspension towers alongside the roller shutter joints. They are also located at the north end of the north side suspension span and mid way along the south approach span deck. A similar type of joint also exists in the central reserve of the south approach span deck. All the joints are largely original to the construction of the Bridge. The joints comprise pairs of steel plates, one of which slides over the other. The lower plate is fixed, and the upper plate is held down by bolts to enable it to held down against the lower plate. The top surfaces of the plates form a smooth surface for pedestrians and cyclists, although there is a step between the upper and lower plates. 'As built' drawings of the joint have been included in Appendix A and photographs in Appendix B.

6.2 Maintenance History

From available records there has been limited maintenance to the joints. The joints appear to be largely original, with no significant changes.

6.3 Current Issues

The joints appear to be working well. However the step between the upper and lower plates does provide a potential tripping hazard to pedestrians and the smooth surface can be slippery particularly when wet. Since the original construction the sliding plates have become worn, by rubbing against each other resulting in a loss of thickness. This ultimately weakens the plates particularly against the weight imposed by maintenance vehicle loads.

6.4 Options for the Joints

6.4.1 Options Considered

Two options for repair of the joints have been considered and these have been discussed in detail below. In summary the options are:

a) Continue with current maintenance regime;

b) Completely refurbish the existing joint;

An option to completely replace the joint with another type was considered, but none was identified that be suitable for the location, given the construction of the deck, that would offer any advantages over the existing type of joint.

6.4.2 Continue with Current Maintenance Regime

This option is effectively a 'do-nothing' option and involves continuing with current routine maintenance and repairs to ensure continued safety and reliability.

The advantages of this option are that it retains a proven joint system that appears to continue to fulfil its design requirements. As the joint requires little maintenance the cost remains low and investment already made in repairing the joint is retained. As maintenance is low, this option also results in limited disruption to pedestrians and cyclists.

This option does have some disadvantages. The step between the sliding plates remains a tripping hazard to pedestrians and the upper surface of the plates still form a slippery surface. The worn plates will continue to wear and corrode and will ultimately become too thin to support vehicle wheel loading. Another disadvantage is that the joint is not water tight, but it is understood that this is not a particular issue.

The evaluation of the costs of this option is dependent on how much work is done and over the time period considered. A single joint could be refurbished as and when necessary and this would cost in the order of £25,000.

6.4.3 Completely Refurbish Existing Joint

This option considers retaining the existing joint but to totally refurbish it to eliminate the disadvantages of keeping the existing joint as it is (previous option). The joint could be dismantled in sections, sent away and completely refurbished to effective ‘as-new’ condition. This will allow the foot / cycle way to remain open for use, albeit temporarily narrower during repairs.

The upper surfaces of the sliding plates could be modified to incorporate a recessed anti-slip surface to reduce a potential hazard. The underside of the upper sliding plate could incorporate phosphor bronze wear pads to reduce friction between the plates and general wear. Finally the leading edge of the upper sliding plate could be tapered to reduce the height of the tripping hazard, although care would be needed to ensure the plate is not weakened in the process.

The advantages of this option is that it retains the design of a proven joint system but effectively provides an ‘as-new’ joint that will require limited maintenance for up to 30 years. The design of the plates could incorporate some or all of the features described above to reduce the disadvantages of the ‘do-nothing’ option. No modification to the existing structure would be necessary.

Disadvantages are the tripping hazard will remain, although this can be reduced. In addition the joint would be no more water tight than the existing.

A cost to completely replace all the joints is in the order of £251,000 including preliminaries and a nominal amount for traffic management. It is assumed there will be no traffic delay costs. The estimated time to replace one joint is about 1 week, although it is thought this time could be brought down with practice.

7 Approach Span Deck Joints

7.1 Description of Existing Deck Joints

At the north end of the north suspended side span and also mid way along the south approach viaduct (at pier S3) to the main bridge there are further deck joints in the carriageway. These joints are the comb type with interlocking fingers. As with the other joints, the joints are original to the construction of the bridge.

The 'as-built' drawings do not indicate the original design range of movement required for each joint. From the drawings the joint in the south approach spans are larger than the joint at the end of the north suspended side span. The south approach viaduct joint has an extreme physical movement range of 280mm, but the design movement range will be smaller than this. Similarly the north side span joint has an extreme physical movement range of 178mm, but again the design movement range will be smaller than this. Based on their service, there is no reason to assume that the range allowed for in any of the joints is not adequate.

The south joint comprises a series of steel comb plates, 908mm wide, with fingers 305mm long. These plates are both sides of the structural gap, with the fingers interlocking with the opposite plate. On one side of the gap the comb plates are welded directly to the deck construction and the ends of the fingers to these plates a steel bar has been welded to the underside of the fingers. On the other side of the gap the comb plates are held down to the deck construction with sprung bolts. The ends of the fingers to these plates rest on the steel bar that is under the fingers of the opposite plate. Each bolted down plate can be lifted independently for inspection and maintenance purposes. The north joint is of similar construction, except the plates are 610mm wide with fingers 203mm long. 'As built' drawings of the joint have been included in Appendix A and photographs in Appendix B.

7.2 Maintenance History

There is limited information on maintenance history of the comb joints. 'As-built' drawings indicate that the holding down bolts to the comb plates were replaced in 1970. The original holding down bolts were 'Dowpac' liquid spring units and these were replaced with conventional bolts with steel springs. Individual comb plates have been lifted by FETA to give an indication of overall condition and for general maintenance.

7.3 Current Issues

All the joints are still functioning as designed, but since the original construction have now become worn from general traffic usage and movement of the joints themselves.

The fingers of the bolted down comb plates slide over the support bar under the fingers of the opposite plate with the movement of the deck. The top edge of the support bar and the underside of the fingers have worn resulting in a loss of support of the fingers. There appears to be evidence that the fingers have bent downwards as a result of traffic loading. The north side span joint is also misaligned in a vertical direction with the south side (side span) of the joint being higher than the north approach span side.

Also as a result of traffic loading the top surfaces of the plates have worn down. This is most apparent at the ends of the fingers where they now taper in thickness. The running surfaces of the plates have little wheel skid resistance, particularly when wet.

7.4 Options for the Joints

7.4.1 Options Considered

Four options for repair of the joints have been considered and these have been discussed in detail below. In summary the options are:

a) Continue with current maintenance regime;

b) Completely refurbish the existing joint;

c) Completely replace the existing joint with a new comb joint;

d) Completely replace the existing joint with a multi-element type.

7.4.2 Continue with Current Maintenance Regime

This option involves keeping the joints as they are and undertaking essential repairs as and when necessary to ensure the continued safety and reliability of the joint system. It is effectively a 'do-nothing' option.

The advantages of this are similar to the other existing bridge joints for this option. The joint has proven itself and appears to fulfil its design requirements. Similar to the roller shutter joints, this option has low initial costs and makes use of the investment in the repairs already undertaken. Any necessary work would be on either a reactive or short term notice basis.

The disadvantages of this option are also similar to the other existing bridges joints. The joints have become excessively worn and further wear will continue at an increasing rate. This could lead to ultimate failure of components that may create a safety hazard. Types of failure could include fracture of individual teeth, failure of the comb plate holding down bolts or weld failures from fatigue. In addition, with increasing wear, the teeth will deform further adding to a poor traffic ride quality and higher impact loading on the joint. The issues of the poor skid resistance of the traffic surface would also not be addressed. As discussed with the roller shutter joints, undertaking reactive work may be difficult to time with the preferred periods for traffic management and the availability of resources.

The advantages and disadvantages of this option can be summarised in the following table:

Advantages	Disadvantages
1. Relatively low short term costs	1. Joint will result in an increasing financial liability as more components wear and potentially fail.
2. Retains a proven joint	2. Possible safety risk from failure.
3. Makes use of any investment already made in repairs	3. Would be politically unacceptable to close lanes or a whole carriageway to undertake emergency repairs.
	4. Suitable workforce or specialist equipment to undertake repairs at short notice may not be available.
	5. Weather conditions may not be suitable for emergency repairs.

As with the roller shutter joints, it is difficult to evaluate the costs of this option as it is dependent on how much work is done and over the time period considered. Traffic management and traffic delay costs will be relatively higher than for other options as works will be done over a number of short periods.

7.4.3 Completely Refurbish Existing Joint

This option also involves retaining the existing joint, but considers a thorough refurbishment of the whole joint construction to effectively return it to an 'as new' condition. Like the previous option this retains a proven joint that reuses the existing support structure, but repairs can be undertaken on a planned basis and possibly take advantage of carriageway closures for other works. Based on the usage of the existing joint the life of the joint to the next major refurbishment would be up to 15 years.

The work involved in a complete refurbishment would depend on a condition survey of the existing joints, but could include replacing the comb plates, the support bar, and holding down bolts and springs. The drainage system would also need repairing / replacing. As with the roller shutter joint, repairs can be undertaken on a piecemeal basis; where for some of the work traffic management can be limited to single lanes of a carriageway. However, full carriageway closures for most operations and for the plates near the centre of the carriageway will be needed. As with the roller shutter joint, repairs are likely to take a number of weeks, especially if done on a piecemeal basis.

The advantages of this option include retaining a joint with proven ability and a there would be a good chance of the joint refitting after the refurbishment work. No modifications to the structure supporting the joint will be necessary and the increasing maintenance liability (financial and safety) will be removed in short term.

The main disadvantage with this option is that as the joint is extensively worn and refurbishment will practically involve replacing the entire joint anyway. A replacement joint is discussed in section 7.4.4 below.

The advantages and disadvantages of this option can be summarised in the following table:

Advantages	Disadvantages
1. No modifications to existing support structure (although some repairs may be required).	1. Repair works will be so extensive that the joint will be effectively replaced.
2. Repairs can be done in stages and sometimes within one carriageway lane meaning less disruption to traffic.	
3. Proven design, known to work, familiar to maintenance team.	
4. Up to 15 years before next major refurbishment (depending on traffic usage)	

For a full refurbishment of all the comb joints, including the replacement of the comb plates and supporting bar, traffic management and preliminaries is in the order of £346,000 (excluding traffic delay costs). The time required to refurbish one joint would be two to three weeks, although as with the other joints experience may reduce this time. Consideration can be given to working on more than one joint in a carriageway at a time with some consequent savings in traffic management costs.

7.4.4 Completely Replace Joint with new Comb Joint

As discussed in the previous option, refurbishment will effectively result in a replacement joint. This option considers the full replacement of the joint. It has the advantage over the previous option in that with a new joint system the manufacturer considers the availability of improved materials and designs. A new joint assembled in a factory environment rather than on site will result in a more durable finished product with less maintenance. Replacing the whole joint will also require a shorter time period for traffic management on the bridge. Overall traffic management requirements would be similar to that of the option for a full refurbishment.

Improved materials and designs that could be considered include incorporating skid protection into the traffic surfaces of the plates, using harder wearing steels and improved drainage systems. Current designs of comb joints do not use the supporting bar that the existing joints have so there is less scope for general wear in the joints.

There are several manufacturers of this type of joint. These include companies such as Mageba ,Ekspan, Freyssinet (CIPEC), and Sollinger Hutte.

The advantages and disadvantages of this option can be summarised in the following table:

Advantages		**Disadvantages**	
1.	Skid protection can be milled into new finger plates	1.	Some modification to existing support structure may be needed.
2.	Few wearing parts	2.	Joint needs to be fitted to tight tolerances and may not fit precisely enough.
3.	Improved drainage system		
4.	Improved steels		
5.	Retains advantages of existing joint		
6.	No major refurbishment needed for up to 20 years.		

For a full replacement of all the comb joints the total cost, including traffic management and preliminaries would be very similar to a full refurbishment, i.e. in the order of £360,000 (excluding traffic delay costs). Also the time required to replace one joint will be similar to a full refurbishment at about two to three weeks, although as with the other joints experience may reduce this time. Consideration can be given to working on more than one joint in a carriageway at a time with some consequent savings in traffic management costs.

7.4.5 Completely Replace Joint with Modular Expansion Joint

As with the roller shutter joints an alternative type of joint could be considered in place of the comb joint and that is the modular type of joint. For this location the number of beams required to make up the joint will be less than a replacement for the roller shutter because of the reduced movement range. The number of beams would be four and in theory across the joint this would fit. However, as with the roller shutter joint, there would need to be extensive modification to the ends of the bridge deck and it is likely that there is insufficient depth in the deck to accommodate this type of joint.

Although this type of joint would be working well within its limits (unlike with the roller shutter joint) it is still not recommended. This type of joint has many moving parts and is unlikely to achieve the long term durability that a simpler comb joint would have. Many of the disadvantages highlighted for this type of joint as a replacement for the roller shutter type remain for this location also. For these reasons this type of joint has not been considered further.

As with the roller shutter joints, costs for this option are difficult to evaluate as detailed work would be required to establish what modifications would be required to the existing support structure. Also, similarly, as this option is not recommended no work has been done to establish costs. The time period to fit the joint would take a number of weeks therefore it is thought this type of joint would be uneconomic in terms of traffic management and delay costs.

8 Conclusions & Recommendations

8.1 Conclusions

All the three types of bridge deck expansion joints have generally performed well, but have now reached the end of their service lives and are now becoming a safety and maintenance liability. The repair or replacement of all the expansion joints should now become a priority as the rate of wear will rapidly increase. Although the Bridge was constructed over 40 years ago there are no new types of joints that are considered to have the potential to perform better than the existing.

There are a number of considerations that need to be taken into account before works should begin. These include traffic management considerations, programme, access, resources, advance works, procurement, future maintenance, planning consents and health and safety.

A number of options have been considered for each type of bridge deck joint. For the roller shutter type joint, five options were examined. These included continuing with the current maintenance regime, a full refurbishment, or a complete replacement with a new roller shutter joint or an alternative joint type. For the sliding plate type joint in the foot / cycle ways two options were examined. These were also continuing with the current maintenance regime or a full refurbishment with improvements to the design. The third type of joint is the comb joint. For this four options were examined. These included continuing with the current maintenance regime, a full refurbishment, or a full replacement with a new comb joint or an alternative multi-element steel girder joint.

8.2 Recommendations

For the options considered for each type of bridge deck joint the following is recommended. The recommendations are based on minimal disruption to the local road network, value for money and long term costs and maintenance.

For the roller shutter type joints it is recommended that the all of joints are replaced with a new roller shutter type joint. This option has the advantage over the others in ensuring that the whole joint 'works together' by being able to be manufactured to tighter tolerances than repairing or refurbishing the existing joint. Advantage can be taken of improved harder steels, a more robust link plate hinge mechanism and a better traffic running surface. This option is also likely to result in the least time for traffic management on the highway. The cost of this option, excluding traffic delay costs is estimated to be in the order of £2.51m. Improved access to the joint will be necessary for the works. This could be installed in advance of the main works and it will also serve for future maintenance and inspections.

For the sliding plate joints in the foot / cycle way it is recommended that the sliding plate joints are fully refurbished with the plates incorporating an anti slip surface for path users and also PTFE pads between the plates to reduce friction. The cost of this option is estimated to be in the order of £251,000.

For the comb joints it is recommended that this joint, as with the roller shutter joint, is completely replaced. Refurbishment will practically involve the entire replacement of the joint anyway without the advantage of using improved materials and designs. The cost of this option, excluding traffic delay costs, is estimated to be in the order of £360,000.

The total sum for all the joint work combined is £3.12m.

To progress the work on the joints, it will be necessary to further develop each of the preferred options into detailed designs, specifications and works contracts. The work will also require advance planning for programme, publicity and improvements in access. With further detailed development, and discussions with suppliers and fabricators more accurate costs and timescales can be calculated to assist with forward planning and procurement.

9 References

1. ‘As-Built’ Construction drawings.

2. Correspondence and report from Demag Lauchhammer, dated 1975.

10 Appendices

Appendix A: GENERAL ARRANGEMENT DRAWINGS OF EXISTING JOINTS

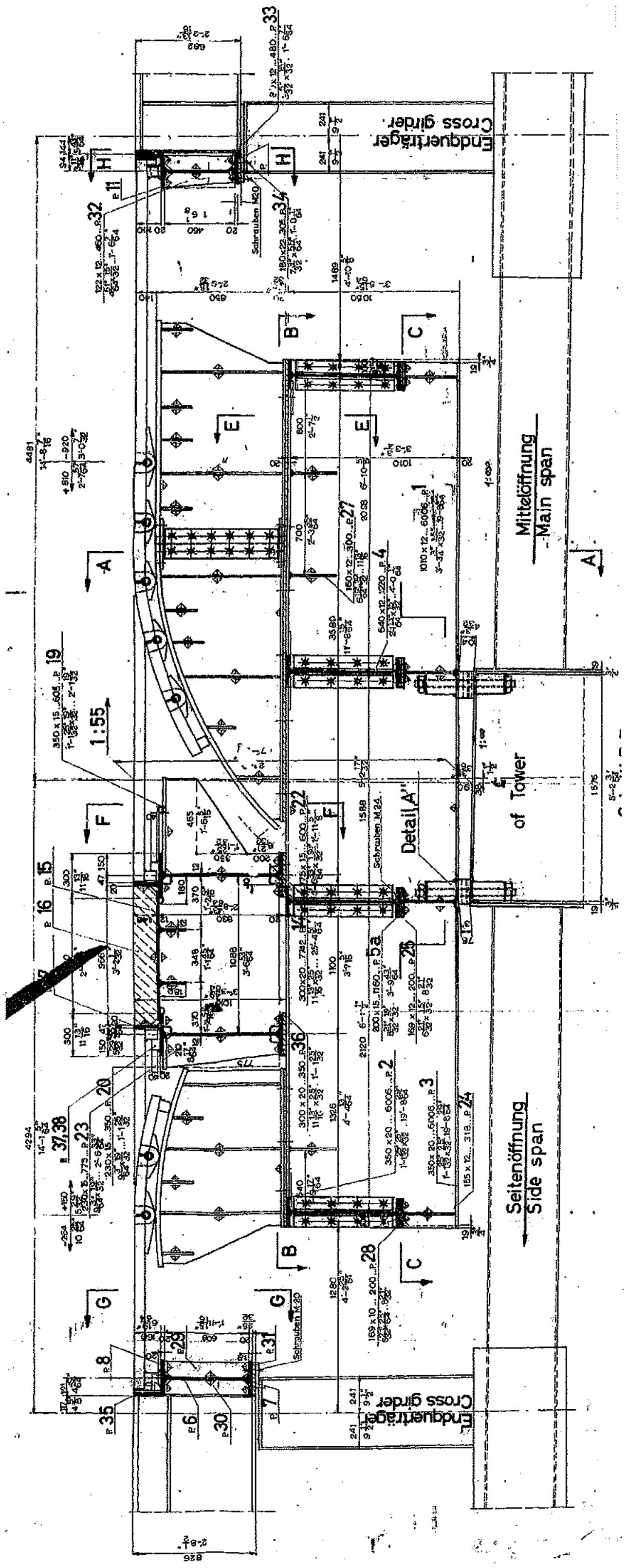


Fig 1 – Typical Section through Roller Shutter Joint

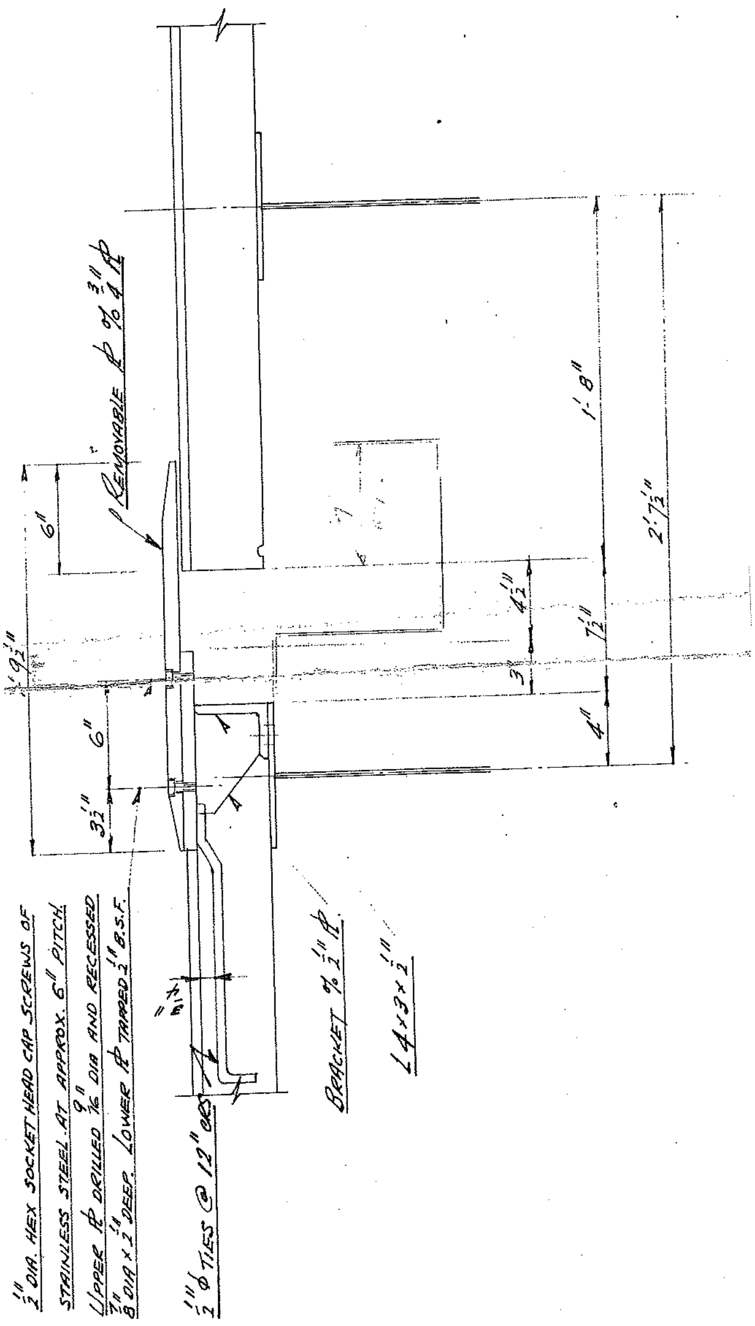


Fig 2 – Typical Section through Foot / Cycle Way Joint

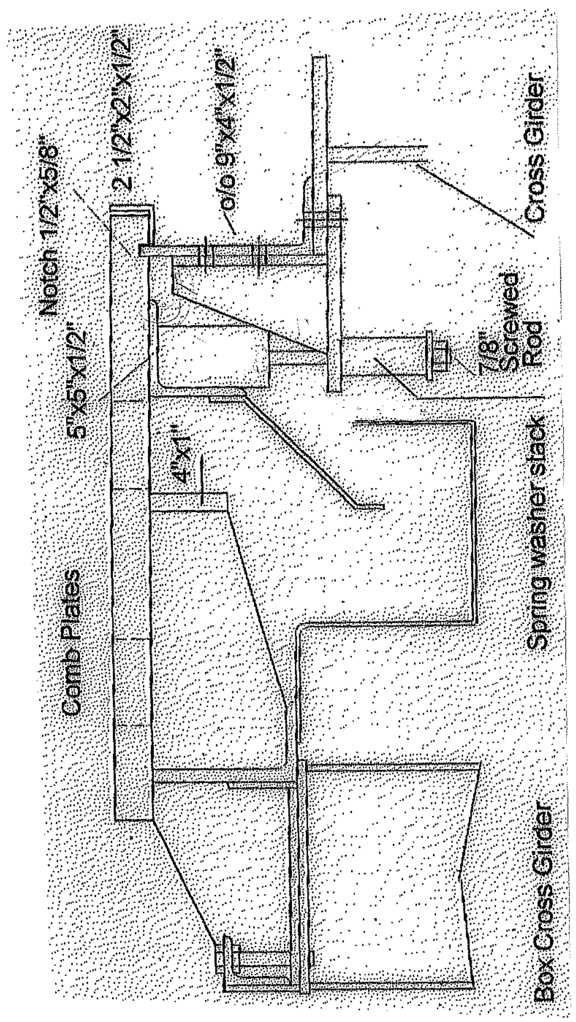


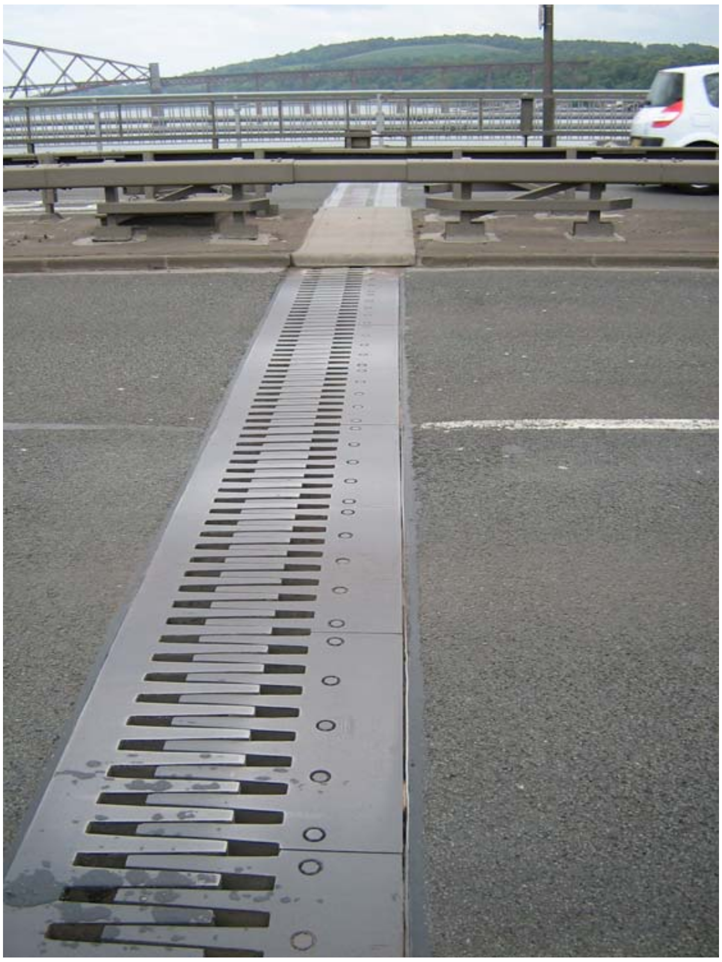
Fig 3 – Typical Section through Comb Joint

Appendix B: PHOTOGRAPHS

Photograph 1 – Roller Shutter Joint, View of Curved Link Plate Support Beam

Photograph 2 – Roller Shutter Joint, Link Plate Train

Photograph 3 – Sliding Plate Joint in Foot / Cycle Way



Photograph 4 – Typical View of Comb Joint

Appendix C: DETAILS OF MANUFACTURERS / SUPPLIERS AND JOINT INFORMATION

C.1 Manufacturers and Suppliers

Name	Address	Telephone Number	Contact Name
Mageba	Solistrasse 68, 8180 Bulach, Switzerland		
Maurier Sohne	Head Office Frankfurter Ring 193, D-80807 Munchen, Germany		
Ekspan	Compass Works, 410 Brightside Lane, Sheffield, S9 2SP		
Freyssinet Limited	6 Hollingswood Court, Stafford Park 1, Telford, TF3 3DE		
Sollinger Huette.	1 Unity Lane Misterton, Crewkerne, Somerset		

Atkins Highways and Transportation
260 Aztec West
Park Avenue
Almondsbury
Bristol BS32 4SY

Telephone +44 (0)1454 617617
Fax +44 (0)1454 618844

area2@atkinsglobal.com
www.atkinsglobal.com/transportation

ATKINS