Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 38 (1982)

Artikel: Bearings and expansion joints for bridges

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DOI: https://doi.org/10.5169/seals-29525

Bearings and Expansion Joints for Bridges

Appuis et joints de dilatation des ponts

Auflager und Dilatationsfugen bei Brücken

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SUMMARY
The paper reviews recent experience in the United Kingdom and overseas relating to trends in theory and practice of bearing and expansion joint design for bridges. References will be made to the new Specification for Bridge Bearings embodied in the new British Standard BS 5400: Part 9, Bridge Bearings. This is the first British Standard to cover the major types of bearings used in Bridges in one document. The importance of installation of bearings and expansion joints will be emphasised and in relation to experiences of the author over the last twenty years.

RESUME
Le document traite d'expériences théoriques et pratiques en Grande-Bretagne et outre-mer en relation avec l'évolution des appuis et joints de dilatation des ponts. De nouvelles règles pour des appuis de ponts sont incorporées dans les nouvelles recommandations britanniques BS 5400: partie 9, appuis de ponts. C'est la première recommandation britannique qui couvre, en un seul document les principaux appuis de ponts. L'importance d'une installation d'appuis et de joints de dilatation est illustrée sur la base d'expériences faites par l'auteur dans les vingt dernières années.

ZUSAMMENFASSUNG
Der Bericht behandelt neuere Erfahrungen in Grossbritannien und in Übersee bezüglich der Planung von Auflager und Dilatationsfugen für Brücken. Es handelt sich dabei um eine neue Spezifizierung für Brückenauflager, welche in der neuen britischen Norm BS 5400 verankert ist: Teil 9, Brückenauflager. Dies ist die erste britische Norm, welche die hauptsächlichen Auflagertypen die im Brückenbau verwendet werden in einem einzigen Dokument zusammenfasst. Die Wichtigkeit der Installation von Auflagern und Bewegungsfugen wird aufgrund der zwanzigjährigen Erfahrung des Autors hervorgehoben.

1. TRENDS IN THEORY AND PRACTICE

1.1

In the Introduction to his book published in 1971 [1] the author stated that bearings and expansion joints caused more difficulties for the bridge engineer than practically any other part of the structure. The experience of the decade since that was written has not served to alter that view.

1.2

There is little doubt that bearings with a minimum of moving parts perform well. The designs evolved in the last 30 years, such as the laminated and contained elastomeric bearings, together with the use of the PTFE sliding interface types have proved a notable development of great value to the bridge enigneer. The development of multi-span bridges fully continuous for distances up to one mile has been possible by the use of sliding bearings. Such structures have demonstrated good riding qualities and low maintenance because the continuity over the piers has simplified the protection of the bearings against ingress of dirt and moisture from the road deck. The types of elevated roads with curved alignments and complex junctions have stimulated the design of robust bearings able to accommodate movement and rotation in both longitudinal and lateral directions.

1.3

There is little doubt that good design and manufacture of bearings and expansion joints is required but just as important is adequacy of installation and sound construction techniques for both the sub-structure and the super-structure. There are the majority of examples where performance of structures is excellent with a trouble-free service life.

1.4

Nevertheless cases have arisen where the author's firm has been called in by the Client to investigate problems stemming both from inadequacies in the bearings themselves and deficiencies in the bridge structure around the bearing. These can be extremely difficult to deal with, especially on heavily trafficked roads, and the cost of repair and maintenance can be very high in proportion to the initial cost of the bridge. These matters will be reviewed later in this paper but from the theoretical point of view, whilst the trend towards heavy loads and continuity of structure has been beneficial, it must be allied to first class detailing by the engineer to ensure that his intensions are fully realised on site.

2. SPECIFICATION OF BRIDGE BEARINGS

2.1

Up to the middle of this century bridges relied on roller, rocker or metal sliding bearings to permit movement. With more advanced designs to make full use of the materials employed and increased use of skewed and curved bridges to carry modern high speed roads over obstructions, the need arose for bearings to take movement in more than one direction. New types of bearings have been developed taking advantage of the new materials arising from improved technology. No doubt others will be developed in the future but it will be necessary to ensure that they are at least as reliable as those already in service.

2.2

BS 5400 : Part 9 is the first British Standard dealing comprehensively with the design, manufacture and installation of bearings for steel, concrete and composite bridges. It does not cover concrete hinges, nor bearings for moving bridges (e.g. swing and lift bridges). Also it does not include bearings made with proprietary materials such as Fabreeka and Bonafy but provision is made for the use of such materials, provided the Engineer is satisfied as to their long term suitability for the function intended. The document is split into two sections; Part 9.1 is a Code of Practice and gives rules for the design of bearings. Part 9.2 specifies the materials, method of manufacture and installation of bearings.

2.3

The design section is written in limit state terms as used throughout BS 5400. The terminology used for differing types of bearing is defined. This is necessary as Engineers tend to use bearing terminology loosely which can give rise to confusion as to what is really meant when referring to bearings by named type. The design section gives an overall framework in which the bearings are to be used and then deals with specific requirements for the various types of bearing and bearing materials.

2.4

Information in respect of frictional resistance of PTFE sliding surfaces has been brought up to date and the effect of temperature on the stiffening of elastomer has been recognised. The permitted shear strain of elastomeric bearings under horizontal movement has been increased to 0.7 and the method of their design generally brought in line with the U.I.C. Code [3].

2.5

The one area in which it has not been possible to give much detailed advice is in connection with pot bearings, the effectiveness of which is largely dependent upon the seal preventing the rubber from extruding between the piston and pot wall. The design expertise for such bearings is mainly in the hands of specialist bearing manufacturers.

2.6

Because of the high friction values associated with metal to metal sliding surfaces and complete seizure if not kept lubricated or corrosion is not prevented, modern sliding bearings usually rely on PTFE or similar low friction non corroding synthetic materials to provide the sliding surface. This has been recognised in the new Code and there is no information given on friction coefficient values or bearing stresses for metal to metal contact other than for guides.

2.7

In general, rolling, rocking and sliding surfaces have to meet the serviceability limit requirements, whereas the main supporting structure of bearings has to be designed for the ultimate limit state as set out in Part 1 of BS 5400 [4].

2.8

The Specification section covers the materials and manufacturing process most commonly employed in the manufacture of present day bearings. Quality control procedures have not been covered but performance tests have been outlined. It is hoped that a suitable quality control procedure can be set up in conjunction with the Agrement Board. Essential installation requirements have been laid down in the specification section.

3. LESSONS OF EXPERIENCE WITH BEARINGS

3.1

Bearing failure can result from a number of causes, e.g. damage or displacement following an accident, attack by chemicals, fire, corrosion of contact surfaces, but probably the greatest cause of bearing malfunction, particularly of modern bearings, is due to inadequate or improper installation. It is not unknown for bearings to be installed upside down. It cannot be stressed too strongly that care in the installation of bearings is of the utmost importance.

3.2

Bridges are usually designed with an expected life in excess of 100 years [4]. Modern bearings and bearing materials have not been proved in service for this length of time so it is advisable to make provision in the design of bridges for bearing replacement should this be found to be necessary. Facilities for correcting the effects of differential settlements, etc., should be provided unless the structure has been designed to accommodate such movements.

3.3

Regular inspection of bearings should be made so that any potential trouble is detected before serious damage is done to the structure. There should be adequate space around bearings to allow for inspection and maintenance in service. In certain circumstances, such as when piers or abutments are high or over water, it may be advisable to incorporate some form of travelling staging in the bridge design to facilitate inspection.

3.4

To ensure that the moving surfaces are not contaminated it is essential that bearings are not dismantled after leaving the manufacturer's works. Although steel bearings may be bolted directly to steel structures or steel plates cast into concrete structures, provided that they are within the tolerances required for the bearings, it is usual to lay bearings on some form of bedding. Commonly used materials are cementitious or chemical resin mortar, grout or dry packing [5]. It is essential that any bedding material, whether above or below the bearing, extends over the whole area of the bearing. It is also important that there are no hard spots and to this end any temporary packing used during erection of the bridge deck should be removed and the voids filled with bedding material.

3.5

The choice of bedding material is influenced by the method of installing the bearings, the size of gap to be filled, the strength and setting time required, and the composition and workability of the bedding material must be specified with those criteria in mind. Formwork should be sealed around bearings and the bearings, particularly the working surfaces, protected against grout leakage during the casting of insitu concrete bridge decks. Top plates should be supported and care taken not to displace or distort bearings during the concreting operations.

3.6

Evidence so far indicates that if designed and installed properly, modern bearings perform satisfactorily in service. Some problems encountered are outlined below:

3.7

Elastomeric bearings will take a considerable amount of maltreatment before failure unless grossly inferior materials are used. However, localised overloading due, for example, to uneven seating can cause breakdown of the bond between elastomeric and steel reinforcing plates. Unreinforced elastomeric strips can squeeze or work their way out under certain circumstances. Small seating plinths can disintegrate under shear forces generated by elastomer bearings and the seatings should extend at least 50mm beyond the edge of the bearing.

3.8

Disintegration of poorly prepared seatings is one of the most common causes of bearing failure. This problem has recently been highlighted at the Gravelly Hill motorway inter-change outside Birmingham, England. Here the bearing seatings have disintegrated and allowed the deck support beams to drop causing tension cracks in the locally unsupported deck slab [6]. (Fig 1a and Fig 1b)

3.9

At another project it is thought that incorrectly proportioned constituents (too much hardener plus a small quantity of water in the aggregate) led to the failure of 2" high epoxy resin bearing plinths when the precast concrete beams were lowered onto the bearings.

3.10

Incorrect installation procedures led to the failure of bearings supporting a viaduct over a river estuary. Here, large mechanical bearings were to be set on 12mm thick pads of polyester resin mortar with a sheet of polythene placed on top of the mortar bed to break the bond between the bearing and the mortar. The mortar was domed, the intention being that surplus material would squeeze out when the fixing bolts were tightened down. In practice the large quantity of resin mortar needed for each bearing required that it be made up in a number of mixes and consequently the material could not be considered as entirely homogeneous. On removing the damaged bearings it was found that the polythene sheeting had rucked. Both these results led to a non-uniform support to the bearing causing failure.

3.11

Leaking expansion joints can lead to corrosion of metal bearings. Unsuitable materials can give rise to problems. Many of the 18500 sliding rocker bearings installed in the Midland Links viaduct are not functioning as they should. The bearings are made of three rolled steel plates, the middle one heavily chamfered to allow the top plate to rotate. The steel deck beams rest directly on the top plate with no special sliding medium at the steel to steel interface apart from an initial coating of molybdenum disulphide. Some of the bearings have seized and those that still slide do so very reluctantly. Attempts to introduct lubricant between the sliding surfaces have proved ineffective [7]. (Fig 1a)

3.12

In a similar manner, the steel deck beams of Vauxhall Bridge over the River

Thames in London, built about 1906, rested directly on steel plates bedded on cill stones. Over the years these corroded and seized to the beams. Movement of the deck caused the front of the cill stones to break away. In 1976 the steel bearing plates were replaced by laminated rubber bearings set on new precast concrete bed stones. (Fig 2a and Fig 2b)

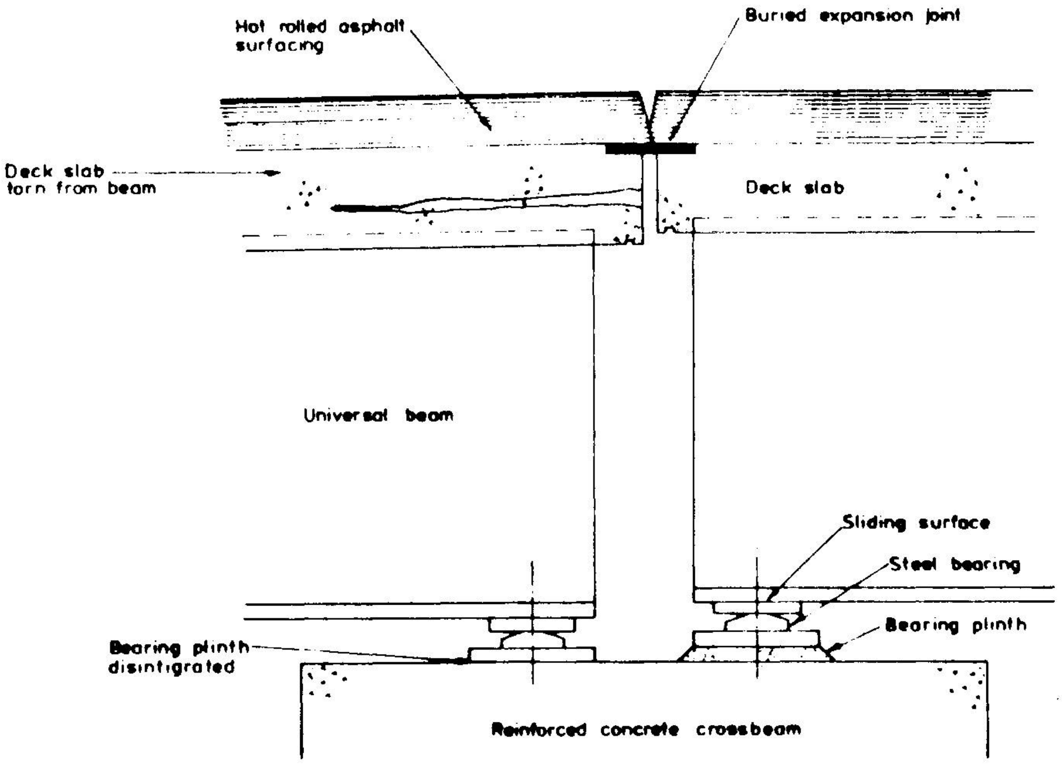

Fig. 1a Midland Links Viaduct - Detail of Bridge Bearings

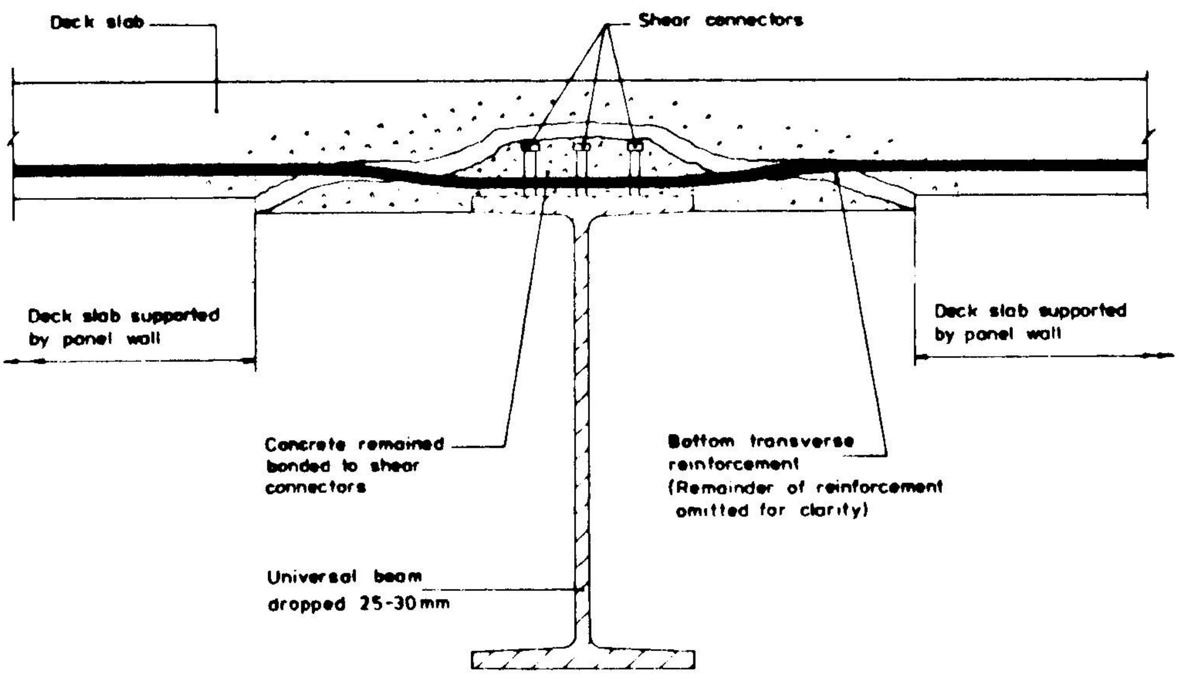

Fig. 1b Midland Links Viaduct - Typical Cracking in Deck Slab over Beams

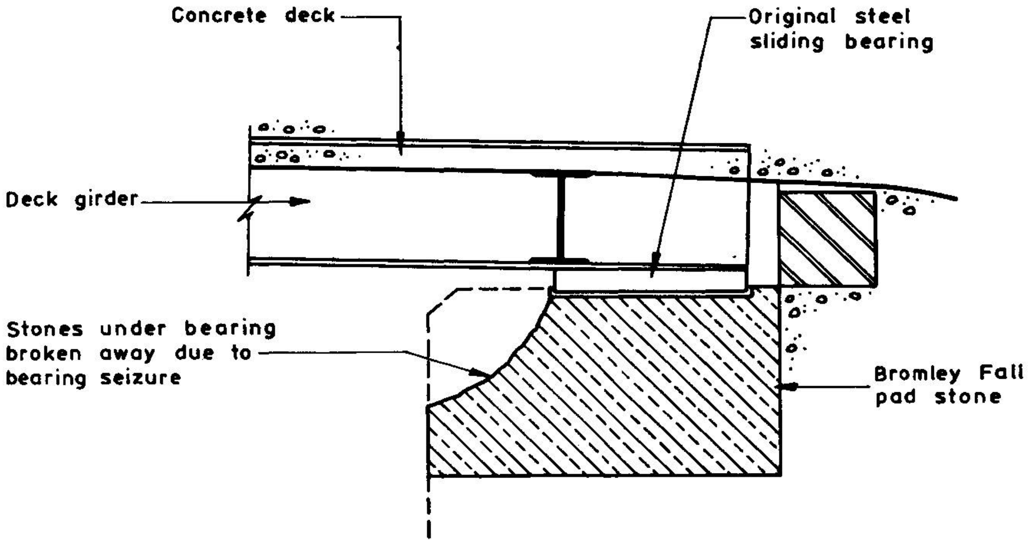

Fig. 2a Vauxhall Bridge - Original Bearing

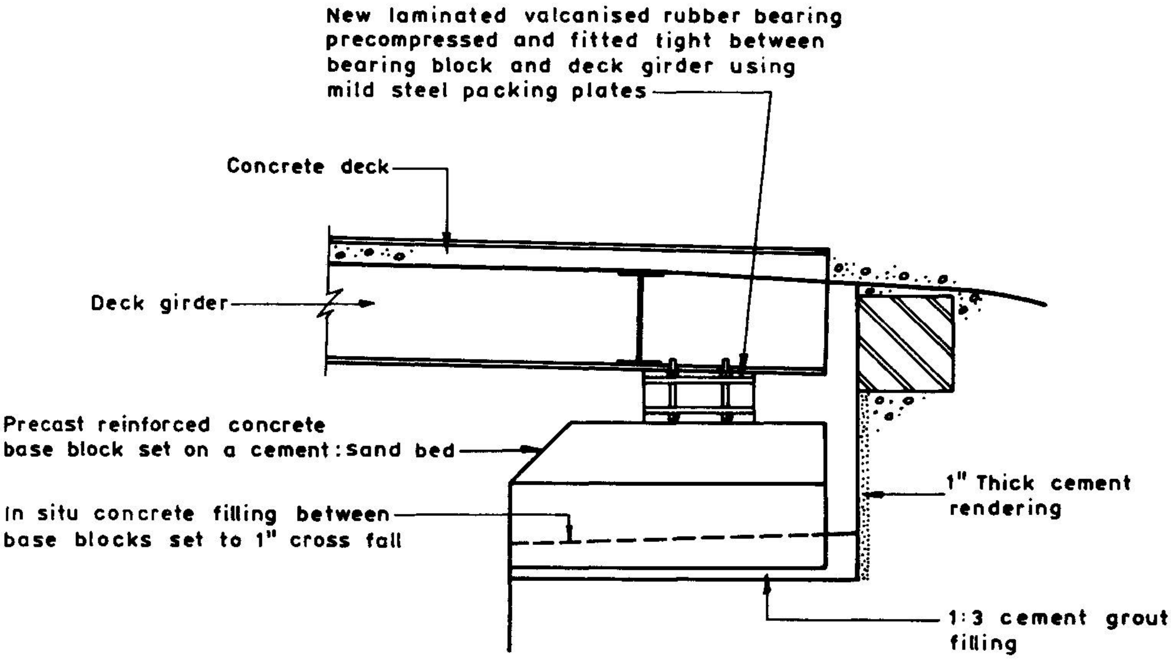

Fig. 2b Vauxhall Bridge - New Bearing in Position

3.13

The abutment bearings of Wandsworth Bridge over the River Thames in London consisted of large knuckle leaf bearings supported on a bank of four flat sided forged steel rollers tied together with side bars bolted to each roller. The rollers ran on a bottom casting. As the bearings were subject to uplift, the lower casting of the leaf bearing was tied down to the bottom casting by four 1½" diameter bolts which passed through slotted holes in the middle, or lower leaf bearing, casting. The bottom casting in turn was bolted down to the concrete abutment bearing shelf. The bridge was built in the late thirties and inspection of the bearings in 1973 indicated that although the main castings and forged steel knuckle pins were in good condition, the forged steel rollers were badly corroded with no sign of any lubrication having been applied or protection against the entry of dirt or moisture. Several of the side bars had come adrift due to corrosion of the fixing bolts and a number of the tie down bolts had broken or bent due to the heads binding on the intermediate casting. The bearings have subsequently been replaced by steel rocker bearings incorporating a PTFE/stainless steel sliding element. These have been set on new bearing plinths. (Fig 3a and Fig 3b) No provision had been made for an expansion joint in the deck surfacing, which consequently cracked at the abutment, allowing water to penetrate down to the bearings.

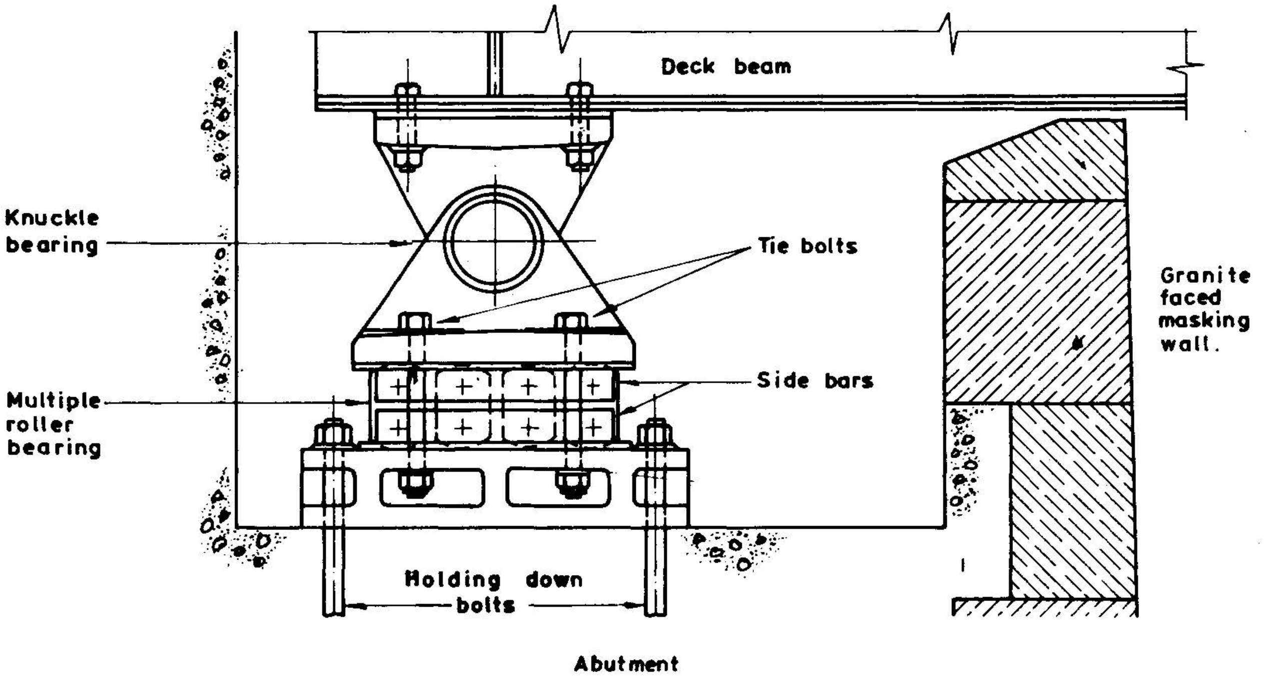

Fig. 3a Wandsworth Bridge - Original Bearing

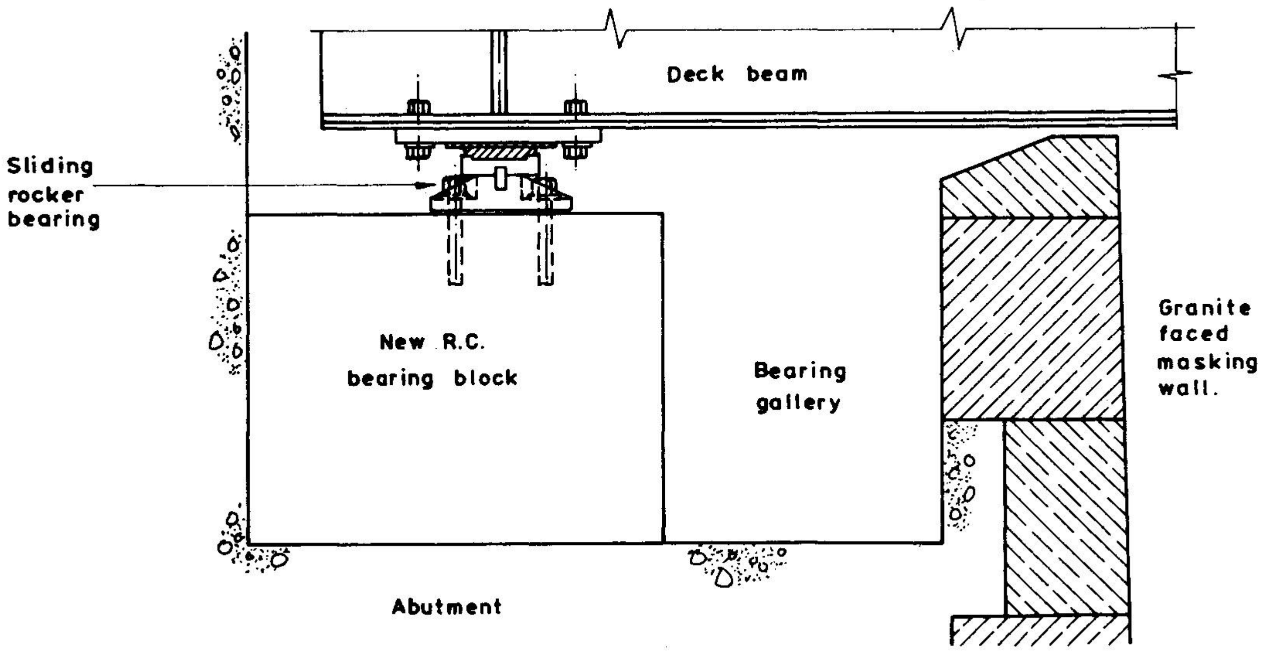

Fig. 3b Wandsworth Bridge - New Bearing in Position

3.14

In the case of bearings carrying the steel portal frames supporting part of the elevated motorway known as Westway in London, England, two problems became apparent in use. The bearings consist of a lower casting housing a block of rubber which supports an upper piston casting. Let into the upper surface of the piston is a sheet or proprietary material known as DU which consists of a 1/16 inch thick bronze plate onto which is sintered a bronze/PTFE matrix. The DU material is bedded on an 1/8 inch thick layer of asbestos based compressible material to take up any local high spots. Overlaying the DU material and forming a sliding surface with it is a stainless steel sheet fixed to a top casting. In order to prevent dirt and dust getting between the sliding surfaces, scraper bars are provided to wipe the stainless steel sheet in each direction of travel and the bearings are enclosed by removable side and end plates.

3.15

Some time after installation it was observed that the stainless steel had buckled on certain bearings. It was found that on these and other bearings the stainless steel sheet was binding on the unmachined shoulder of the piston at each end of the DU material. This was due to the elastic deformation of the portal leg base, which was formed from 1 inch thick steel plate, stiffened internally and resting on the 3 inch thick top casting of the bearing. Although only of the order of 0.03 inch at the extreme edge, this was sufficient to take up all the working clearance which had deliberately been kept to a minimum to reduce the possiblities of dust contamination of the sliding surfaces. The problem was rectified by inserting additional stainless steel/DU sandwiches and forming a slot in the shoulders by the "Metalock" method and wedging down the material above to provide additional working clearance. (Fig 4)

3.16

On some bearings excessive friction of up to 20% was recorded compared to the design value of 5%. This was found on examination of a dismantled bearing to be caused by the presence of particles of ferrous and cementitious materials normally associated with a construction site. This problem was also rectified by the use of new stainless steel/DU sandwiches. All the other Westway bearings, which include elastomeric, pot and biaxial curved sliding types have performed without trouble for over ten years.

3.17

Surprisingly, urban elevated roads seem to be prone to damage by fire, often caused by vandals setting alight flammable material stored underneath. As far as our experience is concerned no bearings have been harmed following fires although a number of decks have had to be repaired. But there must always be a first time.

3.18

Other problems that have come to light include roller bearings which have overrun their design travel so that the gear pinions ran off the end of the guidance rack and were sheared off when trying to re-engage on their return; end flanges sheared off rollers due to insufficient allowance for side thrust on these bearings. Compatibility of steelwork fabrication with the drawings is necessary if the bearings are to function in accordance with the design.

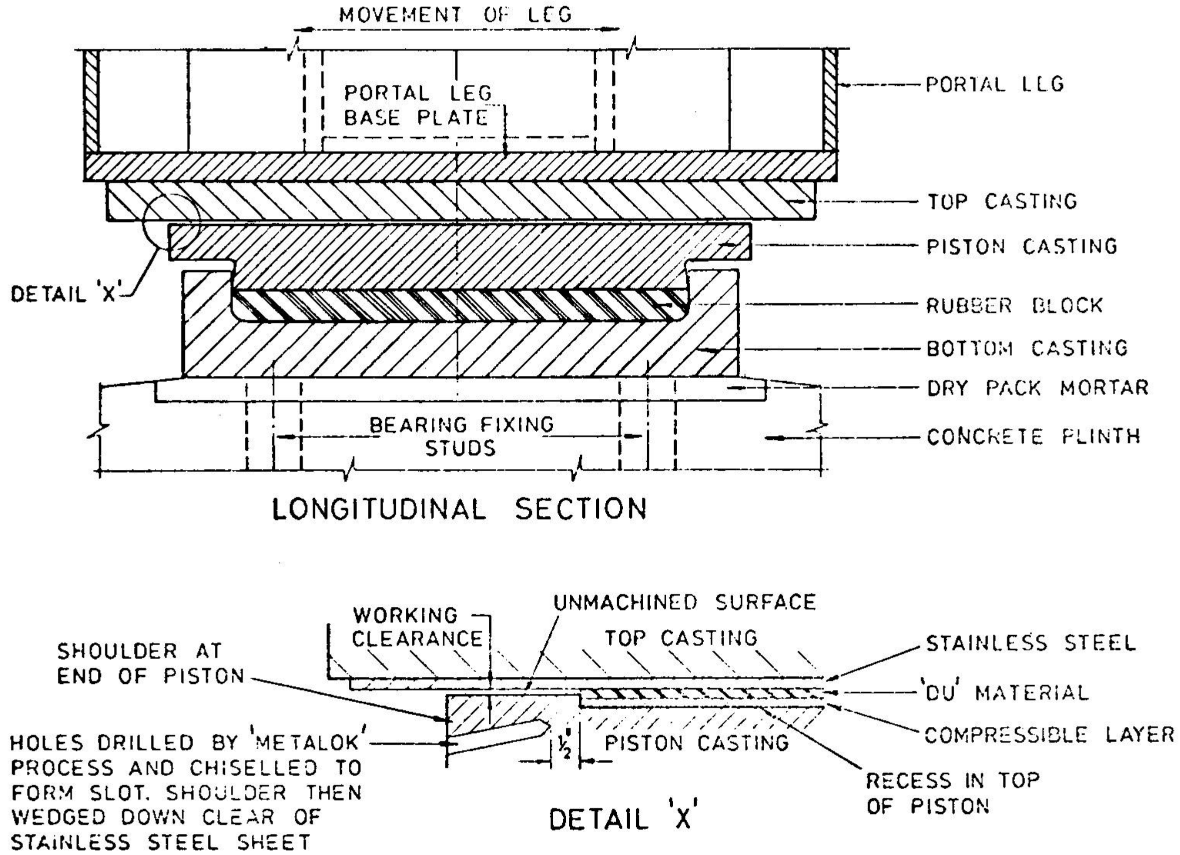

Fig. 4 Westway Section 6 - Details of Bearings

3.19

Replacing bearings can be a very difficult operation unless suitable provision has been made in the design of the bridge structure for proper access to the bearings and jacking of the bridge deck to be undertaken. Long [8] has dealt with the problems of replacing bridge bearings.

3.20

Elastomeric bearings should not be subjected to tension stresses at any time. One problem in this respect is the initial rotation due to the hog or precamber of precast prestressed beams when these are first landed on the bearings unless they are temporarily supported until the bedding mortar hardens, which can be an expensive operation. A recent innovation to overcome this problem is Andre Load Plugs (ALPS) which is currently the subject of a patent application.

3.21

ALPS are simple elastomeric plugs, which fit into holes in the body of the main bearing and stand proud in order to carry the initial loading of structural precast and prestressed beams. (Fig 5) The plugs are of a rubber compound formulated within tight limits which give the right combination of flexibility and compressive strength to ensure that the beam is supported clear of the bearing at any angle of rotation likely to be encountered during installation.

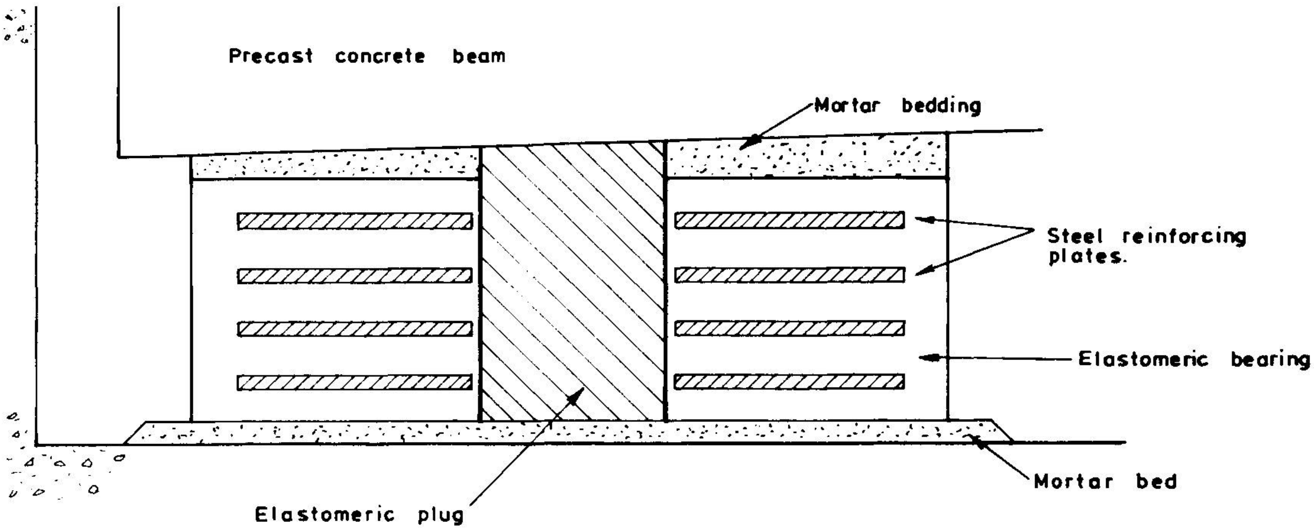

Fig. 5 Andre Load Plug

3.22

Once the beam has been lowered into place, the elastomeric plugs will carry its weight and accommodate any tendency to hog or sag. In this way, the engineer can ensure that the bedding mortar distributes the load evenly between the soffit of the beam and the top surface of the bearing. ALPS are an integral component of the bearing and remain in position when the full loading is applied. It will be interesting to gain experience of their performance in the future.

4. DEVELOPMENT OF EXPANSION JOINTS

4.1

It is important to appreciate that expansion joints are located in the most vulnerable position possible on any bridge, situated at surface level where they are subject to impact and vibration of traffic and exposed not only to the effects of natural elements such as water, dust, grit, ultra-violet rays and ozone but also the effects of man applied chemicals such as salt solutions, cement alkalis and petroleum derivatives.

4.2

To function properly, bridge expansion joints must satify the following conditions:

- accommodate all movements of the structure, both horizontal and vertical;
- withstand all applied loadings;
- have a good riding quality without causing inconvenience to any class of road user (e.g. cyclist, pedestrian);
- not present a skid hazard;
- be silent and vibration free in operation;
- resist corrosion and withstand attack from grit and chemicals;
- require little or no maintenance;
- allow easy inspection, maintenance and repair.

Penetration of water, silt and grit must be effectively prevented or provision made for their removal.

4.3

Advice on the selection, design and installation of expansion joints is given in a number of publications [1, 9, 10] . Selection of joint type is largely determined by the total range of movement to be accommodated. In multi-span viaducts one large joint is preferable to a number of small ones unless the span arrangement is such as to permit continuous surfacing over the joints.

4.4

With structures curved in plan or with skew joints, the relative movement may not be normal to the line of the joints. (Fig 6a) This can lead to binding of the elements or high shear forces in filler materials which may be exuded and carried off by the traffic, so causing ultimate failure. It is therefore important to assess this transverse displacement and to design the joint accordingly or eliminate the movement by restraining the bridge either at the joint or preferably at the bearings.

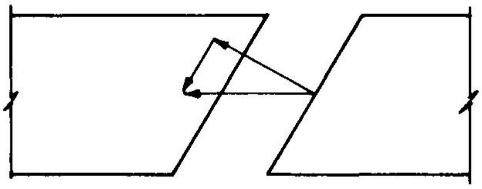

Fig. 6a Normal and Shear Displacements across Skew Joint

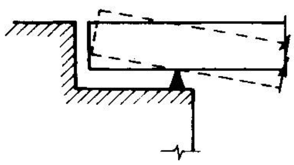

Fig. 6b Discontinuity of Joint due to End Rotation

4.5

A similar type of problem may be experienced through excessive flexural rotation at the joint (fig 6b) but, by arranging the end bearing and expansion joint in the same vertical plane, the discontinuity in the vertical direction can be minimized and the motion reduced to a purely horizontal displacement. On joints designed for small movements, this may also be overcome by providing an articulated running-on slab.

4.6

For movements of less than 5mm (0.2in), it is usually considered that no special provision is necessary, and for movements up to about 20mm (0.8in), the most popular treatment is for a gap-filled joint with continuous surfacing. (Fig 7) This can be a very satisfactory joint if carefully formed; the filling is protected by the surfacing which also absorbs much of the impact. The joint itself will not be waterproof, so it is always expedient to provide drainage under the joint to avoid staining on abutments and columns.

4.7

For movements up to about 50mm (2.0in) the most popular type of joint is the preformed flexible sealing strip compressed between nosings. (Fig 8) These joints are particularly suitable where pedestrian, cycle or animal traffic has to be accommodated as they provide a continuous surface. However, the engineer should satisfy himself that arrangements for accommodating kerbs, edge beams and medians are adequate as it is often at these points that trouble starts.

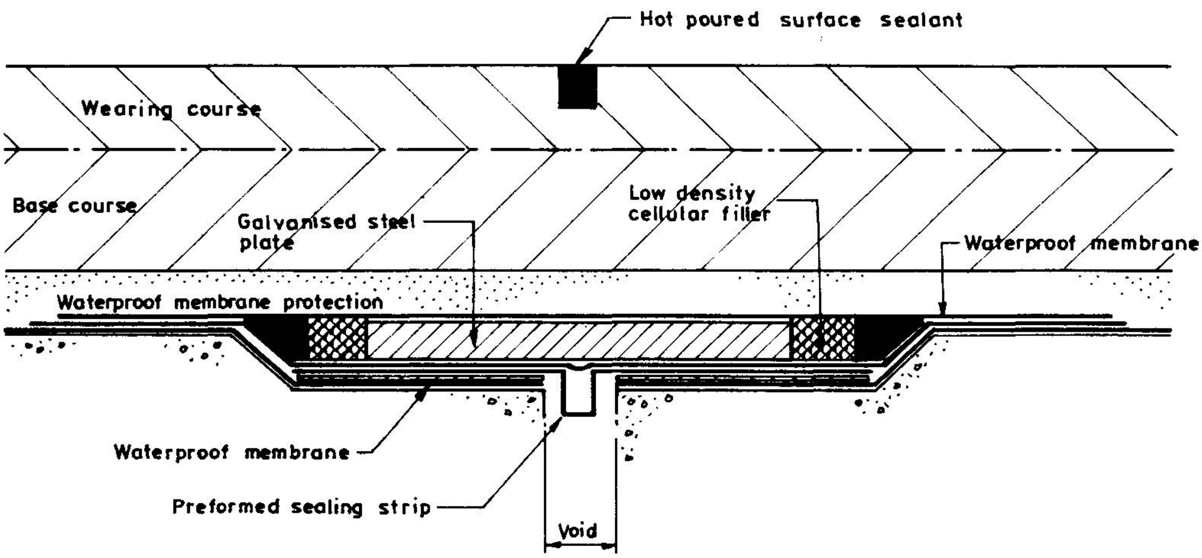

Fig. 7 Buried Deck Expansion Joint for Movements ± 10

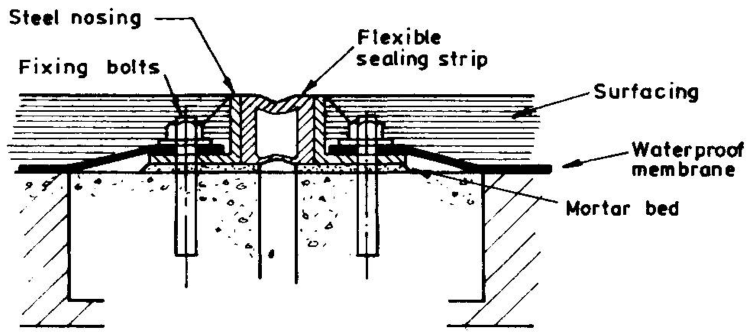

Fig. 8 Typical Expansion Joint for 20 - 50 mm Movement

4.8

Most of the cellular fillers are based on rubber or neoprene, although foamed and expanded plastics are used. Neither solid rubber or neoprene nor expanded neoprene are now recommended, as the former are expensive in relation to the small permissible compressive strains and the latter appears to suffer loss of elasticity at low temperature and with time.

4.9

Although the normal wearing properties are good, they are subjected to severe treatment and prone to damage; provision for easy maintenance is therefore essential. It is the author's opinion that these joints should be conservatively regarded as gritproof rather than waterproof. It is therefore prudent to provide at least elementary drainage on the underside and to arrange surface slopes and gully positions so as to prevent as much water as possible from reaching the joint.

4.10

During the early 70's epoxy mortar nosings were popular due to their relative cheapness and ease of maintenance but these have not always stood up well in service, the deterioration usually being attributable to poor workmanship at installation. Very many epoxy nosings have been replaced. One material favoured for this purpose is Monojoint HAC, a cement based nosing material incorporating wire fibre reinforcement. This effectively eliminates the two major factors thought to contribute to the failure of epoxy nosings; i.e. the differing coefficients of expansion of concrete and epoxy mortar causing shear forces on the bond plane and the exothermic action of epoxy mortar under cure producing shrinkage stresses. Another material used for replacing epoxy nosing joints and repairing damaged buried joints is Therma-joint. This consists of a combination of single sized roadstone aggregate and a specially formulated rubberised bitumen compound. Reports indicate that this material is standing up well under traffic conditions.

4.11

If steel sections are used to form the nosings they should be of robust construction. Many joints have been proved unsatisfactory because of failure of the fixings and, where angles are used to reinforce the opposing edges of the structure, care should be taken to achieve adequate compaction of the concrete under the angles. It is also advisable to provide suitable protective treatment to the holding-down arrangements in this region. Reinforcement used as the cast-in anchorage should be attached to the plates with full-strength welds.

4.12

A variant of the joint incorporating a preformed seal comprises a flexible gland or strip of reinforced neoprene set in nosing blocks of solid neoprene, reinforced with steel plate, which are bolted down to the bridge deck and abutment structures.

4.13

An alternative to the cellular preformed sealer consists of a shaped slab of neoprene reinforced with steel. (Fig 9). Movement is accommodated by shearing strains in the elastomeric material which is specially shaped and often reinforced with steel plates to enable the joint to span the expansion gap without deflecting significantly under load. The joint is bolted down flush with the wearing surface and, as it can be manufactured in one continuous piece to any desired length, it is waterproof, although care must be taken with the details at kerbs and edges. To reduce the hazard of skidding prevalent with wet rubber, some anti-skid treatment, usually grooving of the top surface, is applied.

4.14

Joints for large movements are usually of the open type using sliding plates, cantilever or propped cantilever tooth or comb blocks. (Fig 10) Modular compression sliding systems have been developed over the last decade. It is seldom practical to seal joints where the total movement exceeds 50mm (2in) and adequate provision must therefore be made for the disposal of surface water, grit, salt, etc., with easy access for maintenance. Because of the passage of surface waters through the joint and splashing in and around the collector system, it is vital that adequate protective treatment should be applied to any parts of the joint exposed to these corrosive elements.

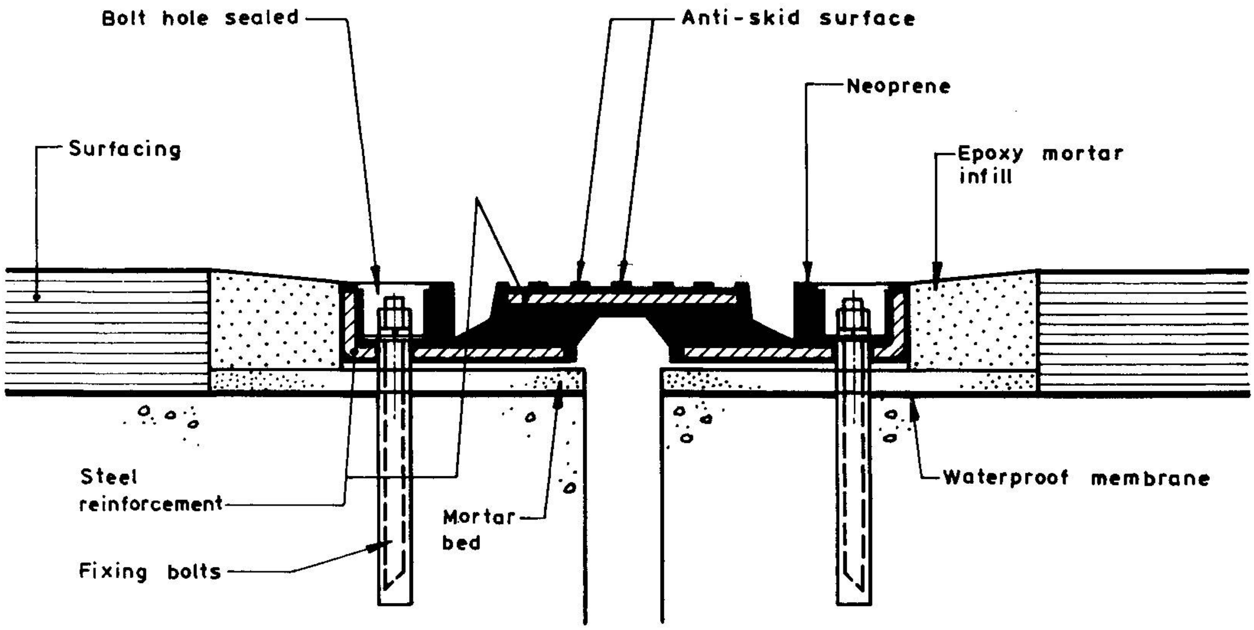

Fig. 9 Cushion Joint

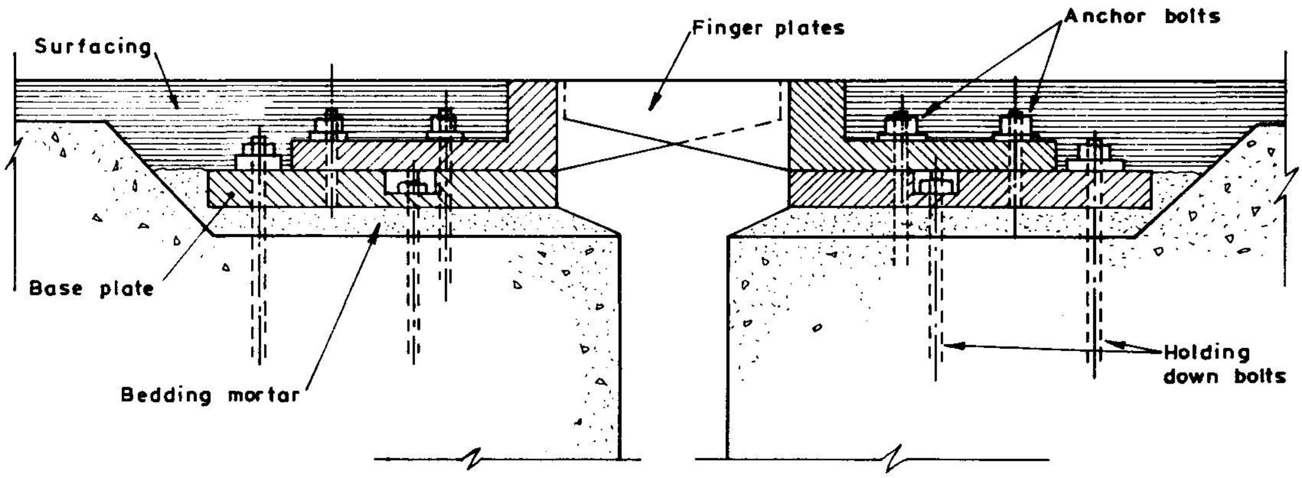

Fig. 10 Cantilever Joint

4.15

For movements up to about 130mm (5in), toothed plates can be cut from a plate 40mm (1½") thick but for larger movements it is preferable for the comb blocks, having long narrow teeth tapering in depth to suit the applied moment to be cast or fabricated by welding. Castings may be made from either cast steel or spheroidal cast iron: the latter is preferred as it gives less trouble in the casting process.

4.16

On motorways where cyclists and pedestrians are excluded, a smoother ride can be obtained without cover plates but on all purpose roads covers are necessary on safety grounds to reduce the gaps between the teeth. If cover plates are required on comb joints, they should be securely fixed and preferably welded to the teeth at frequent intervals to prevent chatter. Because of chatter, sliding plate joints are not popular for carriageways but they do offer a cheap solution to footway joints if care is taken to keep them free from grit. The CIPEC joint for movements up to 160mm (6in), incorporates an elastomeric compression sealing element below the teeth which are triangular in plan to allow for shear displacements.

4.17

Modular expansion joints consist of a series of compression seals between shaped metal beams running the length of the joint. The longitudinal separation beams are supported on short cross beams spanning the joints. Provision has to be made for the cross beams to slide on their supports during expansion and contraction of the joint. Problems related to modular compression sealing systems have been expounded by Watson [11]. These include buckling, bending and tilting of the separation beams, objectionable noise and leaking. These problems are overcome in the Maurer joint by welding the separation beams to individual support beams which, in turn, are held under pressure on glass fibre reinforced PTFE resilient bearings. (Fig 11) The seals are mechanically locked into the separation beams and do not rely on compression or adhesion for maintaining watertightness. The Maurer joint is manufactured to high dimensional standards. The adjacent concreting and fixing of reinforcement has to be of similar standards if the joint is to fit properly.

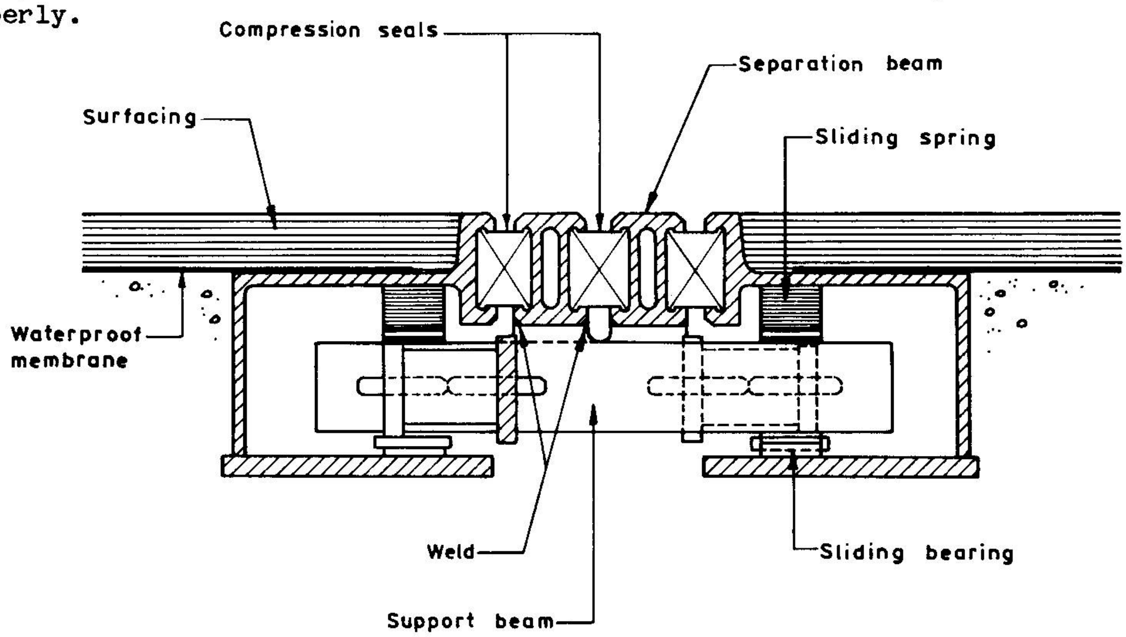

Fig. 11 Maurer Expansion Joint

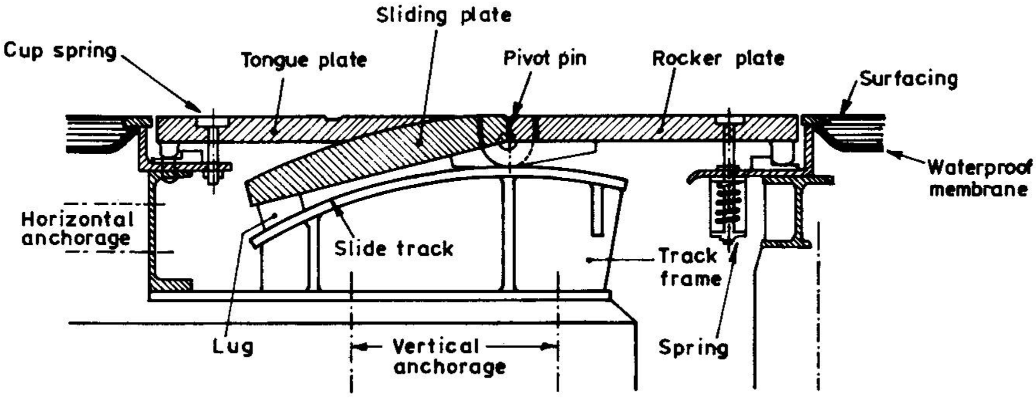

Fig. 12 Rolling Leaf Joint

4.18

For very large movements, rolling leaf or articulated plate type joints, as produced by Demag AG, are recommended. (Fig 12) These joints are robust and have a good service record. Where such joints or any joint which presents a large area of metal as the running surface are used, the skid risk can be high but can be effectively reduced by a coating of calcined bauxite in an epoxy resin mix.

5. ACKNOWLEDGEMENTS

The preparation of drafts for BS 5400: Part 9 was carried out by the Author's firm under a contract with the Department of Transport. The drafter was Mr. R.G. Bristow whose assistance in the preparation of this paper is gratefully acknowledged.

The document, which has been issued for public comment, was prepared by a sub-committee of the British Standards Institution under the chairmanship of Dr. O.A. Kerensky, FRS, FEng, and issued under the authority of the BSI Technical Committee for Steel, Concrete and Composite Bridges.

Greater London Council have graciously permitted publication of details of Structures under their jurisdiction.

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