

Development of Durable Anchorage Systems For Bridge Expansion Joints

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Bridge — Expansion Joint Anchorage

**DEVELOPMENT OF DURABLE
ANCHORAGE SYSTEMS FOR
BRIDGE EXPANSION JOINTS**

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SUMMARY

Many anchorage systems of bridge expansion joints in the medium movement range have failed within a relatively short period of time after their installation. The embedded anchor devices have become loose and have caused the expansion joints to be noisy under traffic impact and the adjacent concrete deck to deteriorate. Since the repair of loose expansion joints is costly and creates hazardous driving conditions, the goals exist to minimize the need for bridge expansion joint repair and to provide longer service lives for bridge expansion joint systems.

The Washington State Department of Transportation (WSDOT) generally specifies strip seals and compression seals for waterproofing expansion joints in the medium movement range. The strip seals are retained by either steel extrusions or elastomeric pads. The compression seals are retained by steel angles. The retainers are in turn anchored to the concrete through studs or bolts. The retainers also armor the concrete adjacent to the joint against the impact from traffic. Presently, the selection of retainers/armors and the design of their anchorage systems are based on engineering judgement through the adoption of previous designs or modifications to those designs in the case of unsatisfactory performance records.

WSDOT initiated this research project to evaluate various designs used for medium movement range bridge expansion joint anchorage systems and their performance. The research aimed at exploring the possibility of incorporating more effective designs and improved materials into the construction of the WSDOT'S bridge expansion joint anchorage systems. After the performance of various domestic and foreign designs were assessed, factors affecting the anchorage system performance and failure were identified. Accordingly, improvements in the anchorage system components, which are built in conjunction with the anchor devices, were recommended to reduce the intensity of traffic impact loads transmitted to the anchor devices. Subsequently, an analytical procedure was developed to quantify the intensity of the dynamic traffic loads

transmitted to anchorage devices and to design anchor devices to resist those loads. Finally, a second phase project, consisting of laboratory research, was recommended to verify and/or modify the recommendations of this work.

The flexibility of the retainer/armor plays a significant role in the magnitude of the dynamic load transmitted to the anchorage zone. Metallic retainers/armors should be designed to be as flexible as possible to reduce the intensity of the impact load transmitted to the anchor devices and their embedding materials. This can be done by reducing their thickness and/or providing capability for cantilever behavior. Unlike metallic retainers/armors, elastomeric pad retainers/armors offer a substantial amount of elasticity. Although this condition mitigates the intensity of the load transmitted to the anchorage, it subjects the elastomer to creep and fatigue failure. The failed elastomer cannot reduce the intensity of the load transmitted to the anchorage and may cause its failure. Thus, for expansion devices with elastomeric retainers/armors, the failure of elastomer may determine the effective service life.

Of special importance in the durability of anchorage systems is the material embedding the anchor bolts or studs. Usually, the embedding material is the conventional concrete used in the structural deck. However, the embedding material is subject to impacts from the anchor devices. This condition requires materials that are more ductile and shock absorbing than the conventional structural concrete, while having sufficient strength. Recently, various materials have been developed that offer high ductility and sufficient strength to satisfy the requirements for embedding materials. The more promising of those materials are discussed in this report.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

This section summarizes the findings of this report on the performance of bridge expansion joint anchorages and on the design and construction factors affecting that performance. The findings are based on the analyses of available information presented in the body of this report.

1. Because of the influence of many construction and environmental factors, a consistent performance pattern of a certain type of bridge expansion joint anchorage system does not exist. However, when the performance is generalized, among the three types of expansion joint systems (i.e., joints with strip seals, compression seals, and metal reinforced cushion seals), joints with metal reinforced cushion seals have performed the worst, while the best general performance has been from joints with compression seals retained by steel angles. The performance of joints with strip seals retained by steel extrusions has been in between those two systems. However, joints with strip seals retained by elastomeric pads have not performed well.
2. Traffic impact loads are transmitted to the armors, through which they are transmitted to the anchor devices. Vertical tire impact loads are mainly absorbed by the concrete supporting the armor. However, after the removal of the load, the rebound of the system exerts vertical impact loads on the armor in the opposite direction, which are then transmitted to the anchor devices. Horizontal impact loads are caused by tire friction/traction. The horizontal impact loads can be transmitted to the anchor devices through the armors upon their exertion. The flexible

armors can significantly reduce the intensity of the loads transmitted to the anchor devices.

3. Two major modes of structural failure of expansion devices may be distinguished. In the first mode, the impact forces transmitted to the anchor devices are so great that the anchor bolts or studs break loose in the concrete, causing the concrete adjacent to the expansion device to spall. This mode of failure is a characteristic of anchor devices with rigid edge beams, such as steel extrusions used in conjunction with strip seals, or steel angles used with compression seals. The second mode of failure is a characteristic of strip seals with elastomeric pad retainers and of elastomeric cushion seals. In this mode of failure, the impact forces transmitted to the anchor devices are not initially severe because of the extensive elasticity of the transmitting medium (i.e., the elastomer). However, those forces and their corresponding repeated deformations cause the elastomer to fail. The failed elastomer does not reduce the intensity of the impact loads when transferring them to the anchor devices. In time, that condition causes failure of the anchor devices.
4. Anchor devices are typically 0.625-in.-diameter studs or bolts and are installed 1 ft. on center to ensure against their rupture under repeated impact forces. Anchor studs are usually used in conjunction with steel edge beams. The studs are welded to those beams, and the deck concrete is cast directly around them. Anchor bolts are either anchored similarly or they are set in holes made in the bridge deck concrete after the concrete has been cast. The holes are usually drilled in the concrete. The setting of anchor bolts in drilled holes (either in mortar or as expansion devices) makes their location most accurate, but such bolts usually have less pull-

out strength and exhibit much more slip under service loads than cast-in-place bolts.

5. Anchor devices are typically about 4 in. long. Headed studs, or bolts with washer plates, are usually used with that embedment length to enhance the pull-out strength. Alternatively, anchor devices may be hooked or tied to the adjacent deck reinforcing steel.
6. Usually, anchor devices are embedded in the same type of concrete as that used to construct the structural deck. However, the embedding materials are subject to impact from the devices. Materials with the same strength but greater ductility and energy absorption than conventional structural concrete are desirable for the anchorage concrete.
7. One resilient material that has been used to embed expansion joint anchorages is elastomeric concrete. Because of its relatively low strength, elastomeric concrete has usually been used with a certain type of anchorage that is not anchored deep in the structural deck concrete (i.e., sinusoidal anchorage). Use of elastomeric concrete with this type of anchorage is especially suitable for modification of expansion joints during overlaying of bridge decks. Elastomeric concrete has generally shown satisfactory field performance. Descriptions are provided in Chapter 2 and Chapter 3.
8. Steel anchor devices embedded in concrete are affected by roadway de-icing salt. Therefore, they are subject to electrochemical galvanic corrosion, since electrical continuity usually exists between these devices and the bridge deck's reinforcement. The expansion caused by metallic corrosion can rupture the concrete surrounding the anchorage. However, note that the anchor device will also be subject to corrosion if it deteriorates the surrounding concrete under traffic impact. In other words,

corrosion of the anchor device and deterioration of the surrounding concrete promote each other.

RECOMMENDATIONS FOR DESIGN AND CONSTRUCTION OF ANCHORAGE SYSTEMS

In this section procedures are recommended for the design, construction, and maintenance of bridge expansion devices in order to prolong their service life under impact from traffic. These recommendations may need to be modified on the basis of the results of supplementary laboratory research.

Design

1. The parameters of interest for the design of anchor devices are their diameter, embedment length, spacing, and distance from the concrete edge. The type of anchor device (e.g., headed versus unheaded stud) is also of interest. The systematic analytical procedure developed and presented in this report can be tentatively used to examine the adequacy of those parameters for determining the satisfactory long-term performance of bridge expansion joint anchorage systems. Also presented in this report is an example illustrating how the analytical procedure applies to an actual expansion joint. The rationale used for this purpose is based on the flexibility of the expansion device under dynamic loads. The procedure developed can analyze various types of expansion devices with metallic or elastomeric components. Once the loads being transmitted are determined, the anchor devices are checked for their resistance to shear and tension failure. The strength of both the device itself and the embedding concrete must be checked. Failure can be caused by the anchor device pushing against the concrete laterally or by the anchor device pulling out of the concrete.

2. Systems should use steel edge beams with the least possible rigidity in order to reduce the intensity of the impact loads transmitted to the anchor devices. Flexibility can be built into the steel edge beams by reducing the thickness of the beam or by providing the capability for a cantilever behavior in the plane vertical to the direction of the joint. On the other hand, steel edge beams should be thick enough to be sufficiently strong and to resist corrosion. While a steel thickness as small as 0.20 in. may provide sufficient strength for typical bridge applications, a thickness of 0.375 in. may be needed to allow for long-term section loss due to corrosion. Therefore, by protecting steel edge beams against corrosion, thinner sections with higher flexibilities can be utilized.
3. Elastomeric components transmit impact loads to the anchorage, and they must have adequate fatigue strength to maintain their integrity under the repeated deformations and in the type of environment in which they perform. The rate of creep of the elastomeric components should be known so that the time when their hold-down anchor bolts must be tightened can be predicted accurately. Also, designs should consider the possibility for deformation and wear of the elastomer surrounding the bolt and covering the reinforcing metal. That deformation or wear can result in enlargement of the slot and rocking of the elastomer.
4. Anchor studs and bolts should be either corrosion resistant or epoxy coated to prevent their galvanic corrosion and subsequent rupturing of the surrounding concrete.

Construction

1. When anchor devices are cast directly into the concrete, proper consolidation of the surrounding concrete is essential. Inadequate consolidation results in a low strength material with poor fatigue and

inferior bond qualities. Such conditions promote loosening of the anchorage and spalling of the concrete.

2. Joint rebates should be boxed out to the correct level to eliminate use of bedding materials and their possible deterioration under traffic impact.
3. Recently, various materials have been developed with sufficient ductility and strength that they can be classified as shock absorbing embedment materials. Among those materials are glass fiber reinforced concrete, slurry infiltrated fiber concrete, and elastomeric concrete. The construction procedures for these materials lend themselves well to filling the block-out and embedding the bridge expansion joints' anchor devices. Detailed descriptions are provided in Chapter 2. Glass fiber reinforced concrete and slurry infiltrated fiber concrete have not been used as bridge expansion joint anchorage embedment materials. Thus, laboratory and field experiments are necessary to predict their performance. However, elastomeric concrete has been used in the field and has generally performed satisfactorily. Presently, several proprietary elastomeric concrete joint systems are available on the market. Material specifications and testing are needed for acceptance of an elastomeric concrete joint system when information on its field performance is lacking.
4. When the riding surfaces for expansion joint assemblies are not set properly relative to the adjacent roadway surface, excessive impact loads, noise, and snowplow damage can be expected. The top edge of the joint should be set not less than 0.125 in. nor more than 0.188 in. below the adjacent roadway surface.

Maintenance

1. Strip seals with inverted arch membranes accumulate roadway grit in the recess of the joint. When the deck expands, the non-resilient grit exerts

local pressure on the steel edge beam and can cause the adjacent concrete to spall. Thus, it is important to clean the joint regularly .

2. Wheeltrack wear of the roadway causes greater impact loading on the expansion joint. Wear is especially a problem with asphalt concrete surfaces. The worn areas adjacent to the expansion joint should be repaired, possibly with polymeric mortars.
3. In elastomeric components, creep of the elastomer can cause hold-down bolt torque dissipation and loosening of the anchorage. After the initial installation, the nuts of the hold-down bolts should be retorqued to compensate for creep. Welding the nuts after the creep has occurred may prevent further looseness under traffic action.
4. In elastomeric components, the rubber plugs covering the hold-down bolts eventually loosen under traffic and are subsequently lost. Replugging the bolt holes can result in the same problem, since the cause of the problem is usually that the bolt is not centered properly in the hole. Alternatively, unplugged bolt holes may be filled with asphaltic or polymeric materials.

SUMMARY OF ADVANTAGES AND DISADVANTAGES OF VARIOUS EXPANSION JOINT SYSTEM COMPONENTS

Edge beam

Steel edge beam

Advantage: Resists failure under impact from traffic and distributes the impact load relatively uniformly among anchor devices.

Disadvantage: The impact load transferred to the anchorage can be higher than the impact load exerted on the beam; the beam is subject to corrosion; and it is relatively expensive.

Aluminum edge beam

Advantage: Offers same advantages as steel edge beams; but less likely to corrode; and is relatively inexpensive.

Disadvantage: May react with fresh concrete; is not thermally compatible with cured concrete, and thus may cause concrete cracking; and is subject to snowplow damage.

Elastomeric edge beam

Advantage: The impact load transferred to the anchorage can be less than the impact load exerted on the beam.

Disadvantage: Is subject to failure under traffic impact and to snowplow damage, which may cause non-uniform distribution of the impact load among the anchor devices, as well as looseness of the beam.

Anchorage

Welded studs

Advantage: Integral part of the edge beam, preventing beam looseness under traffic impact.

Disadvantage: Are suitable only with metal edge beams in cast-in-place construction; and fresh concrete corrosion problem can develop if stud is made of aluminum.

Anchor bolts

Advantage: Can be placed in drilled holes.

Disadvantage: Enlargement of the anchor slot and looseness of the edge beam are possible under traffic impact.

Cast-in-place anchor devices

Advantage: Offer high pull-out strength.

Disadvantage: Do not provide high accuracy with respect to anchor bolt location; and the embedding concrete may not be consolidated well.

Placed-in-drilled-hole anchor devices

Advantage: Offer high accuracy with respect to anchor bolt location.

Disadvantage: The pull-out strength is sensitive to construction procedures and is generally low.

Anchorage embedding material

Elastomeric concrete

Advantage: High resilience reduces impact loads transmitted to the embedding material; is suitable for modification of expansion joints when bridge decks are overlaid; and generally satisfactory performance records exist.

Disadvantage: Is a relatively low strength material, for use as part of the structural deck.

Glass fiber reinforced concrete

Advantage: Offers both high elasticity and high strength; satisfactory performance records exist about its use as a nosing

material; and the construction procedure lends itself to filling block-out.

Disadvantage: No performance records exist about its use as an embedding material.

Slurry infiltrated fiber concrete

Advantage: Offers both high elasticity and high strength; and the construction procedure lends itself well to filling block-out.

Disadvantage: No performance records exist about its use as an embedding material.

Seal

Strip seal

Advantage: Is easy to install and relatively maintenance free.

Disadvantage: Accumulates roadway grit in the recess of the joint, which can cause damage to the adjacent concrete during warm temperatures when the joint tends to close.

Compression seal

Advantage: Does not accumulate roadway grit in the joint.

Disadvantage: Is relatively difficult to install and may pop out under traffic impact.

CHAPTER 1

INTRODUCTION

Many anchorage systems of bridge expansion joints in the medium movement range (2 to 5 in.) have failed within a relatively short time after their installation. The embedded anchor devices have become loose and the concrete has spalled under the armor. The result of the anchorage failure has been that the loose expansion joints have been noisy under traffic impact and have further contributed to the deterioration of the adjacent concrete deck. Because the repair of loose expansion joints is costly and creates hazardous driving conditions, the need for bridge expansion joint repair should be minimized, and longer service lives for bridge expansion joint systems should be provided.

OBJECTIVES

The Washington State Department of Transportation (WSDOT) initiated this investigation with the following objectives:

- to evaluate the design, construction, and performance of bridge expansion joints in the medium movement range, and
- to develop more durable anchor devices for bridge expansion joints to prolong their maintenance-free service period.

RESEARCH APPROACH

The research explored the possibility of incorporating more effective designs and improved materials into the construction of WSDOT's bridge expansion joint anchorage systems. After the performance of various domestic and foreign designs was assessed, factors affecting the anchorage systems' performance and failure were identified. Accordingly, improvements in the anchorage system components, built in conjunction with the anchor devices, were recommended to reduce the intensity of traffic impact loads transmitted to the anchor devices. Subsequently, an analytical procedure was developed to

quantify the intensity of the dynamic traffic loads transmitted to anchor devices, and to design anchor devices to resist those loads. Finally, a second research phase, consisting of laboratory work, was recommended to verify and/or modify the recommendations developed as a result of this work.

CHAPTER 2

REVIEW OF THE DESIGN AND CONSTRUCTION OF ANCHORAGE SYSTEMS

Usually, expansion devices in the medium movement range include strip seals and compression seals. Certain types of metal reinforced elastomeric cushion seals are also installed to accommodate a medium amount of superstructure movement (2 to 5 in.). Generally, the WSDOT specifies strip seals and compression seals for expansion joints in the medium movement range. Presently, the design of anchorage systems for expansion joints is based on engineering judgment developed through the adoption of previous designs or where there has been an unsatisfactory performance record, through modifications to those designs.

A bridge expansion joint assembly usually consists of the following: (1) the seal, which waterproofs the joint; (2) the retainer/armor, which retains the seal in the joint and at the same time protects the adjacent concrete against the traffic impact; and (3) the anchor devices, which fasten the retainer/armor to the concrete. Blockouts, or formed recesses in the ends of bridge deck spans, receive the expansion joint assemblies. Usually the assemblies are installed after the deck slab has been constructed to prevent the placement of the concrete deck from rotating the span end. The blockouts are then filled with concrete to embed the anchor devices and fill the gaps.

STRIP SEALS

In this system the seal (gland) is retained by steel extrusions, aluminum extrusions, or elastomeric pads. The retainer/armor is in turn anchored to the concrete with devices incorporating various designs.

Steel extrusions

Figures 1 and 2, from the WSDOT bridge design manual, depict two different types of anchorage systems for steel extrusions. The anchorage in Figure 1 is designed for

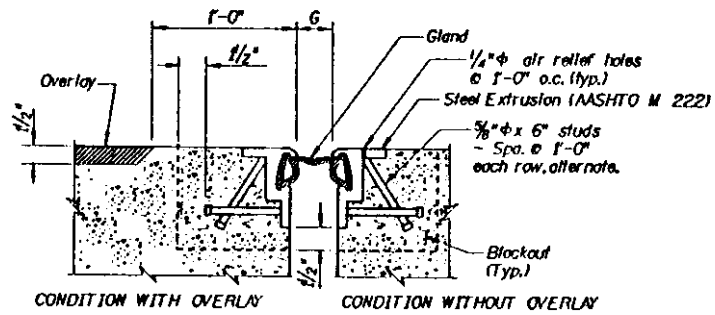


Figure 1. Strip Seal with Steel Extrusions;
Anchorage for Normal Traffic Volume

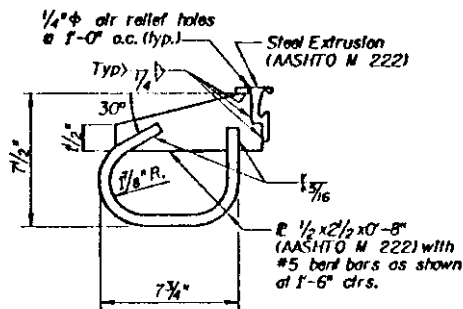


Figure 2. Strip Seal with Steel Extrusions;
Anchorage for High Traffic Volume

normal traffic. It consists of alternate diagonal and horizontal studs embedded in the blockout concrete. The anchorage in Figure 2 is designed for high traffic. It ensures a stronger attachment to the concrete and consists of a welded plate and reinforcing bar.

Figure 3 illustrates a steel extrusion with a sinusoidal anchorage. (1) In this system, anchorage deep in the deck concrete is not necessary. Thus, it is suitable for modification of expansion joints during overlaying of bridge decks.

In Figure 4, the steel extrusion is placed and anchored to the concrete in the bottom of the blockout. (2) The anchoring is done by means of hold-down bolts cast directly into the underlying concrete. Note the shape and orientation of the steel extrusion (edge beam) in Figure 4. The beam has the potential to bend elastically in the plane vertical to the direction of the joint and to absorb some of the horizontal and vertical impact shocks from traffic.

Generally, steel extrusions offer high strength, but they act as rigid edge beams. Because of their rigidity, they transmit a great amount of impact load to the anchor devices. Steel extrusions can be made in sections so that they have a minimum amount of rigidity, while still having adequate strength. Figure 5 shows two such steel edge beams used in Pennsylvania (Figure 5-a; (3)) and Germany (Figure 5-b, (4)). Both beams are made of relatively thin metal and also offer flexibility in bending through a cantilever behavior, as discussed previously. In Figure 5-b, the steel extrusion is only 0.20 in. thick. Aside from flexibility and strength, steel extrusions should be sufficiently thick to satisfy corrosion requirements. Most states use a minimum steel thickness of 0.375 in. which allows for long-term section loss caused by corrosion. (5)

Aluminum extrusions

Figure 6 presents two types of aluminum extrusions. The type in Figure 6-a retains a conventional gland. The type in Figure 6-b retains a gland that depends on the clamping pressure to create a seal. (5) Both of the aluminum extrusions are anchored to the concrete by means of hold-down bolts. Figure 7 shows details of an anchorage for the aluminum

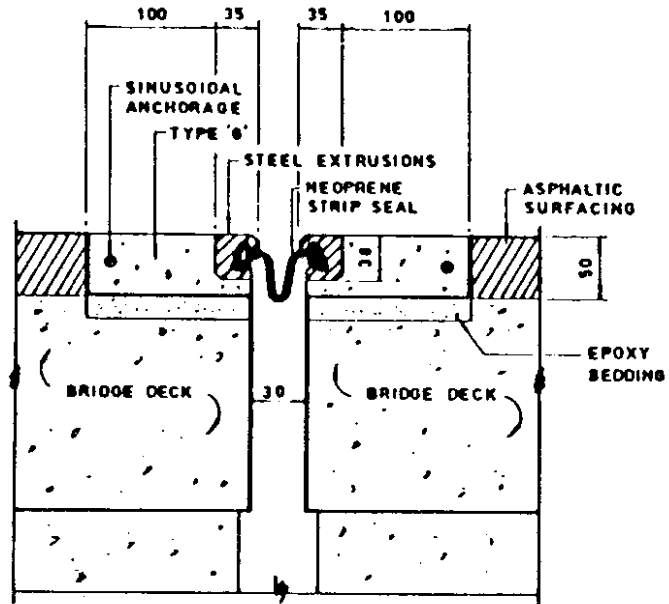


Figure 3. Strip Seal with Steel Extrusions and Sinusoidal Anchorage. (1)
 (dimensions in millimeters; 1 millimeter = 0.039 in.)

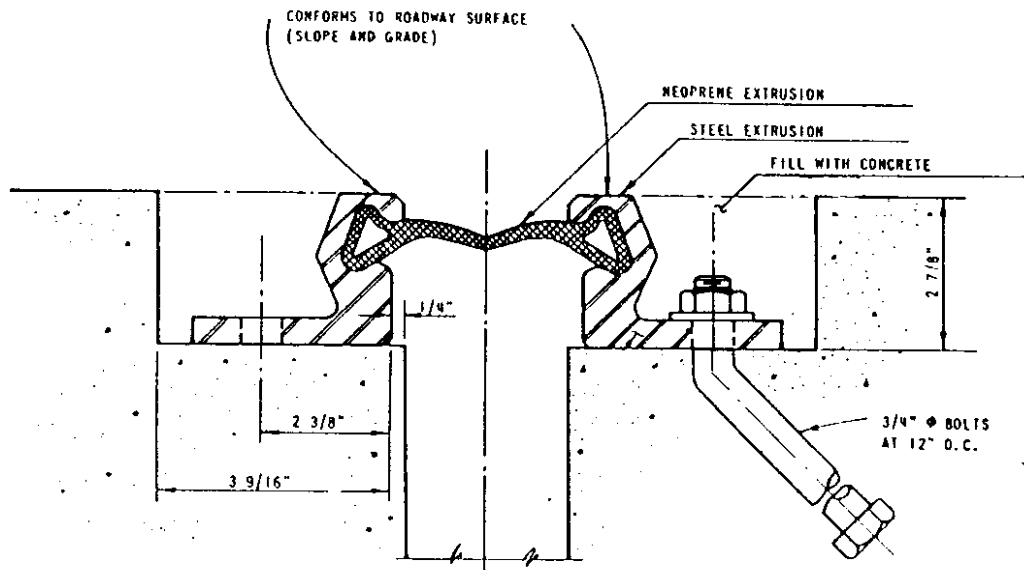
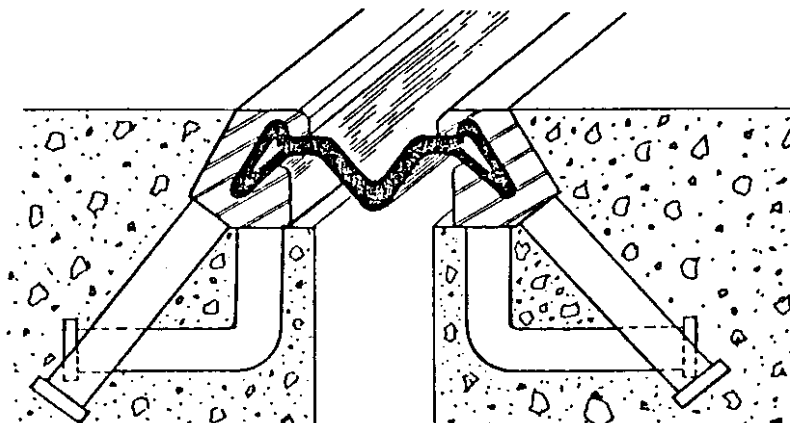
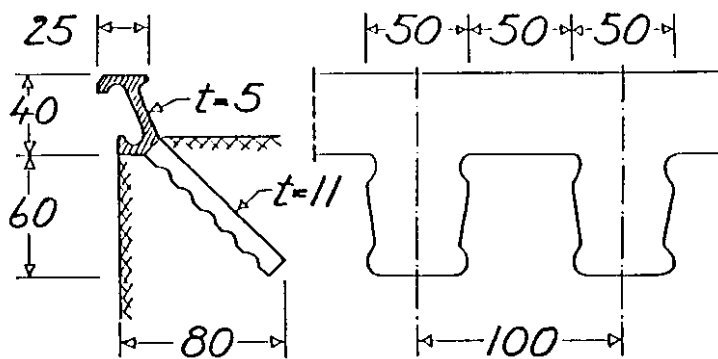


Figure 4. Strip Seal with Steel Extrusions and Hold-Down Bolts for Anchorage. (2)



(a) from Reference 3



(b) from Reference 4

Figure 5. Two Types of Strip Seal with Light and Flexible Steel Extrusions (Dimensions in Millimeters; 1 millimeter = 0.039 in.)



(a)



(b)

Figure 6. Strip Seals with Aluminum Extrusion;
(a) conventional gland, (b) continuous gland

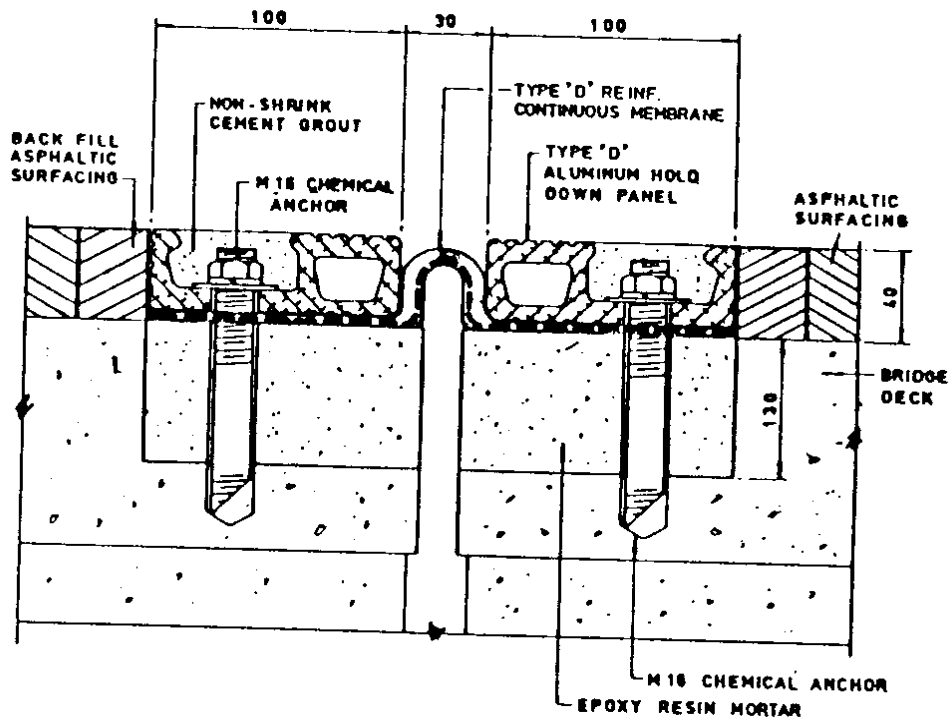


Figure 7. Details for Anchoring an Aluminum Edge Beam to Concrete
(Dimensions in Millimeters; 1 millimeter = 0.039 in.) (1)

edge beam shown in Figure 6-b. In that anchorage, hold-down bolts are resin grouted into holes drilled in the underlying concrete. These devices must be placed after the bridge deck concrete has hardened. Otherwise, there is a likelihood of a reaction between the aluminum and the fresh concrete.

Unlike steel edge beams, aluminum edge beams are relatively flexible. Thus, they have the potential to transmit lower levels of impact load to the anchor devices. Aluminum offers less strength, but it has performed satisfactorily, with regard to wear and corrosion. (6)

Elastomeric pads

Strip seals with elastomeric pad retainers are generally of two types, as shown in Figure 8, which is taken from the WSDOT bridge design manual. In the first type, the gland is integrally molded to the pads (Figure 8-a). In the second type the gland extends under the pads (Figure 8-b), and it depends on the clamping pressure to provide a seal. Both types are anchored into the concrete by means of hold-down bolts. The bolt holes in the pads are then plugged with neoprene, or filled with various materials such as epoxy or other types of sealants.

The elastomeric pads are usually metal reinforced. They absorb much of the shock from the impact loading through their elastic deformation, thus transmitting relatively low load levels to the anchorage. The pads are subjected to many cycles of high magnitude strain. The number of cycles and the amount of that strain depends on the nature of the traffic. The elastomeric pad must have sufficient fatigue strength to withstand this repeated deformation.

COMPRESSION SEALS

In compression seals, the seal is an elastomer that is usually retained by steel edge beams each in the shape of an angle. Anchorage of the steel angles to the concrete is accomplished in basically the same manner as it is done for strip seals with steel edge

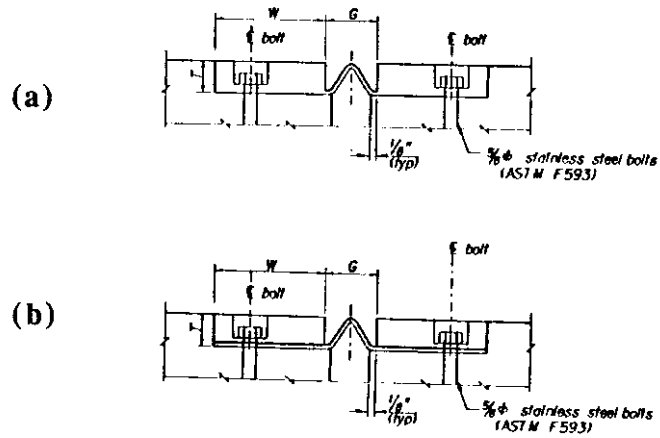


Figure 8. Strip Seal with Elastomeric Pad Retainers;
(a) Gland Integrated with Retainer; (b) Gland Extended Under the Retainer

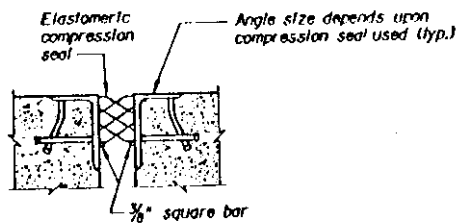


Figure 9. Compression Seal;
Anchorage by Alternative Vertical and Horizontal Studs

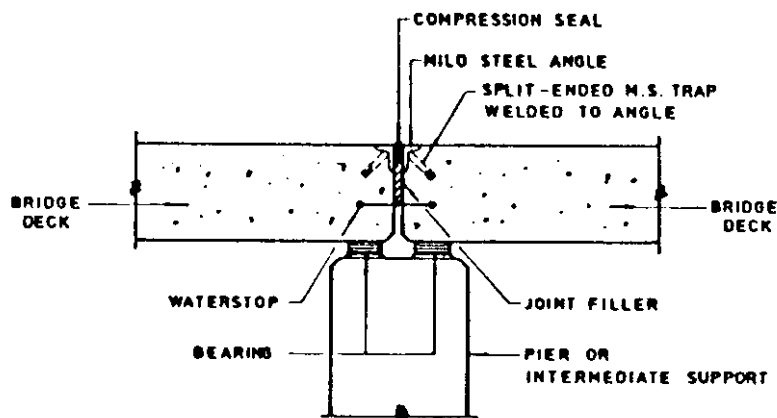


Figure 10. Compression Seal, Anchorage by Diagonal Studs (L)

beams. Figure 9, from the WSDOT bridge design manual, shows anchorage by means of vertical and diagonal studs welded to the angles and cast in the bridge deck concrete. Figure 10 shows a method of anchoring the angles, used in Hong Kong, that incorporates diagonal anchor devices.

ELASTOMERIC CUSHION SEALS

One expansion device of this nature, used in Pennsylvania, is shown in Figure 11.

(3) The metallic plates in the elastomeric cushion distribute the wheel load over the joint. The cavities in the elastomer accommodate joint movement through shear deformations of the elastomer.

Elastomeric cushion seals are generally anchored to the concrete by means of hold-down bolts. The bolt holes in the elastomer are then plugged with the same material. The loss of hole plugs is a common problem after several years of exposure to traffic. Figure 12 presents a different system of anchorage for an elastomeric cushion seal experimented with in Virginia. (7) In this system the anchor bolts are located outside of the elastomeric cushion. The bolts secure to the concrete two angles (one on each side), which are in turn fastened to the elastomer. In this particular system the nuts that fasten the angles to the elastomer were spot welded to the angles to prevent the nuts from working loose under traffic. The trough on each side of the elastomeric cushion seal, and over the anchor bolts, is filled with an asphaltic material.

Because of the high elasticity of the elastomer, cushion seals transmit low levels of impact load to the anchorage. However, they strain extensively with each cycle of traffic loading. Thus, of importance to the structural durability of the expansion device is the fatigue strength of the elastomeric cushion.

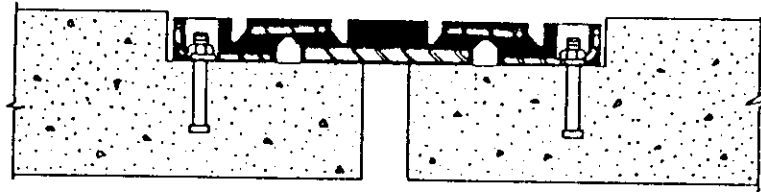


Figure 11. Elastomeric Cushion Seal with Hold-Down Bolts for Anchorage (3)

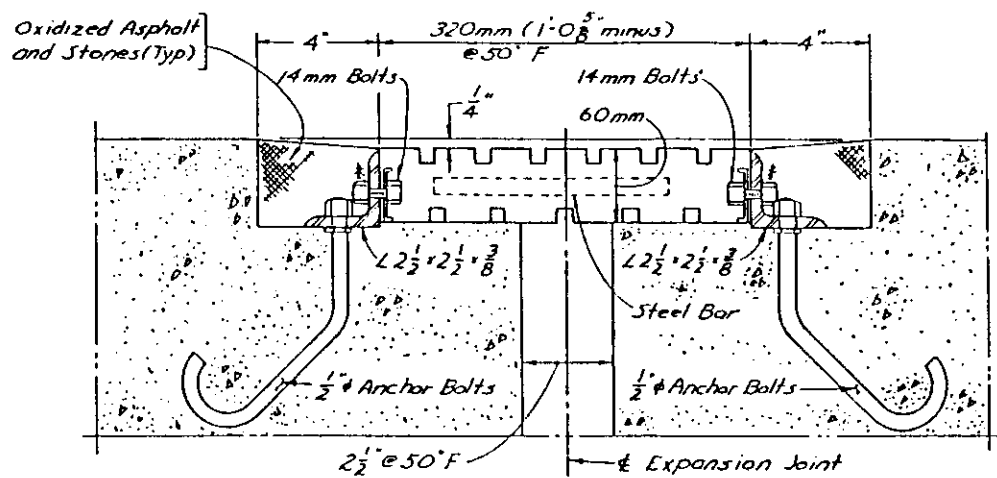


Figure 12. Elastomeric Cushion Seal with Hold-Down Bolts for Anchorage Located Outside of the Elastomer, Royston (7) (1 millimeter = 0.039 in.)

ANCHORAGE SYSTEM COMPONENTS

Anchor Devices

Anchor studs and bolts are generally 0.625 in. in diameter and are installed 1 ft. on center to ensure against their rupture under the repeated forces transmitted to them. Anchor studs are usually welded to the steel edge beams and cast directly into the block-out concrete. Anchor bolts are either cast directly in the block-out concrete, or they are set in holes made in the bridge deck concrete after the concrete has been cast. The holes are usually drilled in the concrete. In view of the importance of the location of the anchor bolts, the latter procedure is preferred. However, the pullout strength of bolts anchored in holes, either in mortar or with expansion devices, is inferior to that of cast-in-place bolts. (L, §) Anchor devices should have sufficient embedment length within the concrete to prevent their pulling out from concrete. Otherwise, they are hooked or tied to the adjacent reinforcement. (1) Headed studs, or bolts with washer plates, may be used to compensate for the embedment length and add to the pull-out strength. The embedment length with headed studs is typically 4 in.

In order to increase the fatigue life of the anchorage system under repeated traffic loading, the concrete embedding the anchor bolts can be prestressed with prestressing tie bolts. This is shown in Figure 13. This procedure prevents stress reversal and assures that the stresses in the bolt and concrete are always in the same direction (tension in bolt, compression in concrete), thus providing a longer fatigue life.

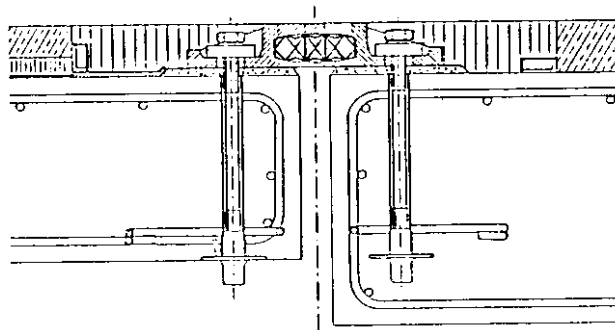


Figure 13. Expansion Joint Fixed by Prestressing of the Bolts (6)

Back-fill materials

Back-fill materials are used to fill any gaps that remain after anchorage of the expansion devices. Those gaps are either troughs accommodating the hold-down anchor bolts, or they are construction joints between the expansion device and the roadway. Below are described a few examples of the application of back-fill material.

Figure 4 shows concrete as a back-fill material used behind the steel edge beam to fill the trough and to cover the hold-down bolts. Figure 7 presents two types of back-fill material. The first type is an asphaltic material that fills the construction joint between the aluminum edge beam and the asphalt concrete roadway. The second type is a non-shrink cement grout that fills the gap in the edge beam and covers the hold-down bolts. In Figure 11 the construction joints between the elastomeric cushion seal and the deck surface are filled with an asphaltic sealant. In Figure 12 an asphaltic material fills the trough behind the elastomeric seal and protects the hold-down bolts.

The interface between the back-fill materials and the adjacent materials (i.e., roadway material) is subject to deterioration because of the differences in their physical properties. Interface defects can occur because of shrinkage of the back-fill material or differential wear of the two joining materials. Experience has shown that asphaltic materials perform best as back-fill material when placed next to an asphaltic wearing surface, and cement mixes perform best when placed next to a concrete surface. (1)

Bedding materials

Bedding materials are used to box out up-to-level, oversize rebates in the bridge deck. Cement, epoxy, and glass fiber reinforced concrete have been used for this purpose. Bedding materials should bond well to the bridge deck concrete. Materials such as epoxies, which are not thermally compatible with concrete, lose their bond with concrete in time. In addition, bedding materials should not be too rigid, or they will be subject to cracking and deterioration under traffic impact. Rigid epoxies have not performed well. (1) The performance of glass fiber reinforced concrete has been better than epoxy mortars

because of its ductility. However, the best procedure is to box-out joint rebates to the correct level, thus eliminating use of bedding materials.

Embedding materials

These materials embed anchor bolts or studs in the block-out and/or concrete deck. Usually, the anchorage assembly is embedded in the same type of concrete that is used to construct the structural deck. However, the characteristics of the embedding materials are especially important. Embedding materials are subject to impacts from the anchor devices. This condition requires materials that, while sufficiently strong, are more ductile and shock absorbing than conventional structural concrete. Back-fill materials may also need the same engineering properties as embedding materials, since they may be subject to impacts from the armors. In some systems there is no delineation between back-fill and embedding materials. This is because the latter fills the block-out up to the level of the deck surface. Examples are shown in figures 1, 3, 5, 9, and 10.

Recently, various materials have been developed that offer high ductility and sufficient strength to satisfy the requirements for embedding materials. Among those materials are glass fiber reinforced concrete, slurry infiltrated fiber concrete, and elastomeric concrete.

Glass fiber reinforced concrete (GFRC). This material has mainly been used for manufacturing precast concrete building panels. It has also been used for back-filling and nosing of bridge expansion joints. (1) Reference 9 provides detailed information on the mix design and manufacturing of GFRC building panels. For the building panels, chopped glass fibers are combined with a cement/sand/water slurry and deposited from a hand-held sprayhead into the form. Although this process requires compaction of the sprayed layers, it lends itself well to filling the block-out in the case of bridge expansion joints, provided that proper mix consistency and vibration are employed to achieve sufficient consolidation. GFRC can be made as thin as 0.25 in. (9) A mix with 5 percent fiber content by weight can develop 2,000 psi tensile strength and 4,500 psi

flexural strength in 28 days in conjunction with about 1 percent elongation. (9) These engineering properties are three to four times those of a conventional structural concrete.

Slurry infiltrated fiber concrete (SIFCON). Generally, in a fiber-modified concrete, fibers and concrete are pre-mixed and then placed in the mold. By contrast, for SIFCON, fibers are spread in the mold first, and then a cement/fly ash/water slurry is added to fill the remaining space in the mold. SIFCON mixes, which incorporate 12 percent by volume of 1-inch-long steel fibers and use cement/fly-ash/microsilica/water slurry, have shown up to 15,000 psi compressive strength with a corresponding strain of 2 percent. (10) Significant improvements in tensile strength and tensile elongation have also been reported. (10)

SIFCON has been used experimentally to rehabilitate bridge deck concrete. (11) The material has also been used to provide cast-in-place plastic hinges between columns and prefabricated beams in anticipation of seismic events. (10) The construction procedure for SIFCON makes the material practical for filling bridge expansion joint block-outs.

Elastomeric concrete (EC). EC has been used in the United States experimentally over the past ten years for modification of expansion joints during the rehabilitation and overlaying of bridge decks. The states of Florida, New York, and Texas have used the material. Because of its relatively low strength, EC may not replace structural bridge deck concrete. Therefore, it should mainly be used as a back-fill or nosing material rather than an embedding material. However, EC can be used as an embedding material when the anchorage does not extend deep into the structural deck, as with, for example, the sinusoidal anchorage shown in Figure 3. Presently, several proprietary EC systems are available (e.g., Wabocrete, Ceva-Crete, Delcrete, Harcrete).

EC consists of resin as binder and an aggregate. The binder and aggregate are usually heated and mixed to form a viscous elastomeric mixture. The mixture is then placed next to the expansion joint, and it may be heated (vulcanized), utilizing heat chambers, to cure and form a monolithic connection with the surrounding materials. (12)

The Texas State Department of Transportation has developed material specifications for EC for bridge expansion joint applications. (13) The Texas specifications require a minimum wet bond strength to concrete of 200 psi, a minimum compressive stress of 750 psi (measured at 5 percent deflection), and a minimum resilience of 75 percent (measured as percentage of recovery when the compressive load is removed).

CHAPTER 3

PERFORMANCE OF ANCHORAGE SYSTEMS

An NCHRP study (8) surveyed highway agencies nationwide regarding the performance of bridge expansion joint systems, including the performance of their anchorage systems. (8) Twenty-seven highway agencies responded to that survey. The Pennsylvania Department of Transportation investigated the field performance of bridge expansion joints in that state, including the performance of the anchorage devices. (3) A similar investigation was conducted by the Kentucky Department of Transportation. (14) An ACI publication presented a paper from Hong Kong that described the performance of various bridge expansion joint anchorage systems in that region of high density traffic (1). The AASHTO Manual for Bridge Maintenance discusses the performance of and problems with expansion joint anchorage systems. (2) The following is an assimilation and analysis of the information obtained in the foregoing investigations, and information from WSDOT's routine bridge inspections.

Because of the influence of many construction and environmental factors, a consistent performance pattern of a certain type of expansion joint anchorage system does not exist. However, when the performance is generalized, among the three types of expansion joint systems (i.e., joints with strip seals, compression seals, and metal reinforced cushion seals), joints with metal reinforced cushion seals have performed the worst, while the best general performance has been from joints with compression seals retained by steel angles. The performance of joints with strip seals retained by steel extrusions has been in between those two systems. However, joints with strip seals retained by elastomeric pads have not performed as well as those retained by steel extrusions.

Two major modes of structural failure of expansion devices may be distinguished. In the first mode the impact forces transmitted to the anchor devices are so great that the

anchor bolts or studs break loose in the concrete, causing the concrete adjacent to the expansion device to spall. This mode of failure is mainly characteristic of anchor devices with rigid edge beams, such as steel extrusions used in conjunction with strip seals, or steel angles used with compression seals.

The second mode of failure is characteristic of strip seals with elastomeric pad retainers and of elastomeric cushion seals. In this mode of failure, the impact forces transmitted to the anchor devices are not initially severe because of the extensive elasticity of the transmitting medium (i.e., the elastomer). However, those forces and their corresponding repeated deformations cause the elastomer to fail. The elastomer is usually secured to the deck concrete by hold-down anchor bolts. The failed elastomer does not reduce the intensity of impact loads when it transfers them to the anchor bolts. In time, that condition causes failure of the anchor bolts.

PERFORMANCE OF ANCHORAGE OF ELASTOMERIC COMPONENTS

An indication of the performance of expansion joint anchor devices can be obtained from the results of the NCHRP survey of highway agencies in 1977. (9) This work analyzed performance data reported by 27 respondents to the NCHRP survey and found that almost all of the anchorage failures reported were associated with elastomeric cushion type expansion devices secured to the concrete by means of hold-down bolts. The average age of those installations was four years, and their average ADT was 2,500. Note, however, that the results of the NCHRP survey indicate relative performance only; they do not mean that other types of expansion devices necessarily perform satisfactorily. This is because the reported data were not the result of a comprehensive bridge expansion joint survey. Among the failed anchor devices, 63 percent of the failures were identified with anchor device pull-out, 19 percent were identified with shearing of anchor devices, and 12 percent were identified with loosening of nuts. Among the anchor devices failed by pull-out, 81 percent were drilled-in-concrete expansion bolts.

As mentioned earlier, the failure of an anchor bolt that secures a metal reinforced elastomer to the bridge deck concrete is generally initiated by the failure of the elastomer. The elastomer may fail in different ways. The elastomer is subject to surface tear under traffic impact. This results in a lack of integrity in the elastomer, which prevents the elastomer from distributing the load properly among the anchor bolts. The elastomer surrounding the bolt is subject to deformation and wear due to horizontal loading (friction/traction loading), which causes enlargement of the bolt slot and rocking of the system. The elastomer placed under the bolt nut deforms and creeps under vertical loading and causes dissipation of the bolt torque and looseness of the nut. Finally, loss of the bolt hole plugs results in surface deterioration and deformation of the elastomer around the hole, which results in exposure of the tip of the bolt. Under this condition, the bolt is subject to direct impact from traffic. Otherwise, a sound elastomer should be able to provide sufficient elasticity to reduce the intensity of the loads transmitted to the anchor device. Also, since this type of construction usually uses hold-down bolts placed in drilled holes, the pull-out strength of the bolts may be inferior as a result of sensitivity to workmanship. Thus, the pull-out mode of failure may occur even in the absence of the elastomer failure.

On the basis of their survey of Pennsylvania bridge expansion joints, Dahir and Mellot reported that problems associated with the use of metal reinforced elastomeric systems ranged from tear caused by pounding of traffic to poor anchorage. (3) They reported missing strips of the elastomer along the expansion joint, and pull-out and yielding of the anchor devices. In some cases movement of the anchor bolt in the anchor slot contributed to the failure by wearing and enlarging of the slot and by wearing the bolt to the point that it yielded. In the slot, the elastomer surrounding the bolt can deform and wear under horizontal impact loading. That wear can continue until the reinforcing metal is exposed to the bolt in the slot. This is probably the main reason for the slot enlargement noticed in the Pennsylvania survey. Pull-out and rupture of hold-down bolts, as well as

elastomer breaking away from its reinforcing metal, were also reported by Tung on the basis of his survey of bridge expansion joints in Hong Kong. (1)

Data from a survey of bridge expansion joints in Kentucky showed that in some installations the tear of elastomer, as well as loss of the bolt hole plugs and deterioration of the elastomer around the bolt hole, began in about five years under an ADT of 3,000 or less. (14) In one installation (i.e., an elastomeric cushion seal) severe deterioration along the expansion joint assembly occurred in 12 years under traffic of about 20,000 ADT. The deterioration included tear and misalignment of the elastomer and loss of several strips of the elastomer, as well as loss of backfill sealant material. Hilton reported the performance of an experimental elastomeric cushion seal bridge expansion joint in Virginia after five years of service under traffic of about 4,000 ADT. (7) The elastomer exhibited severe sagging (i.e., 1 inch), which impaired the ride quality. Spalling of the edge of concrete shoulder adjacent to the elastomeric element has been reported. (9) That spalling is probably the result of a lack of firm support by the elastomer for traffic.

PERFORMANCE OF ANCHORAGE OF METALLIC COMPONENTS

Although because of their rigidity, metallic retainers/armors may transmit impact forces higher than those associated with the basic wheel force to their anchor devices, the overall performance of such anchor devices has been more satisfactory than that of elastomeric components. There are several reasons for this result. First, unlike elastomeric components, metallic components are strong enough to hold their integrity without tearing under repeated loading, thus distributing the load uniformly among the anchor devices. Second, metallic components do not wear, deform, creep, and cause looseness of their anchor bolts as happens with elastomeric components. Third, metallic components, because of their nature, are usually secured to bridge deck concrete by means of cast-in-place welded studs, which provide an integral system with the armor and also offer high pull-out strength. A disadvantage of steel armors is that they corrode. However, this

problem can be overcome by protecting the armor with an epoxy, or by using a thicker section. The former alternative is preferable because the rigidity of the armor is then reduced.

The failure of the anchorages of steel armors usually begins with spalling of the concrete cover over the horizontal welded stud. (21, 22) The horizontal stud is usually subject to a significant amount of shear force as a result of the rebound of the armor once the tire load has been removed. This concept is discussed in detail in Chapters 4 and 5. Consolidation of the concrete under the armor can mitigate this problem by making the embedding concrete stronger. After the failure of the horizontal stud, the impact load is totally transmitted to the vertical stud. Overloading the vertical stud results in complete failure of the anchorage.

Spalling of the concrete cover over the horizontal stud can also result from galvanic corrosion and expansion of the horizontal anchor device. That corrosion is possible because of bridge deck salting and electrical continuity between anchor devices and the bridge deck reinforcement. The occurrence of galvanic corrosion adjacent to expansion joint edge beams has been documented by the researchers during half-cell testing of many bridge decks in Washington. Another factor that can promote corrosion of anchor devices is the presence of voids in the concrete embedding those devices. That concrete must be well consolidated during construction. However, note that the anchor device will also be subject to corrosion if it deteriorates the surrounding concrete under impact from traffic. In other words, corrosion of the anchor device and deterioration of the surrounding concrete promote each other.

Aluminum retainers/armors are less expensive than steel retainers/armors, but they can be subject to snow plow damage if they are not installed properly. Also aluminum is not thermally compatible with concrete. Thus, when it is anchored to concrete, the possibility of concrete cracking exists. Cracks perpendicular to the edge beam and located

along the edge beam have been reported in an aluminum edge beam installation in New York. (23)

PERFORMANCE OF BACKFILL, BEDDING, AND EMBEDDING MATERIALS

The performances of various types of backfill and bedding materials were discussed in Chapter 2 under "Anchorage System Components." In the same place three types of embedding materials were introduced. Those were glass fiber reinforced concrete (GFRC), slurry infiltrated fiber concrete (SIFCON), and elastomeric concrete (EC). To the researchers' knowledge, no GFRC or SIFCON have been installed in conjunction with bridge expansion joints. However the characteristics of those materials, as discussed in Chapter 2, promise satisfactory construction and performance when used as embedding materials for expansion joint anchorage.

On the other hand, EC has been used as an embedding material for a long time, mainly in conjunction with the sinusoidal anchorage shown in Figure 3, so its performance can be evaluated. EC for expansion joints was first introduced in Europe (France and Germany) in the early 1970s. At least 11 years of satisfactory performance in France, with no evidence of spalling, cracking, or debonding, have been reported. (12) The first installations of EC in the United States were placed in New York in 1979. One project of EC and sinusoidal anchorage was built in Nevada in 1980. This work consisted of 600 feet of expansion joint installed on four sets of twin bridges in the east-west interstate. (22) At the time the bridges were only five years old and had experienced two installations of bolt-down cushion seal systems before requiring replacement. In 1985, the five-year performance of those EC installations was reported. (22) The expansion joint transition areas performed satisfactorily and did not experience failure patterns of cracking, debonding, or spalling due to impact loading and environmental loading. At least six years of satisfactory experience with over 20,000 feet of EC installed in North America have been reported. (22)

Presently, several proprietary EC joint systems are available in the market. The physical properties and performance of those systems may not necessarily be the same. However, an indication of their performance can be obtained through laboratory testing and development of criteria for the key material parameters. This has been done through a decade of experience with EC. The Texas Department of Highways and Public Transportation has developed a material specification for ECs for use as expansion joint material, based on laboratory testing. (13) The key parameters for the performance of EC are strength, flexibility, and bond to the surrounding concrete. Note that the flexibility of EC is the result of the elasticity of its binder. Thus, the characteristics of the binder are also of interest. The Texas specifications for EC requires a minimum compressive stress of 750 psi (measured at 5 percent deflection), a minimum resilience of 75 percent (measured as percent recovery when the compressive load is removed), and a minimum wet bond strength of 200 psi. Usually, high flexibility is obtained in EC at the expense of bond strength. For the binder the Texas specifications require a minimum impact resistance of 7 ft-lb.

TIPS ON CONSTRUCTION AND MAINTENANCE OF EXPANSION JOINTS TO PROLONG THE LIFE OF THEIR ANCHORAGE

The ideal conditions for which the anchorage systems are designed fail to include several factors that can contribute to the systems' failure. Below, the more important of those factors are discussed.

- Strip seals with inverted arch membranes accumulate roadway grit and dirt in the recess of the joint, especially in cold weather when the joint is relatively wide. During periods of warm weather, when the deck expands, the non-resilient grit exerts local pressure on the steel armors. This condition can result in spalling of the adjacent concrete. (2) This phenomenon may be a reason that compression seals perform better than strip seals.

- When anchorage devices are cast directly in concrete, proper consolidation of the concrete around the anchorage is essential. Inadequate consolidation of that concrete can result in a weak material, which bonds poorly with the anchor device. This condition promotes loosening of the anchorage and concrete spalling. Also, that concrete should have minimum shrinkage.
- When the riding surfaces of expansion joint assemblies are not set properly relative to the adjacent roadway surface, excessive impact loads and/or noise can be created. The top edge should be set not less than 0.125 in. nor more than 0.188 in. below the adjacent roadway surface. (§)
- Wheeltrack wear of the roadway creates greater amounts of impact loading on the expansion joint. Wear is especially a problem with asphalt concrete surfaces. The worn areas adjacent to the expansion joint may be filled with polymeric mortars.
- Forces from snowplow blades contribute to the failure of elastomeric components and, to some extent, aluminum components. This is especially a problem when the expansion joint assembly is not set properly relative to the roadway surface.
- In elastomeric components, deformation and wear of the elastomer surrounding the hold-down bolt is possible. This results in enlargement of the slot and rocking of the joint. Elimination of the elastomer between the bolt and the reinforcing metal may eliminate that problem.
- In elastomeric components, creep of the elastomer is possible. This creep may cause hold-down bolt torque dissipation and anchorage looseness. At least 7 days after the initial torquing, the nuts of the hold-down anchor bolts should be retorqued to compensate for creep. (§) Welding of the nuts after the creep has totally taken place may prevent further looseness under traffic action.

- In elastomeric components, rubber plugs used to cover the hold-down bolts eventually become loose under traffic and are subsequently lost. This happens when bolts are not properly centered in the hole. Loss of the plugs can result in accumulation of water and salt in the hole, which in turn causes corrosion and deterioration of the anchorage. Uncovered bolt holes may alternatively be filled with asphaltic or polymeric materials.
- Steel extrusions must be at least 0.375 in. to allow for long-term section loss caused by corrosion. However, thicker edge beams transfer higher levels of impact load to the anchorage. Protecting steel extrusions with epoxy coating will allow the use of thinner sections.
- Steel anchor bolts and studs placed in the concrete are exposed to roadway de-icing salt. Therefore, they are subject to electrochemical galvanic corrosion, since electrical continuity usually exists between these devices and the bridge deck reinforcement. The expansion caused by the metallic corrosion can rupture the concrete surrounding the anchorage. WSDOT's field investigations of bridge decks has shown that half-cell corrosion potentials are usually more negative (an indication of galvanic corrosion) near bridge expansion devices. Epoxy coating of anchor devices can prevent this problem.
- Anchor bolts grouted into drilled holes may be of poorer quality than cast-in-place anchor devices. Large differences in hole diameter and bolt diameter can result in excessive shrinkage of the grout and reduction in the pull-out strength. That difference should not exceed 0.25 in. for cement grouts. (15) For resin grouts the difference is usually very small, and it should not exceed the resin manufacturer's recommendations.
- Joint rebates should be boxed out to the correct level to eliminate the use of bedding materials (e.g., epoxy mortar, cement mortar, or glass fiber

reinforced cement mortar) and their deterioration under traffic impact. If bedding materials are necessary, glass fiber reinforced cement mortar may be used for a better performance.

CHAPTER 4

AN ANALYTICAL PROCEDURE FOR THE DESIGN OF BRIDGE EXPANSION JOINT ANCHORAGE

Presently, the design of bridge expansion joint anchorage systems is based on engineering judgement developed through the adoption of previous designs or modifications to those designs where the systems have performed unsatisfactorily.

This chapter provides an analytical procedure for designing such anchorage systems. Generally, the parameters of interest for anchorage design are the anchor devices' (e.g., studs and bolts) diameter, embedment length, spacing, and their distance from the concrete edge. The type of anchor device (e.g., unheaded studs and bolts versus headed ones) is also of interest. Anchor devices should be designed for two load conditions. First, they and their embedding concrete must resist the repetitions of service truck loads during the structure's service period (i.e., fatigue design). Second, they must resist the maximum permissible truck load that can occur occasionally during the service period. The design procedure presented here is specifically for fatigue design, since that consideration usually governs design. However, this procedure can be easily adapted to the maximum permissible load design.

The first step in designing an anchorage system is to determine the traffic loads transmitted to the anchor devices. The rationale used here for this purpose is based on the flexibility of the expansion device under dynamic loads. Once the loads transmitted have been determined, the anchor devices are designed to have adequate shear and tension strength. Further, they are designed so that the concrete embedding them does not fail. That failure can result from the anchor device pushing against the concrete, and/or it can result from the anchor device pulling out of the concrete.

DETERMINATION OF THE LOADS TRANSMITTED TO THE ANCHORAGE

Koster has shown that when dynamic traffic impact loads are exerted on an expansion joint edge beam, they cause its vibration. (4) The nature of that vibration and the speed of the moving load determine the dynamic loads transmitted to the edge beam and its anchor devices. Note that the traffic impact loads are the static loads multiplied by impact factors dependent on roadway roughness and the vehicle's spring system. The loads transmitted can be lower or higher than the impact loads, depending on both the flexibility of the expansion device and the time during which the impact is exerted (i.e., vehicle speed).

Two factors determine the intensity of the loads transmitted to the edge beam and its anchorage. Those are "impact frequency" (F_i) and "vibration frequency" (F_v). The impact frequency relates to the moving vehicle's impact time and depends on its speed (V) and the length of its tire's bearing surface (L). The impact frequency, with the "impact period" defined as twice the impact time, is as follows:

$$F_i = \frac{V}{2L} \quad \text{Equation 1}$$

The vibration frequency is a characteristic of the edge beam and depends on its mass (m) and spring stiffness (k). The vibration frequency is as follows:

$$F_v = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad \text{Equation 2}$$

On the basis of the equation between a spring's action and reaction (4), the relation between the impact load exerted on the system (P_i) and the load transmitted to the system (P_t) is as follows:

$$\frac{P_t}{P_i} = \frac{1}{\left(\frac{F_i}{F_v}\right)} \quad \text{Equation 3}$$

Generally, Equation 3 is valid for $\frac{F_i}{F_v} > 2$. (4) Both low impact frequencies and high vibration frequencies can make the ratio of $\frac{F_i}{F_v}$ fall below 2. For low impact frequencies, conditions approach those for static loading so that $\frac{P_t}{P_i}$ approaches 1. High

vibration frequencies represent rigid expansion joint systems, which have little give and therefore transmit all the impact load to the edge beam. Here again, $\frac{P_t}{P_i}$ approaches 1. However, regardless of the magnitude of F_i or F_v , when $\frac{F_i}{F_v}$ approaches 1, there is a possibility of resonance effects between the wave of the impact load and the vibration of the elastic system. Koster has shown that for this condition, the maximum of $\frac{P_t}{P_i}$ equal to 1.7 can be expected. (4) Equation 3 and its associated limits, as discussed, are graphed in Figure 14. It is clear from Figure 14, that for an elastic system the load transmitted to the edge beam does not exceed the impact load exerted, except in the resonance region. The load transmitted to the edge beam becomes smaller than the impact load when either the speed of the vehicle is increased (increasing F_i), or the flexibility of the expansion joint system is increased (decreasing F_v).

Of concern in the design of an anchorage is the magnitude of the load transmitted to the anchor device, rather than that transmitted to the edge beam. When a vertical impact (caused by vehicle weight) acts on the edge beam (Figure 15-a), the load transmitted to the edge beam is mainly taken by the concrete directly under it. Only an insignificant portion of the impact load is carried by the anchor device. However, once the impact load has been removed, the rebound of the elastic system creates a load in the system in the opposite direction. The magnitude of the rebound load depends on the damping coefficient of the vibrating system, and at its peak it can equal the transmitted load for an undamped system. The rebound load is carried primarily by the anchor devices, since there is a lack of support for the edge beam under this condition (Figure 15-b). The vertical rebound load can cause anchorage to fail, because the vertical anchor devices can pull out of the concrete, or because the horizontal anchor device can split the concrete cover. In addition to this vertical rebound load, the edge beam is subjected to dynamic horizontal loads caused by braking and/or acceleration of traffic (Figure 15-c). The horizontal load tends to pull the horizontal anchor device out of the concrete and to push the vertical anchor device against the

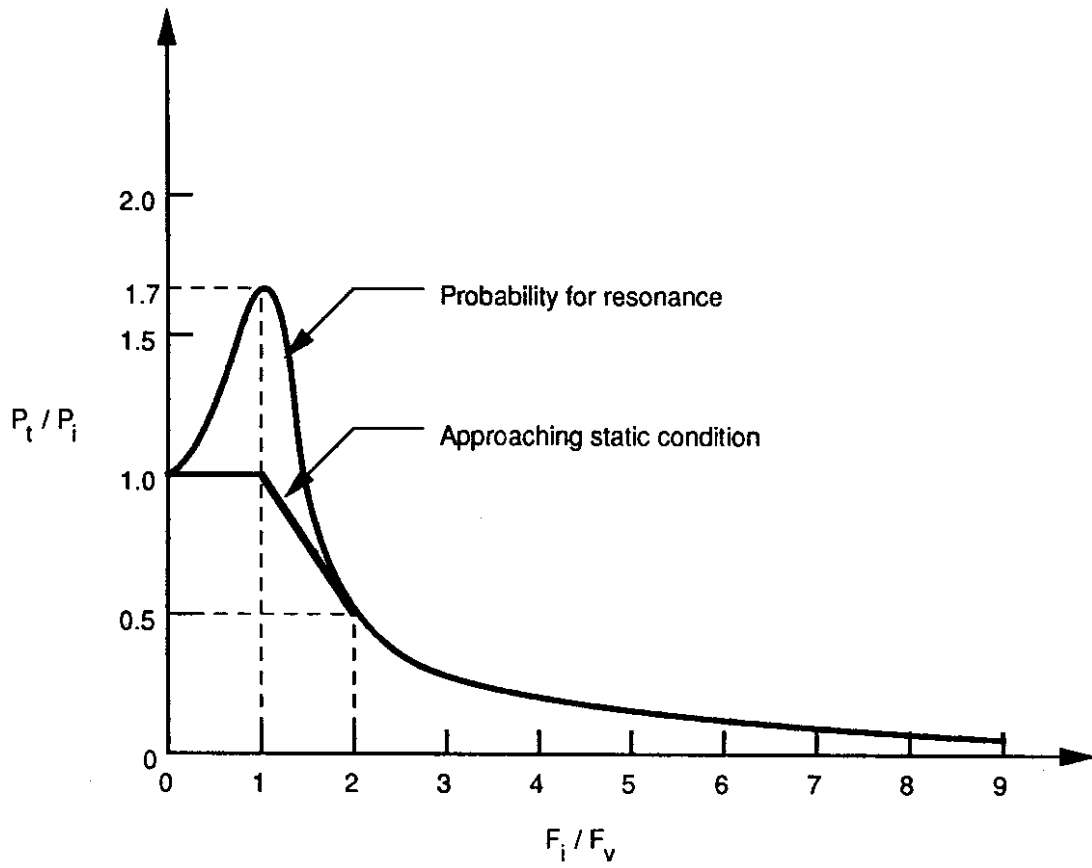


Figure 14. Relation between Impact Load, Transmitted Load, Frequency of Expansion Joint, and Traffic Speed (adapted from Koster, ref. 4)

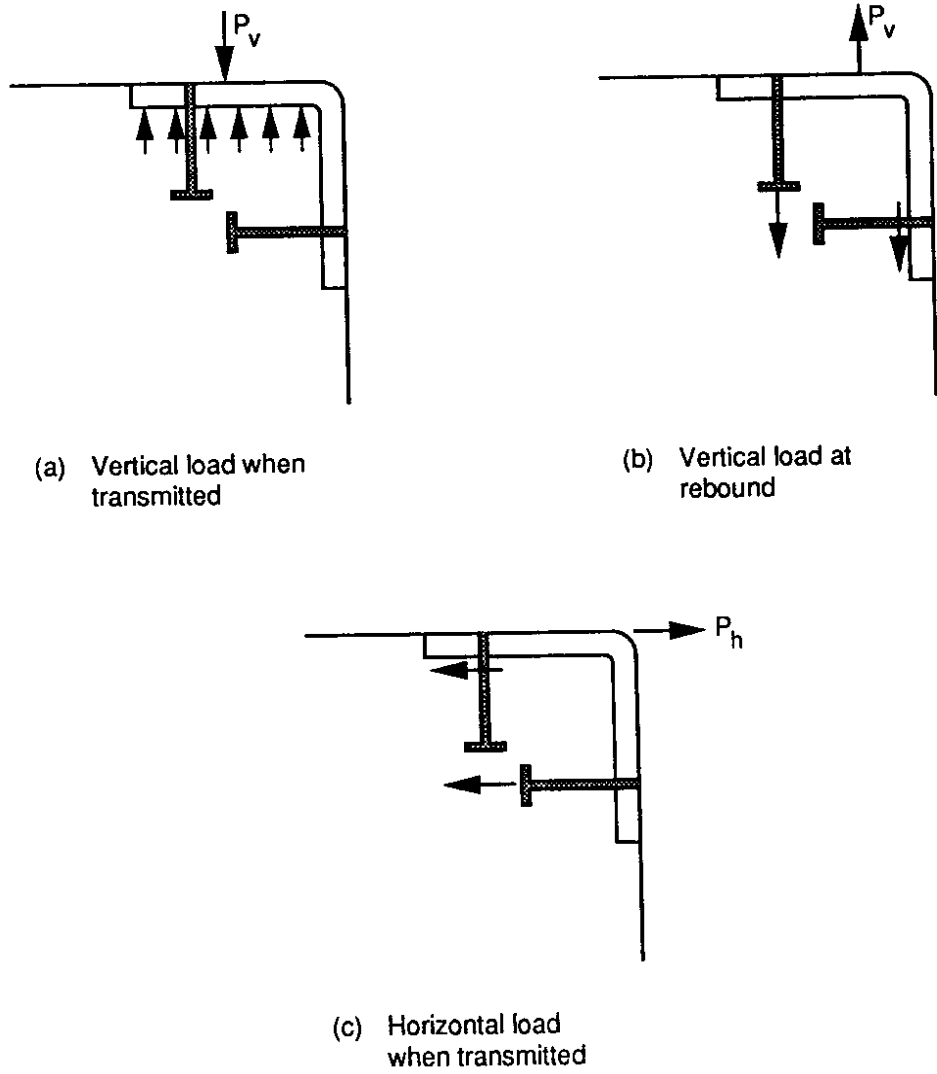


Figure 15. Distribution of Traffic Impact Loads to Expansion Joint Anchor Devices

concrete, again making splitting likely along the line of the anchor. Unlike vertical rebound loads, horizontal loads are transmitted to the anchor devices at the time of their exertion. Thus, the vertical rebound loads and horizontal loads do not act simultaneously.

The vertical component of the design load

On the basis of the prior discussion, the following equation is suggested for determining the vertical component of the design load for anchor devices.

$$P_v = (K_i) \times (K_1) \times (K_d) \times (K_r) \times R \tag{Equation 4}$$

Equation 4 converts the maximum operative truck axle weight (R) to the vertical component of the design load (P_v). The factors in that equation are as follows:

K_i This factor represents the amplification of the truck axle weight due to impact. K_i depends on the overall roughness of the bridge deck, bridge approaches, and the roughness of the expansion joint. (16) It also depends on the spring system of the truck and the speed of the traffic. K_i is generally between 1.15 and 1.35 (4), but depending on the road roughness, it can be as high as 1.7. (16) Repair of potholes, elimination of ruts, and correction of the road profile at the joint can significantly decrease the value of K_i. (16) For design purposes an average value of 1.50 seems appropriate.

K₁ If the horizontal portion of the edge beam is flush with the roadway surface, it may not fully receive the vertical impact loading exerted by the tire. K₁ determines the portion of the vertical impact loading exerted on the edge beam. K₁ is obtained from the following equation adapted from the work by Koster (4):

$$K_1 = \frac{(w + g)}{L} \geq 1 \tag{Equation 5}$$

in which w = width of the horizontal part of the edge beam,
g = width of the joint (gap), and
l = tire bearing length

Of course, if the edge beam protrudes above the roadway surface, K equals unity.

K_d This factor converts the axle impact load to the load transmitted to the edge beam. It takes into account the characteristics of the elasticity of the joint and the duration of the impact. As shown in Figure 14, K_d (i.e., $\frac{P_t}{P_i}$) can have a value between zero and 1.7. For steel edge beams seated on concrete, K_d may fall in the resonance region because of the extremely low flexibility of the joint system in the vertical direction causing very high frequencies of vibration (F_v). For example, for a rigidly supported steel beam, F_v can be around 100 Hz. (4) That magnitude of F_v , when substituted for F_i in Equation 1, gives a traffic speed of 80 mph for a tire bearing length equal to 7 in. This condition corresponds to $\frac{F_i}{F_v} = 1$, or resonance. Thus, all traffic speeds up to 80 mph fall in the resonance region with K_d between 1 and 1.7 (Figure 14). Thus, for steel beams seated on concrete, an average value of 1.35 for K_d is suggested for design purposes. The design of the edge beams should incorporate elasticity concepts to mitigate the level of the impact load transmitted to the beam. An example is a beam that offers elasticity in bending under vertical loading through the cantilever action of its upper horizontal face (figures 4, 5-b).

For elastomeric armors (edge beams with elastomeric bearings) seated on concrete, F_v can be around 10 Hz. (4) Assuming that the lowest repeated traffic speed is 40 mph, F_i will be 50 Hz, and $\frac{F_i}{F_v}$ will be 5. According to Figure 14, this condition corresponds to a K_d of about 0.3. Thus, for elastomeric armors seated on concrete, K_d equal to 0.5 is suggested for design.

K_r This factor represents the loads created in the expansion device as a result of the rebound of the elastic system. K_r can be calculated using the following equation:

$$K_r = \frac{(1 + D)}{2} \quad \text{Equation 6}$$

where D is the ratio of two successive peak amplitudes for the same direction ($D < 1$). D can in turn be obtained from the following equation:

$$\ln(D) = \frac{-2\pi n}{\sqrt{1-n^2}} \quad \text{Equation 7}$$

where n is the damping ratio (the ratio of the vibrating system's damping coefficient to its critical damping coefficient).

Koster (4) has reported that the reciprocal of D equals 1.35 for the average elastomeric spring. The latter value of D gives a K_r equal to 0.87, according to Equation 6, for elastomeric armors. Further, the latter value of D corresponds to a damping ratio (n) of 5 percent, according to Equation 7.

The available literature does not give appropriate D values for steel beams seated on concrete. However, this type of construction should have a higher critical damping coefficient than an elastomeric construction because of its lower flexibility. This should in turn result in a lower damping ratio (n) for steel beams seated on concrete, meaning that their vibrations decay at a slower rate. If a damping ratio (n) of 2 percent is assumed, then from Equation 7, D will be 0.88, and from Equation 6, K_r will be 0.94 for steel edge beams supported by concrete. A reduction in the thickness of the edge beam and an increase in the spacing of its anchor devices should produce more flexibility for steel edge beams for rebound of the system.

Horizontal component of design load

Horizontal loads are exerted on bridge expansion joints at the road level because of braking or acceleration of traffic (friction or traction loads). These loads are dynamic and

can act on the expansion device in such a way that they separate the armor from the concrete. Thus, because they act directly on the edge beam, they are more likely to cause damage than the vertical loads, whose action depends on the rebound characteristics of the elastic system.

The following relation is suggested for determining the horizontal component of the design load for anchor devices:

$$P_h = (K_i) \times (K_h) \times (K_l) \times (K_d) \times R \quad \text{Equation 8}$$

Equation 8 converts the maximum operative truck axle load (R) to the horizontal component of the design load (P_h). The factors in Equation 8 are as follows.

- K_i** This factor represents the amplification of the truck axle weight at the joint, caused by impact. K_i for the horizontal design load is the same as K_i for the vertical design load. Thus, for general design purposes, K_i equal to 1.50 is suggested.
- K_h** This is the ratio of the horizontal to vertical impact load at the bridge expansion joint. K_h values varying from 1/3 (4) to 1/2 (16) have been reported. Multiplication of this ratio by the impact truck axle weight gives the horizontal impact load acting at the road level. Depending on the intensity of the braking and acceleration on the bridge (e.g., bridge on a slope or close to an intersection), a horizontal to vertical impact load ratio of 1/3 to 1/2 should be used.
- K_l** The horizontal portion of the edge beam or the elastomeric pad, when flush with the road surface, may not receive the entire horizontal load from the tire. K_l determines the portion of the horizontal load that is exerted on the expansion device. K_l for horizontal loads is the same as K_l for vertical loads and is obtained using Equation 5.
- K_d** This factor takes into account the dynamic aspects of the horizontal loading, and converts the horizontal load exerted on the edge beam to the horizontal

load transmitted to the edge beam. K_d for horizontal loads is basically the same as K_d for vertical loads. Thus, it can be obtained using Figure 14 and the discussion presented for the vertical value of K_d . Accordingly, for elastomeric armors K_d is suggested to equal 0.5, and for a horizontally rigid system (such as the systems shown in figures 1, 2, 9, and 10 with steel armors anchored horizontally to the concrete) K_d is suggested to equal 1.35.

However, an increase in the spacing of the anchor devices can produce more bending flexibility in the armor, thus decreasing the intensity of the load transmitted to the anchor devices. Also, a steel edge beam that is not anchored to the concrete horizontally and that offers elasticity in bending by cantilever action when subjected to the horizontal load qualifies for a lower amount of K_d . Examples are the edge beams shown in figures 4 and 5-b. In these cases the thickness of the vertical portion of the edge beam determines its flexibility and therefore K_d . While a thickness such as 0.2 in. offers a sufficient amount of flexibility, a thickness such as 0.8 in. is effectively rigid. (4) Tests have shown that the dynamic load capacity of a 0.2 in. thickness associated with a cantilever arm of 1.5 in. is about 1.8 times that of a 0.8 in. thickness associated with a cantilever arm of 4.5 in. Therefore, for the type of steel edge beams discussed, K_d values may vary from 1.35 to $\frac{1.35}{1.8} = 0.75$, depending on the bending flexibility of the edge beam created by cantilever action.

Distribution of design loads to vertical and horizontal anchor devices

Three cases for differing anchor configurations are considered below.

Case 1. Case 1 comprises steel edge beams anchored with both horizontal and vertical welded studs. A general scheme is shown in Figure 15, and actual examples are shown in figures 1 and 9. As discussed earlier, the horizontal and vertical loads are not

exerted simultaneously. The horizontal friction/traction load is applied while the tire is on the edge beam (Figure 15-c), whereas the vertical rebound load is applied upon removal of the tire (Figure 15-b). The horizontal load, transmitted to the edge beam, tends to pull the horizontal stud out of the concrete, and it pushes the vertical stud against the vertical concrete cover. This puts the horizontal stud in tension and the vertical stud in shear. The vertical rebound, on the other hand, tends to pull the vertical stud out of the concrete, and it pushes the horizontal stud against the horizontal concrete cover. This puts the vertical stud in tension and the horizontal stud in shear. The vertical and horizontal studs' share of the transmitted load depends on the embedded studs' stiffness in shear and tension. Hawkins has shown that welded studs embedded in concrete have about the same stiffness in shear and tension. (17) Thus, the load transmitted (either vertical rebound or horizontal friction/traction) may be assumed to be distributed equally between vertical and horizontal studs.

Case 2. In this case the metal edge beam (or the elastomeric retainer/armor) is secured to the concrete by means of vertical hold down bolts only. Examples are shown in figures 7, 8, 11, and 12. The vertical rebound tends to pull the bolt out of the concrete by tension, and the horizontal friction/traction pushes the bolt against the vertical concrete cover by shear. Both the vertical rebound and the horizontal friction/traction are transmitted fully to the bolt.

Case 3. This case comprises metallic edge beams anchored to the concrete through vertical hold-down bolts placed in the bottom of the block-out. An example is shown in Figure 4. This case is the same as Case 2, except that the vertical rebound load is distributed between the bolt and the block-out concrete covering the bolt. While some of that load tends to pull the bolt out of the concrete, the rest tends to separate the block-out concrete from the adjoining deck concrete by the principle of direct shear. Thus, bolts in Case 3 are subject to less tension than those in Case 2, for an equal amount of transmitted rebound load. For design purposes, it is reasonable to assume that the bolt's share of the

vertical rebound load is 75 percent of the total rebound load. Laboratory tests are needed to determine the actual ratio.

THE DESIGN CAPACITY OF THE ANCHORAGE

For a satisfactory design, the loads exerted on the anchorage should not exceed the anchorage's design capacity (i.e., the nominal capacity multiplied by capacity reduction factors). The design capacity of the anchorage is the smaller of the capacity of the anchor devices and the capacity of the embedding concrete.

The design capacity of the anchor device

An anchor device is subject to tension and shear. The design tension capacity of a stud (or a bolt) can be found using Equation 9.

$$T = 0.6F_y \times \left(\frac{\pi d^2}{4}\right) \leq 24,000 \times \left(\frac{\pi d^2}{4}\right) \quad \text{Equation 9}$$

in which T is the design capacity of the stud (or bolt) in lbs,
 d is the stud (or bolt) diameter in inches, and
 F_y is the stud (or bolt) yield strength in psi.

Equation 9 incorporates a capacity reduction factor of 0.6, as well as a maximum tensile strength of 24,000 psi, assuming the number of loading cycles is over 2,000,000 (AISC loading condition 4 and loading category A).

The design shear capacity of a stud (or bolt) may be obtained from Equation 10.

$$S = 0.36F_y \times \left(\frac{\pi d^2}{4}\right) \leq 8,000 \times \left(\frac{\pi d^2}{4}\right) \quad \text{Equation 10}$$

where S is the design shear capacity in lbs,
 d is the stud (or bolt) diameter in inches, and
 F_y is the stud (or bolt) yield strength in psi.

Equation 10 incorporates a capacity reduction factor of 0.36 and a maximum shear strength of 8,000 psi, assuming the number of loading cycles over 2,000,000 (AISC loading condition 4 and loading category F).

The design capacity of concrete

The capacity of the embedding concrete depends on both its strength to prevent the tensioned stud (or bolt) from pulling out and on its strength to endure the pressure from the laterally forced stud (or bolt). The capacity of the concrete can depend on the shape of the anchor device (i.e., unheaded versus headed anchor device).

Unheaded anchor device. In this case, the design capacity of the concrete to prevent the tensioned anchor device from pulling out depends on its bond with the embedding concrete and can be obtained from Equation 11, presented by researchers Cziesielski and Friedman. (18)

$$T_c = 0.57 \times (f_{cb}) \times (l) \times (\pi d) \quad \text{Equation 11}$$

where T_c is the allowable tension force in the stud (or bolt) in lbs to prevent bond failure of the concrete,
 l is the embedded length of the stud (or bolt) in inches,
 d is the diameter of the stud (or bolt) in inches, and
 f_{cb} is the bond strength between concrete and a deformed anchor device in psi.

According to German standards, f_{cb} can be obtained from Equation 12 for deformed bars. (18)

$$f_{cb} = 0.53 \times (f'_c)^{0.67} \quad \text{Equation 12}$$

in which f'_c is the compressive strength of the concrete in psi.

Note that Equation 11 is not valid for covers of less than 3 bar diameters. Equation 11 incorporates a capacity reduction factor of 0.57, but it does not consider load repetitions. This may be done by substituting the compressive strength of the concrete in fatigue in Equation 12 for f'_c . The fatigue compressive strength of concrete for 1,000,000 load cycles is about 0.5 times its compressive strength, when the lower stress limit is zero, which is the case with the anchor devices. (19)

The design capacity of concrete to bear pressure from a laterally forced anchor device may be obtained from Equation 13, presented by Cziesielski and Friedman. (18)

$$S_c = \frac{330 \times (a) \times (b) \times (f'_c) \times (d^{2.1})}{(344 + 320c)} \quad \text{Equation 13}$$

where S_c is the allowable shear force in lbs in the stud (or bolt) to prevent the failure of the concrete cover in bearing or its splitting,
 d is the diameter of the stud (or bolt) in inches,
 c is the projecting length of the anchor device in inches (see Figure 16 for c ; c is zero for welded studs), and
 a and b are dimensionless parameters representing the mode of failure based on the depth of cover and anchor device spacing, as shown in Figure 16.

In Equation 13, f'_c is the compressive strength of the concrete in psi. The equation incorporates a capacity reduction factor of 0.67, but without consideration for load repetitions. To compensate for the load repetitions, f'_c is suggested to equal the fatigue strength of the concrete (i.e., 0.5 times the compressive strength). That reduction is appropriate whether the failure is in bearing or in splitting. (19). The embedment length has no effects on the pressure exerted on the concrete as long as it is at least 5 bar diameters. Lesser embedment lengths cause higher pressures on the concrete and result in allowable shear forces lower than that given by Equation 13.

Headed anchor device. Headed studs or anchor bolts may be used to compensate for reduced embedment lengths. For headed studs (or bolts), the design capacity of the embedding concrete to prevent the anchor device from pulling out can be obtained from Equation 14, developed by Bode and Roik. (20)

$$T_c = 6.58 \times (a) \times (l^{0.5}) \times (1 + d_h) \times (f'_c)^{0.5} \quad \text{Equation 14}$$

where T_c is the design capacity of the concrete to preventing the tensioned anchor device from pulling out,

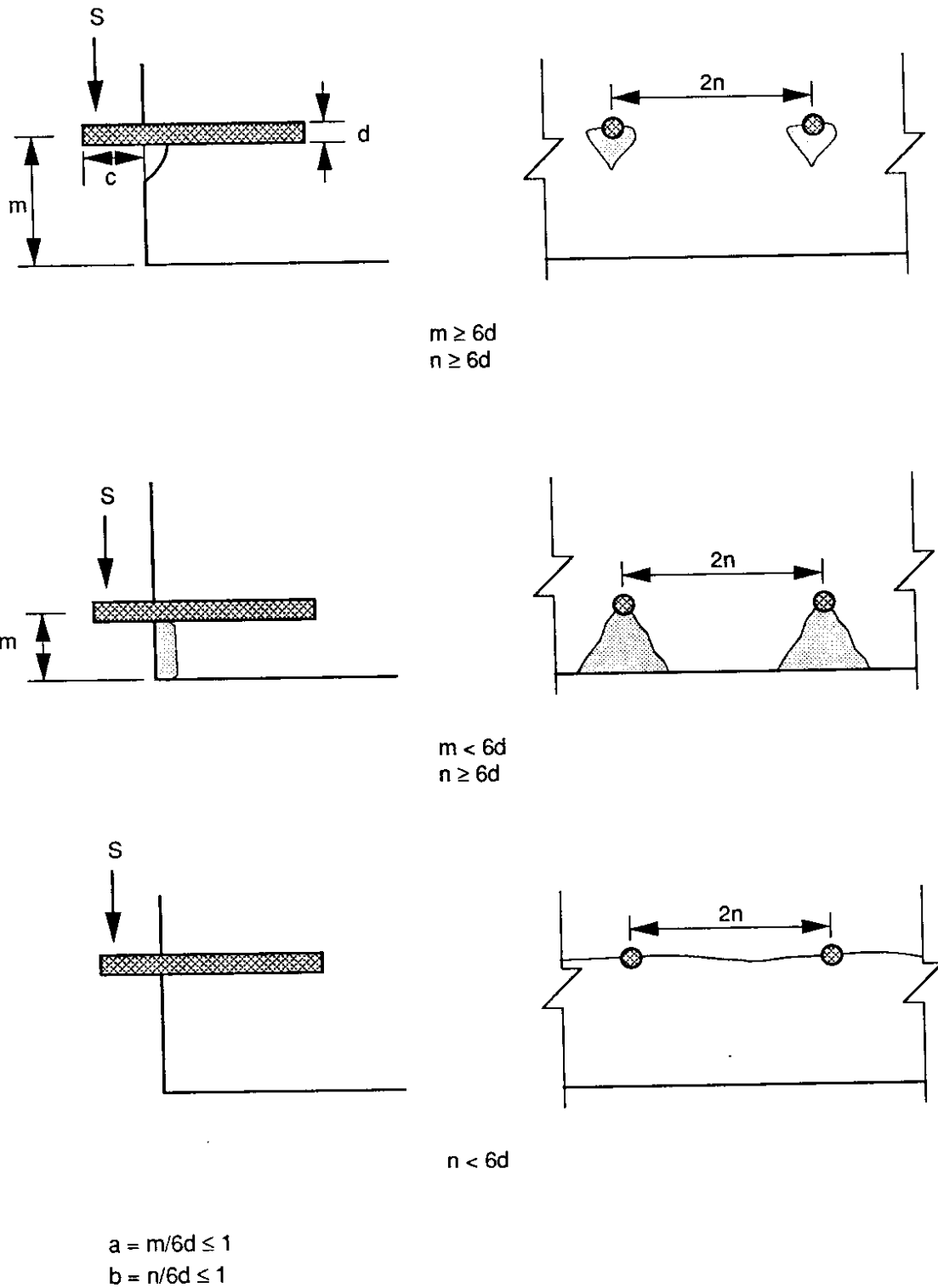


Figure 16. Modes of Failure for Concrete Subject to Pressure from Laterally Forced Anchor Device (adapted from ref. 18)

- l is the embedded shaft length in inches,
- d_h is the diameter of the stud head in inches,
- f'_c is the compressive strength of concrete in psi, and
- "a" is a factor that incorporates the effects of concrete cover depth.

The magnitude of "a" is obtained from Equation 15.

$$a = \frac{(c)}{(1.5 \times l)} \geq 1 \quad \text{Equation 15}$$

in which c is the cover depth in inches.

Equation 15 is a simplified version of the original equation presented in Reference 20. The original equation accounts for the effects of the concrete compressive strength, but those effects are insignificant for the range in compressive strengths likely for bridge decks.

Equation 14 was developed for Nelson studs and the corresponding variations in stud head and shank diameter. Tests reported in Reference 20 included studs as large as 0.87 in. in shank diameter and 1.37 in. in head diameter, and studs as small as 0.39 in. in shank diameter and 0.75 in. in head diameter. Also, Equation 14 incorporates a capacity reduction factor of 0.33, but it does not consider the effects of cyclic loading. As discussed previously, for resistance against cyclic loading, the fatigue strength of concrete in compression (i.e., 0.5 times the compressive strength) may be used in Equation 14 instead of f_c.

For headed studs and bolts, the design capacity of the embedding concrete to bear the pressure from the laterally forced anchor device should be the same as that for the unheaded anchor device, since that capacity is mainly affected by the diameter of the anchor device and embedment length. Thus, Equation 13 and the corresponding discussion should be valid for headed as well as unheaded devices.

CHAPTER 5

EXAMPLE OF THE USE OF THE ANALYTICAL PROCEDURE TO DESIGN EXPANSION JOINT ANCHORAGES

This example problem illustrates how the systematic analytical procedure developed in Chapter 4 is applied to an actual bridge expansion joint. In the example problem, the analytical procedure is employed as a first trial to check the long-term structural capacity of an expansion joint anchorage design, and to suggest modifications for the second trial in the case of an inadequate capacity.

DESCRIPTION OF EXAMPLE PROBLEM

The expansion joint to be examined is illustrated in Figure 17. It consists of a compression seal retained by two steel angles, which also armor the concrete. The angles are anchored to the concrete by means of alternative welded vertical and horizontal studs. The joint has an average width of 3 in. during the year. The bridge is built on slope and is subject to one million repetitions of HS-20 truck loading during its service period.

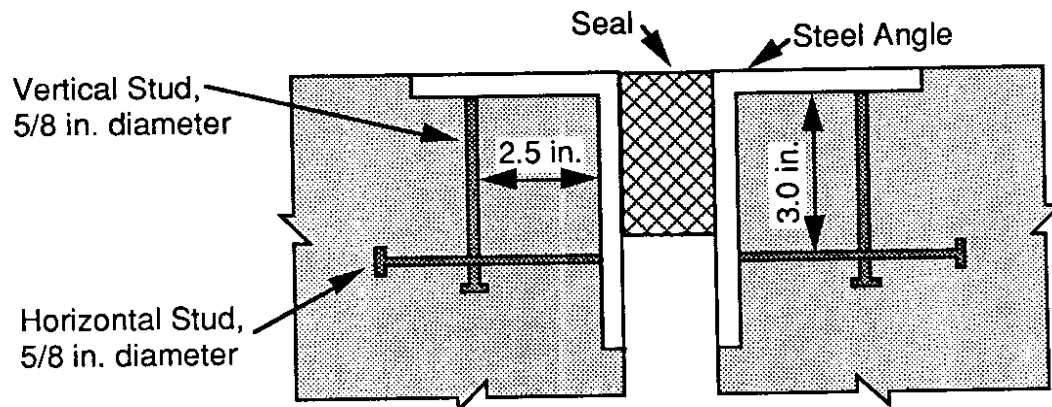


Figure 17. Expansion Joint Examined in the Worked Example

In the first trial design the armors are two L 4 x 3-1/2 x 3/8, with the horizontal leg being 3-1/2 in. and the vertical leg being 4 in. The studs are made of steel with 60,000 psi yield strength. The stud shaft is 0.625 in. in diameter, and it is 4 in. long. The head diameter is 1 in. The studs are spaced 12 in. on center. The clear concrete cover depth for the vertical studs is 2.5 in., and it is 3 in. for the horizontal studs. The embedding concrete has a compressive strength of 4,500 psi.

STEP ONE. DETERMINE THE DESIGN LOADS ENDURED BY THE ANCHORAGE

Vertical rebound load

$$P_v = (K_i) \times (K_l) \times (K_d) \times (K_r) \times R \quad \text{Equation 4}$$

in which

$$P_v = \text{vertical rebound load in lb/ft}$$

$$K_i = 1.50; \text{ impact factor for average road roughness}$$

$$K_l = \frac{(w + g)}{L} \geq 1; \text{ factor representing effective portion of tire load}$$

$$= \frac{[(3.5 \text{ in.}; \text{ horizontal leg of angle}) + (3 \text{ in.}; \text{ average joint width})]}{(7 \text{ in.}; \text{ tire bearing length})}$$

$$= 0.92$$

$$K_d = 1.35; \text{ factor for dynamic load transmitted to steel armor}$$

$$K_r = \frac{(1 + D)}{2}; \text{ rebound factor}$$

$$= \frac{[1 + (0.88; \text{ ratio of successive peak amplitude for rigid system})]}{2}$$

$$= 0.94$$

$$R = \frac{(32,000 \text{ lb}; \text{ truck axle load})}{(10 \text{ ft. truck effective width})}$$

$$= 3,200 \text{ lb/ft}; \text{ distributed truck axle load}$$

then

$$P_v = (1.50) \times (0.92) \times (1.35) \times (0.94) \times 3,200$$

$$= 1.75 \times 3,200$$

$$= 5,604 \text{ lb/ft}$$

Horizontal friction/traction load

$$P_h = (K_i) \times (K_h) \times (K_l) \times (K_d) \times R \quad \text{Equation 8}$$

in which

$$P_h = \text{horizontal friction/traction load in lb/ft}$$

$$\begin{aligned}
K_i &= 1.50; \text{ same as vertical load condition} \\
K_h &= 0.5; \text{ for bridge on slope} \\
K_l &= 0.92; \text{ same as vertical load condition} \\
K_d &= 1.35; \text{ same as vertical load condition} \\
R &= 3,200 \text{ lb/ft; same as vertical load condition} \\
\text{then } P_h &= (1.50) \times (0.5) \times (0.92) \times (1.35) \times 3,200 \\
&= (0.93) \times 3,200 \\
&= 2,981 \text{ lb/ft}
\end{aligned}$$

STEP TWO. DISTRIBUTE THE DESIGN LOADS TO THE VERTICAL AND HORIZONTAL ANCHOR DEVICES

The welded studs have about the same stiffness in shear and tension. Thus, the loads transmitted to the anchorage (i.e., P_v and P_h) are distributed equally between the vertical and horizontal studs. The vertical rebound (P_v) and horizontal friction/traction (P_h) do not occur simultaneously.

Considering the spacing of the studs (i.e., 12 in.), a vertical stud is subject to

$$\begin{aligned}
\frac{P_v}{2} &= \frac{5,604}{2} \\
&= 2,802 \text{ lb tension load; and} \\
\frac{P_h}{2} &= \frac{2,981}{2} \\
&= 1,491 \text{ lb shear load.}
\end{aligned}$$

On the other hand, a horizontal stud is subject to

$$\begin{aligned}
\frac{P_h}{2} &= \frac{2,981}{2} \\
&= 1,491 \text{ lb tension load; and} \\
\frac{P_v}{2} &= \frac{5,604}{2} \\
&= 2,802 \text{ lb shear load.}
\end{aligned}$$

STEP THREE. DETERMINE THE DESIGN CAPACITY OF THE ANCHOR DEVICES

The tensile capacity of the studs

$$T = 0.6F_y \times \left(\frac{\pi d^2}{4}\right) \dagger 24,000 \times \left(\frac{\pi d^2}{4}\right) \quad \text{Equation 9}$$

in which T = stud tensile capacity for 2 million load repetitions in lb

F_y = 60,000 psi; stud yield strength

d = 0.625 in.; stud shaft diameter

then $T = \frac{(24,000) \times (3.14 \times 0.625^2)}{4}$

$$= 7,359 \text{ lb}$$

$T > 2,802 \text{ lb}$; then vertical stud O.K.

$T > 1,491 \text{ lb}$; then horizontal stud O.K.

The shear capacity of the studs

$$S = 0.36F_y \times \left(\frac{\pi d^2}{4}\right) \dagger 8,000 \times \left(\frac{\pi d^2}{4}\right) \quad \text{Equation 10}$$

in which S = stud shear capacity for 2 million load repetitions in lb

F_y = 60,000 psi; stud yield strength

d = 0.625 in.; stud shaft diameter

then $S = \frac{(8,000) \times (3.14 \times 0.625^2)}{4}$

$$= 2,453 \text{ lb}$$

$S > 1,491 \text{ lb}$; then vertical stud O.K.

$S < 2,802 \text{ lb}$; then horizontal stud Not Good; shear failure of horizontal stud possible

Alternative designs to prevent shear failure of horizontal stud

1. Increase stud diameter.
2. Decrease stud spacing (this alternative is the least preferred, since it can increase the rigidity of the beam).

STEP FOUR. DETERMINE THE DESIGN CAPACITY OF THE EMBEDDING CONCRETE

Concrete capacity for vertical stud pull-out

$$T_c = 6.58 \times (a) \times (l^{0.5}) \times (1 + d_h) \times (f_c^{0.5}) \quad \text{Equation 14}$$

in which

$$T_c = \text{pull-out capacity of concrete in lb}$$

$$a = \frac{(c)}{(1.5 \times l)} \geq 1; \text{ factor for effects of shallow cover depth}$$
$$= \frac{(2.5 \text{ in.; cover depth})}{[1.5 \times (4 \text{ in.; shaft length})]}$$
$$= 0.42$$

$$l = 4 \text{ in.; shaft length}$$

$$d_h = 1 \text{ in.; stud head diameter}$$

$$f_c = (0.5) \times 4,500$$

$$= 2,250 \text{ psi; fatigue strength of concrete for 1 million load cycles}$$

then

$$T_c = (6.58) \times (0.42) \times (4^{0.5}) \times (4 + 1) \times (2,250^{0.5})$$

$$= 1,312 \text{ lb}$$

$T_c < 2,802 \text{ lb}$; then vertical stud Not Good; diagonal pull-out cracking progressing from stud head possible

Alternative designs to prevent diagonal pull-out cracking caused by vertical stud

1. Increase cover depth.
2. Select armor angle with smaller horizontal leg.
3. Increase stud shaft length.
4. Decrease spacing of studs (this alternative is the least preferred, since it can increase the rigidity of the edge beam).

Concrete capacity for horizontal stud pull-out

$$T_c = 6.58 \times (a) \times (l^{0.5}) \times (1 + d_h) \times (f_c^{0.5}) \quad \text{Equation 14}$$

in which

$$T_c = \text{pull-out capacity of concrete in lb}$$

$$a = \frac{(c)}{(1.5 \times l)} \geq 1; \text{ factor for effects of shallow cover depth}$$
$$= \frac{(3 \text{ in.; cover depth})}{[1.5 \times (4 \text{ in.; shaft length})]}$$

$$= 0.50$$

$$l = 4 \text{ in.}; \text{ stud shaft length}$$

$$d_h = 1 \text{ in.}; \text{ stud head diameter}$$

$$f'_c = (0.5) \times 4,500$$

$$= 2,250 \text{ psi}; \text{ fatigue strength of concrete for 1 million load cycles}$$

then $T_c = (6.58) \times (0.50) \times (4^{0.5}) \times (4 + 1) \times (2,250^{0.5})$
 $= 1,492 \text{ lb}$

$$T_c > 1,491 \text{ lb}; \text{ then horizontal stud O.K.}$$

Concrete bearing capacity for vertical stud

$$S_c = \frac{330 \times (a) \times (b) \times (f'_c) \times (d^{2.1})}{(344 + 320c)} \quad \text{Equation 13}$$

in which $S_c = \text{bearing capacity of concrete for vertical stud in lb}$

$$a = \frac{(m)}{(6 \times d)} \geq 1; \text{ factor for effects of cover depth}$$

$$= \frac{(2.5 \text{ in.}; \text{ cover depth})}{[6 \times (0.625 \text{ in.}; \text{ stud diameter})]}$$

$$= 0.67$$

$$b = \frac{(n)}{(6 \times d)} \geq 1; \text{ factor for effects of stud spacing}$$

$$= \frac{(12 \text{ in.}; \text{ stud spacing})}{[6 \times (0.625 \text{ in.}; \text{ stud diameter})]}$$

$$= 1$$

$$f'_c = (0.5) \times 4,500$$

$$= 2,250 \text{ psi}; \text{ fatigue strength of concrete for 1 million load cycles}$$

$$d = 0.625 \text{ in.}; \text{ stud diameter}$$

$$c = 0.00 \text{ in.}; \text{ zero for welded studs}$$

then $S_c = \frac{(330) \times (0.67) \times (1) \times (2,250) \times (0.625^{2.1})}{(344)}$
 $= 539 \text{ lb}$

$$S_c < 1,491 \text{ lb}; \text{ then vertical stud Not Good; spalling of vertical concrete surface possible}$$

Alternative designs to prevent vertical concrete surface spalling

1. Increase cover depth.
2. Increase stud diameter.
3. Select armor angle with smaller horizontal leg.
4. Decrease stud spacing (this alternative is the least preferred, since it can increase the rigidity of the edge beam).

Concrete bearing capacity for horizontal stud

$$S_c = \frac{330 \times (a) \times (b) \times (f'_c) \times (d^{2.1})}{(344 + 320c)} \quad \text{Equation 13}$$

in which S_c = bearing capacity of concrete for horizontal stud in lb

$$\begin{aligned} a &= \frac{(m)}{(6 \times d)} \geq 1; \text{ factor for effect of cover depth} \\ &= \frac{(3 \text{ in.; cover depth})}{[6 \times (0.625 \text{ in.; stud diameter})]} \\ &= 0.80 \end{aligned}$$

$$\begin{aligned} b &= \frac{(n)}{(6 \times d)} \geq 1; \text{ factor for effect of stud spacing} \\ &= \frac{(12 \text{ in.; stud spacing})}{[6 \times (0.625 \text{ in.; stud diameter})]} \\ &= 1 \end{aligned}$$

$$\begin{aligned} f'_c &= (0.5) \times 4,500 \\ &= 2,250 \text{ psi; fatigue strength of concrete for 1 million load cycles} \end{aligned}$$

$$d = 0.625 \text{ in.; stud diameter}$$

$$c = 0.00 \text{ in.; zero for welded studs}$$

then
$$\begin{aligned} S_c &= \frac{(330) \times (0.80) \times (1) \times (2,250) \times (0.625^{2.1})}{(344)} \\ &= 707 \text{ lb} \end{aligned}$$

$S_c < 2,802 \text{ lb}$; then vertical stud Not Good; spalling of horizontal concrete surface possible

Alternative designs to prevent horizontal concrete surface spalling

1. Increase cover depth.
2. Increase stud diameter.
3. Select armor angle with smaller horizontal leg.

4. Decrease stud spacing (this alternative is the least preferred, since it can increase the rigidity of the edge beam).

CHAPTER 6

SUGGESTED RESEARCH

Below is suggested further laboratory studies and field demonstrations to verify and/or modify the recommendations of the current investigation.

TASK 1. EXPERIMENT DESIGN

Of importance to the design of bridge expansion joint anchorages are the dynamic loads transmitted to the anchor devices. The loads endured by the anchorage can be calculated by knowing the frequency of the vibrations of the expansion joint assembly and the damping ratio of the vibrating system, as discussed previously in this report. In this task, laboratory experiments will be designed in which various rigid and elastomeric expansion joints will be installed in concrete and subjected to impact loads to measure the frequency and damping characteristics. Impact loading will continue to measure the capacity of the systems as well.

Also, laboratory experiments will be designed to evaluate the effectiveness of the three shock absorbing materials introduced in this report as potential embedding materials for anchor devices (i.e., glass fiber reinforced concrete, slurry infiltrated fiber concrete, and elastomeric concrete). In those experiments anchor devices will be installed in blocks made of the three shock absorbing materials and subjected to both dynamic pull-out and dynamic shear loads simulating traffic impact loads. The number of load repetitions until failure of the embedding material will be determined and compared to that of control specimens made of conventional bridge deck concrete. If satisfactory results are obtained, field demonstration projects will be designed to install bridge expansion joints in several bridges using the experimental shock absorbing embedding materials. In those field demonstrations the practicality and performance of the new materials will be evaluated.

TASK 2. LABORATORY TESTS

This task will include laboratory experiments conducted in accordance with the designs produced in Task 1. The University of Washington's Civil Engineering Structural and Materials Laboratories are available for the laboratory tests.

TASK 3. DEVELOPMENT OF FINAL RECOMMENDATIONS

On the basis of the analysis and interpretation of the test data and the background data available from the current investigation, final recommendations for the design and construction of durable expansion joints will be made for WSDOT's consideration.

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