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Bascule Leaf Fabrication and Erection Tolerances: Where Structure Meets Machine

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DOUBLE TREE HOTEL AT UNIVERSAL STUDIOS
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Introduction

Objective

The intent of this paper is to discuss the steel fabrication and erection tolerances of bascule leaf structures, the factors that affect the alignment of critical components of these structures and specialized techniques used to achieve the alignment to the required tolerances. This paper focuses on trunnion bascule leaves, the most common type of movable bridge, although many aspects of this discussion are appropriate for other types of movable spans. Trunnion bascule bridges are unique structures that have special alignment requirements different than other types of steel structures. While the steel framing of bascule leaves is generally constructed to steel fabrication tolerances in the magnitude of 1/16" to 1", bascule leaf machinery mounted on these structures (e.g., trunnion assemblies, rack assemblies, hydraulic cylinders, span lock guides and receivers, live load shoes, etc.) generally require alignment to machine tolerances in the magnitude of 1/1000". Although many of the steel industry fabrication and erection tolerances are appropriate for this type of structure, there are other critical aspects of alignment that require greater precision that must be considered in order to ensure that the bridge will operate properly and provide years of safe and reliable operation. Knowledge of the various fabrication and erection tolerances for a bascule span is also needed in the design of the structure.

Review of Current Practice

Even though trunnion bascule bridges have been constructed for more than 100 years, there still is not a well defined set of specifications that address the special fabrication and erection requirements, tolerances and alignment criteria for this type of structure. The AASHTO design specifications are not complete in the specification on limits of accuracy and thus it is usually up to each owner, who may decide to pass on these responsibilities to the contractor or design consultant, to establish the limits. As such, project specifications have not been consistent and have resulted in widely varying practice throughout the movable bridge industry. Where requirements have not been well defined, fabricators and erectors have been left to interpret the owner's intent and where necessary apply judgment, which in most cases is in the contractor's best interest. "Standard industry practice" is difficult to define as the practice varies widely throughout the industry. Some owners have provided performance specifications leaving the details of how to achieve the final product up to the contractor, fabricator and erector. Others have defined detailed alignment requirements, many of which have not been well thought out and have been difficult if not impossible to achieve with the standard equipment and practices used in steel fabrication facilities. Both poorly defined specifications and overly stringent specifications have resulted in unnecessarily higher bid prices as contractors, fabricators and erectors have had to factor the cost of risk into their bid, not knowing whether the work would be rejected. Disputes often occur between erectors and fabricators over responsibility of work that is out of specification. Inspectors have had difficulty in assessing whether the product meets the specifications and intent of the design. Owners and contractors have been left to argue over whether the final product is acceptable. As such, the movable bridge industry is in need of consistent and clearly defined specifications for this work. Until a comprehensive specification for bascule leaf fabrication and erection is prepared, it is recommended that contractors, fabricators and erectors continue to be required to prepare detailed fabrication, erection and alignment procedures in advance of the work.

The following summarizes the current governing documents for dimensional control in the fabrication and erection of bascule bridges in the United States.

Structural Steel:

- *ASTM A6, General Requirements for Rolled Structural Steel Bars, Plates, Shapes and Sheet Piling*: Addresses mill tolerances on rolled shapes and plates that are the basic building materials for steel bridge construction. Dimensional tolerances for plates include thickness, width, length, flatness, waviness and camber. Dimensional tolerances for shapes include length, depth, flange width, thickness, sweep, camber, squareness, and offset. These provisions apply to the material from the mill when it is delivered to the fabricator.
- *AASHTO/AWS D1.5, Bridge Welding Code, Chapter 3 (Workmanship)*: Addresses steel fabrication tolerances of welded members including member straightness, camber, sweep, web-flange offset, web flatness, flange tilt, girder depth, stiffener fit-up and straightness, and bolted connection fit-up. Once the steel has been fabricated, the dimensional provisions of ASTM A6 are superseded by these provisions.
- *AASHTO/NSBA Steel Bridge Collaboration Steel Bridge Fabrication Guide Specification* (NEW): Addresses additional fabrication tolerances for contact and bearing surfaces, bolt holes, plate bending, member heat curving, cambering and straightening, and bolted splices.
- *AASHTO Standard Specifications for Highway Bridges, Division II (Construction)* and *AASHTO LRFD Bridge Construction Specifications*: These documents include very limited information on structural steel dimensional control requirements.

There currently is no document that defines dimensional controls for steel bridge erection. The AASHTO/NSBA Steel Bridge Collaboration is currently developing a steel bridge erection standard; however, this document was not available at the time this paper was published and is not expected to specifically address erection tolerances for movable bridges.

Machinery:

With the exception of recommended fits and surface finishes, specific tolerances for fabrication and alignment of movable bridge machinery are not specifically defined in the AASHTO Standard Specifications for Movable Highway Bridges or the AASHTO LRFD Movable Highway Bridge Design Specifications. Division III (Materials and Workmanship) and Division IV (Erection) of the AASHTO Standard Specifications address only general alignment requirements using terms such as "best machine shop practice" and "parts shall be fitted together accurately" and "aligned with the utmost accuracy". These specifications imply that the limits of accuracy be left up to the individual owner, design engineer and/or contractor.

The following sources and documents are referenced in the design specifications and are frequently used in the performance of the machinery work:

- Alignment tolerances for gears are addressed by the American Gear Manufacturer's Association (AGMA) standards for Open Gearing.
- Alignment tolerances for rolling element bearings are defined by the American Bearing Manufacturer's Association (ABMA) standards.
- Fits for machinery parts are defined by the American National Standards Institute (ANSI/ISO) B4.2, Preferred Metric Limits and Fits. AASHTO Specifications recommend fits for various components.
- Surface finishes are defined by the American Society of Mechanical Engineers (ASME) B46.1, Surface Texture (Surface Roughness, Waviness and Lay). AASHTO Specifications recommend surface finishes for various components.

Construction to the tolerances in the above sources and documents has resulted in widely varying results. The above documents do not address all machinery alignment tolerances required to construct a proper working bridge and there is a great deal of interpretation in the application of the information to movable bridges, as the information has not been developed specifically for this application. As these documents cover a wide range of machinery applications, there are many choices and decisions that must be made in properly applying these documents. In general, it takes experienced engineers, contractors, fabricators and erectors to interpret and properly apply this information.

There are many elements of a bascule bridge that are critical to the safe and reliable operation and that must be properly aligned. The following discussion highlights the alignment tolerances, factors affecting the alignment and specialized practices used during shop fabrication and field erection to achieve alignment to the required tolerances.

Bascule Leaf Steel Framing

Trunnion bascule leaves consist of a steel framework of welded plate girders and rolled steel members that pivot about a horizontal axis and is balanced by a counterweight. This framework typically consists of main longitudinal load carrying elements (bascule girders or main girders) that support the floor framing system and counterweight, and transfer loads to the piers. Most trunnion bascule leaves consist of a pair of bascule girders (or trusses), although there have been trunnion bascule spans with three or four bascule girders. Each bascule girder is typically fitted with a trunnion assembly and live load shoe. The bascule leaf is supported on and pivots about the trunnion assembly and the live load shoes serve as an additional support that provides stability while traffic is on the span.

PHOTO 1: Typical Trunnion Bascule Span

Floor systems typically consist of transverse members (floorbeams and brackets) that span between or cantilever outboard the bascule girders. The floorbeams and cantilevered brackets support longitudinal stringers that support the roadway deck and sidewalk flooring.

The overall framework is typically braced with horizontal diagonal bracing. Other specific elements including the floorbeams and cantilevered brackets are additionally braced to prevent weak axis bending when the bascule leaf is operated.

The operating machinery (e.g. racks for electric motor or hydraulic motor drive systems, or hydraulic cylinders) that moves the bascule leaves is attached at strategic locations to the structure.

Counterweights are typically constructed of cast-in-place reinforced concrete supported by transverse members (counterweight girders or trusses) that span between the bascule girders. Additional vertical and horizontal bracing frames are often provided within the counterweight to stiffen the structure during concrete placement and transfer the loads from the counterweight to the counterweight girders and bascule girders. However, some bascule leaves utilize a steel counterweight box that spans between the bascule girders and supports steel and concrete ballast.

The decks on trunnion bascule spans are typically lightweight to reduce the weight that must be balanced. Lightweight decks most often consist of steel open grid flooring systems (i.e. panels consisting of a grid of interlocked steel bars) although, many decks also consist of conventional reinforced concrete slabs, orthotropic deck systems, and Exodermic deck systems (similar to steel grid flooring except made composite with a thin concrete deck on top of the steel grid). Sidewalk flooring can consist of the same system as the roadway deck, although is usually a lighter steel or aluminum grating.

The construction of bascule leaves generally consists of shop fabrication and field erection. The shop fabrication consists of fabrication of individual steel components and shop assembly and alignment of the framework. Once the shop assembly and alignment is complete, the framework is dismantled into individual components or subassemblies for cleaning and painting, and shipment to the job site for erection.

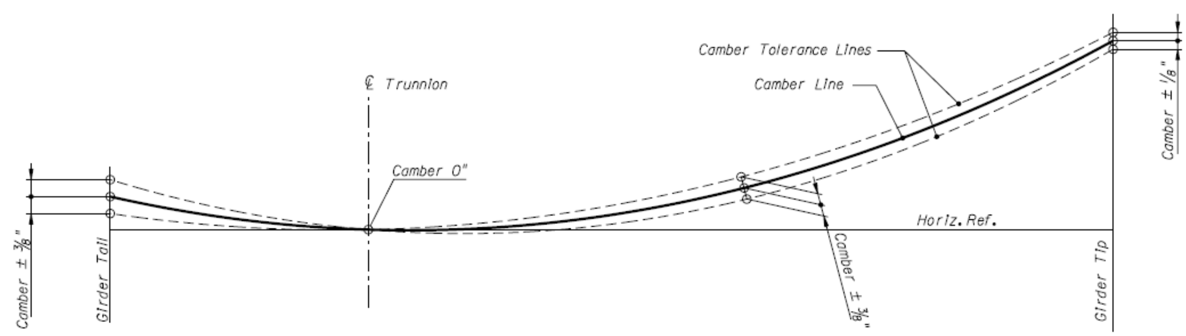
Individual Member Fabrication

General tolerances for fabrication of individual steel components are defined in *ASTM A6* and, Chapter 3 of *AASHTO/AWS D1.5 (Bridge Welding Code)*. For the most part, these tolerances are directly applicable to the fabrication of the various bascule leaf components (e.g. bascule girders, floorbeams, cantilevered brackets, stringers, lateral bracing, counterweight framing, etc.) However, because of the unique design and construction of bascule leaves many of the fabrication tolerances are not directly applicable or are not practical for use in the fabrication. The *Bridge Welding Code* recognizes that “Other dimensional tolerances not covered shall be individually determined and mutually agreed upon by the Contractor and Engineer with proper regard for erection requirements.” Special tolerances may be established for structural, workmanship or aesthetic reasons.


PHOTO 2: Bascule Girder Web Layout

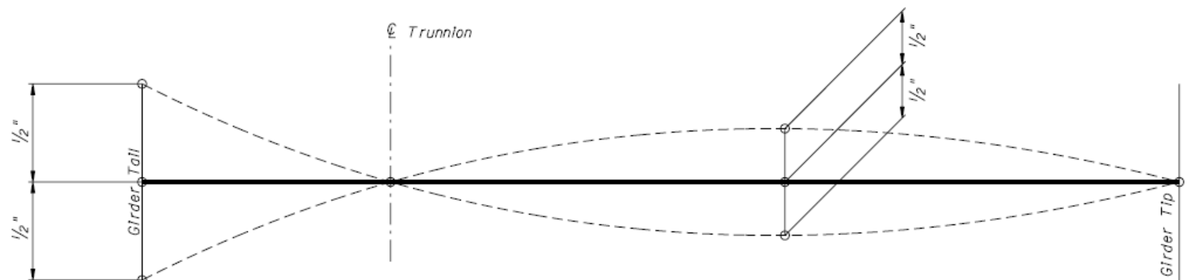
During fabrication, the location of the center of the trunnion is established on each bascule girder. Horizontal and vertical reference lines that intersect the center of the trunnions are marked on the web plates prior to cutting and are maintained throughout fabrication and assembly. The top and bottom of the girder and the two ends of the girder are measured and marked relative to the horizontal and vertical reference lines respectively. These measurements are typically made using steel tape or survey, and the plates cut to steel fabrication tolerances. Per the *Bridge Welding Code*, the depth of plate girders greater than 72" can vary by +5/16" and -3/16", measured at the center of the web. The tolerances at bolted field splices in the girder must typically be tighter than this to avoid thin fill plates. The tolerance on the length of plate girders is not specifically addressed; however, it is reasonable to expect that for girders in excess of 100′ in length that the girders can be measured and cut to ±1/2". This tolerance should easily accommodate typical operational clearances. A rough cut undersized hole in the girder web, slightly under the size of the hole for the trunnion hub, is also cut at the center of the trunnion.

Once each bascule girder has been fabricated, girder straightness and camber are checked and brought into tolerance using typical heat straightening practices. Adjustments in straightness and camber are typically made with the girders in an unloaded condition. Straightness and camber tolerances in the *Bridge Welding Code* are not completely useful or appropriate for bascule girders as they were developed for typical fixed bridges with multiple longitudinal plate girders and concrete decks with or without designed haunches. Camber deviations are typically measured between supports as the offset between the arc of the specified camber and the actual location of the steel while the girder is in the unloaded condition. The deviations are expected to occur gradually over the length of the member. However, this definition is not exactly applicable to bascule leaves as they are cantilevered structures. Maximum camber and thus maximum deviation on bascule girders typically occurs at the tip of the leaf. As the deck at the tip of the bascule leaf must align closely with the deck of an adjacent bascule leaf or fixed span deck, the camber must be more accurately controlled. The *Bridge Welding Code* specifies limits on camber for spans greater than 100′ and without a designed haunch as ±3/4", which is significantly greater than what can be accommodated at the tip of the leaf to meet deck alignment criteria. Similar to camber verification, during shop assembly and alignment, bascule leaves are supported at close intervals along the length of the girders including at the tip of the girders to achieve the required unloaded condition. As the horizontal reference line through the trunnions is used as a primary control feature in establishing the girder geometry, the bascule girders should be supported with this reference line set level. Rotating the bascule girders about the trunnions to adjust the elevation at the tip of the girders instead of properly correcting the camber can adversely affect the geometry along the remainder of the girder. The tail of the bascule leaf will typically raise or lower due to this rotation. Also, because this reference line is often used to align other elements of the bascule leaf such as racks and hydraulic cylinder clevises, the amount of machining of the bottom flange needed to align the racks typically increases (see “Rack Shop Alignment”) or the position of the cylinder clevises relative to the structure is affected (see “Hydraulic Cylinder Shop Alignment”.) As such, in order to control the geometry at the tip of the girders (i.e. the roadway deck should typically align within ±1/8"), it is recommended that the camber at the tip of the leaves by limited to ±1/8". Furthermore, as the control on the cross slope at the tip of the bascule girders is also critical to meet the deck alignment tolerances, the differential camber between bascule girders at the tip of the leaves should be limited to ±1/8". These strict limitations on camber variation are not unreasonable as they are similar to the camber limitations at interior supports specified in the *Bridge Welding Code*. Camber variations between the trunnion and tip of the leaves and at the tail of the leaves can be allowed to vary by ±3/8".



CAMBER TOLERANCE DIAGRAM

The *Bridge Welding Code* specifies permissible variations in straightness of 1/8" per 10 ft. on bridges with diaphragms, cross frames, lateral bracing, etc. provided the member has sufficient lateral flexibility to permit forced adjustment without damaging the structural members or its attachments. Straightening the bascule girders during assembly using forced adjustment is not recommended as the distortion can affect the alignment of the trunnions and racks attached to the girders, especially if installed and aligned in advance of the assembly. Because the bascule girders must be accurately aligned horizontally at the trunnions and at the tip of the bascule leaves, variations in the straightness will typically only affect the framing between the trunnion and tip of the girders and/or between the trunnion and tail of the girders. The bascule leaf framework typically consists of floorbeams spanning between the bascule girders and thus it is not practical to accommodate this amount of variation without forced adjustment of the girders. To illustrate, for a pair of 100′ girders the potential offset between girders could vary as much as 2½" (i.e. each girder could be out of straightness by 1¼" in opposite directions), which is significantly more than can be accommodated in a typical floorbeam connection. Furthermore, although the operational clearances of most bascule leaves can accommodate this magnitude of variation, the operational clearances may not be adequate when these tolerances are combined with other steel fabrication and erection tolerances and bascule pier construction tolerances. As such, it is recommended that a maximum offset due to variations in straightness be limited to 1/2" for bascule leaves.



STRAIGHTNESS TOLERANCE DIAGRAM

Other fabrication tolerances including web flatness and flange tilt are also checked and adjusted as necessary. These tolerances are described in detail below under “Trunnion Shop Alignment” and “Rack Shop Alignment.”

After sweep and camber correction, additional reference lines and control points are established on the girder for use in alignment during shop assembly. A reference line representing the longitudinal axis or centerline of the bascule girder is established and marked along the length of the girder flange. The reference line is a best-fit approximation of the center of the web along the length of the girder and is typically marked along the top of the top flange and/or bottom of the bottom flange. The *Bridge Welding Code* limits the lateral variation between the centerline of the web and the centerline of the flange to ±1/4". The reference line is used in establishing machine set-ups and measuring alignment during shop assembly. Control points along the reference line are also established to designate the intersections of the trunnions, floorbeams, etc.

Bascule Leaf Shop Assembly

Once the fabrication of the individual components is completed, they are brought together and fully shop assembled and aligned.

<u>Dimensional Control</u>:

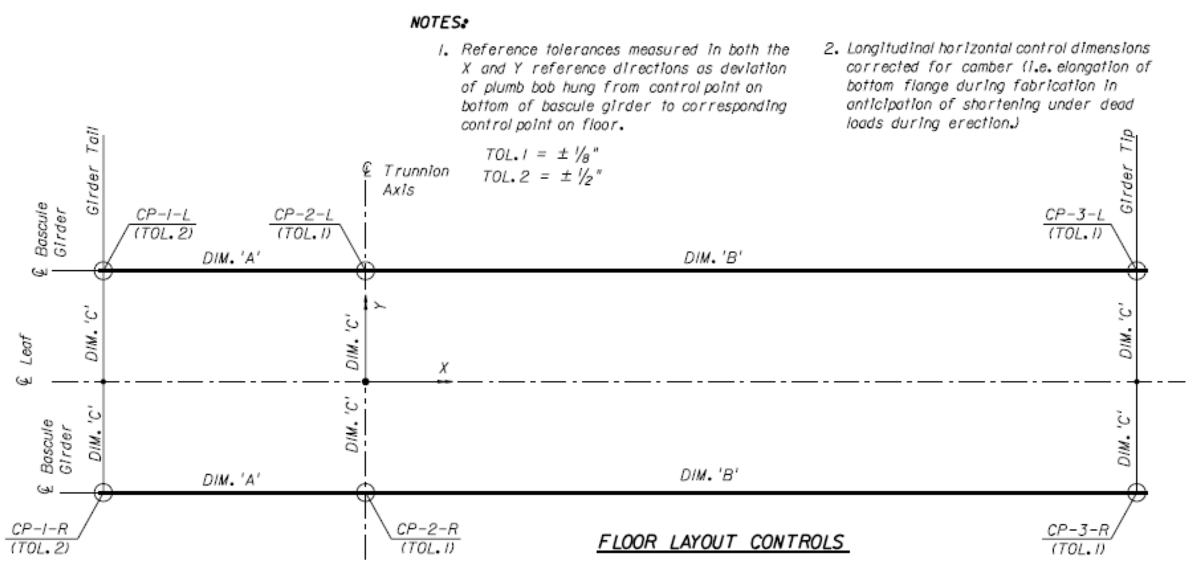
Before the shop assembly is performed, a dimensional control plan should be established. Measurement of the bascule leaf dimensions on a daily or even continuous basis during shop assembly is important to verify that the structure has not moved due to the work. However, common measurement techniques such as direct measurement by steel tape or conventional digital survey are generally not practical for this


PHOTO 3: Leaf Shop Assembly

purpose. Because bascule leaf structures are irregular in shape the dimensional control points are typically not located in a single horizontal plane. The measurement of the distance between two control points in three-dimensional space is not by itself useful information and in many cases the space between the control points is obstructed. Measurement by survey is somewhat cumbersome and not practical for daily measurements. There is usually not a single location that a survey instrument can be set up that has unobstructed line of sight of all the control points and thus the instrument must usually be set-up numerous times to measure all the required information, which increases the inaccuracy of the measurements and the time to obtain the measurements. Both of these methods of measurement are time consuming and not conducive to daily use. As such, fabricators have developed means to quickly verify the dimensional controls so that the measurements can be performed daily or even more frequently.

PHOTO 4: Leaf and Floor Control Points

Most fabricators use a floor layout accurately surveyed and marked on the assembly floor in advance of the assembly operations for use in measuring and verifying the bascule leaf alignment during assembly. The floor layout consists of a series of control points permanently marked on the floor (typically punch marks or scribe lines on a steel plate secured to the floor) located below key control points on the bascule leaf. A circle representing the alignment tolerance is inscribed about the control point. As the trunnion axis is the most important control feature, the floor layout is usually measured and surveyed relative to this axis. As described earlier, similar control points are also marked on the bascule girder top and bottom flanges and other members (typically using scribe lines or punch marks as permitted.) As the components are assembled, plumb bobs are dropped from the control points on the bottom of the girders and compared to the control points on the floor. If the plumb bobs are outside the tolerance circle, the structure is out of alignment and must be brought back into alignment by adjusting the position of the components. The amount the structure is out of tolerance is recorded on dimensional control daily record sheets. Typical control points are shown below.



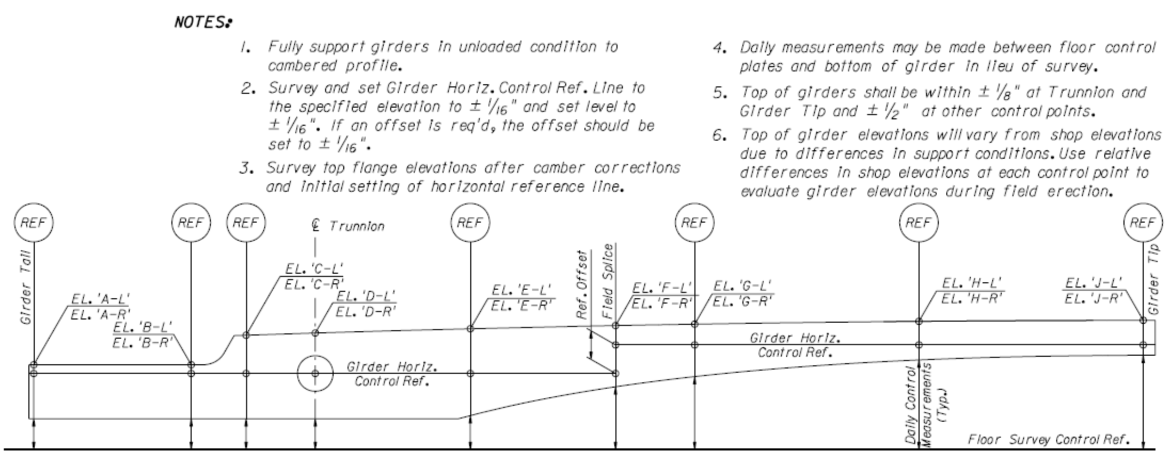
The dimensional control procedures should address the accuracy of the various measurement devices and methods. Measurement devices (e.g. digital and optical surveying equipment, tapes, micrometers, levels, scales, etc.) and methods must be sufficiently accurate to measure to the level of accuracy required for the specific measurement taken. For example, if the alignment tolerance on a specific element is ±1/16" the accuracy of the measurement must be at least ±1/32".

PHOTO 5: Optical Tooling

PHOTO 6: Machinist Scale

As the control points are critical in establishing the proper alignment of the bascule leaf, it is recommended that the floor layout and control points on the bascule girders be independently verified. It is recommended that the control points on the floor and the bascule girders are accurately surveyed to a tolerance of ±1/16" of the theoretical locations and that the plumb bobs are located over the control points on the floor to a tolerance of ±1/8". As the control points on the bascule leaf used in the daily verification checks are typically located on the bottom of the bascule girders, it is important that the girders are plumb to ensure that the top of the girders are also in acceptable alignment. A tolerance on plumbness of ±1/8" over the height of the girder, measured at the control points, is recommended.

The bascule leaf is typically supported in the unloaded and fully cambered condition during shop assembly. As such, care must be taken in using the correct dimensions for the control points. The bottom flange of the bascule girder is purposely fabricated longer than the final detailed dimension, recognizing that it will shorten under load. Similarly, the top flange is purposely fabricated shorter, recognizing that it will elongate under load. As the control points represent the intersection of the bascule girder and some key feature such as the centerline of the trunnion or the centerline of the floorbeam at the tip of the leaf, the adjusted dimensions affect the location of the control points on the floor and bascule leaf.



BASCULE GIRDER ELEVATION CONTROL

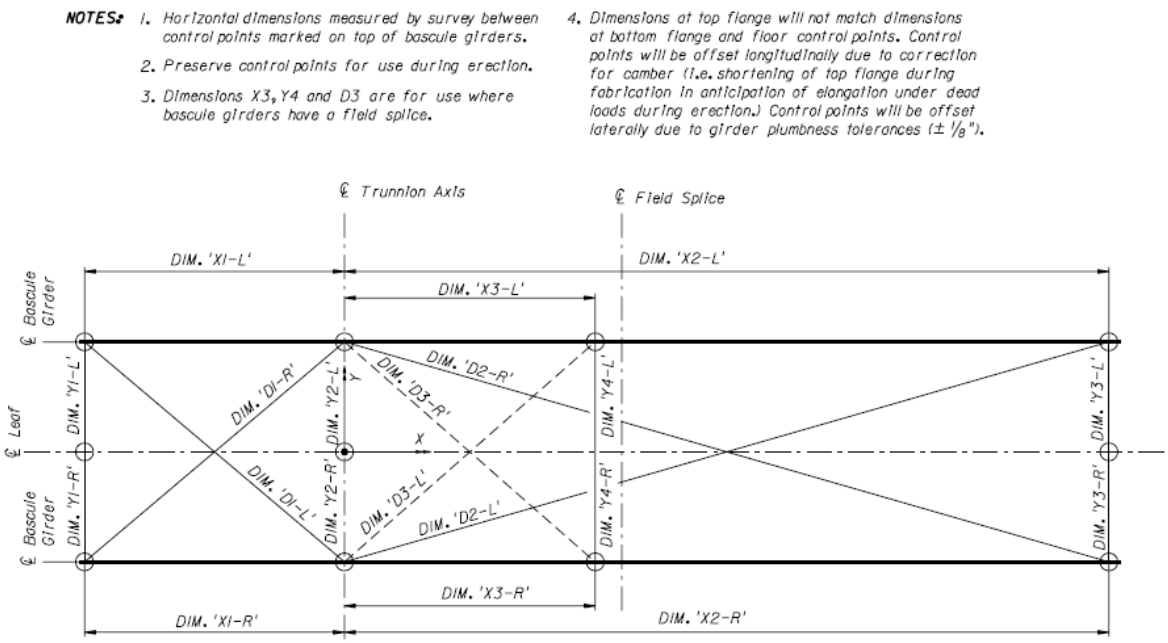
The vertical dimensions of the bascule leaf including the elevation of the trunnion axis and elevations of the top of the bascule girders at critical locations (e.g. centerline of trunnion axis and centerline of floorbeams) are also important. A survey level can be set-up and used to readily measure the elevations on a daily basis. Similarly, the height of the bottom of the bascule girder above the floor control points can also be used as a basis for vertical dimensional control provided that the elevation of each of the plates marked with the control points are surveyed and accounted for in the verification. The vertical dimensional controls should similarly recognize that the bascule leaf is supported in the unloaded and fully cambered position.


PHOTO 7: Shop Assembly of Steel Open Grid Deck

Because of tight tolerances for deck construction on bascule leaves (i.e. the requirement for uniform bearing of the steel grid deck on the steel framing or the requirement to minimize variations in concrete deck haunches that affect the span balance) and typical variations in steel grid deck panels, the tops of the deck support members (e.g. bascule girders, floorbeams and stringers) should be aligned as close as practical. Per the *Bridge Grid Flooring Manufacturers Association*, steel grid deck panels have permissible variations in camber of 0.003 x length of the panel, which equates to 3/16" to 5/16" over the length of a typical deck panel span length, and 0.005 x width of the panel, which equates to 1/2" over an 8′ wide panel. Fortunately, the deck panels are relatively flexible and will deflect somewhat under their own weight. For panels that are attached to the structure with fillet welds, as is customary, but do not bear uniformly on the steel, the *Bridge Welding Code* permits root openings up to 3/16" without adjusting the attachment weld size. Root openings up to 5/16" can be permitted provided that the attachment weld size is increased by the amount the root opening is in excess of 3/16". For bascule leaves with a steel grid deck panels spanning over three or more supports and bearing directly on and attached directly to the steel supports, it is recommended, that the maximum difference in elevation between adjacent supports, including spacer bars, not exceed 1/8" and that the maximum difference between any two supports along the length of the deck panel not exceed 1/4". For bascule leaves with concrete filled steel grid decks or Exodermic decks spanning over three or more supports, temporarily supported on leveling screws and with variable concrete haunches, it is recommended, that the maximum difference in elevation between adjacent supports not exceed 1/4" and that the maximum difference between any two supports along the length of the deck panel not exceed 1/2" so that the thickness of the haunches are relatively consistent. The top of the deck supports at the tip of the bascule leaves should be aligned level or to the specified cross slope within ±1/8".

The trunnion alignment is also critical and should be verified along with the rest of the dimensional control measurements. The trunnion alignment measurements are discussed in detail below in "Trunnion Shop Alignment."

Once each bascule leaf has been fully assembled and properly aligned to the specified tolerances, the holes for the connections drilled and reamed and before disassembly for cleaning and painting, a final survey of the structure should be performed and recorded and the as-built drawings updated. Unlike the daily verification checks, the final alignment survey should document the final as-built dimensions through survey to the control points. These dimensions should include the longitudinal, lateral and diagonal dimensions between the control points, the relative elevations of the control points referenced to an arbitrary control (e.g. usually the elevation of the trunnion axis), trunnion, rack and hydraulic cylinder upper clevis alignment measurements, etc. This information should be made available to the erector in advance of the bascule leaf erection. Based on the final dimensions, the erector may decide to make adjustments in the some of the critical dimensional controls. The erector may also reference this information during the assembly as needed. As the erector will be working above the waterway, he will not have easy access to the control points on the underside of the bascule leaves. As such, it is recommended that the final survey be performed to the control points on the top of the structure where the erector has easier access to the control points. Care should be taken to preserve the control points during shop cleaning and painting so that they are available during erection.



FINAL SURVEY CONTROL

Leaf Assembly:

Because the bascule leaves should be supported in the unloaded and fully cambered condition. An adequate number of supports should be provided throughout the leaf to eliminate the affects of deformation due to gravity. The supports should be located near control points, but should not interfere with the ability to perform the dimensional control checks or other required work. The supports should be stable, should readily accommodate adjustments in the components and should be capable of securing the position of the components without distortion.

PHOTO 8: Shop Assembly Temporary Support

Devices such as come-alongs, chainfalls, clamps, jacks and blocking are commonly used to adjust and temporarily secure the position of the various components during the assembly, although they should not be used to distort or hold the structure in a distorted condition. A certain number of holes are typically drilled undersize as the work progresses and drift pins or temporary bolts installed to maintain the alignment. Holes for the bolted connections should generally be installed with the leaf fully assembled and properly aligned to the required tolerances. However, advances in computer numerical control (CNC) allow the boltholes on one side of the connection to be installed in advance of the assembly. These holes can be used as a template to drill and ream the holes on the opposite side of the connection. Some fabricators have drilled and reamed final holes in some connections as the assembly progresses to help hold the alignment as the work progresses at some risk. If inaccuracies in the alignment are found and adjustments are required after these connections are drilled and reamed, significant rework may be required.

Bascule Leaf Field Erection

Dimensional Control:

Similar to shop assembly and alignment, a dimensional control procedure should be established before erection begins. The alignment of critical elements of the bascule leaf should be measured and compared to the required tolerances before the bolted connections throughout the bascule leaf are tightened and the final holes for the machinery are drilled and reamed. Once the structure has been erected and aligned to the required tolerances a final survey of the control points of the structure and measurement of the final alignment of the machinery including trunnion assemblies, racks, hydraulic cylinder clevises, span lock assemblies and live load shoes should be performed to document this information for the record and potential future use.


PHOTO 9: Bascule Pier Prior to Erection

Prior to bascule leaf erection, a control survey of the bascule piers should be performed and the primary survey controls should be established. Similar to shop assembly, the longitudinal control axis (e.g. usually the bridge and bascule leaf centerlines) and the trunnion axis are typically the most critical alignment controls during bascule leaf erection. These controls must typically be established first and the other critical alignment controls (e.g. centerline of trunnion bearing support pedestals, hydraulic cylinder lower clevises, driver machinery, etc.) established relative to these. Critical features of the bascule piers such as the location of the bascule pier slabs, columns and walls relative to the trunnion axis and bridge baseline of survey should be measured by survey to verify that adequate operational clearances are provided. On double-leaf bascule spans, the relative location of these elements on both piers should be compared to each other and adjustments in the location of the bascule leaves made as necessary to produce a best-fit alignment. Various support elevations including the top of trunnion columns, live load shoe supports, machinery floors, and hydraulic cylinder lower clevis supports should similarly be checked. The control survey should be performed well in advance of the erection so that any required corrective measures can be performed. The as-built dimensions of the bascule leaves should be reviewed to determine if adjustment in the overall location of the bascule leaves, trunnion bearing supports or hydraulic cylinder lower clevises relative to the bascule piers should be made.


PHOTO 10: Field Survey

Thought should be given to methods used in performing the alignment measurements well in advance of the steel erection. Similar to shop assembly and alignment, the measurement devices and methods must be sufficiently accurate to measure to the level of accuracy required for the specific measurement taken. Thought should be given to the placement of surveying instruments and at what point during the construction the measurements should be taken to maximize the accuracy. For example, as much of the initial layout should be performed as practical in advance of the steel erection, as the steel members will typically obstruct direct sight lines between the instrument and targets. Bascule pier columns and walls can similarly obstruct sight lines and require multiple instrument set-ups. In general, the greater number of times the survey instrument must be set-up, the lower the accuracy. Furthermore, it may be advantageous to have portions of the approach superstructure in place for use in establishing the longitudinal control surveys. The bascule pier decks are often not constructed until after the bascule leaf erection is performed. Set-up of the instrument on the approach deck can typically provide the best set lines of the bascule pier machinery floors where the most critical alignment controls are established. The instrument can also be set-up on the approach span superstructure to sight the tip of the girders as the leaf is raised and track the movement.

Erection:

The bascule leaves should generally be aligned in the field to the same accuracy as they were aligned in the shop. However, because of differences in how the bascule leaves are supported in the shop and how they are supported in the field, the bascule leaf structure can undergo deformations that affect the alignment. Additional changes in the alignment can occur during erection as a result of tolerances in the bolt holes and deformations in drift pins and temporary bolts that occur before final tensioning of the bolted connections, especially when a heavy part of the structure is temporarily hung from the connection without other support (e.g. when the tip half of the bascule girder is cantilevered from the tail half of the girder by the bolted field splice.) Twisting of the bascule leaf can occur if the bascule girders are not uniformly supported at the live load shoes or are not adequately blocked during placement of the counterweight concrete. If the bascule leaf is significantly nose heavy during field erection and the live load shoes are not adjusted to produce equal reaction, the bascule leaf can twist. A small amount of twisting at the live load shoes or tail of the leaf can translate to significant differential movement at the tip of the leaf. The balance of a bascule leaf can also have an affect on the alignment of the structure. Care should be taken not to lock in a twist in the leaf by tightening connections or placing the counterweight concrete with the leaf already twisted.

Depending on the stiffness of the floor framing and counterweight framing systems, experience has shown that the cross slope of the bascule leaf can be adjusted somewhat by differentially adjusting the live load shoes. However, significant twisting of the leaf is generally undesirable and should be minimized as this often results in built-in residual stresses not specifically designed for, unequal dead load reactions on the live load shoes, and possible trunnion and rack misalignment. This operation is significantly more effective if performed before the deck and counterweight concrete are installed and before the field bolted connections (e.g. bascule girder field splice and floorbeam to bascule girder connections) have been fully tightened. As concrete decks are significantly stiffer, especially when made composite with the structure, it generally is not practical to significantly adjust the cross slope once the concrete deck has been placed.

In addition to the alignment of the various machinery components (e.g. trunnions, racks, hydraulic cylinder upper and lower clevises, span locks, and live load shoes, addressed below) the alignment of the deck, deck joints and traffic railing are also critical.

The bascule leaf deck including sidewalks should typically be aligned to the adjacent fixed deck or between adjacent bascule leaves to within ±1/8". Although span locks can draw two misaligned leaves and their decks together, this is generally not desirable, as it requires twisting or lifting both bascule leaves, which often results in loss in contact of the live load shoes. When the live load shoes are not in solid contact, the bascule girders and floorbeams will undergo additional deflections not specifically designed for.

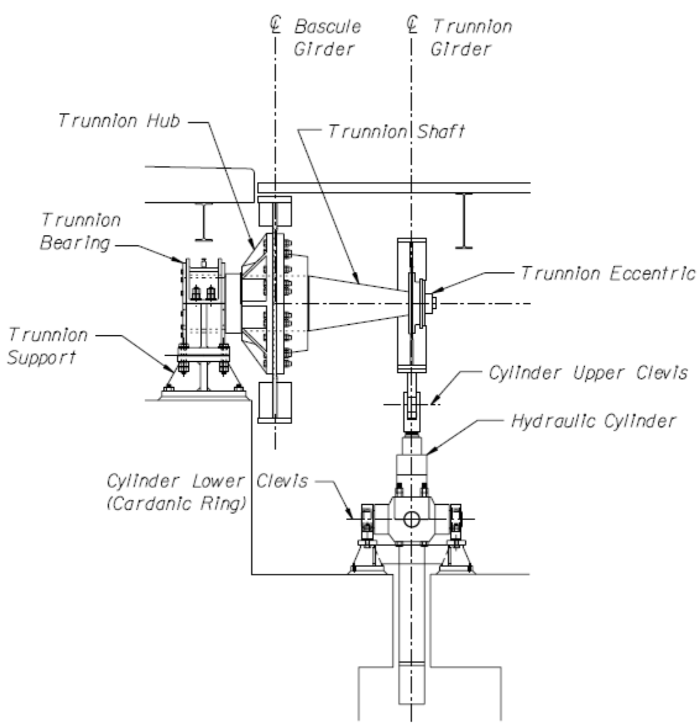
Longitudinal deck joints must typically be set to 1/2" or less in order to meet ADA requirements and pedestrian and bicycle safety requirements. This joint opening dimension is typically adequate to accommodate bascule leaf operational clearances and temperature movements. Transverse deck joints are permitted to be up to 1¼". This larger joint opening width is typically to accommodate the larger temperature movements in the bascule leaf longitudinal direction.

Per AASHTO, traffic railings should typically be aligned to within 3/8" to reduce potential snag hazards for vehicular traffic.

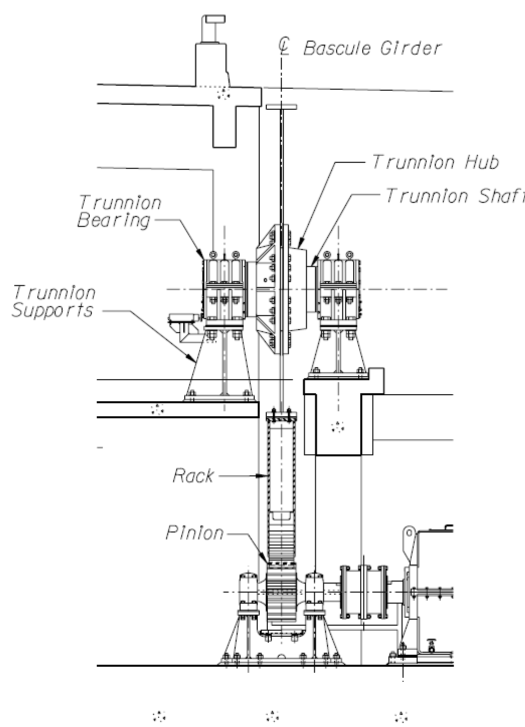
PHOTO 11: Bascule Leaf Transverse Joint

Trunnion Assemblies

A trunnion bascule leaf rotates about a fixed horizontal axis (trunnion axis) and the leaf is supported on and pivots about trunnion assemblies. There are different trunnion assembly configurations, but the most common is a steel shaft fixed to the web of the bascule girder that is supported on and pivots within bearings supported on the pier. Trunnion assemblies are commonly configured in a simple configuration with a bearing on each side of the bascule girder or in an overhung configuration with a bearing on the outboard side of the bascule girder. With the overhung configuration, the inboard end of the trunnion shaft is supported on a trunnion girder to provide stability. The bearings commonly consist of bronze sleeve bearings in a cast steel pillow block or spherical roller bearings in cast steel housing. The shaft is typically installed into a hub with an interference fit and the shaft-hub assembly installed into a hole in the bascule girder web with an interference fit. The interference fits are typically on the range of ISO H7/s6 to H7/u6 or ANSI FN2 to FN4 Fit. An interference fit is provided to maintain contact pressure between the parts under the maximum loads so that the parts do not loosen move relative to one another and wear. The amount of the interference fit is dependent on the relative magnitude of the contact pressure from the interference fit and the contact pressure from the applied loads.



OVERHUNG TRUNNION



SIMPLE TRUNNION

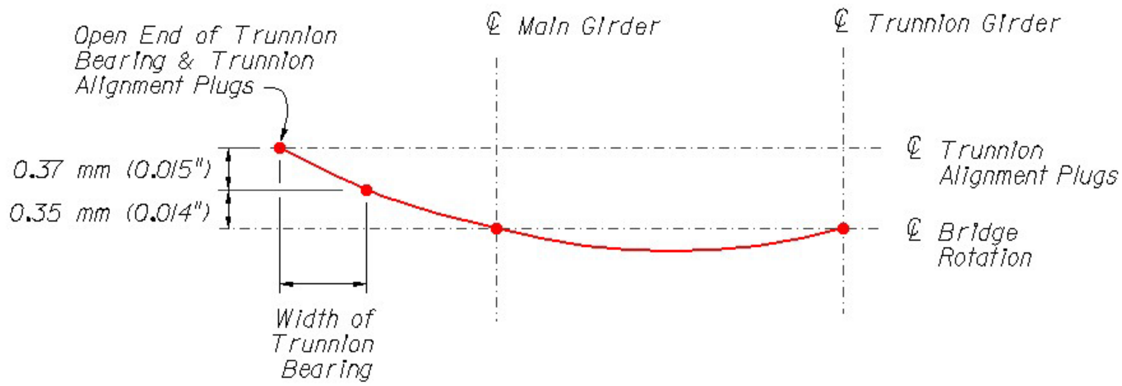
Factors Affecting Trunnion Alignment

The trunnion axis is one of the primary dimensional control features for construction of a trunnion bascule bridge. The trunnion assemblies must be properly aligned to prevent premature wear of the trunnion bearings and to reduce out-of-plane web distortions that introduce fatigue damage. The alignment of other components such as the operating machinery (e.g. racks or hydraulic cylinders) is dependent upon the trunnion axis. These components must be properly aligned to the trunnions to prevent premature wear. The bascule leaf steel structure must be properly aligned to the trunnion axis to maintain required clearances between the moving structure and adjacent fixed structure. As such, the bascule leaf structure should be fabricated, shop assembled and field erected about the trunnion axis.

The trunnion assemblies must be properly aligned to each other. The main consequence of trunnion misalignment is wobbling of the trunnion shaft during operation, which can result in the following:

- *Cyclical Structure Deformation:* Trunnion wobble can cause out-of-plane distortion of the bascule girder web. This can cause fatigue cracks in the web if the magnitude of out-of-plane distortion is relatively high. Trunnion wobble can also result in wear (usually by way of fretting) between trunnion hub and bascule girder web, especially where the proper interference fit has not been provided. This wear will work to increase the clearance between the hub and bascule girder web and will typically accelerate as the clearance increases. Eventually excessive clearance can result in trunnion hub bolt failures. Trunnion wobble is often identified by popping noises emanating from the bascule girder and trunnion assemblies as slip occurs between parts and/or as a thin web buckles under the twisting.
- *Edge Loading of Trunnion Bearing Bushings:* On trunnion bearings with bronze sleeve bushings, trunnion wobble typically results in edge loading of the shaft journal against the bronze bearing bushings which significantly increases contact pressure. This high contact pressure can yield in premature wear or cracking of the bushings. Spherical bearings (spherical roller or plain bearings) can eliminate this concern in certain configurations (e.g., overhung trunnion configuration) as the bearing rotates to accommodate the wobble.

The trunnion shaft is a structural element that will deflect under the large applied gravity loads (i.e. weight of the bascule leaf.) This deflection must be considered in the alignment of the trunnion assemblies. The trunnion bearings are typically supported on rigid supports that do not move. During erection, when the weight of the leaf is transferred to the trunnions, the trunnion shaft deforms and the bascule leaf structure settles downward relative to the supports by the amount of the deflection. As the gravity loads are always acting downward, the trunnion shaft will maintain the deflected shape in a vertical plane throughout operation of the leaf. As such, the center of rotation of the bascule leaf is an axis that passes through the center of the trunnions at the centerline of each bascule girder, not an axis that passes through the center of the bearings or ends of the shaft. With a properly aligned symmetrical trunnion configuration, the deflection of the shaft should not introduce any wobble in the shaft. However, the deflection of the trunnion supports can also affect the trunnion alignment and can introduce wobble even when the trunnion is properly aligned. If the inboard support is not rigid which is often the case for an overhung trunnion configuration the deflection of the inboard support must be accounted for in the alignment. The flexibility of the inboard support can also change as the leaf rotates when the stiffness in the plane of the gravity loads changes during operation (e.g. a longitudinally spanning trunnion girder.) The wobble can be minimized by maximizing the stiffness of the inboard support or designing an inboard support that does not change with the rotation of the leaf. The wobble can also be minimized by determining the alignment where the inboard end moves the least over the full operation. Where some wobble exits, it is preferable to use a spherical bearing that accommodates the wobble and does not introduce edge loading to the bearing bushing.



TRUNNION DEFLECTION

Trunnion Shop Alignment

It is desirable for the trunnions to be aligned as accurately as practical. Experience has shown that it is practical to align the trunnion assemblies to within ±0.010" of the trunnion axis. There are two basic procedures that have been used to successfully establish the trunnion alignment to these tolerances in the shop during bascule leaf fabrication and assembly:

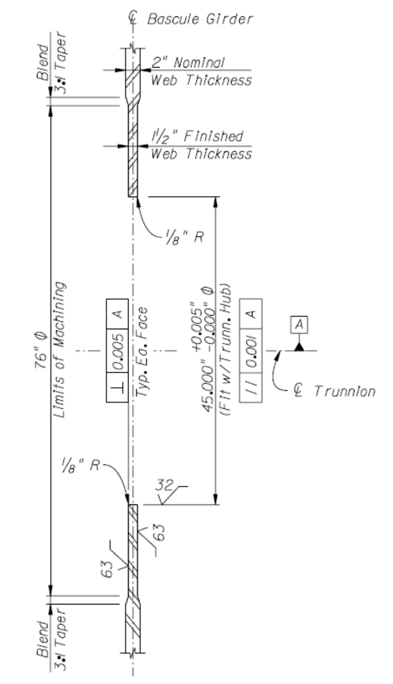
1. Fabricate the bascule leaf steel and machine the bascule girders using the control lines on each girder for reference. The girders should be set upright and not on their sides while this work is performed so that the affect of the gravity will not easily deform the girders about their weak axis. It is recommended that both girders for a bascule leaf be set-up together and machined relative to each other to reduce the risk that they will not align properly relative to each other during assembly. After machining, install the trunnions into the girders prior to leaf assembly. Align the bascule girder assembly by jacking the girders and aligning the trunnion assemblies to the reference trunnion axis. The advantage of this approach is that the trunnion assemblies will be in place for use in verifying the alignment. The disadvantage is that it is difficult to jack and align the large heavy girders to the required accuracy. This approach also increases the risk that the structure will have built in distortions from the jacking.

2. Fabricate the bascule leaf steel and assemble and align the steel relative to the reference layout. Machine the bascule girders about the trunnion reference axis while the leaf is fully assembled. Disassemble the leaf assembly and install trunnion assemblies. The advantage with this approach is that the machining is performed while the leaf is assembled and thus the machining is relative to the complete assembly. The disadvantage with this approach is that the trunnion assemblies are not installed while the leaf is assembled and thus verification of the alignment to the trunnion assemblies cannot be directly verified. However, because of the machined surfaces and interference fit, there is little risk that the trunnions can be installed improperly and introduce misalignment. Alternatively, the trunnion assemblies could be installed while the leaf is assembled; however, it is difficult to install the trunnions with the girders upright.

Because the bascule leaf structure is fabricated and assembled to structural steel tolerances, the surfaces of the girder webs are not exactly parallel and there is waviness in the plates from the rolling process. Thus, in order to achieve the alignment to these tight tolerances and to prepare the bascule girders to accept the trunnion assemblies, the surfaces of the webs of the girders must be accurately milled and the hole in the webs accurately bored. Machining is performed using a portable milling and boring machine. When the machining is performed with the leaf fully assembled, the machine is set-up and aligned about a single alignment wire at the center of the trunnion axis. A separate set-up of the boring bar is required to machine each girder; however, as the machine is set-up around a common reference line the machined surfaces are aligned to each other. When the leaf assembly is to be performed after machining and trunnion installation, a single set-up of the boring bar may be possible if the girders can be placed close enough together. For simple trunnion configurations, only the bascule girders need to be machined. For overhung trunnion configurations, both the bascule girders and trunnion girders need to be machined.

PHOTO 12: Portable Web Milling Machine

In order to achieve the final trunnion alignment of ±0.010", the bore in the web of the girder must typically be machined parallel to the trunnion axis within ±0.005" and the surface of the web must be machined to within ±0.010" of a plane perpendicular to the trunnion axis. The accuracy of this machining is critical as once the web of the bascule girder is machined to accept the trunnion hubs, the alignment of trunnion relative to bascule girder is set, and the only way to change the relative alignment of these two elements is to distort the web.



WEB MACHINING DETAIL

Because of structural steel mill tolerances and fabrication tolerances, it should be anticipated that additional web material stock will be needed above the required design thickness to allow removal of material from the webs during machining. Web plates for bascule girders are typically ASTM A709 Grade 50 material with thicknesses typically ranging from 1" to 3" and widths typically ranging from 96" to 144" at the trunnions. The tolerance for flatness of web plates from *ASTM A6* is typically from 7/8" to 1" over the width of the plate for this material and size range. The tolerance on straightness of girders from the *Bridge Welding Code* is 1/8" per 10 ft. and the tolerance for flatness of web plates is d/150, where "d" is the girder depth or panel dimension between stiffeners. The bascule girders may not be perfectly plumb when oriented for machining the webs. A tolerance of ±1/8" over the height of the girder should be considered for this purpose. Although the orientation of the girder longitudinal axis relative to the trunnion axis may not be perfectly perpendicular, this affect is generally negligible when considering the other factors (e.g. ±1/4" over a 100′ girder translates to only approximately ±0.010" over the area to be machined.) Most hub flanges and areas to be machined are typically less than 60" diameter and thus when considering all of the above tolerances applied over this dimension the expected maximum amount of material removal is less than 1/2". The amount of material removed from each side is approximately the same, but occurs in opposite locations. Thus, it is recommended that the web stock be increased 1/2" over what is required by design and limit the final thickness of the machined area to the design thickness.

The amount of machining and spot facing on the trunnion hub flange should be coordinated with the web machining in determining the grip length of the trunnion hub turned bolts. It is recommended that a tolerance on the finished thickness of +1/8", -0", which is equal to approximately a single thread pitch, be specified so that the nut does not bottom out on the shank.

The location of the trunnion axis must be accurately positioned relative to the shop floor layout or bridge field layout using survey. In the shop, the trunnion axis is typically established first, as the trunnion axis is the primary control for the leaf assembly, and the floor layout is typically set relative to the trunnion axis.

Trunnion Field Alignment

Final alignment of the trunnions (i.e. alignment of the trunnion assemblies relative to the reference axis) is typically to a tolerance of ±0.010". However, the reference axis must also be aligned to the bridge survey controls. On double-leaf bascule spans, the trunnion axis for the two leaves must also be aligned to each other. It is reasonable to expect that the trunnion axis (e.g. alignment wire) is located and aligned relative to the specified location to the following tolerances:

Horizontal Location:	±1/8" (±0.125")
Horizontal Variance:	±1/32" (±0.030")
Vertical Elevation:	±1/16" (±0.060")
Vertical Variance:	±1/32" (±0.030")

During shop assembly, the bascule leaf structure is typically supported on falsework located directly under the bascule girders. As such, there typically is no load on the trunnion assemblies and thus no deflection of the trunnion shaft. However, during field erection, the bascule leaf structure will eventually be supported on the trunnions and the trunnion shaft will deflect. Also, deflection of the trunnion supports can introduce wobble even when the trunnion is properly aligned. Deflection of the trunnion shaft and supports can be calculated but this calculation is sometimes quite complex and is not always accurate. As such, it is sometimes more accurate to measure the deformation. During shop assembly, the trunnion shaft is typically unloaded. During field erection, there are usually both times when the trunnions are loaded and when they are unloaded. The amount of the deflection can be measured using dial indicators or optical survey and a machinist scale.

Overhung trunnion assemblies are typically provided with eccentric assemblies, wedge assemblies or other means to adjust the trunnion alignment at the inboard end of the shaft. Eccentric assemblies consist of a set of circular hubs with off-centered holes inserted into the web of the trunnion girder, into each other and over the inboard end of the shaft. When the hubs are rotated relative to each other, the inboard end of the shaft will move vertically and/or horizontally. Similarly, with wedge assemblies, sets of steel wedges both above and below and either side of the trunnion shaft are mounted in a housing connected to the web of the trunnion girder. When the wedges are adjusted, the inboard end of the shaft will move vertically and/or horizontally. The eccentric and wedge assemblies can typically accommodate radial movement of the inboard end of the trunnion shaft of 1/2". The amount of adjustment should be minimized as much as practical, as the web of the bascule girder is distorted when the inboard end of the shaft is moved. It is preferable to initially set the eccentrics or wedge assemblies in the shop in their centered position so as to maximize the

PHOTO 13: Overhung Trunnion Eccentric

available field adjustment. Final adjustments of the trunnions should be performed in the field after the erection is complete and all dead weight is placed on the bridge. Once the final alignment is achieved, the eccentrics and wedge assemblies are locked in position using turned bolts, set screws, etc.

The ends of the trunnion shaft are typically on a slope as a result of the deflected shape of the shaft. In order to avoid edge loading on the bearing bushing, the trunnion bearings should be aligned to the sloped shaft (i.e. the bearing assembly can be tilted so that the bushing is parallel to the sloped shaft journal.) The shaft journal should set solidly and uniformly at the bottom of the bronze bushing. The radial clearances between the journal and the bushing (ISO H8/f7 or ANSI RC4 Fit) should gradually increase from the bottom to the top. Feeler gages can be used to verify the clearances. In addition, a machinist level (graduations of 1/10,000" per ft.) can be placed on the top of the journal and on the flange of the bearing housing lower half to verify that that the two shaft journal and bushing are parallel. It is typically not necessary to slope a spherical bearing as this type of bearing can accommodate the slope of the shaft. As it is difficult to accurately compute the slope of the deflected trunnion shaft journal, and the deflection is not exactly known until the total load is applied, the setting of the bearings is often a trial and error process. A lead sheet or similar soft pliable material can be placed in the bottom of the bearing housing while the load is temporarily on the trunnions to determine the amount to adjust the slope.

PHOTO 14: Trunnion Bearing Feeler Gauge Measurements

PHOTO 15: Trunnion Bearing Machinist Level Measurement

The steel weldments that support the trunnion bearing must also be accurately positioned and leveled. Adjustment is typically provided using leveling bolts built into the weldments and a grout bed under the base, which is placed after the weldment is aligned. In addition, adjustable shims are typically placed between the bearing base and the support weldment. In order to avoid tapered shims when the trunnion bearing must be sloped, the support weldment should be accurately leveled with the top surface of the weldment set parallel to the slope of the trunnion bearing.

The reinforcing steel in the floor below the trunnion supports should be surveyed and accurately placed so that the reinforcing steel is not hit when the holes for the anchors are drilled. Cast-in-place anchors are not recommended as this potentially reduces the available adjustment of the trunnion supports. Cast-in-place anchors must be installed during bascule pier construction, well in advance of bascule leaf erection. Based on experience, horizontal adjustment in the location of the trunnion supports is often required during field erection and alignment of the bascule span.

Trunnion Alignment Tools

Stanchions: A stanchion is a fixed stand mounted on the floor or adjacent wall used to support, adjust and fix the location of an alignment wire or laser that establishes the trunnion axis. There is typically one stanchion on each side of the leaf located outboard the trunnion ends. A stanchion typically includes a means for adjusting, fixing the location and quickly reestablishing the location of the wire or laser.

PHOTO 16: Alignment Wire Stanchion

Alignment Wire: Piano wire is the most commonly used type of wire used in trunnion alignment due to the high tensile strength and small diameter.

The alignment wire is typically set in a groove on the stanchion, and is usually deflected over a sheave or roller with suspended known weight to tension the wire and reduce the sag. The sag of the wire must be accounted for in the alignment. The catenary of wire can be calculated using the known weight of the wire, the span length, and tension in the wire from a known weight with adjustments for any friction from the deviation of the wire over a support. However, because variations in sag can occur due to variations in wire stiffness, friction in rollers, etc. it is recommended that the calculated sag be verified through measurement using optical survey and a machinist scale. The relative location of the wire at the inboard and outboard ends of the trunnion shaft must be accounted for when measuring the alignment.

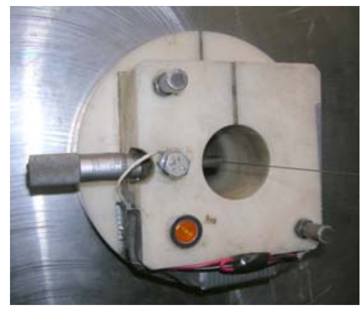


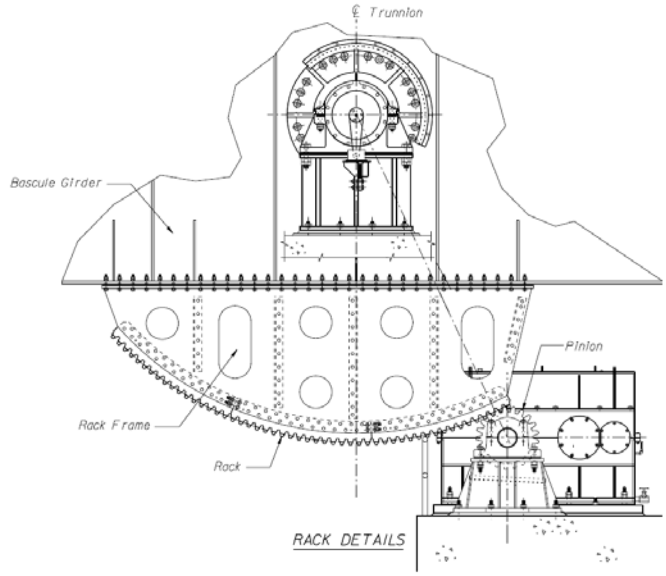
PHOTO 17: Alignment Wire Gauge

PHOTO 18: Alignment Wire Micrometer Measurement

A number of different methods have been developed to measure the alignment of the trunnion shaft to the wire. During shop assembly and field erection, trunnion alignment is measured frequently to verify that the alignment is being maintained as shop assembly or field erection takes place. To more easily make these measurements, many fabricators and erectors use custom machined devices inserted into the trunnion bore hole. One such device is a "go-no go" (electrical tell tale) gauge set to the specified tolerance and fit within the center bore hole through the center of the trunnion shaft. These devices are fit into the bored center-hole of the trunnion shaft and are machined to the radius of the bore hole, less half the diameter of the wire and the alignment tolerance. Where the sag in the alignment wire must be accounted for, three sets of gauges are typically fabricated: one for use below the wire, one for use above the wire and one for use on either side of the wire. The steel gauge is electrically connected to the alignment wire and a light bulb. The gauge is rotated within the bore-hole and if the gauge contacts the wire the light bulb will light indicating that the trunnion is out of alignment. Another such device is a custom machined micrometer that fits within the center bore hole through the center of the trunnion shaft that accurately measures the vertical and horizontal distance from the side of the bore-hole to the wire. A less accurate method that has been used is to measure the location of the wire using a machinist scale.

Lasers: Lasers are typically set-up on an adjustable fixed stanchion at the outboard end of one trunnion with the beam of light centered on and aimed through the center bore-hole through the trunnions to the outboard end of the opposite trunnion. Clear targets (e.g., sheets of acetate) with cross hairs and a circle representing the allowable alignment tolerance marked on the target are secured to each end of each trunnion shaft. The location the beam of light as it passes through the clear target is compared to the marked alignment tolerance circle. Higher quality lasers with less light dispersion can more accurately measure. Accurate alignment of the laser and targets is important in the accuracy of the measurement.

Racks



The most common type of machinery used to operate trunnion bascule leaves are mechanical systems with racks (i.e. a segment of a large circular spur gear) attached to the bascule leaf structure. The rack is driven by a pinion (i.e. smaller spur gear that is part of the drive train located on the pier). In most cases, the racks are attached to the underside of the bascule girders below the trunnions within a rack frame, but they can also be attached to other areas of the bascule girder or to other parts of the structure. Because the rack rotates with the bascule leaf as it operates, it is important for the rack to be accurately aligned to the trunnion axis. Proper contact must be made between the rack and pinion teeth throughout operation to prevent premature wear of the teeth. The involute profile of the rack and pinion teeth is intended to create continuous and uniform line contact across the face of the teeth as the teeth roll over each other during meshing. The teeth must be accurately aligned to achieve proper contact.

Factors Affecting Rack Alignment

The racks should not be completely attached to the bascule girders and aligned until field erection of the leaf is complete as deformations in the structure during field erection can affect the rack alignment. The difference in how the structure is supported during shop assembly and field erection can result in deformations and changes in the rack alignment. During shop assembly the bascule girders are typically supported at discrete points along the length of the girders to the fully cambered profile. During field erection, the bascule girders are supported on and cantilever from the pier and thus deflect as the erection progresses under the weight of the installed elements. Much of the final weight is not added to the structure in the shop including counterweight ballast, grid deck panels and/or deck concrete, barriers, span lock assemblies, etc. The deflection of the cantilevered bascule girders causes the bottom flange of the girder to shorten. If the rack is attached to the girder before the dead load deflection takes place, the rack frame will also shorten at the attachment to the girder and cause the rack to become elliptical in shape and possibly twist. Out-of-plane deformations of the bascule girders as a result of twisting can occur when the girders lack adequate stiffening and bracing and there is differential deflection between the bascule girders or significant deflection in the floorbeams or counterweight framing. The out-of-plane deformations are significantly more difficult to account for in the final rack alignment. As such, the following is recommended:

- Detail the bascule girders with adequate stiffening and bracing at the trunnions,
- Detail floorbeams and counterweight framing with adequate stiffness to reduce end rotations,
- Provide adequate falsework to prevent leaf twist during counterweight construction,
- Detail the bascule leaf structure with a symmetric configuration that minimizes differential deflection and leaf twisting.

As some deformations are expected from the different support conditions and from dismantling, handling, shipping and erecting the bascule leaves, it is recommended that the bascule girder and rack frame design allow for field adjustment and alignment of the rack. Once the bottom flange of the bascule girder is machined to accept the rack assembly, the alignment of the rack relative to the bascule girder and trunnion is set and the only practical method of adjusting the alignment of the rack relative to the trunnion axis is through use of shims.

Rack Shop Alignment

Preliminary alignment of the racks in the shop including shop machining of the bascule girders to receive the rack frames is recommended. Due to the presence of pier walls, trunnion bearings, pedestals and columns, it is significantly more difficult to accurately set-up and machine the girders in the field and measure the position of the rack relative to the trunnion axis. Final alignment should be performed after erection and final deformations have taken place. Because of steel mill and fabrication tolerances, the area of the bascule girders to receive the rack frames should be machined to a uniform surface aligned to the trunnion axis. Machining is typically performed using a portable milling table. The surface of the milling table is typically surveyed horizontally and parallel to the plane of the trunnion axis using optical equipment and a machinist scale. The table is also aligned with its longitudinal axis perpendicular to the trunnion axis. The bascule girder surfaces should be machined so that any point on the surface is within ±0.010" of a plane parallel (or perpendicular) to the trunnion axis. Similar to machining the bascule girder webs for the trunnion assemblies, additional material stock, beyond what is required for the design, should be provided for this machining. The following factors and recommended tolerances should be accounted for in establishing the amount of required machining:

PHOTO 19: Flange Milling Operations

PHOTO 20: Portable Milling Table

- Plate flatness and thickness variations from plate rolling and distortion during fabrication (±1/8" per 10 ft.)
- Girder plumbness in assembly (±1/8" over girder depth)
- Flange warpage and tilt (Flange toe offset from line perpendicular to web 1/100 of flange width or 1/4", whichever is greater)
- Girder depth relative to center of trunnion (±1/8")
- Girder tilt about trunnion axis (±1/16" per 10 ft.)

An additional thickness of 1/2" over that required by design has typically been found to be adequate for this purpose.

The racks can be accurately located to the center of the trunnion in the shop using a combination of a trammel and optical survey instruments. A trammel is a device that attaches to the end of the trunnion shaft and contains a pointer at a radial distance from the trunnion axis equal to the rack pitch radius. The instrument is used to check the position of the rack pitch line by pivoting the trammel about the trunnion shaft and comparing the pointer to the pitch line inscribed on the outside face of the racks. Dial indicator gages can also be mounted to the frame to track parallelism of rack. The trammel frame must be of sufficient stiffness to prevent deformations that might affect the accuracy of the results. The bascule girder should be oriented vertically when using the trammel so that gravity is not acting about girder, rack frame and trammel weak axis. AGMA standards establish the radial run-out tolerances for the rack. For the range of size of racks on most trunnion bascule bridges, the rack pitch line should typically be concentric with the trunnion axis to within ±0.030".

To help insure that tooth contact will be uniform across the face of the teeth, the outside face of the rack should be parallel to a plane perpendicular to the trunnion axis within ±0.020". As it is not practical to rotate the bascule leaf about the trunnions in the shop, the perpendicularity of the rack relative to the trunnion axis can be verified using optical survey and a machinist scale. An optical instrument can be set-up perpendicular to the trunnion axis, but offset from the bascule girder, by surveying the machined surface of the trunnion web (or machined surface of the end of the trunnion shaft if the trunnions are already installed) and sighting a machinist scale.

PHOTO 21: Rack Alignment Trammel with Pointers and Dial Indicators

Once the preliminary rack shop alignment is achieved, the racks can be temporarily held in their relative alignment using temporary undersize bolts. As there is no elastic shortening of the bascule girder bottom flange at the point directly below the trunnions, final turned bolts or temporary dowels pins can be installed at this location to secure the position (i.e. radial position of the rack pitch line relative to the trunnion.

Rack Field Alignment

Final alignment of the rack in the field is typically checked by measuring a combination of tooth contact, backlash and lateral position of the rack as the leaf is rotated. Tooth contact is typically measured by examining the contact pattern of the meshing gear teeth using blueing compound applied to the teeth. The leaf is raised and lowered using the drive machinery to achieve contact. The bascule leaf should be properly balanced so that the tooth contact force is similar to what is expected under normal operation. For AGMA Quality 6 spur gears or higher, which is commonly used on trunnion bascule spans, tooth contact should typically be such that 80% of the teeth have solid contact over no less than 70% of the tooth width, while the remaining 20% of the teeth should have solid contact over no less than 50% of the tooth width. Backlash between meshing teeth should be measured at the pitch line using feeler gages and should closely match AGMA standards. The backlash should typically not vary over the width of the teeth by more than 0.005" to 0.010". As a trouble shooting tool, the lateral position of the rack can be tracked using dial indicators to measure the outside face of the rack as the bascule leaf rotates. The racks are typically held in position with temporary undersize bolts during the alignment process. Once the final alignment has been verified, the temporary bolts are removed, the holes drilled and reamed to full size and the final turned bolts installed.

Hydraulic Cylinders

Many trunnion bascule leaves utilize hydraulic cylinders to operate the leaves. The hydraulic cylinder consists of a steel tube (body) that houses a piston rod. Hydraulic fluid is pumped into the tube to move the piston rod and the direction of the fluid flow determines whether the piston rod extends or retracts. The fluid pressure acting on the piston generates a force and the cylinder is located at a prescribed distance or moment arm from the trunnion axis such that the force, acting at this distance, creates the required torque about the trunnion to move the leaf.

Factors Affecting Hydraulic Cylinder Alignment

The hydraulic cylinder body is typically attached to the bascule pier and the piston rod is attached to the bascule leaf. The attachments are typically a pin connected clevis that permits rotation. Because the piston rod upper clevis is attached to the bascule leaf, it follows a circular path centered about the trunnion axis as the bridge rotates. As the upper clevis follows the circular path, the cylinder pivots about the lower clevis mounted on the pier. The hydraulic cylinder is of a fixed length based on the stroke of the cylinder (i.e. the total available length of piston rod travel) plus whatever additional length is needed for various components such as the rod bearings and seals, cushions, flow ports, relief valves, end caps, stop tubes, clevis attachments, etc. The geometry of the cylinder and the associated stroke length is dependent on the location of the clevises relative to the trunnion axis. In order to reduce the risk of bottoming out the piston, the cylinder length includes reserve stroke (typically 1/2" to 1") at either end of travel. Inaccuracies in the locations of the clevises will change the cylinder geometry and reduce the reserve stroke; however, small changes (i.e. horizontal and vertical offsets of ±1/8") in the clevis locations can typically be accommodated in the reserve stroke so that the clevises do not have to be located to overly exact tolerances.

PHOTO 22: Hydraulic Cylinder Upper Clevis

PHOTO 23: Hydraulic Cylinder Lower Clevis

The alignment of the cylinder in the lateral direction (i.e. relative lateral position of the upper clevis on the bascule leaf and the lower clevis on the bascule pier) is also important in the operation of the hydraulic cylinders. Because the upper clevis follows a circular path as the bridge rotates, if the upper and lower clevises are not aligned laterally, the hydraulic cylinder will tilt laterally as the bridge operates. The upper and lower clevises typically include spherical bearings that permit lateral tilt of the cylinder and prevent restraint that introduce undesirable lateral forces on the cylinder rod bearings and seals. Although the spherical bearings can typically accommodate lateral tilt of the cylinder up to 3º, the clearances in the clevis assemblies typically govern the amount of permissible tilt. It reasonable to expect that the upper and lower clevises be aligned to each other within ±1/8". This tolerance can easily be accommodated by the spherical bearings and clevis assembly operational clearances.

Hydraulic Cylinder Shop Alignment

Alignment of the upper clevises attached to the bascule leaf is typically established in the shop during bascule leaf assembly. The horizontal location of the upper clevises relative to the trunnion axis can be established using survey reference marks on the shop floor layout and plumb bobs dropped from the center of the clevis. The elevation of the upper clevis can be established using survey to compare the elevation of the alignment wire to the elevation of the trunnion axis. Alternatively, a similar set-up to the trunnion axis (i.e. a separate stanchion and alignment wire or laser) can be set-up so that daily alignment verification checks of the clevises can be made.

Hydraulic Cylinder Field Alignment

Alignment of the lower clevises on the bascule pier is typically established in the field during erection. The field alignment can be established by dropping plumb bobs from the upper clevises and measuring horizontal longitudinal and lateral offsets from the plumb bobs. The elevation of the lower clevises can be established using survey to compare the elevation of the alignment wire to the elevation of the trunnion axis or upper clevis.

The reinforcing steel in the floor below the lower clevises should be surveyed and accurately placed so that the reinforcing steel is not hit when the holes for the clevis anchors are drilled. Cast-in-place anchors are not recommended as this potentially reduces the available adjustment of the clevises. Cast-in-place anchors must be installed during bascule pier construction, well in advance of bascule leaf erection. Based on experience, horizontal adjustment in the location of the bascule leaves is often required during field erection. If the position of the bascule leaves is adjusted, the position of the clevises will be affected. Although, the upper clevises can also be field aligned, the available adjustment is often extremely limited based on the size of steel supports.

PHOTO 24: Lower Clevis Field Alignment Using Plumb Bob

Live Load Shoes

Live load shoes provide additional support and stability for the bascule span while the bridge is subject to vehicular traffic. The live load shoes typically consist of a steel rocker shoe secured to the underside of the bascule girder that bears on a steel masonry plate on the pier. On a double-leaf bascule span, the live load shoes are either located forward of the trunnions and rest on near the front wall of the bascule pier or are located behind the trunnions near the tail end of the bascule leaf and engage an anchor column that resists up-lift. On single-leaf bascule spans, the live load shoe is located at the tip of the leaf and rests on the rest pier.

PHOTO 25: Live Load Shoe

It is important that there is relatively equal and uniform contact between the rocker shoes and the masonry plates to prevent undesirable deformations of the structure. Adjustment of the live load shoe assembly is provided by shims between the rocker shoes and steel structure and a grout bed between the pier concrete and masonry plates. Machining of the bascule girder bottom flange may be warranted if the flange plate is warped or tilted. The masonry plate may be tilted to match the cross slope of the rocker shoe if tilted. Uniform contact is typically defined as 70% line contact across the width of the rocker shoe.

It is important that the live load shoes remain in solid contact and that the reactions on the live load shoes are relatively equal. If one or more live load shoes are not in full contact, the structure can under go additional deformations, not typically accounted for in the design, that increase the maximum stresses and/or fatigue stresses in the structure. Equalizing the reactions on the live loads shoes, maintaining proper leaf balance and aligning the span locks will help ensure that positive contact is maintained.

Equal reactions on the live load shoes can be verified by comparing the amount each bascule girder deflects when the shims are removed from under one girder at a time. In other words, remove the shims under one of the bascule girders and measure the amount the girder deflects while the opposite girder is supported on the live load shoe. Reverse the process for the other girder and compare the deflections. Adjust the shims until the girders deflect an equal amount. Once the loads are equalized the tip of the bascule leaves can be raised or lowered until the decks align by placing or removing an equal amount of shims from each load shoe. Care must be taken to make sure that the deck surface aligns within acceptable tolerances at the tip of the bascule leaves with the load equalized.

Span Locks

Span locks (a.k.a. center locks or nose locks) on double-leaf bascule spans tie the tip ends of two cantilevered bascule leaves together and force the leaves to deflect equally and prevent a discontinuity in the deck as traffic crosses the span. Most span locks consist of a rectangular lock bar supported by a pair of guides on one leaf that engages a single receiver on the opposite leaf. During operation, the lock bar slides across bronze shoes mounted in the rectangular guide and receiver housings. The housings are usually mounted to the side of the bascule girders or in the webs of a transverse member (e.g. floorbeam or cantilevered bracket) that frames into the bascule girders. Lock bars are typically driven or retracted directly using a linear actuator (e.g. electric or hydraulic) or mechanical system with electric motor, speed reducer, and a series of crank arms, links and shafts.

PHOTO 26: Span Lock Bar, Guides and Receiver

PHOTO 27: Span Lock Hydraulic Cylinder Actuator and Power Unit

The guides and receivers should be aligned such that the lock bar bears uniformly over the full length and width of each of the shoes and that the specified total horizontal and vertical clearances are provided. This requires that each guide and receiver be positioned accurately both horizontally and vertically, and angularly about each axis. Span lock systems with conventional guides and receivers typically have a total vertical clearance range of 0.015” to 0.025” between the lock bar and shoes in


PHOTO 28: Cushonlok® Guide and Receiver

order to allow the lock bar to easily drive and retract during operation, and to minimize vertical movement between the lock bar and the guide and receiver shoes under traffic loading. Cushionloks®, a relatively new proprietary span lock system, are gaining popularity, as positive contact is maintained between the shoe and lock bar under traffic loading by using springs behind the shoes to preload the shoe against the lock bar. A total horizontal clearance range of 0.015" to 0.025" between the lock bar and the guides and receiver is used so that the lock bar operates straight and true.


PHOTO 29: Lock Bar End at Receiver

Lock bars typically have a machined taper on both the vertical and horizontal leading edges to assist in the engagement when the guide and receivers are slightly misaligned. The two guides should be properly aligned to each other to keep the lock bar from excessively bearing against the side of the bronze shoes. The guides should also be aligned with the receivers so that the lock bar will drive and retract without excessive force and so that the span locks will not adversely change the alignment of the structure. If the guides and receivers are misaligned, the lock bar will act to draw the two bascule leaves together, vertically and/or horizontally, as the lock bar engages the receiver. If the guides and receivers are misaligned horizontally, the lock bars will deflect the bascule leaf structures laterally. As the structures are relatively stiff in this direction, a relatively small deflection can produce relatively large reactions and corresponding high friction that must be overcome as the lock bars are driven. This movement can also misalign the traffic railings. If the guides and receivers are misaligned vertically, the higher of the two bascule leaves will lift the other bascule leaf upward and possibly off of the live load shoes. This movement can also affect the alignment of the deck.

The span locks should be aligned in the field only after the structure is properly aligned (i.e. the deck surface and traffic railings are aligned and the live load shoes are in solid contact with equal reactions.) The span lock assemblies are usually provided with several means of adjustment including shims between the housing and the supports, oversized holes within the web to allow the housing to be moved vertically or horizontally, shims or other means to adjust the shoes within the housing. Alignment is typically performed by inserting the lock bar through both guides and the receivers and with spacers equal to the required clearances inserted into the gaps, while the housings are loosely mounted to the structure. The holes for the span lock mounting bolts are not typically drilled until final assembly; however, temporary undersize bolts can be used to temporarily secure the assembly while alignment is checked. Once the lock assembly is temporarily secured, the temporary spacers are removed and the lock bar is moved to see that it drives and retracts without resistance and the clearances are checked using feeler gages. Once alignment is verified, the bolt holes are drilled and reamed and the final turned bolts are installed.