HMS HEAVY MOVABLE
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"STABILIZATION OF DOUBLE LEAF BASCULE BRIDGES"

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STABILIZATION OF DOUBLE LEAF BASCULE BRIDGES

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Almost all double leaf bascule bridges consist of two cantilever spans projected toward each other, connected at their tips by a suitable shear lock. Other types of double leaf bascule are comparatively rare, such as those which form arch bridges in the closed position, and are not the topic of this discussion.

Double leaf bascule bridges are possibly the least practical, from a maintenance and operation standpoint, of all commonly used types of modern era movable bridges. They use two separate moving leaves when one would do, with all the associated expense in construction, operation, and maintenance of two totally independent movable bridge leaves. They also join these two moving leaves together for the support of live load, compounding the difficulties. There are advantages to double leaf bascules: they can open and close somewhat more quickly than any other type of movable bridge; a double leaf bascule is less affected by wind loads than a single leaf bascule spanning the same channel width; they use slightly less structural steel than other types of movable bridges with the same load rating spanning the same width of navigation channel; double leaf bascules are less susceptible to collision with vessels navigating past them than other movable bridge types, and they are generally considered more aesthetically pleasing than other types of movable bridges. One might ask, however, whether these advantages are worth putting up with the additional complications, particularly in regard to stabilizing the structures under live load.

STABILIZATION

Double leaf bascule bridges, more so than most other movable bridge types, frequently have problems with seating. These problems arise from several sources. The bridge may be carrying live loads larger than those designed for, overstressing the support system. The bridge stabilizing devices may have suffered deterioration so that they cannot contain the forces imposed on them. The bridge stabilizing devices may be improperly adjusted so that they do not perform their intended function. The entities which contribute to stability of a double leaf bascule include: live load shoes which form stops for each moving leaf as it attains its seated position; center or shear locks forming a vertical tie between the two leaves of a double leaf bascule bridge when in the closed position; live load anchors which are capable of exerting a downward force at the rear of the bridge counterweight; tail locks which form a shear connection at or near the rear of the bridge counterweight, and adjustment of the balance of the moving leaf about its axis of rotation.

STABILIZING COMPONENTS

Live Load Supports

There are two common variations of basic live load support for double leaf bascule bridges:

1. Live load carried by "Live Load Shoes" located under the bascule girder between trunnion or tracks and sea wall (see figure 1).

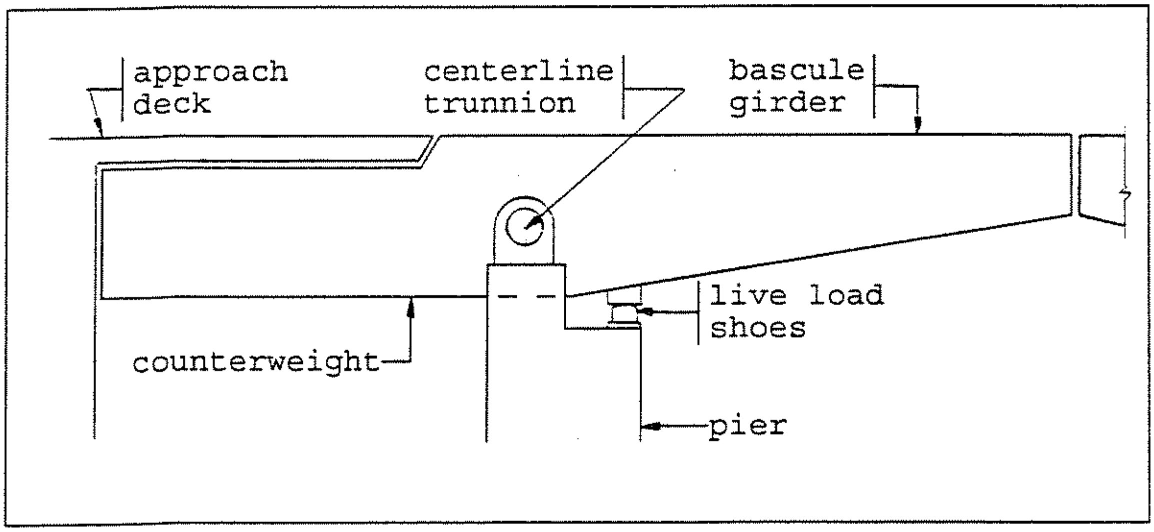

FIGURE 1

This type is used on most double leaf bascules, with the live load shoes placed ahead of the trunnions, as close to the front of the pier as is practical, because of the advantage in reducing the maximum trunnion or track loading. They usually consist of heavy steel castings bolted to the bottom flange of the bascule girders or bottom chord of the trusses, with shims between the casting and the superstructure to allow for adjustment. The live load shoes make contact with matching castings anchored to the pier. This type of support is normally quite durable; the most common mode of deterioration is corrosion when debris is allowed to build up around the castings.

2. Live load carried by trunnions or tracks, with the leaf restrained from rotation by "live load anchorages" located behind the counterweights (see figure 2).

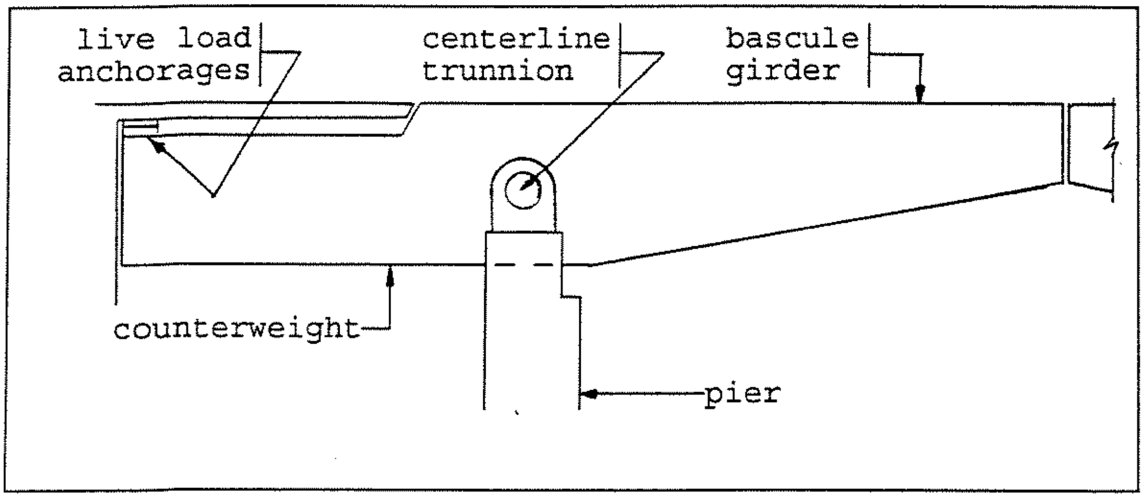

FIGURE 2

As can be seen, the second type adds to load at the trunnions or tracks, by placing live as well as dead load here. The advantage of this type is the possibility of constructing a smaller pier, as the center of rotation can be placed close to the sea wall, and the live load moment taken to the pier within the distance from the centerline of rotation to the rear end of the counterweight. Many rolling lift bridges, and some trunnion bascules, have the live load anchorages placed at the rear of the bascule girders, adjacent to the counterweights. The placement in the rear requires a large superstructure element to act as a tiedown for the rear of the leaf, usually in conjunction with an approach roadway deck. Rear live load anchorages have the disadvantage of higher trunnion loads as indicated above. They tend to be less accessible than forward live load shoes, and are thus more prone to corrosion and maladjustment.

Anchors

Live load anchors used in combination with forward live load shoes are similar to rear live load anchorages but are intended to be set up so that they have small clearances when the main live load shoes are firmly seated (see figure 3).

As load is released at the main supports, i.e., trunnion columns, due to live load on the cantilever arm shifting the center of gravity of the leaf and live load toward the live load shoes, the anchors are supposed to come into contact. In actuality, as it is almost impossible to adjust these components precisely; the anchors usually do no work until the main live load shoes become worn, when the anchors end up taking over the main live load support. After they start carrying the greater part of the live load reaction, they are susceptible to structural failure, and the trunnions begin to take more reaction than they were designed for.

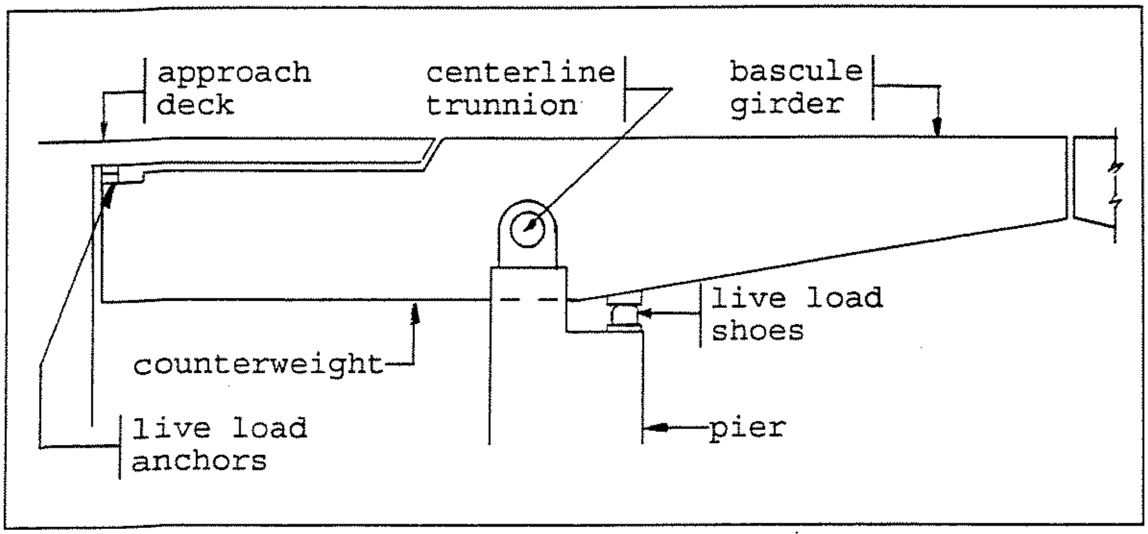

FIGURE 3 - Live load anchors and forward live load shoes

Tail Locks

Tail locks are occasionally used on double leaf bascules, most often when a part of the roadway deck is behind the rotational center of the moving leaf, to provide live load support at the rear of the leaf. The tail locks form a shear connection at the rear of the counterweight to hold the leaf in the closed position (see figure 4).

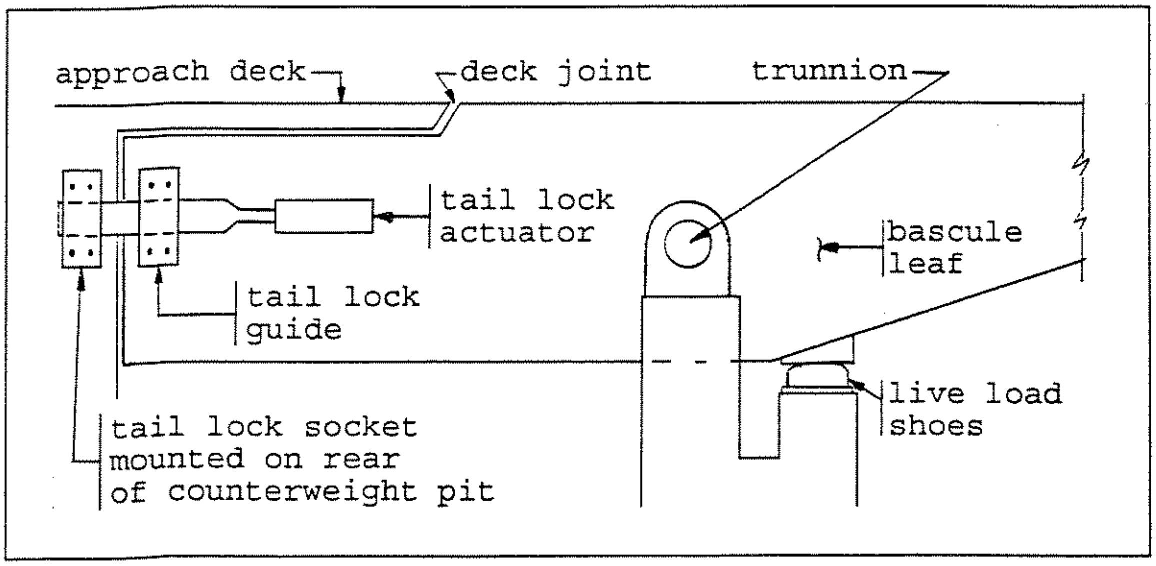

FIGURE 4 - Tail Lock

Most tail locks resemble rudimentary center locks. They usually have no provision for adjustment so they are unlikely to carry any live load reaction, even when newly installed. Tail locks are usually very difficult to reach for maintenance or inspection, and they are consequently usually very worn and out of alignment. Tail locks have frequently been damaged due to actuation when the bridge was not fully closed, and have been deactivated.

Center Locks

Toe end support usually consists of shear center locks which transmit vertical loading to the toe of the mating leaf. Each leaf of a double leaf bascule is a cantilever arm, which supports the dead load of the leaf, and most of the live load. When a live load is near the middle of the bridge, the center locks are intended to provide for the two leaves to share this load, by forcing them to have equal deflection at their tips or toes. But the center locks wear excessively, especially when leaves do not seat firmly at their live load shoes or anchorages, so that the equalization of deflection is lost, and the two leaves bounce as each live load axle passes from one leaf to the other. A new bridge with center locks properly aligned and adjusted to the design clearances may develop excessive vertical play within a year or two of being opened to traffic.

Rolling lifts frequently use rigid jaw-type locks, because the movement of the leaves toward the channel when closing and away from the channel when opening allows such rigid devices to engage and disengage. This requires synchronization of the closure of the two leaves of the bridge, usually performed manually by the bridge operator in a hit-or-miss fashion, so that the jaws can engage. Most of these bridges have wear due to live load action at their center locks increased by inadvertent impacts and interference during opening and closure. Some successful applications of automatic synchronized operation of double leaf rolling lifts have been made.

Trunnion bascules generally use retractible lock bars similar in arrangement to tail locks described above. The retractible lock bars slide in guides and sockets, which are lubricated to minimize wear. The lubricant usually attracts dust, sand and other grits which make it a very effective abrasive compound, wearing away the bar and guide shoe material with every actuation of the lock mechanism, and abrading the bar and socket every time live load causes the span to deflect. Once the clearance at these components has been increased by abrasive wear, impacts at the bearing surfaces from live load add to the rate of increase of the clearance by plastically deforming the shoe and/or bar material. Many older bridges use a mechanical jaw arrangement which functions similarly to the retractible lock bars.

Alignment

Difficulty frequently arises in obtaining proper alignment and effective operation of all span support and stabilization devices. It is a difficult task to achieve proper initial alignment at construction. In-service wear and occasional overloads can cause misalignment of these bridge components even when properly erected. A double leaf bascule bridge with two main girders on each leaf may have as many as eighteen points of support:

Four trunnions or tracks
Four live load shoes
Four live load anchors
Four tail locks
Two center locks

Superstructure

In addition to the stabilizing components mentioned above, the bascule leaf superstructure itself is an important factor in the stability of the bridge. A flexible leaf will deflect more under a given live load than a rigid one, storing more energy as it is bent like a spring under live load. When the live load moves off, especially under impact or high speed, the leaf springs back up, imputing a negative impact on the leaf and possibly causing it to lift off its live load supports. For this reason, bridges carrying heavy high speed traffic should be built much stiffer and heavier than bridges carrying light, slow traffic. The bridge should also be carefully designed and constructed to avoid abrupt changes in roadway profile, particularly at the joint between the leaves, as this adds to impact forces.

Movement of the bascule leaf under live loading, consisting of lifting off of and impacting upon the live load supports, causes damage to all components, particularly the machinery. The damage is most readily apparent in excessive wear at the rack and pinion teeth, but may also show up as wear at the trunnions or tracks. In more unusual cases wear or damage may show up at other drive components, or on the bridge superstructure or substructure. Frequently, damage is readily apparent at the live load shoes, anchors, and other components that are intended to stabilize the leaves.

BALANCE OF BASCULE BRIDGES

The stability of bascule bridges is highly dependent on the condition of their balance; the location of the center of gravity of the span relative to its trunnion or rolling center. The span should be slightly "span heavy" when closed, which means that its center of gravity should be toward the navigation channel from the rotating center of the leaf, when closed to marine traffic. This produces a slight positive dead load reaction at the live load bearings, stabilizing the leaf in the seated position.

Bascule is French for see-saw. All modern bascule bridges consist of a large moving mass of superstructure, deck, and counterweight, which can be considered balanced for structural purposes. The span can be considered essentially rigid for balancing purposes, as it rotates between opened and closed positions. This applies whether it is a simple trunnion leaf, or a rolling lift of the Scherzer or Rall type. It also applies to the many variations on the articulated counterweight type, as developed by Strauss and others, with the counterweight pivoting about an axis or arc separate from the bridge leaf. An exception to this rule are bascules with operating struts or ropes such as many heel trunnions, some early Scherzer rolling lifts, and others, which do not add simply to the balancing calculations, as they move in a different path than the superstructure. The operating strut could be heavy enough to have a noticeable effect on the balance, but this usually only happens with single leaf railroad bridges. Heel trunnion and articulated counterweight bascule bridges have the counterweight rotating about an axis separate from the leaf itself. The counterweight is always in a fixed position with regard to gravitational moment relative to the bascule span on these bridges, due to the parallelogram arrangement of the pivot points (see figures 5 and 6).

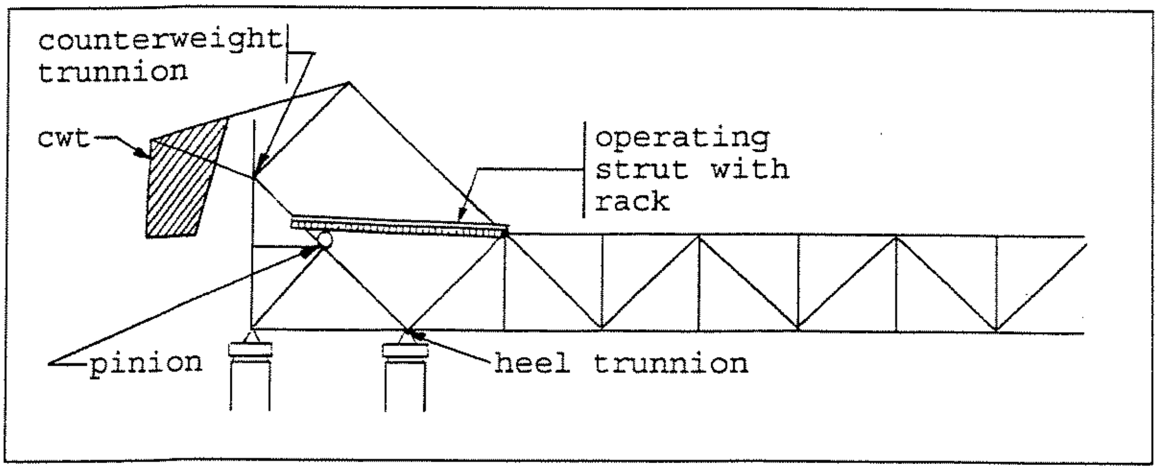

Figure 5 - Heel Trunnion Diagram

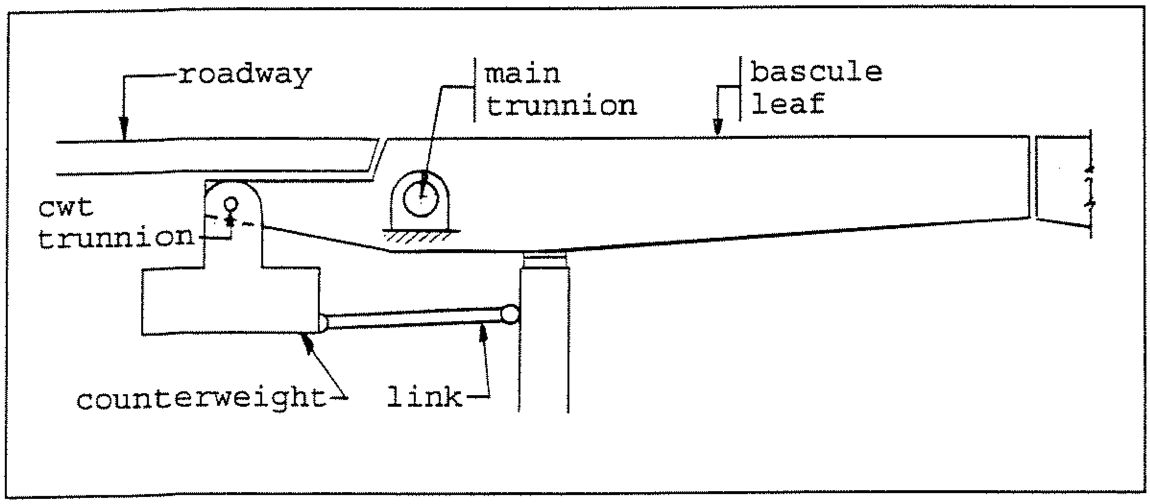

Figure 6 - Articulated Counterweight (Strauss) Diagram

It can be very difficult to achieve a correct balance state, as the amount of imbalance, measured as force at the live load shoes, is usually less than 1% of the dead weight of the moving leaf.

If a bascule bridge leaf were to be exactly balanced, so that its center of gravity was exactly at its center of rotation, the machinery would not have to overcome any gravitational loadings while opening or closing the span. The balance condition described in the preceding paragraph increases the amount of power required to open the leaf because the leaf is actually made to be in a state of unbalance. Opening the span when properly balanced requires lifting the center of gravity through the arc it traverses from the closed to open position. This extra power required is an almost imperceptible fraction of the operating cost of a bridge, and the extra strength required in the operating machinery is negligible compared to other loadings which must be considered in design. Even so, the amount of unbalance should be minimized to the amount necessary for stable seating of the leaf.

Vector Analysis

The position of the center of gravity can be located vertically in such a way that the span heavy unbalance is at a maximum when the leaf is seated, decreases to zero as the leaf opens, and assumes a negative, "counterweight heavy", condition as the span reaches the open position. This ideal condition of balance increases the power requirements only slightly compared to zero imbalance, while providing stable seating for live load. It also provides necessary stabilizing of the span in the open position so that a drop of the open leaf would be prevented should there be a mechanical or electrical failure. The ideal condition of balance is illustrated in Figures 7 and 8.

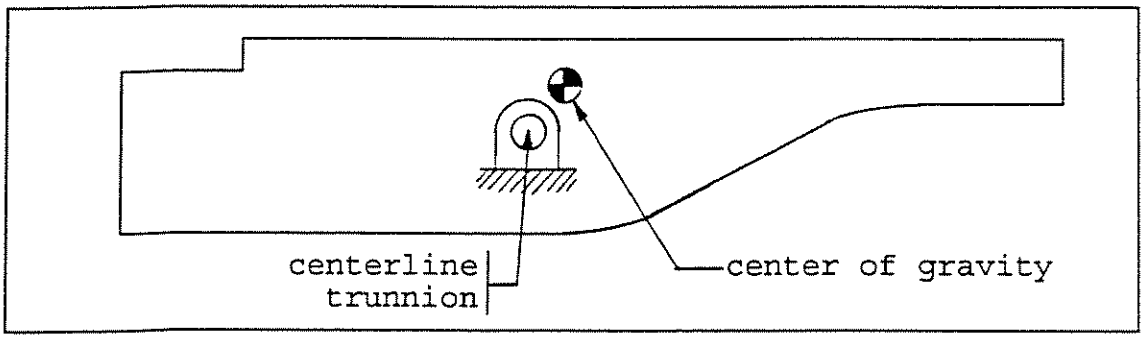

FIGURE 7

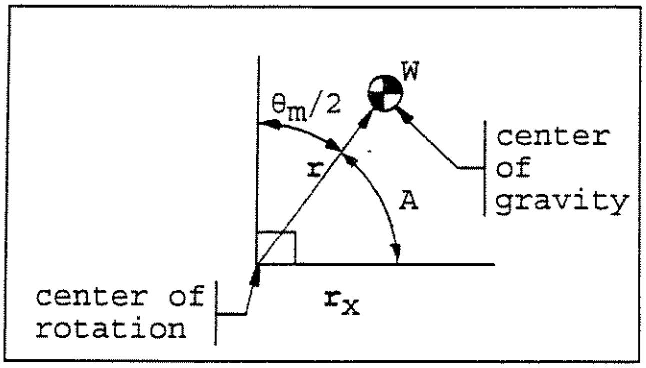

FIGURE 8

The vector "**r**" from the axis of rotation to the center of gravity should be small, to avoid excessive impact forces on seating, and to minimize power requirements. Hool and Kinne, in "Movable and Long Span Steel Bridges", recommend that the horizontal distance from the axis of rotation to the center of gravity should be just enough to cause a moment sufficient to turn the leaf against friction. The friction factor, k, is approximately 15 percent of the total weight of the moving span for a trunnion bascule without antifriction bearings, or 0.9 percent for a rolling lift bridge. These numbers were developed with heavy truss type bascule bridges, such as a typical Chicago bascule, in mind. With a more flexible leaf, or with very low friction trunnions, the amount of imbalance might be increased somewhat. The friction moment is Wr_tk and this is equated to the span weight times the horizontal component of the vector to the center of gravity, when the leaf is closed (θ=0).

$$(1)\quad W\mathbf{r}_x = Wr_tk$$

W = weight of the moving leaf

r = vector from the axis of rotation to the center of gravity of the moving leaf

$\mathbf{r}_x$ = horizontal component of vector **r**

r_t = radius of the bascule trunnion or rolling lift curved tracks

k = coefficient of friction (0.15 for trunnion; 0.009 for rolling lift)

A = angle between $\mathbf{r}$ and $\mathbf{r}_x$

θ = opening angle

θ_m = maximum opening angle

For bascule bridges with bronze-journaled trunnions in the 10 to 30 inch diameter range, the distance "$\mathbf{r}_x$", of the horizontal component of, "$\mathbf{r}$" would range from 0.75 to 2.25 inches. For rolling lift bridges with curved track radii in the 12 to 24 foot range, the distance, "$\mathbf{r}_x$", would range from 1.30 to 2.59 inches.

The angle "A", that the vector from the center of rotation to the center of gravity makes with the horizontal plane, should be chosen so that the maximum opening angle, θ_m, is equally divided about the vertical axis, as shown in Figure 8.

$$(2)\ A = 90-(\theta_m/2)$$

This will result in minimum additional work and wear of the operating machinery during a complete operating cycle while accomplishing the desired gravitational stabilization.

The horizontal component, "$\mathbf{r}_x$", with the leaf closed (θ=0), determines the gravitational seating force at the live load shoes. The horizontal component, "$\mathbf{r}_x$", should be equal to 0.15 times the trunnion radius or 0.009 times the curved track radius, as in equation (1) and equal to "$\mathbf{r}$" times the cosine of "A" when θ=0.

$$(3)\ W\mathbf{r}_x = Wr_tk = W\mathbf{r}\cos(A+\theta)$$

Balancing

The position of the center of gravity must be determined when designing a new bridge, but the condition is sometimes difficult to achieve in the field due to variations between design and construction weights. These construction variations are accommodated by pockets in the counterweights where small weights can be added, removed or shifted. The pockets are usually located so that horizontal and vertical adjustments in the center of gravity can be made. Lateral balance can usually be accommodated, although it is difficult to measure and does not have as profound an affect on operation. It is theoretically possible to build a "bascule" bridge without counterweighting it (which thus makes it not a true bascule bridge), but this is not recommended except for very special situations, such as the extremely small "bridges", found in Bermuda and the Orient. These "bascules" are merely hinged openings at the tips of two cantilever spans, to allow sailboat masts to pass while being very carefully guided.

Existing bridges present additional challenges. Not all designers, past or present, have agreed on the ideal balance condition, helping account for a wide variation in existing balance conditions. Some designers have thought that balance should be exactly opposite that described here as ideal, to reduce power requirements. Modifications such as redecking, strengthening, removing overhead trolley wires and supports, painting, moisture absorption at the counterweight, and build up of debris on the leaf can drastically affect the balance condition of a bridge.

It is important that the balance condition of a bascule bridge be as near ideal as possible to reduce power requirements and machinery wear and assure safe and reliable operation. Determination of the balance condition of existing bridges has frequently been more an art than a science. Typically, trial and error placements of weights with test openings of the bridge were required until an acceptable condition of balance was reached. Observation of motor current demand during test operations has been used as a measure of bridge balance to try to reduce the number of trial and error attempts. Trial and error methods entail considerable time and expense while never assuring that the balance condition is actually known. Many times, crews of laborers have spent days on a bridge, moving weights around, and left with the bridge in no better balance condition than when they arrived.

Vector analysis can be used to accurately determine the imbalance vector of a bascule leaf in a vertical plane of rotation about the rotational axis. The existing span imbalance vector $W\mathbf{r}_i$, can be determined by measuring and recording the operating torque at the rack pinion shafts as the bridge is opened and closed under controlled conditions, such as by using electrical resistance strain gages attached to the shafts. For the method to be valid, friction must be the same, at any particular position, in the opening and closing directions of movement, but it is not essential for friction to be constant during the operation of the bridge while being tested.

With the initial values of "$W\mathbf{r}_i$" obtained by results of this procedure, and the desired final imbalance value of "$W\mathbf{r}_f$" assumed, vector analysis can be used to determine the required weight shift to produce the desired balance condition. Figure 9 illustrates an example of a vector diagram:

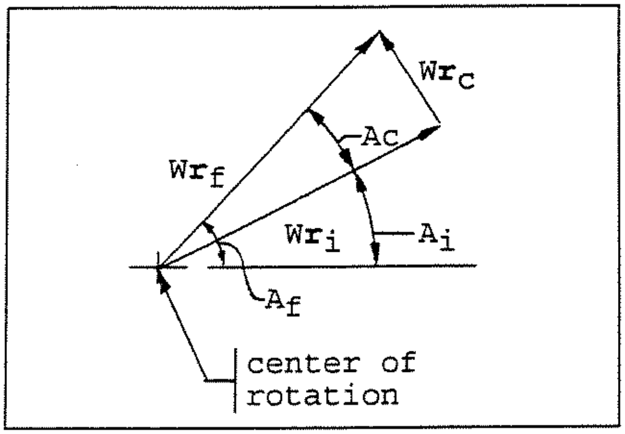

FIGURE 9

The correction vector "$\mathbf{Wr}_C$", for the example shown in figure 9, can be accomplished on the span by shifting small movable weights from the lower to the upper counterweight pockets as shown in figure 10.

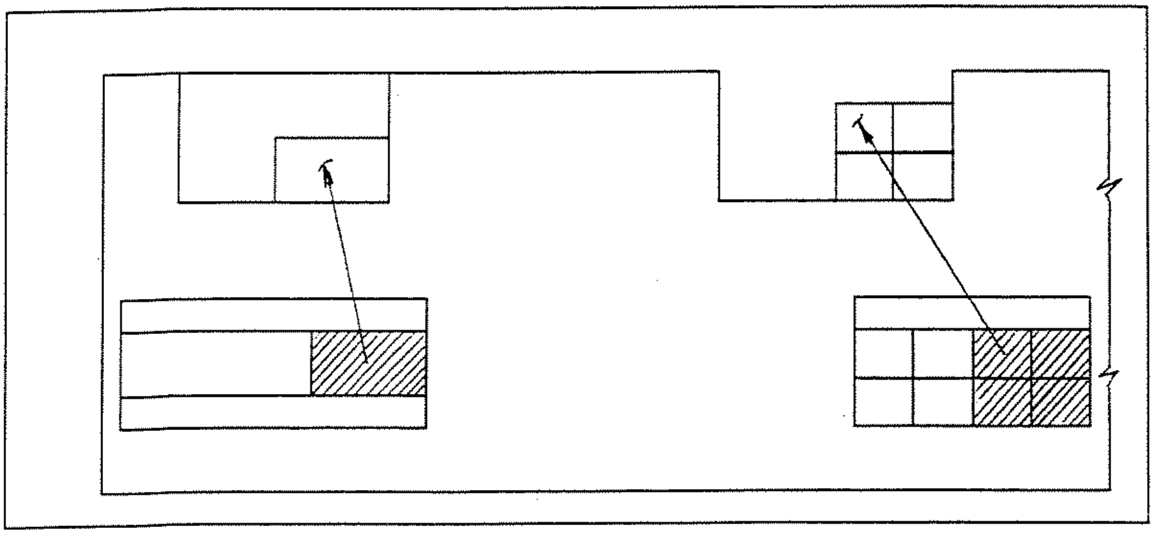

FIGURE 10
Vertical Section at Counterweight Parallel to Roadway Axis

Additional weight can be added or removed, with the understanding that W will change slightly. As the value of the product **Wr** is the critical quantity, an overall weight change does not affect the accuracy or performance of balance adjustment operations. The correction can, in fact, be accomplished solely by adding weights, or subtracting them, in any given situation. Many bridges require the addition of weight on the tip of the cantilever arm in order to properly locate the center of gravity, without any corresponding removal of weight from the counterweight.

There are several sources available for a full discussion of the balancing algebra. Basically, friction can be canceled out, providing it meets the criteria in the text, so that, if wind loads are eliminated by testing on a calm day the imbalance torques at the rack pinion shafts can be readily derived:

$$(4)\quad (T_{up} + T_{dn})/2 = W\mathbf{r} \cos (A + \theta)$$

where: Tup = torques to open
Tdn = torque to close
W = weight of span
r = radius to center of gravity
A = angle from **r** to horizontal
θ = opening angle at measurement

CONCLUSIONS AND RECOMMENDATIONS

Double leaf bascule bridges become unstable because they are poorly designed, poorly constructed, or poorly maintained. They are more susceptible to deficiencies from these causes because they are more delicate than other common types of movable bridges. It is very difficult to correct the faults of a poorly designed bridge, but sometimes possible to correct construction defects. It is very difficult to correct the results of poor maintenance except by replacing the components affected.

A properly designed double leaf bascule bridge should be very rigid, particularly in regard to primary live load deflections.

The leaves of the double leaf bascule should be firmly supported on very solid live load shoes located adjacent to the pier sea wall, as far as possible from the center of rotation.

The balance of the double leaf bascule should be such that a dead load reaction exists on the live load shoes, when the bridge is closed, that is substantially in excess of any possible negative reaction, from live load or other sources.

The roadway surfaces of the double leaf bascule should be formed so that there is no misalignment at the joints, either at the heels of the leaves or at the toes. This applies to profile as well as elevation - the vertical curve should be continuous from one leaf to the other and from each leaf to its approach.

Tail locks should be provided as a backup to the stabilization achieved by balancing. The tail locks should firmly grasp the tail end of each leaf with minimum clearances and hold it in the closed position. This will eliminate the possibility of drive machinery being damaged due to live load deflection.

Center locks should minimize the difference in vertical deflection of the tips of the leaves under live load. They should have little or no clearance for free vertical displacement, while allowing longitudinal and rotational displacement due to thermal, live load or other effects.