BRIDGE REDUNDANCY AND FRACTURE CRITICAL MEMBERS*

Section 1 DEFINITIONS

Fracture Critical Members

The AASHTO Guide Specification for Fracture Critical Bridge Members states that "Fracture Critical Members or member components (FCMs) are tension members or tension components of members whose failure would be expected to result in collapse of the bridge." To qualify as a FCM, the member or components of the member must be in tension and there must not be any other member or system of members which will serve the functions of the member in question should it fail. The alternate systems or members represent redundancy. Redundancy in bridge framing systems and of tension members, along with the necessary definitions, are discussed in the following sections.

Framing Systems

Some knowledge and understanding of the structural framing system is necessary to define and locate fracture critical members. Additional information on this subject is included in Chapter 2 of the "Bridge Inspector's Training Manual 70".

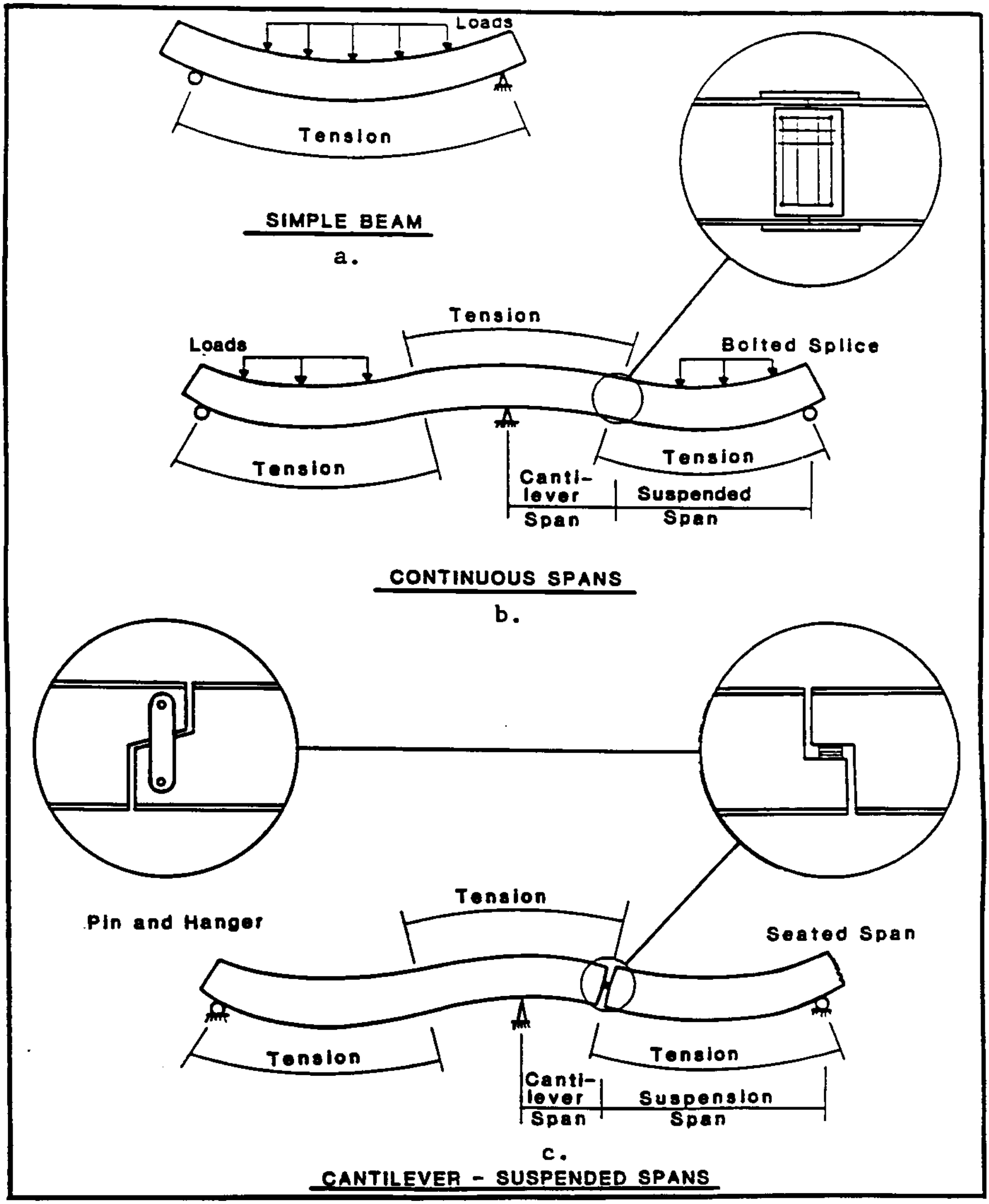
* Chapter 2, Inspection of Fracture Critical Bridge Members. Supplement to the Bridge Inspectors Training Manual (FHWA).

a. Simple Spans. Simple spans consist of a superstructure span having a single unrestrained bearing at each end. The supports must be such that they allow rotation as the span flexes under load. Ordinarily, at least one support is attached in a way that keeps the span from moving longitudinally. Figure 5a is a pictorial presentation of a simple span. Simple spans can be located within other systems as shown in Figure 5c. The span arrangements can be used for either trusses or girders as illustrated in Figure 8.

b. Continuous Support. Spans are considered continuous when one continuous piece crosses three or more supports. Figure 5b shows a two-span continuous structure. Note that the supports at the ends of the continuous units are similar to those at the ends of a simple span. However, because the member is continuous over the center support the magnitude of the member rotation is restricted in the area adjacent to the pier. A bridge may be continuous over many supports with similar rotational characteristics over each interior support.

c. Cantilever and Suspended Spans. Sometimes it is advantageous from a structural standpoint to continue a span over the pier and terminate it near the pier with a short cantilever. This cantilever is ordinarily used to support or "suspend" the end of an adjacent span. This arrangement is shown in Figure 5c. The other end of the suspended span may in some cases be supported by another cantilever or it may rest on an ordinary simple support.

FIGURE 5
BENDING



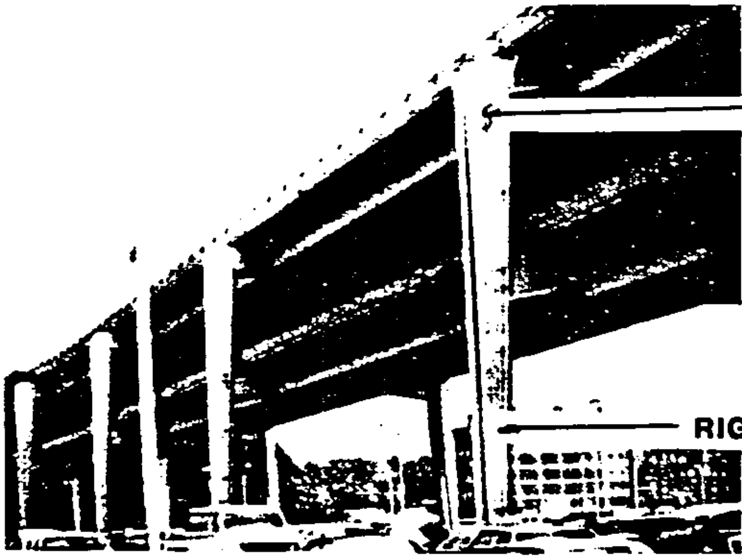
d. Rigid Frames. Rigid frames are frequently used as transverse supports in steel construction, and occasionally used as longitudinal spans. A rigid frame bent example is shown in Figure 6. The term "rigid" is derived from the manner of construction or fabrication which does not allow relative rotation between the members at a joint. A rigid frame may be rigidly attached at the base (fixed) or it may be simply supported.

Stresses

Those stresses which tend to stretch the member are termed tensile stresses. If a member develops a crack in an area subject to tensile stress, the faces of the crack are pulled further apart as shown in Figure 7. Conversely, compressive stresses attempt to shorten the member. Compression is the primary force which acts in columns. A member with a crack subject to compression will tend to have the faces of the crack forced together. Tensile stresses are caused in bridge members and components through bending and/or axial action of the bridge under load.

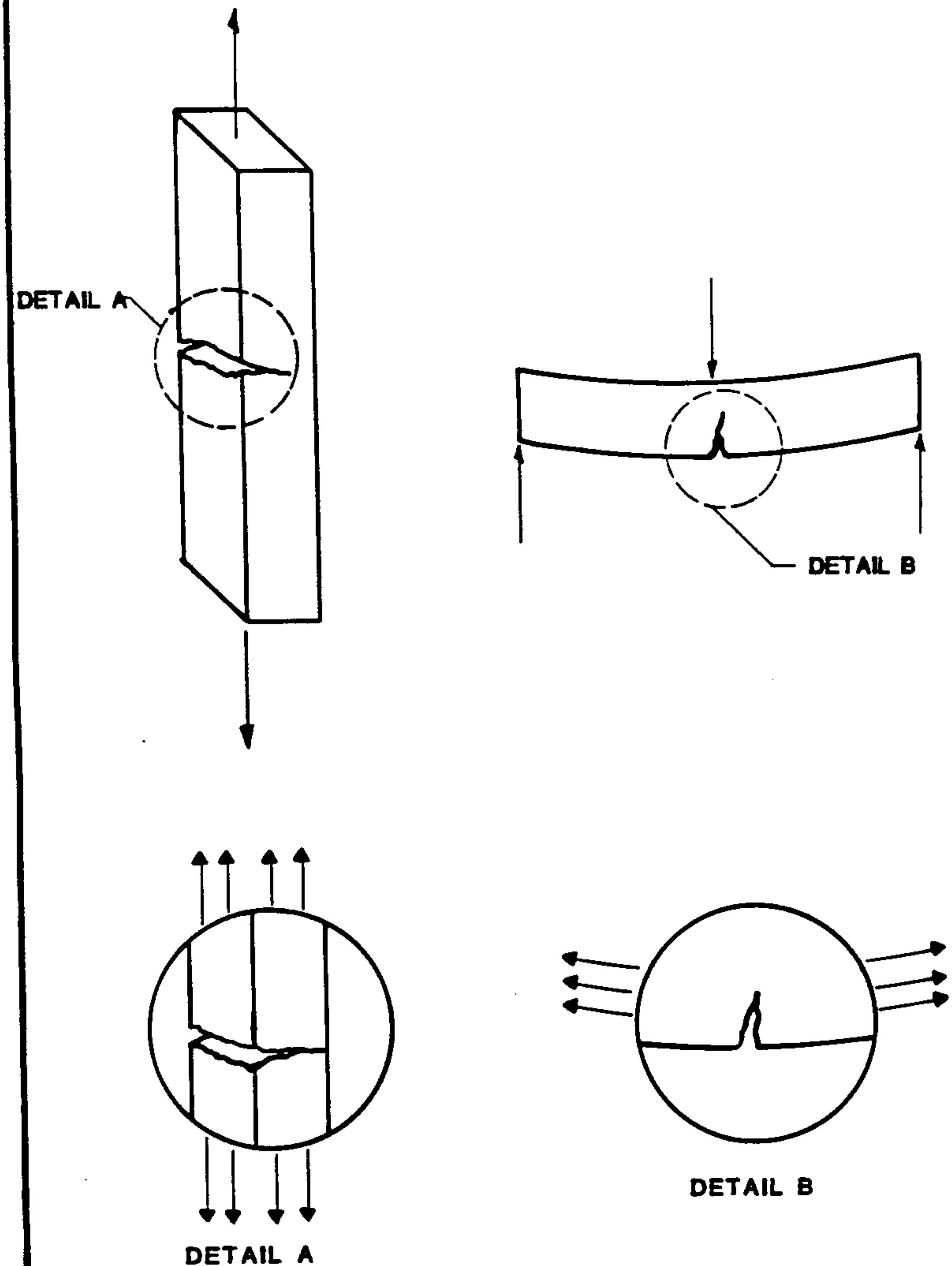
a. Bending. External loads on a simply supported beam create bending which causes a beam to deflect as shown in Figure 5.a. Tensile stresses develop in the lower portion of the beam in simple spans (Figure 5.a) and in the top flange over supports for continuous spans (Figure 5.b). Simple beams are said to be in positive bending, while the portion of continuous spans over the middle support are said to be in negative bending. In positive bending regions, the bottom flange and the lower portion of the web are in tension as illustrated in Figure 5.a. In negative bending regions,

FIGURE 6
RIGID FRAME BENT



Fort Duquesne Bridge, Pennsylvania

FIGURE 7
TENSION STRESS



Cracks being pulled open by tensile forces.

the top flange and the upper portion of the web are in tension as shown in Figure 5.b.

b. Axial. Trusses function in a manner similar to beams. Bending causes the truss to deflect like those shown in Figure 8. In simple span trusses, positive bending causes the bottom chord to be in tension. In continuous trusses, negative bending over the piers causes the top chord to be in tension and positive bending at mid-spans causes the bottom chord to be in tension. Verticals and diagonals may or may not be in tension as explained later in this chapter. The tension tie in a tied-arch bridge is also an example of axial tension, although it may be subject to bending stresses depending on the framing arrangement.

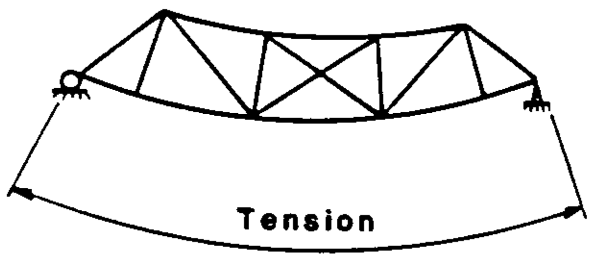
Redundancy

With respect to bridge structures redundancy means that should a member or element fail, the load previously carried by the failed member will be redistributed to other members or elements which have capacity to temporarily carry additional load and collapse of the structure may be avoided. Redundancy in this manual is divided into three parts as further described below: Load Path Redundancy, Structural Redundancy, and Internal Redundancy.

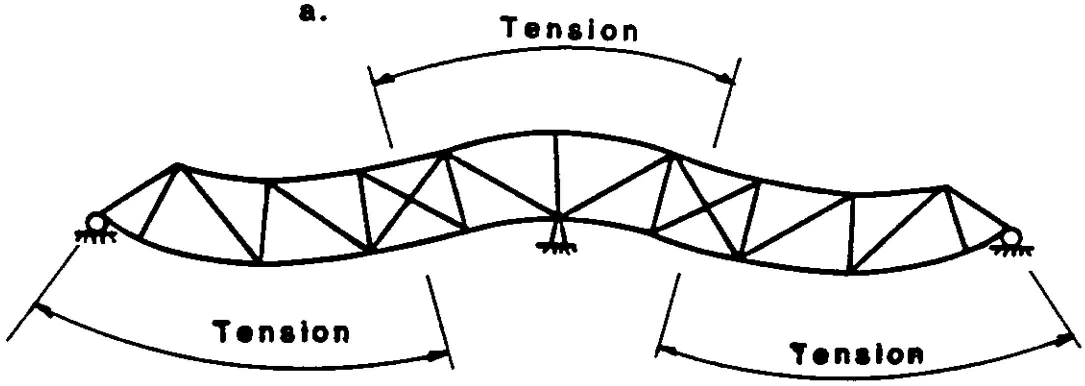
a. Load Path Redundancy. Load path redundancy refers to the number of supporting elements, usually parallel, such as girders or trusses. For a structure to be nonredundant, it must have two or less load paths. A

FIGURE 8

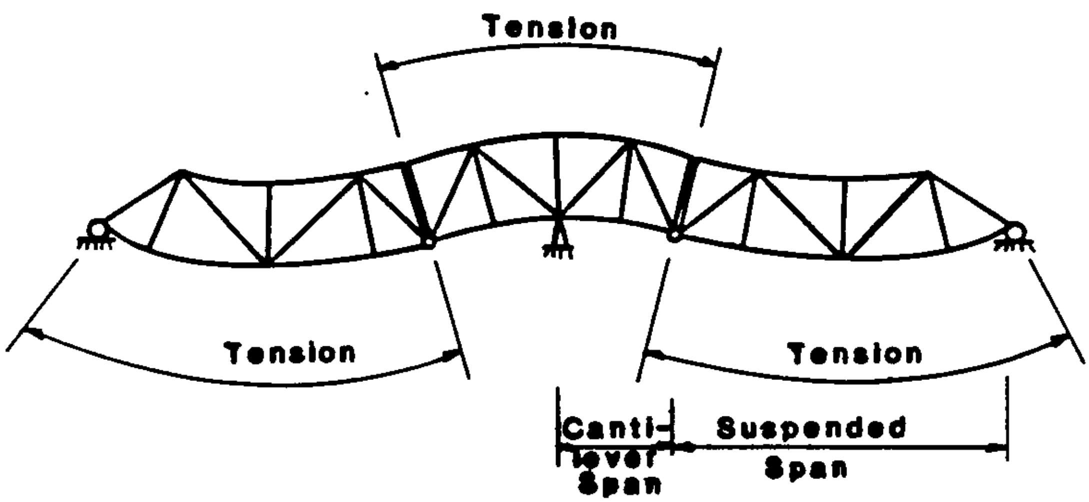
BENDING IN TRUSSES



SIMPLE SPAN
a.



CONTINUOUS SPANS
b.



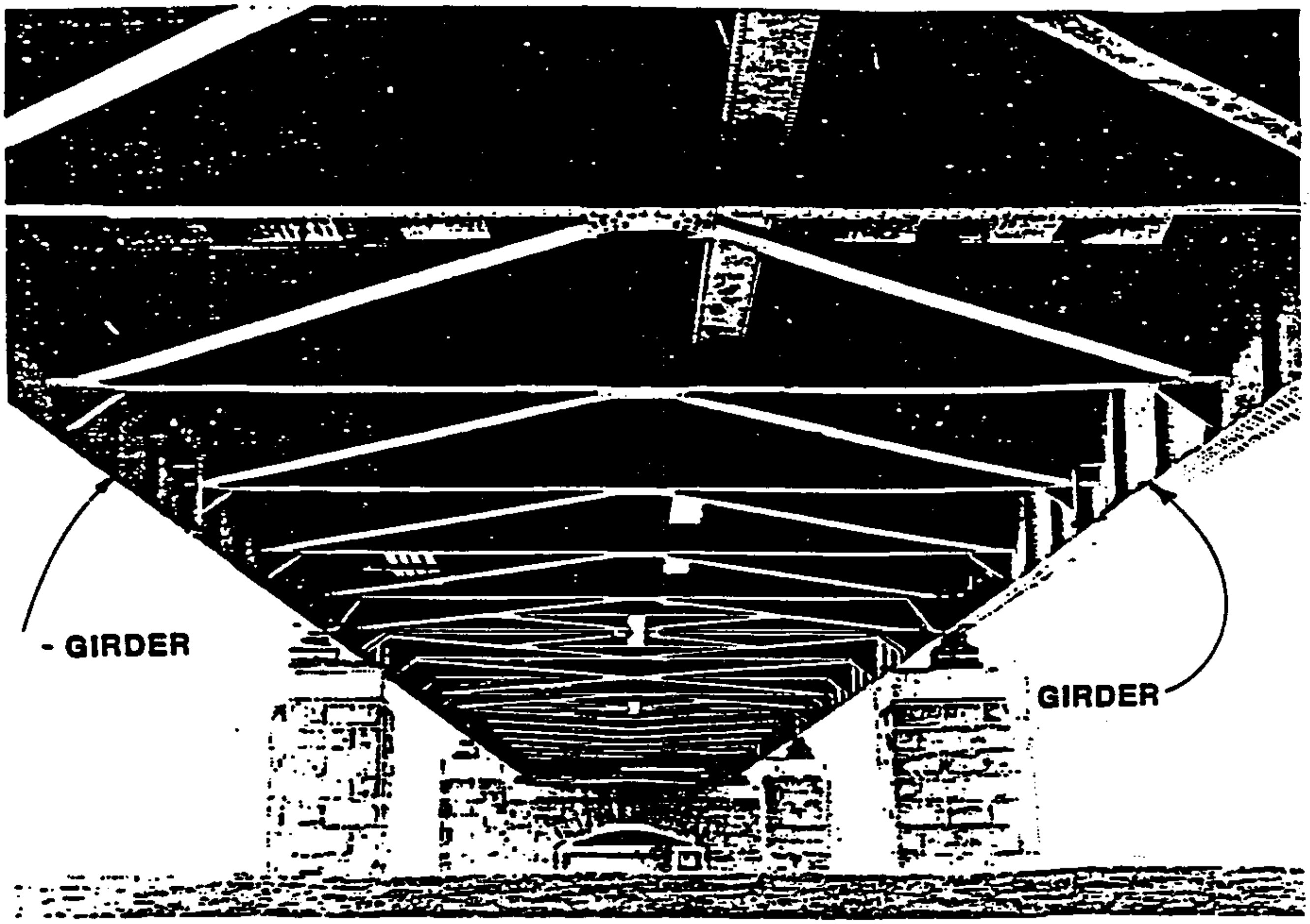
CANTILEVER-SUSPENDED SPANS
c.

framing system which uses only two beams or girders as shown in Figure 9 is nonredundant. Failure of one girder will usually result in the collapse of the sp ., hence the girder is considered to be nonredundant and fracture critical. A multiple load path structure is shown in Figure 10. There would be no FCMs in this structure.

b. Structural Redundancy. For the purpose of this manual structural redundancy is defined as that redundancy which exists as a result of the continuity within the load path. Any statically indeterminate structure may be said to be redundant. For example, a continuous two-span bridge has structural redundancy. In the interest of conservatism, AASHTO chooses to neglect structural redundancy and classify all two girder bridges as nonredundant (AASHTO, Section 10.3.1). The current viewpoint of bridge experts is to accept continuous spans as redundant except for the end spans, where the development of a fracture would cause two hinges which might be unstable.

c. Internal Redundancy. With internal redundancy the failure of one element will not result in the failure of the other elements of the member. The key difference between members which have internal redundancy and those which do not is the potential for movement between the elements. Plate girders, such as the one shown in Figure 11.a, which are fabricated by riveting or bolting have internal redundancy because the plates and shapes are independent elements. Cracks which develop in one element do not spread to other elements. Conversely, plate girders fabricated by welding as shown in Figure 11.b are not internally redundant and once a crack starts to

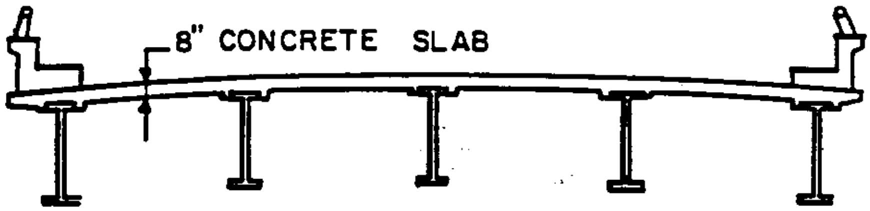
FIGURE 9
TWO GIRDER SYSTEM

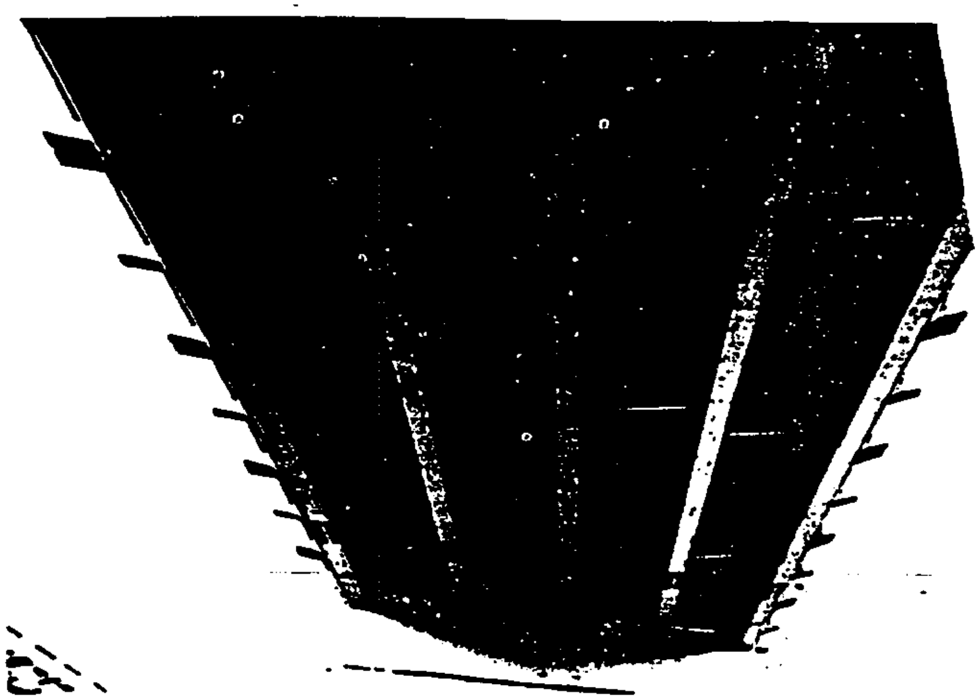


Lateral bracing system on steel two-girder bridge.

SOURCE: FHWA, 1969.

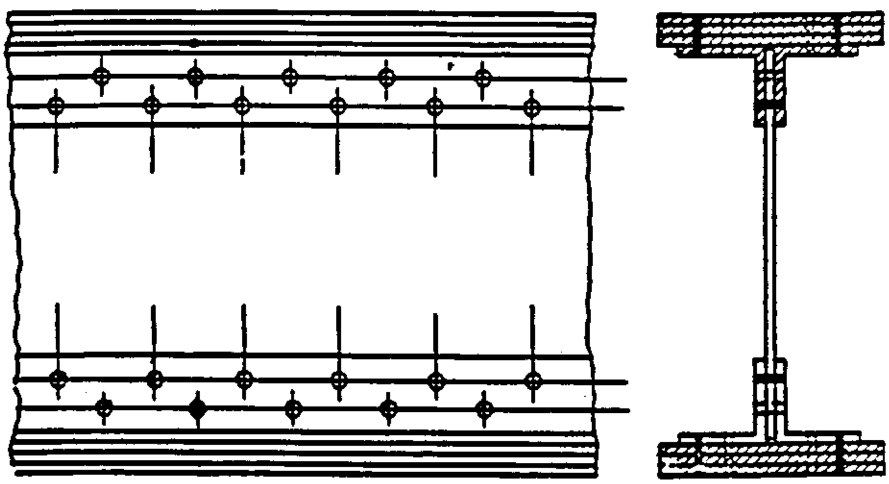
FIGURE 10
MULTI BEAM BRIDGE





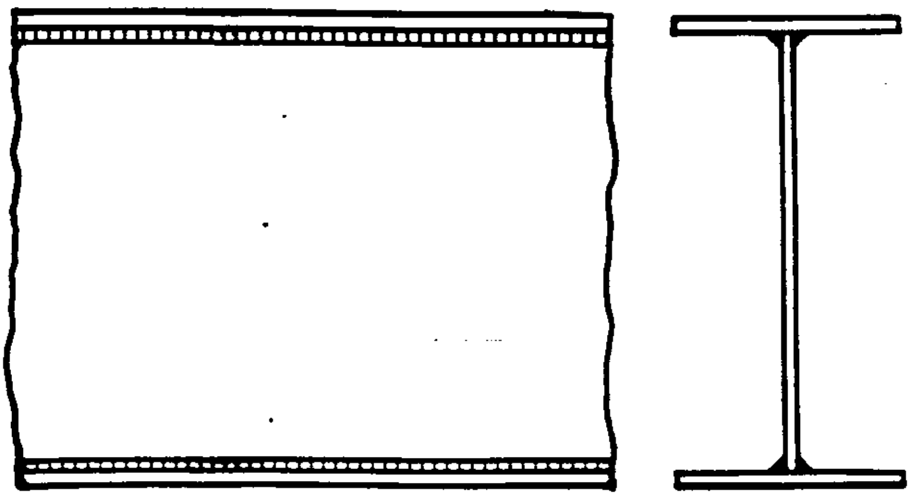
Load Path Redundancy

FIGURE 11
PLATE GIRDER



a.

Riveted Girder



b.

Welded Girder

propagate, it may pass from piece to piece with no distinction unless the steel has sufficient toughness to arrest the crack. Internal redundancy is not ordinarily considered in determining whether a member is fracture critical, but may be considered as affecting the degree of criticality.

Section 2. EXAMPLES

Two-Girder System (or Single Box Girder)

a. Simple Spans. A two-girder framing system is shown in Figure 9. It is composed of two longitudinal girders which span between piers with transverse floorbeams between the girders. Floorbeams support longitudinal stringers.

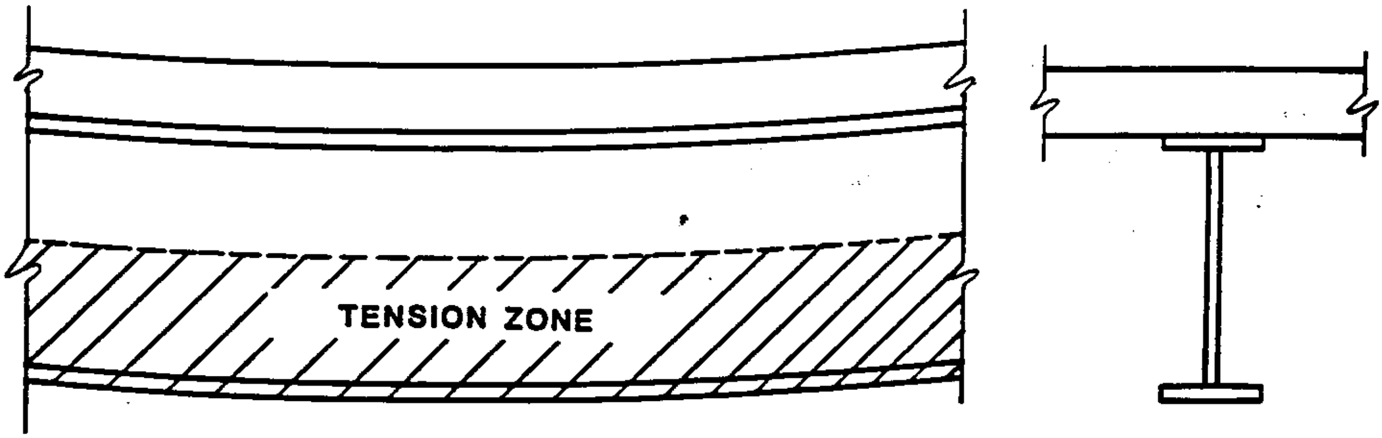
The failure of one girder may cause the span to collapse. These girders may be welded plate girders, riveted plate girders, and steel box beams. The fracture critical elements in all of these girders are in the bottom flange and the web adjacent to the bottom flange as shown in Figure 12.a.

b. Anchor Cantilever. An anchor cantilever span arrangement induces tension in the top flange and adjacent portion of the web in the area over the support as shown in Figure 12.b.

c. Continuous Spans. Continuous spans should be reviewed by a structural engineer or bridge designer to assess the actual redundancy and consequent presence of FCMs. In general, the fracture critical elements

FIGURE 12

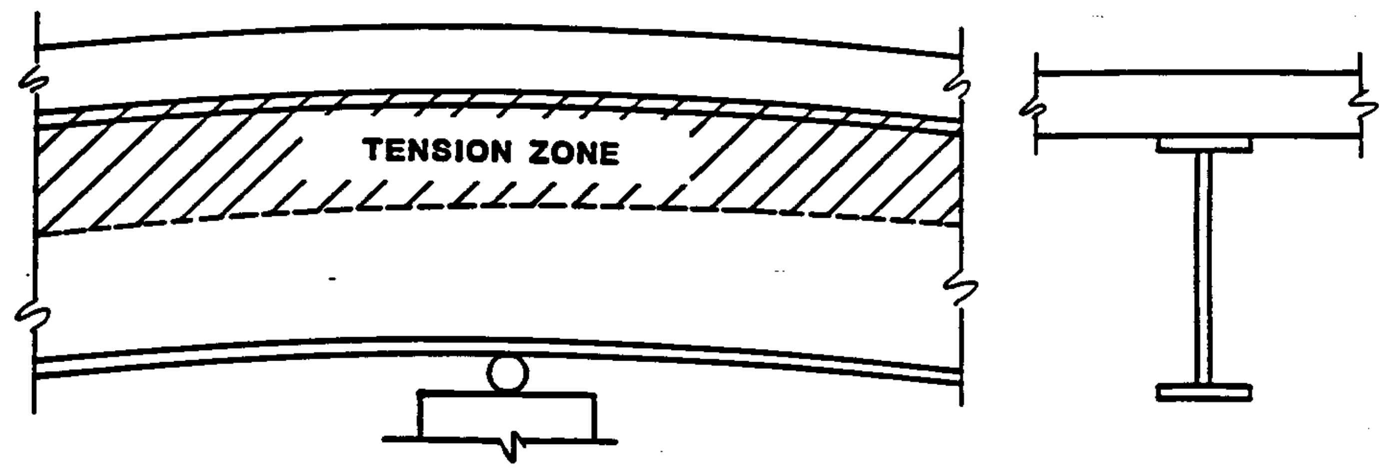
PORTIONS OF A GIRDER IN TENSION



SECTION AT MID-SPAN

a.

Positive Bending



SECTION OVER PIER

b.

Negative Bending

will be located near the center of the spans in the bottom of the girders and over the supports in the top of the girders.

Two Truss Systems

a. Simple Spans. A truss is composed of top and bottom chords, verticals, and diagonals as shown in Figure 13. Trusses types are: pony, through, or deck as shown in Figure 14. Most truss bridges have only two trusses.

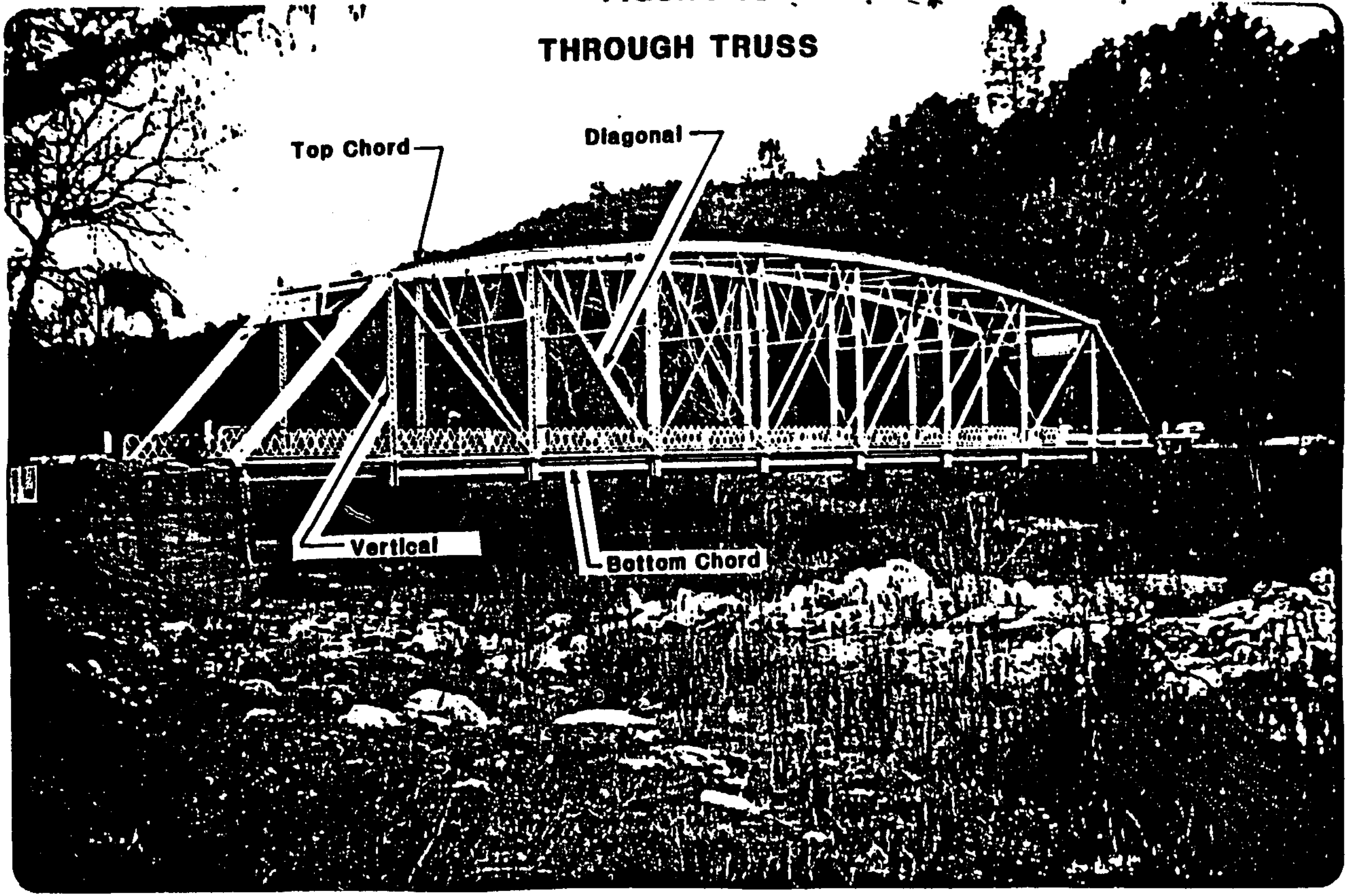
A simply supported truss may be considered a specialized girder with most of the web removed. Since tension members are the critical elements, the bottom chord is of primary concern. It is easy to visualize that the bottom chord must stretch as the span bends which by definition indicates that it is in tension. Fracture of the bottom chord could result in collapse of the span.

The stresses in truss diagonals may either be in tension or compression depending on the geometry of the truss and the load configuration.

A simplified way to determine if a truss diagonal is in tension is to follow the rule of thumb shown in Figure 15. For simple span trusses, diagonals that point upward toward mid-span act like an imaginary arch being in compression while diagonals which point upward away from mid-span act like an imaginary cable being in tension and therefore are fracture critical members. From the point of view of the inspector, all truss members in

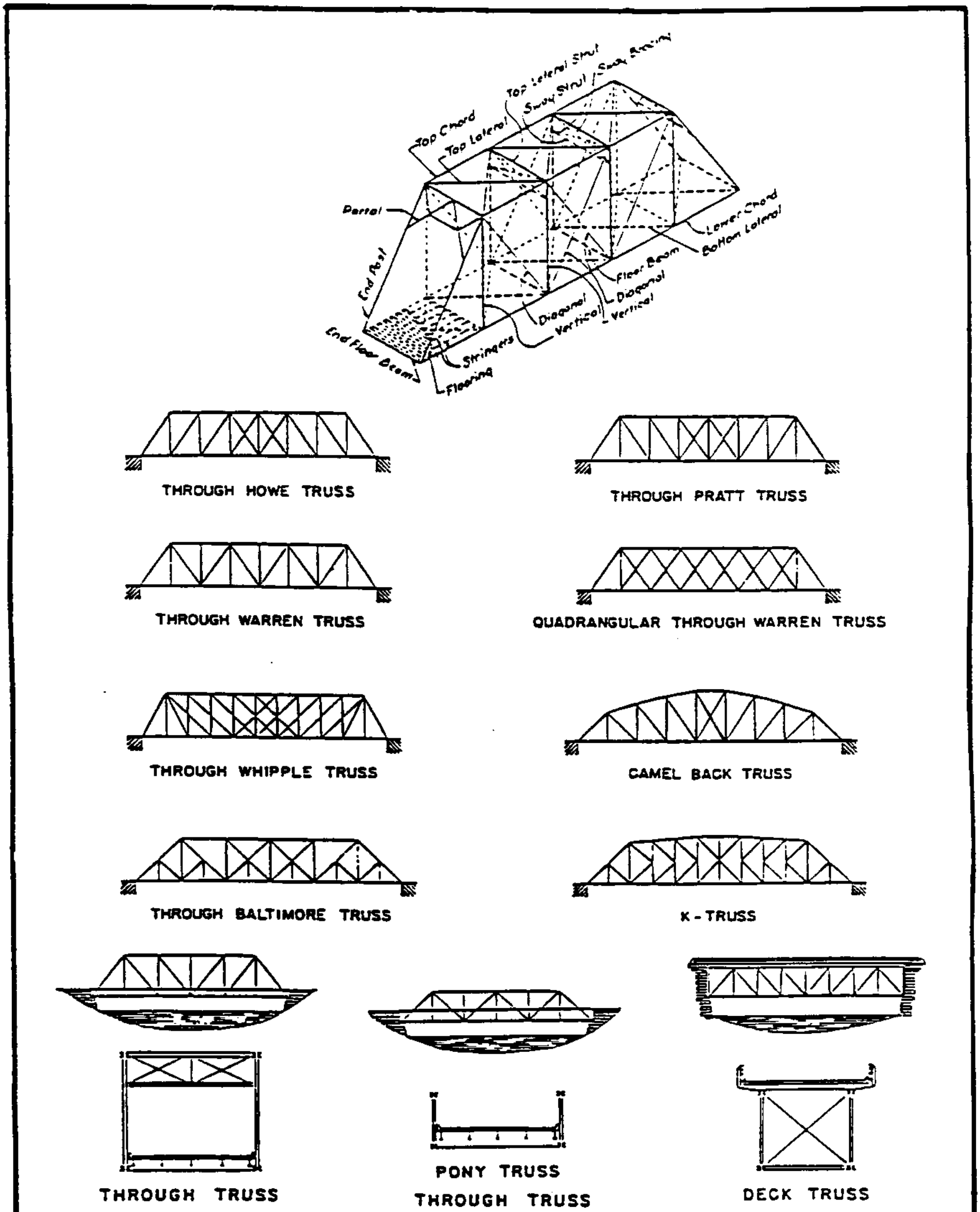
FIGURE 13

THROUGH TRUSS



Member identification in through truss

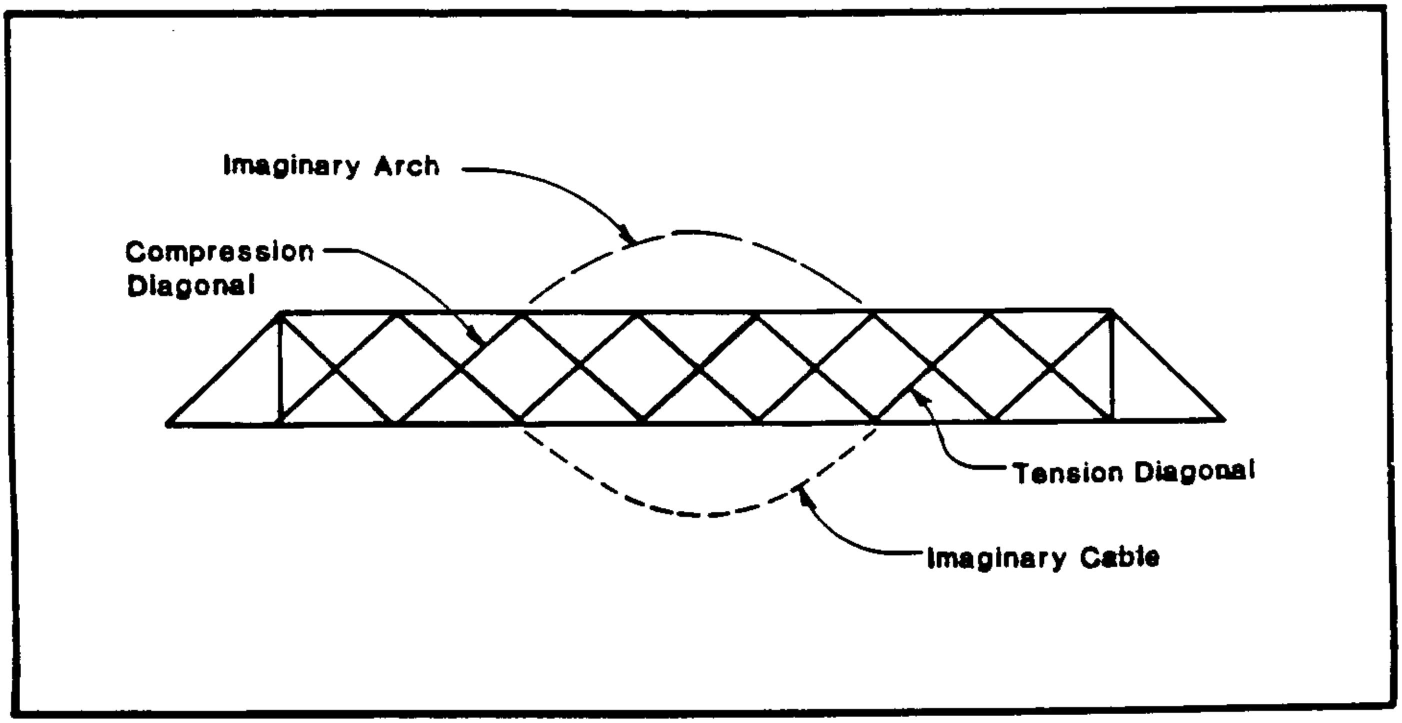
FIGURE 14
TRUSS MEMBERS



SOURCE: FHWA 1969

FIGURE 15

SIMPLE SPAN TRUSS



Simplified method for predicting stress state in diagonals tension should be regarded as fracture critical or an engineer should make a detailed analysis to determine criticality.

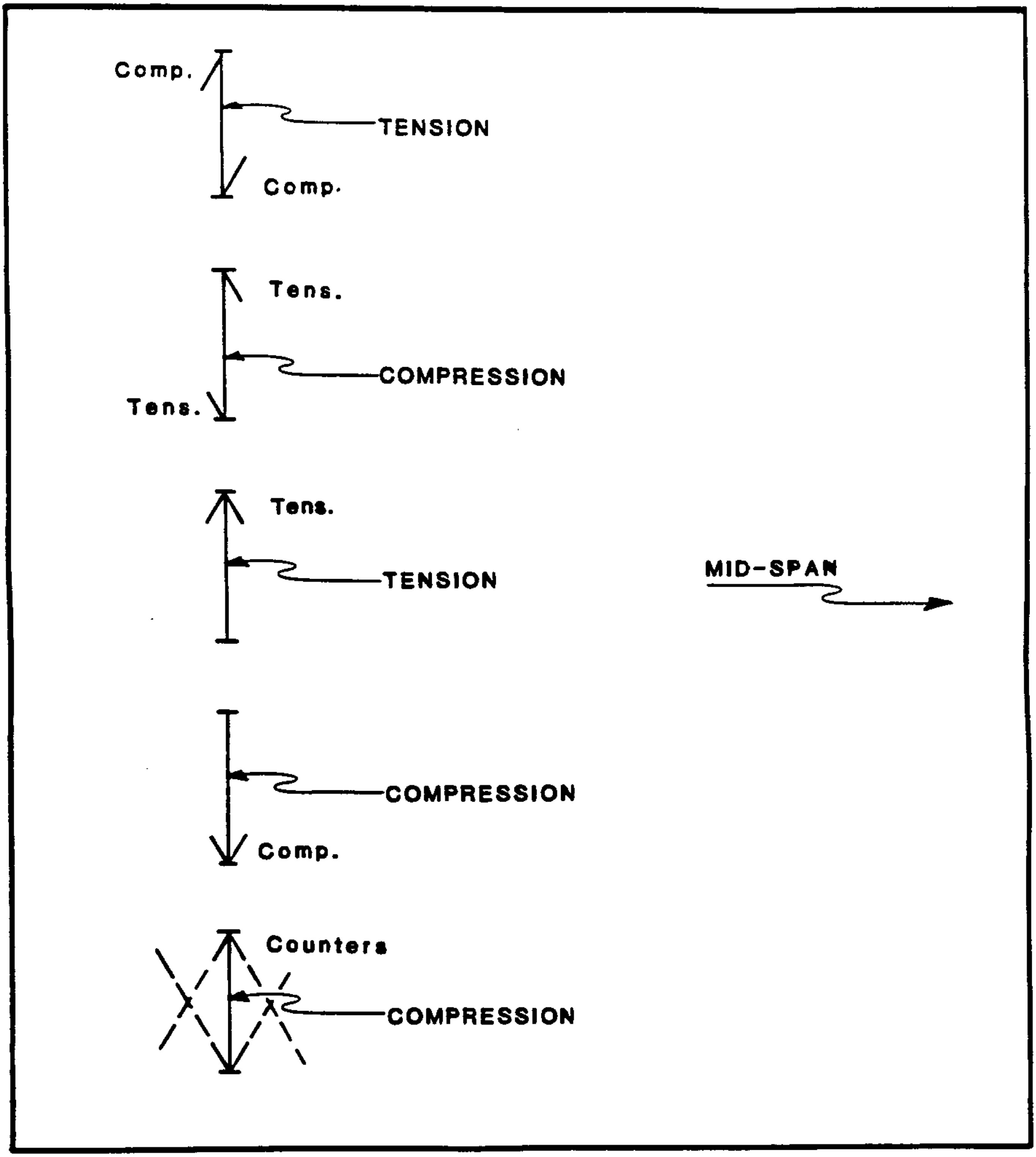
The forces acting on truss verticals can be determined using the rule of thumb which is illustrated in Figure 16. First, the force in a vertical with one diagonal at each end is opposite to the force in the diagonals. If the diagonals are in compression, then the vertical is in tension. Second, the force in a vertical with two diagonals at one end is similar to the force in the diagonal which is nearer to the mid-span. If the diagonal closest to mid-span is in tension, then the vertical is in tension. Third, if a vertical has counters (double diagonals) on both sides, it is in compression.

b. Anchor-Cantilever. The anchor cantilever in a truss system is similar to that in a girder system. In the area over the pier (interior support) the top chord is in tension. In the area near the abutment (end support) the truss is similar to a simple span truss and the same principles apply. From the center of the anchor span to the interior support, the stress arrangement is more complex and should be analyzed by a structural engineer.

c. Continuous Spans. The statements regarding continuous girders are also true regarding continous trusses. In a continuous truss the number of members in tension varies with the loading. Consequently, the determination of which members are in tension and which are fracture critical should be made by an experienced structural engineer. In the Sewickley Bridge (75), a

FIGURE 16

ANALYSIS OF VERTICALS



structure with 119 members, a detailed analysis determined that 66 were tension members and 30 of these were found to be fracture critical. The basic assumption should be that all tension members are fracture critical until a detailed study can be completed. The detailed study should be based on the engineer's knowledge and experience, but the usual procedure is to remove the members one at a time to see if any of the remaining members reach the yield point stress.

Tied Arch

The ties of tied arches, as illustrated in Figures 17 and 18 are fracture critical because tied-arch bridges are nonredundant. The tie girder prevents the supports from spreading apart, is in tension, and is subject to certain other bending stresses where the floorbeams are framed into the tie. In modern designs, the tie girder is often a large welded box girder.

Suspension Spans

a. Eyebar Chain Suspension Spans. The National Bridge Inspection Program began as a result of the collapse of the Silver Bridge shown in Figures 19 and 20. In this type of construction the main suspension member is composed of eyebars fabricated into a chain. Some have as few as two eyebars per link, some have six or more. Figure 21 illustrates a typical critical detail. If members have three or more eyebars they offer some degree of internal redundancy, but members with two or less eyebars should

FIGURE 17

TIED ARCH

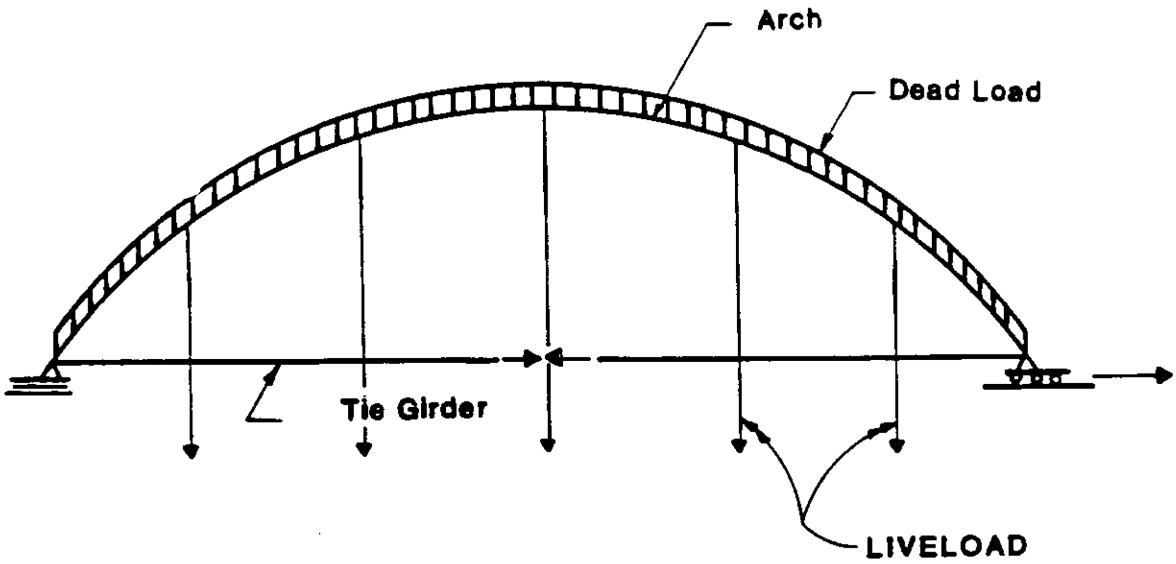
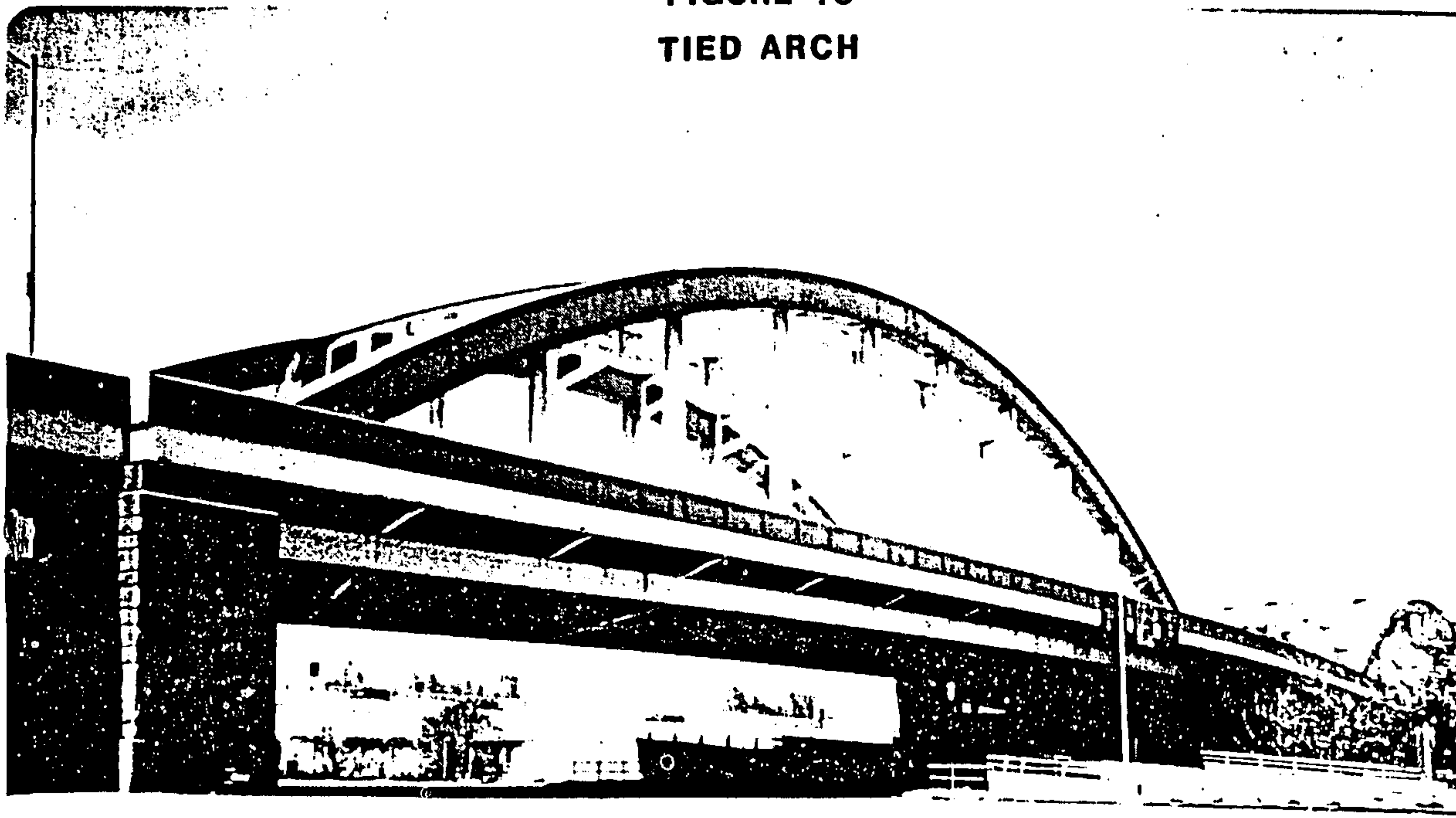


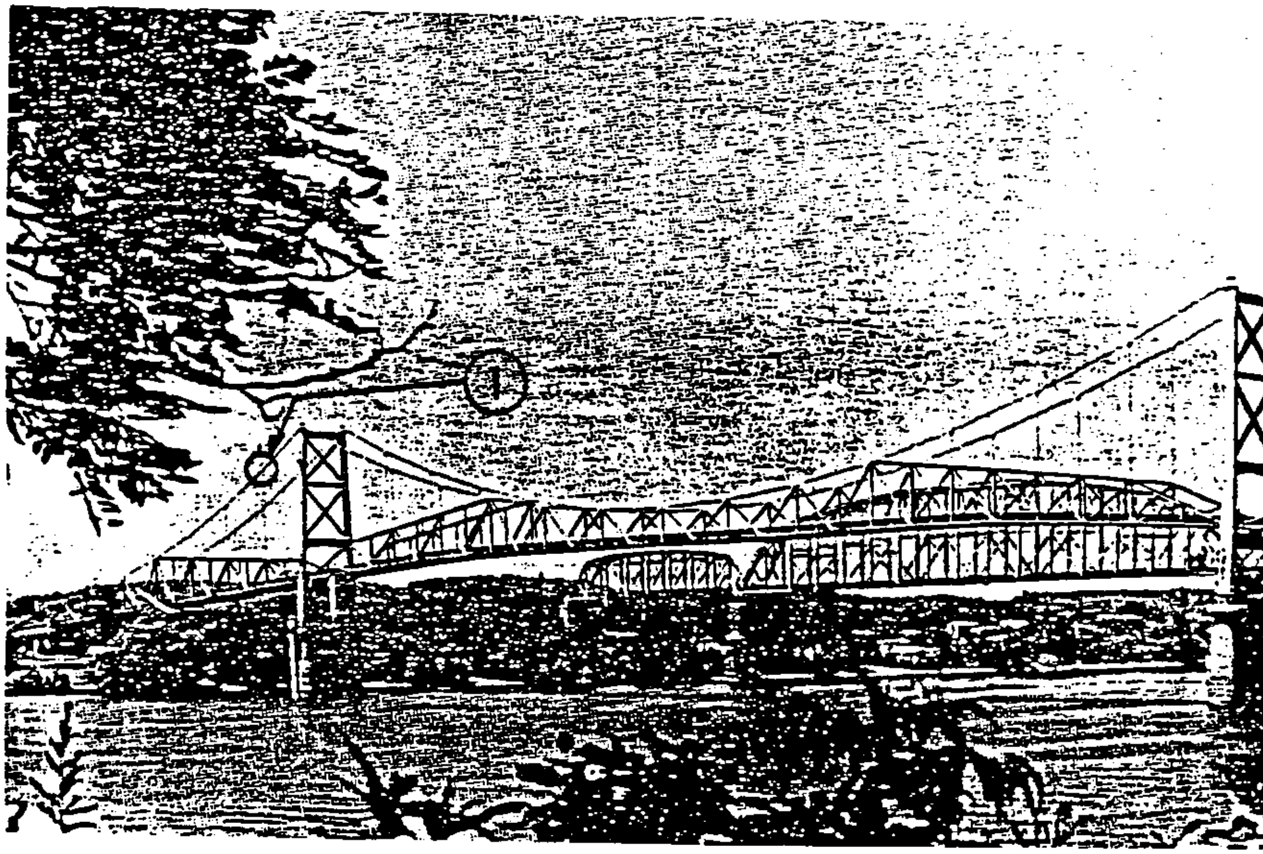
Illustration of applied forces causing tension in tie

FIGURE 18
TIED ARCH



Tied Arch Circa 1950 in Baltimore, Maryland

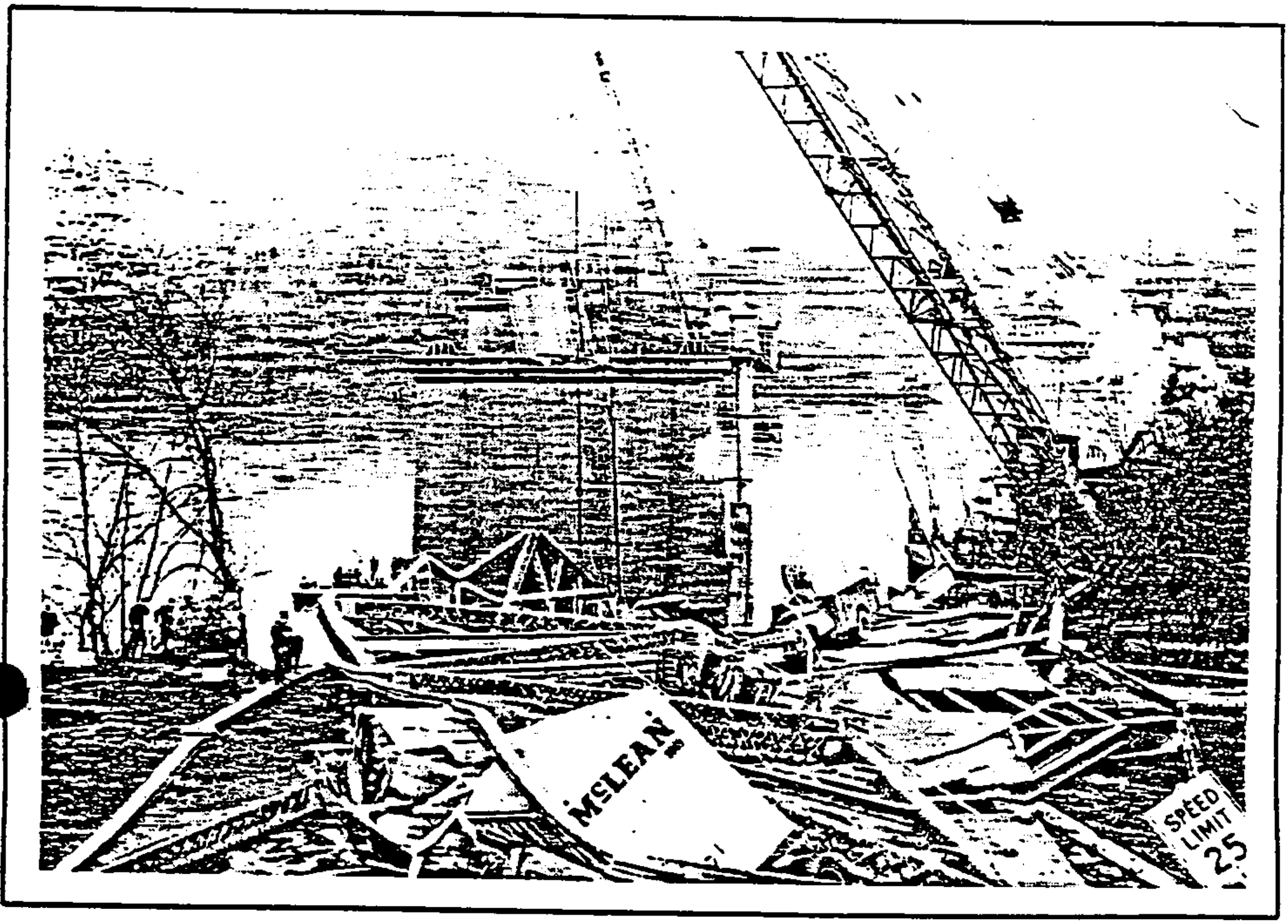
FIGURE 19
SILVER BRIDGE



(1) FRACTURE OCCURRED IN SYMMETRICALLY OPPOSITE LOCATION TO THE RIGHT OF RIGHT HAND TOWER (OUT OF PICTURE).

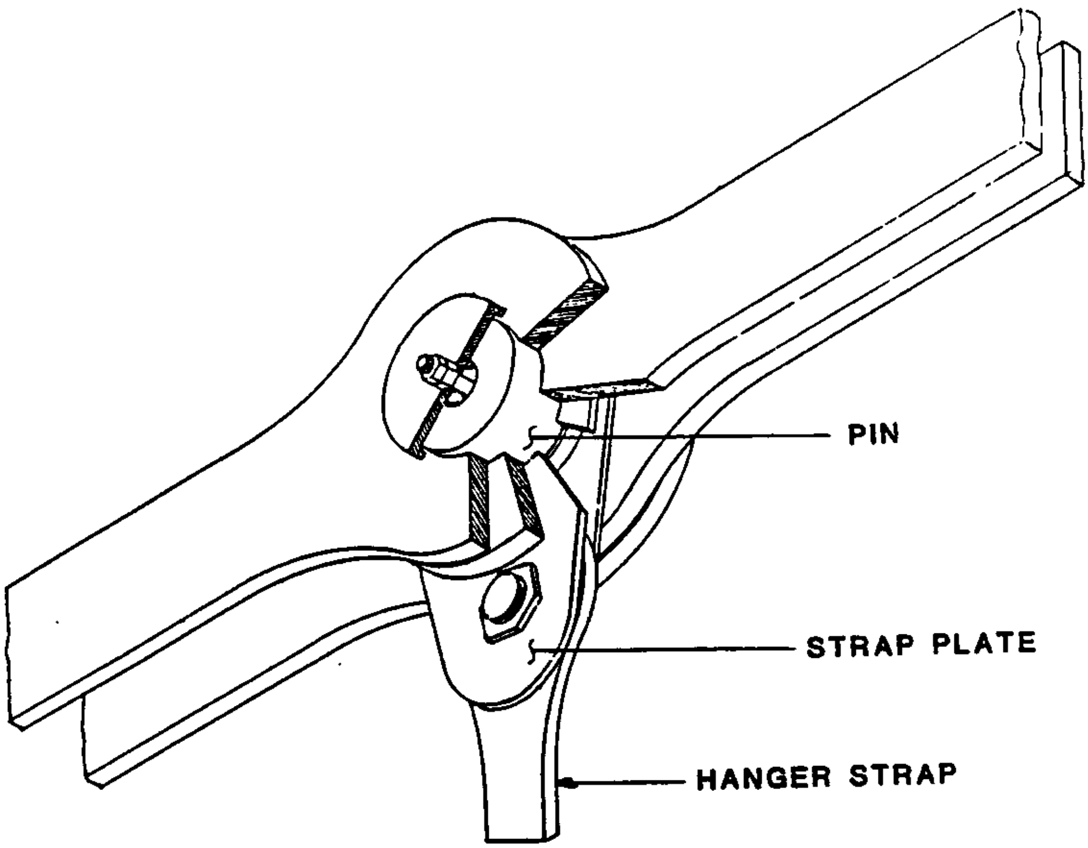
SOURCE: OECD, 1976

FIGURE 20
SILVER BRIDGE AFTER COLLASPE



SOURCE: OECD 1976.

FIGURE 21
EYEBAR CHAIN - HANGER CONNECTION

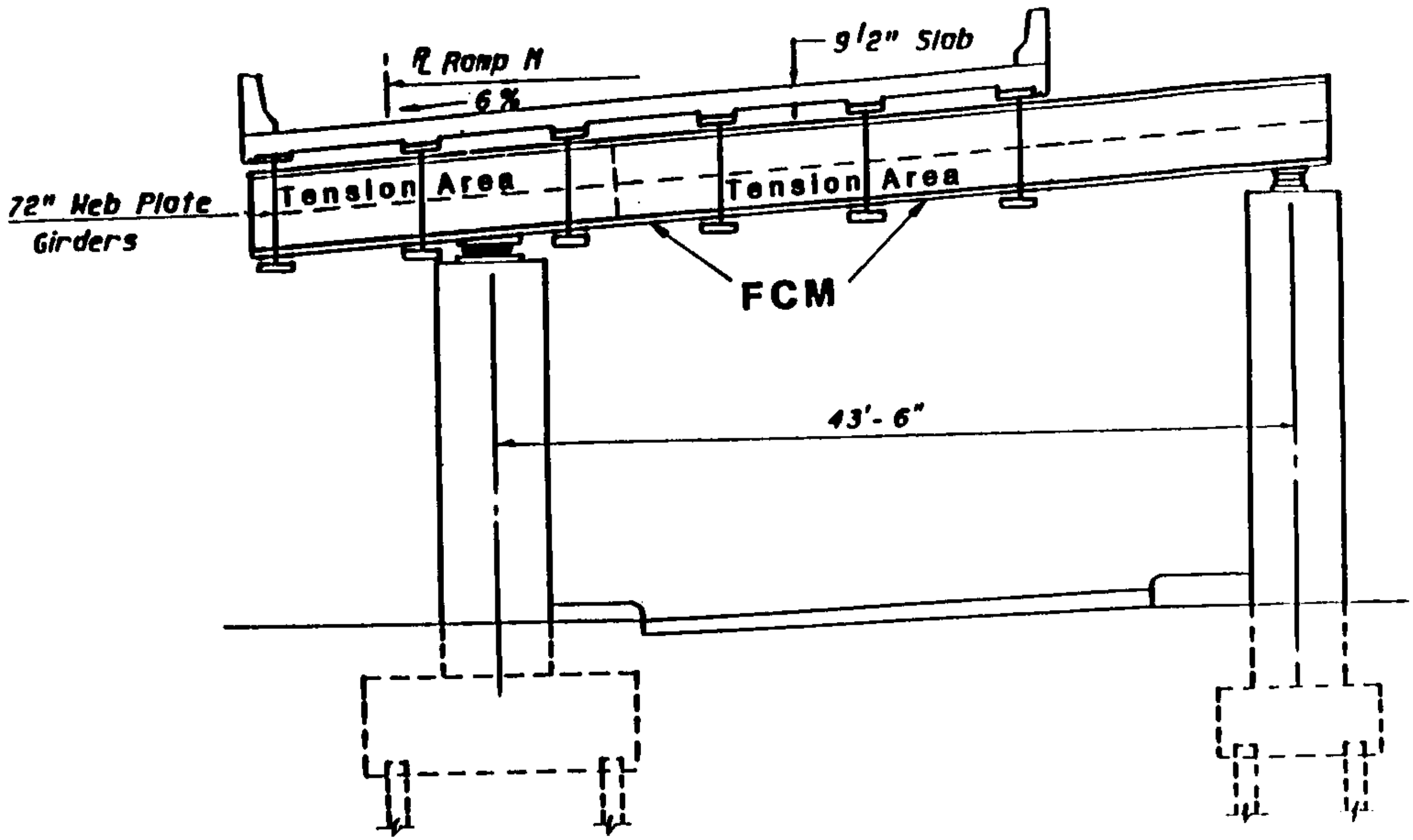


Typical eyebar chain joint for portions of the eyebar chain where the chain was not framed into truss members. Note hanger strap and strap plates in the center of photograph. The strap plate was connected to the top chord of truss members vertically below the eyebar joint. This plate shows makeup of joint C13 north of the Silver Bridge.

NTSB 1970

FIGURE 25

CROSS GIRDER



Location of tension areas in cross girder