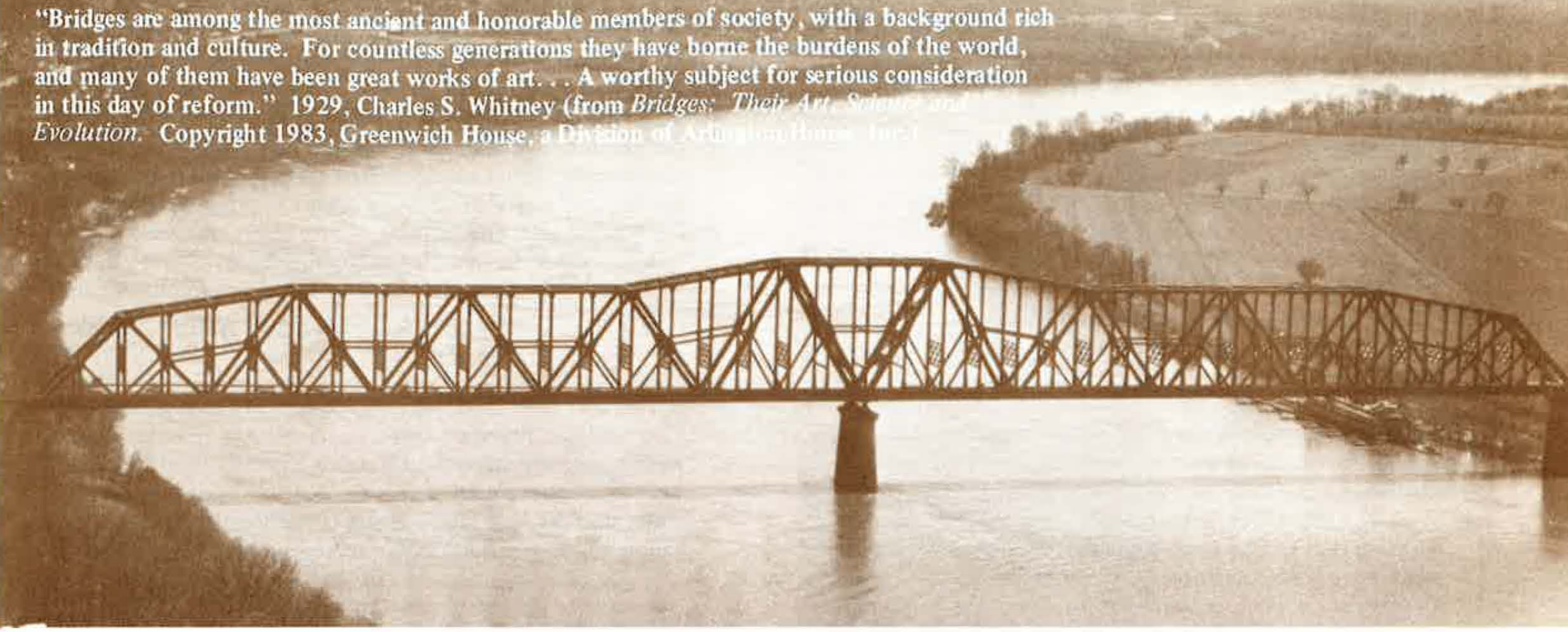


(Courtesy of B&O Railroad Museum Archives—C&O Bridge, Sciotaville, Ohio)

Centuries Later, Bridge Research Continues to Pay Off

Robert J. Reilly, Projects Engineer, Cooperative Research Programs

The United States is in the early stages of what will be a long-term and massive program to rehabilitate and replace many thousands of deficient bridges. In recent years, as awareness of the nation's bridge problems has grown, engineers have turned to research to provide new answers. As an indication of this trend, a growing number of bridge research projects are being referred to the National Cooperative Highway Research Program (NCHRP) by its sponsor, the American Association of State Highway and Transportation Officials (AASHTO). In fact, over the past 3 years, more than one-third of NCHRP's funds has been allocated to studies of problems in the area of bridge engineering, with emphasis on repair and rehabilitation of existing structures.

To justify continued expenditures for research on bridges or in any other area, it must be shown that research provides useful cost-effective solutions to important problems. For example, this article will look at research on the problem of fatigue cracking in welded steel bridge members, where application of the findings has resulted in cost savings many times greater than the investment in the research. This story will serve to illustrate why research on bridge problems is still needed and how it pays off. But, first, a little history.

Old Bridges, Bold Bridges

On May 24, 1983, the 100th anniversary of the opening of the Brooklyn Bridge was celebrated. Reflecting on this outstanding milestone in American bridge building, it would seem like a good idea to place some historical perspective on the interaction between research and the advancement of bridge engineering in modern times.

For more than 2000 years, the stone arch was the main structure-type for major bridges, and many examples can be found in Europe dating back to the Roman Empire and earlier. Stone arches are usually strong, durable, and picturesque, but they do have some limitations—the most obvious being impracticality for long spans.

In the same sense that we would not need to worry about problems like fuel economy and air-quality control if we all still used the horse and buggy, there would be little need for bridge engineering research if we still relied on the stone arch for our major bridges. But modern bridges satisfy today's needs more efficiently, and, clearly, it would be impossible to have the transportation system we have today in the United States, with almost 1 million highway and railroad bridges, if we were confined to using technology developed many centuries ago.

Throughout the 200 years following construction of the first iron bridge in 1779, we can trace a continuous and accelerating series of technological developments from cast iron to wrought iron to structural steel to weldable steel to high-strength steel to weathering steel. At each stage of development, new information became available, usually from research in the broad sense of the word, and offered promise for an advancement in technology. This information was applied in the form of new methods of design and construction; afterwards, new questions frequently arose as a result of these innovations; and research was needed to answer these questions. Research findings are often directly responsible for the incremental steps that comprise the continuing progress of bridge engineering. But, the path to progress is not always smooth, and, as we will see in the following examples, research is also important in solving new problems that result from the application of new technology.

Battling Fatigue

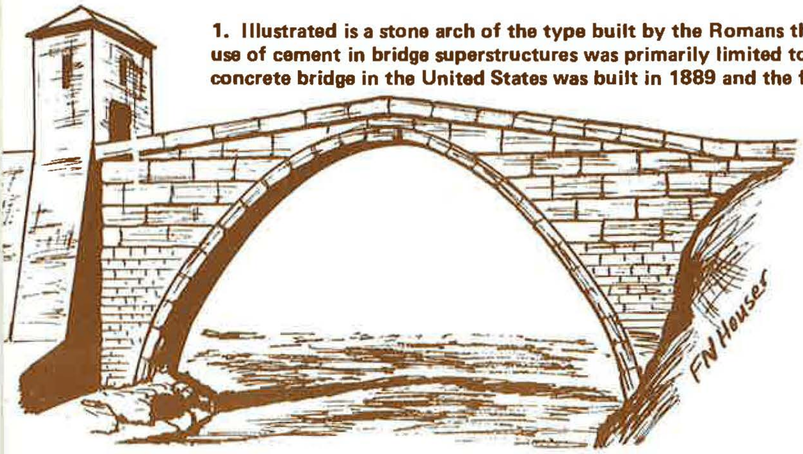
Bridge designers continually attempt to improve their work through innovations such as welding. Because of its inherent economy, the use of welding has grown over the past 20 years to the point where it is now the primary method of fabricating steel bridge members. New design methods, materials, and construction techniques, developed through research, generally advance the quality of the end product. Innovation, however, is not usually possible without some risk, and it sometimes gives rise to new questions related to maintenance, repair, and rehabilitation. As welding technology was applied, solutions to these new questions were developed through research.

One problem has been that the welding process inevitably results in residual stresses and small discontinuities that are of little consequence when the size and number of stress cycles are within acceptable levels. However, many repetitions of loading at even a moderate level can cause fatigue cracks to grow, leading eventually to fracture of the bridge member. The late Vince Lombardi once said that "fatigue makes cowards of us all." That may be going a little too far, but there is no question that fatigue cracking in steel bridge members has made some bridge engineers a little apprehensive at times. To everyone's relief, research has produced answers to important questions and eliminated much of the uncertainty. A number of studies have been directed at the problem of fatigue cracking in welded bridge members, and the benefits resulting from applying some of the findings illustrate the return on investment in research.

As a direct result of research at Lehigh University completed in the early 1970s by John Fisher under the AASHTO-sponsored NCHRP, the fatigue provisions in both the AASHTO and American Railway Engineering Association (AREA) specifications were completely revised between 1974 and 1977, and bridges built since then generally are performing very well. The problem is that many bridges designed using earlier specifications are subjected to numerous loading cycles that are causing cracks to grow at fatigue-susceptible, welded connections. Fortunately, the vast majority of bridges possess enough structural redundancy that the fracture of an individual member does not result in immediate, total collapse of the bridge. But repair of severely cracked members can be costly, and the objective of a recent NCHRP study by Fisher was to develop practical methods to extend the useful life of fatigue-prone connections in existing welded steel bridges. Based on this research, several retrofitting techniques were recommended and subsequently used to solve various fatigue-related problems on many bridges in several states that resulted in the saving of millions of dollars. Three examples are described in the accompanying illustrations.

Applications

The technique of peening the toe of a fillet weld at the end of a cover plate has been applied to several bridges, most notably the Yellow Mill Pond Bridge in Connecticut. In this single example, approximately $1.4 million in repair costs were avoided by using peening to extend the service life at



1. Illustrated is a stone arch of the type built by the Romans throughout Europe. Until the late 19th century, the use of cement in bridge superstructures was primarily limited to mortar for stone masonry. The first reinforced concrete bridge in the United States was built in 1889 and the first prestressed concrete bridge in 1951.

2. The world's first iron bridge was built over the Severn River in England, 1779. Cast iron, used in this bridge and in others built in the early 19th century, has adequate compressive strength but is brittle and weak in tension. This bridge, modeled after masonry arches built during that period, is still standing. However, many other cast iron structures failed soon after construction.

ON BRIDGES

"... In the year 1820 the great highway of the nation, aside from navigable rivers, was the *National Road,* a turnpike commencing at Baltimore and ending in Illinois. ... The vast changes which have occurred since have been witnessed by the present generation. We all know that without the steamboat, the railway, the locomotive and its trains, and without bridges, not one per cent of what has been accomplished could have been done."

John A. Roebling, Report to the President and Board of Directors, Covington and Cincinnati Bridge Company, April 1, 1867.

some 700 fatigue-susceptible locations where serious cracking had not yet developed.

A second technique, also developed during Fisher's research, entails drilling holes in the girder web to remove or arrest the fatigue crack originating at a defect in a structural detail such as the butt-welded splice in a longitudinal stiffener. The technique has been used to retrofit fatigue-prone bridge details in Illinois, Iowa, Minnesota, and Wisconsin, and, starting this year, it will be applied to more than 200 bridges in Virginia.

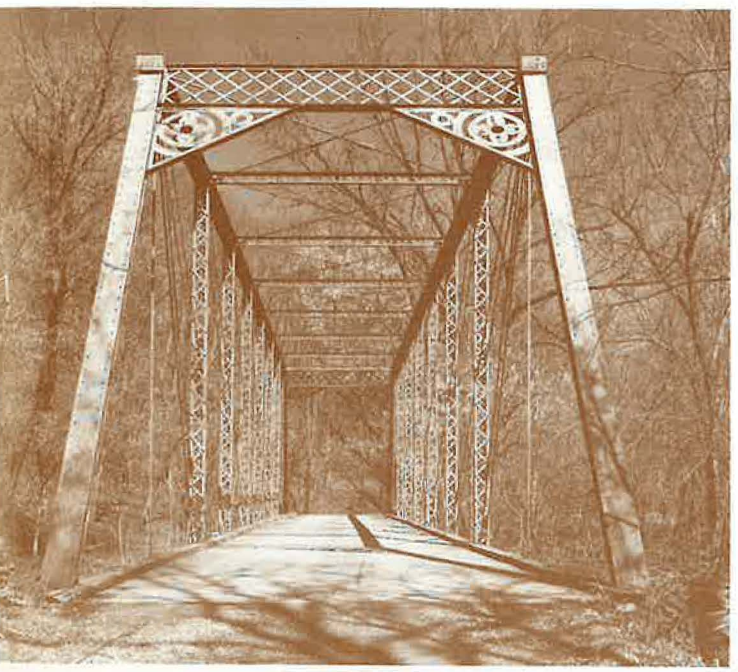
Another solution developed in this study applies to the problem of fatigue cracking caused by out-of-plane distortion of the girder web at the end of a transverse attachment. The technique of drilling holes at the ends of the crack and increasing the length of the gap between the end of the attachment and the tension flange has been used to retrofit many bridges including the Poplar Street Bridge in St. Louis and 36 bridges in Iowa.

Future Returns on Investment

The conditions that led to fatigue problems in these bridges are present in many others in the United States, and it is highly probable that similar fatigue cracking could occur in those bridges. The techniques developed at Lehigh University provide economical alternatives to removal and replacement or other costly measures that are required once a bridge member develops significant fatigue cracks. Therefore, the investment in this research, which already has paid off many times over, will continue to do so in years to come. Considering that, in the future, a major portion of the bridge engineer's energies will be devoted to repair and rehabilitation of existing structures, it is clear that research of the type described here will be needed to provide guidance for cost-effective solutions to a variety of problems.

No technology can be stagnant and remain healthy. Research on bridge engineering will be needed as long as engineers continue to seek better ways of designing, constructing, maintaining, and repairing bridges. In the past 25 years, bridge engineers have made use of many new ideas resulting from research in addition to those already mentioned in the area of welded steel structures. These innovations include prestressed concrete, high-strength steel, box girder construction, modular construction, segmental construction, cable-stayed construction, high-strength bolts, epoxy-coated reinforcement, curved girder construction, adhesives, elastomeric bearings, and drilled shaft foundations. For technology to advance in this field, or any other, researchers will have to continue to (a) provide new information that can lead to innovative practices and (b) help answer practical questions that arise after the new information is applied.

Further information can be found in NCHRP Report 206, Detection and Repair of Fatigue Damage in Welded Highway Bridges, and NCHRP Report 227, Fatigue Behavior of Full-Scale Welded Bridge Attachments, available from the TRB Publications Office.



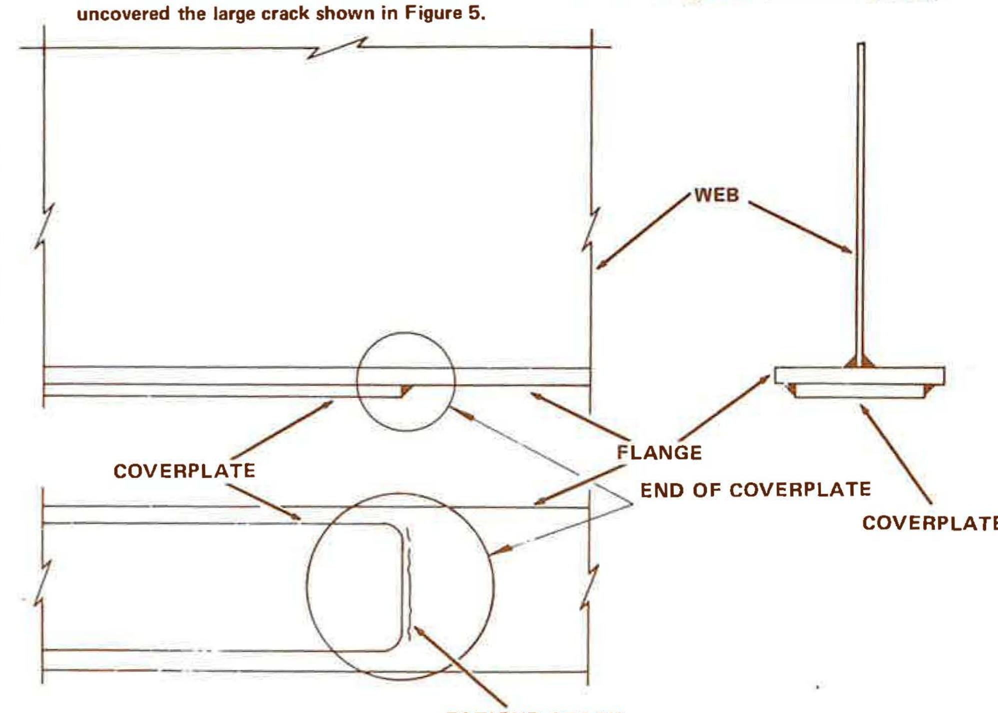
3. With the advent of wrought iron and the superiority of its tension properties to those of cast iron, many wrought iron trusses were built in the United States during the middle half of the 19th century. Pictured is a wrought iron truss built by Penn Bridge Company in Frederick County, Maryland, in 1878.

4. Stone arch bridge (Carrollton Viaduct) carries the original main line of the B&O Railroad over Gwynn's Falls. This is the first railroad bridge built in the United States, 1829. (Courtesy of B&O Railroad Museum Archives)

5. Side view (top) of a cover-plated steel girder shows a fatigue crack starting in the flange at the toe of a fillet weld at the end of the cover plate and extending through part of the web. The same girder (bottom) is viewed from below showing fatigue crack extending through the flange (foreground) and into the web (top of picture).

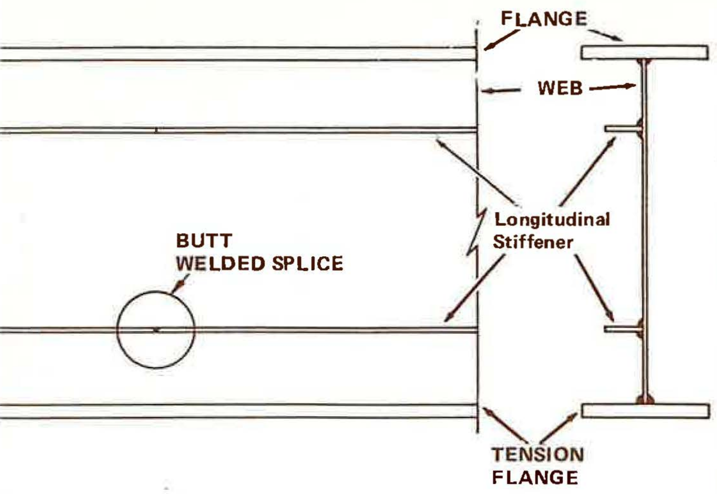
6. The crack shown in Figure 5 was found in the Yellow Mill Pond Bridge on the Connecticut Turnpike (Interstate 95), near Bridgeport, after about 13 years of exposure to a high volume of truck traffic. This bridge has 28 simple spans, each supported by 6 or more girders with all but a few of these girders having 4 cover plate ends, resulting in about 700 fatigue-prone locations.

7. Schematic drawing shows the location of a fatigue crack in the girder flange along the toe of the fillet weld at the end of a cover plate. Fatigue cracks extending part way through the girder flange were found at more than 20 locations in the Yellow Mill Pond Bridge during an inspection that uncovered the large crack shown in Figure 5.



8. Bolted splice used to repair beams with severe fatigue cracking. This method was used to repair several cracked beams at a cost of approximately $2000 each, in the Yellow Mill Pond Bridge.

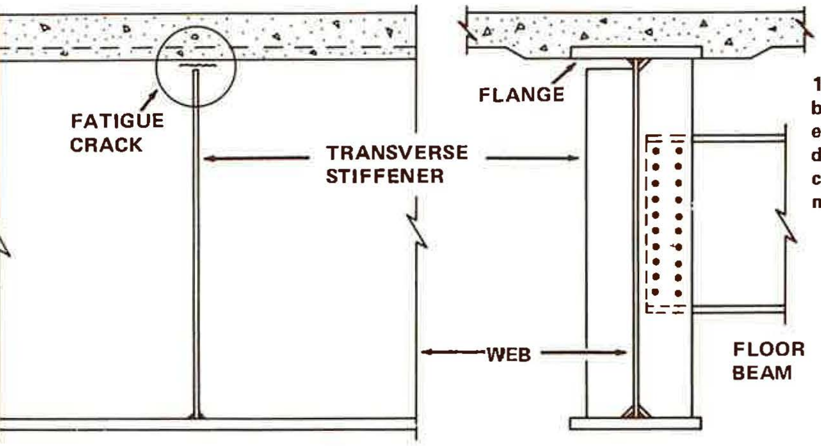
9. Research at Lehigh University has shown that air-hammer peening along the weld toe at the end of a cover plate can extend significantly the fatigue life of a bridge beam. At a cost of about $50/joint, peening was used to retrofit some 700 cover plate ends in the Yellow Mill Pond Bridge, thus avoiding almost certain fatigue cracking problems and the need for costly bolted splices in this heavily traveled structure.



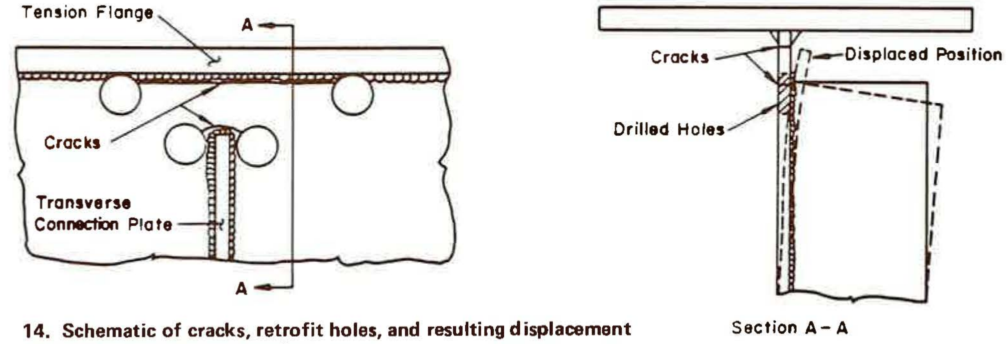
10. Schematic drawing shows the location of a butt welded splice in the longitudinal stiffener of a plate girder. Many such stiffeners are used only for aesthetic purposes and have no structural function; therefore, quality control and nondestructive inspection of these welds frequently have not been the same as for other details. If such a weld is defective and is located in the tension region of the girder, fatigue cracks will grow through the stiffener into the web and eventually destroy the load-carrying capacity of the girder. This problem has developed in many bridges in recent years.

11. Fatigue crack starts at a defective groove weld in the stiffener and extends into the web (top of picture). Research at Lehigh University has demonstrated the effectiveness of a retrofit technique that entails drilling small holes in the web to arrest the crack growth. This technique has already been used on many bridges in several states and is being applied to more than 200 bridges in Virginia. These holes, which are sometimes drilled at a cost of less than $50 each by highway agency personnel during periodic bridge inspections, prevent the crack from growing into the web and eliminate the need for major repairs at a cost of at least $5000 each.

13. Cracking can be seen in this photograph along the flange-web weld near the top of the transverse stiffener, with rust stains running down the web. A retrofit technique developed by John Fisher of Lehigh University has been used to arrest the growth of fatigue cracks and to reduce the severity of out-of-plane deformations in many bridges. This technique involves drilling holes at the ends of the crack and increasing the gap between the flange and the end of the transverse attachment. The total cost of applying this retrofit technique to fatigue-prone members in 36 bridges in Iowa was estimated to be less than the cost of the removal and replacement that would have been required if fatigue cracking were allowed to destroy the girders in just one of these structures.

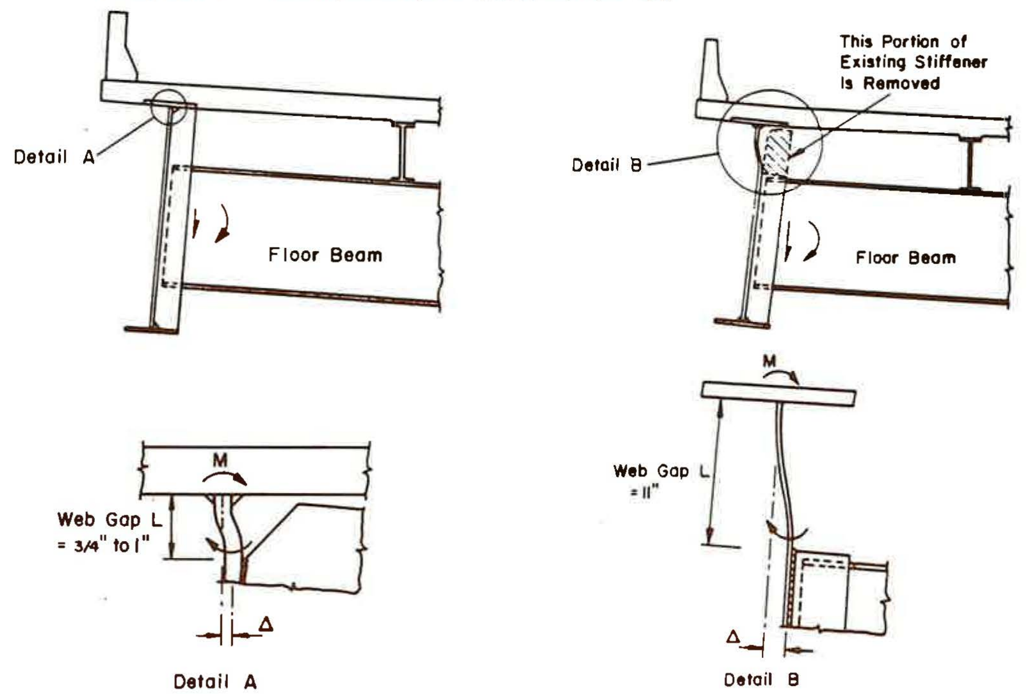


12. Schematic drawing shows a fatigue crack in the girder web between the tension flange embedded in the concrete slab and the end of a transverse stiffener. Cracking is caused by out-of-plane distortion of the web in this unstiffened gap during many loading cycles transferred into the girder web through the transverse members.



14. Schematic of cracks, retrofit holes, and resulting displacement at the end of a transverse stiffener.

15. Through the removal of a portion of the connection plate (stiffener) adjacent to the web gap, as illustrated in Figure 14, the gap can be lengthened to accommodate the displacement with a significant reduction in out-of-plane bending stress. This decreases the stress range throughout the web gap between the web-flange fillet weld toe and the end of the connection plate, so that cyclic stresses are below the fatigue limit. This insures that cracks do not reinitiate from the holes drilled at the crack tips.



ON FATIGUE AND BRITTLE FRACTURE

". . . Two kinds of changes are known which may affect the strength of iron and of all other metals. One of these changes results from oxidation, and is well understood. The other change appears to be caused by a molecular action which impairs cohesion, and consequently the strength of the metal. [This] change to which iron, and in fact all metals are liable, has been investigated by many distinguished men of science. . . . And yet this subject appears to be still open to further researches and experiments. No definite conclusions have been arrived at. On the contrary, the longer the question remains unsolved, the greater appears to be the mystery in which it is apparently shrouded.

It is currently believed that suspension bridges are exposed to great vibrations, and that these vibrations have a tendency to *crystalize*, or to *granulate* (as some prefer) the wire, and that by this process its strength will be gradually destroyed. Now, the fact that the strength of iron, or any other metal, may be impaired by repeated vibrations and concussions, is so well established that no further arguments are needed to prove it. A bell may be readily broken by repeated concussions. A piano wire, although made of the best and strongest material which is known in the art, may be broken by repeated vibrations under tension. Good steel springs may be used and abused many years, but will break at last from the same cause. Railway axles, particularly those of a coarse, crystallized texture, are easily broken by continual vibration and concussion. And so on through the whole chapter of accidents and failures which may occur, when iron or steel is exposed to extreme vibration, under tension or tortion.

But while the fact is acknowledged, that iron may be fractured when exposed to great vibration, tension and torsion, another fact is equally well understood; the same material, when exposed to a *moderate* tension, with very slight or no vibration, will endure and be safe *an indefinite length of time.* Long experience has proved beyond any shadow of doubt, that good iron, if not exposed to a tension exceeding one-fifth of its ultimate strength, and not subjected to strong vibration or torsion, may be depended upon for one thousand years."

John A. Roebling
April 1, 1867