The Brooklyn Bridge, May 24, 1983: A fireworks display and numerous other events commemorated the Centennial of the grand opening of this great bridge, a monument to the genius, courage, and determination of the Roeblings—John, Washington, and Emily. (Photo by M. Norcia, *New York Post*)

BRIDGES – Building on Centuries of Accumulated Knowledge, Research Continues to Pay Off

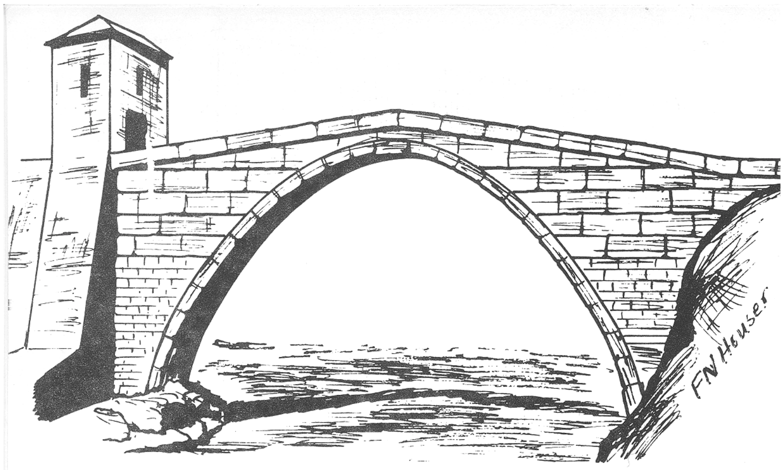
Robert J. Reilly, Projects Engineer, Cooperative Research Programs

The value of bridge-engineering research is sometimes questioned: Why is research on bridges still necessary when men have been building bridges since the beginning of time? To most researchers, who believe the benefits of their work to be self-evident, the answer to such a question is obvious. However, every so often, it can be useful for those who labor, day to day, in a particular field of research to ponder the value of their work and look at what is being accomplished as a result of it.

Growing Concern with Bridge Problems

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

> *"Bridges are among the most ancient and honorable members of society, with a background rich in tradition and culture. For countless generations they have borne the burdens of the world, and many of them have been great works of art. As in most large families, there are numerous poor relatives. The Modern Bridge too often appears as a workman performing its task for a minimum wage, mechanically efficient but uneducated and ignorant of its own ancestry. A worthy subject for serious consideration in this day of reform."* --Charles S. Whitney, 1929 (From *Bridges: Their Art, Science and Evolution*, Copyright 1983, Greenwich House, Division of Arlington House, Inc.)



A stone arch of the type built by the Romans throughout Europe. The world's oldest surviving bridge is a stone arch built in 850 B.C. over the River Meles in Turkey. 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. (Drawing by Frederick N. Houser, Jr.)

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.

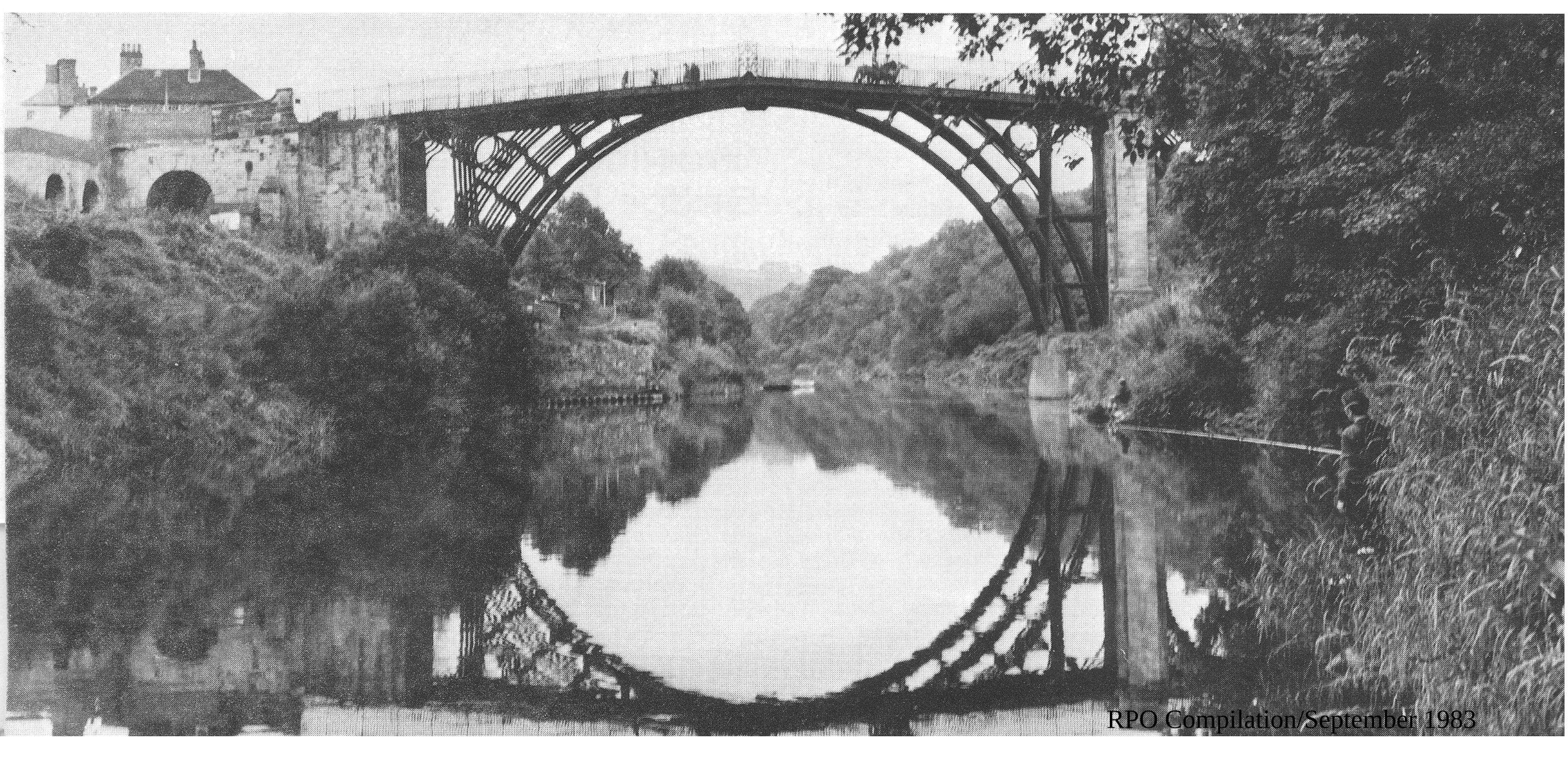
Old Bridges, Bold Bridges

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.

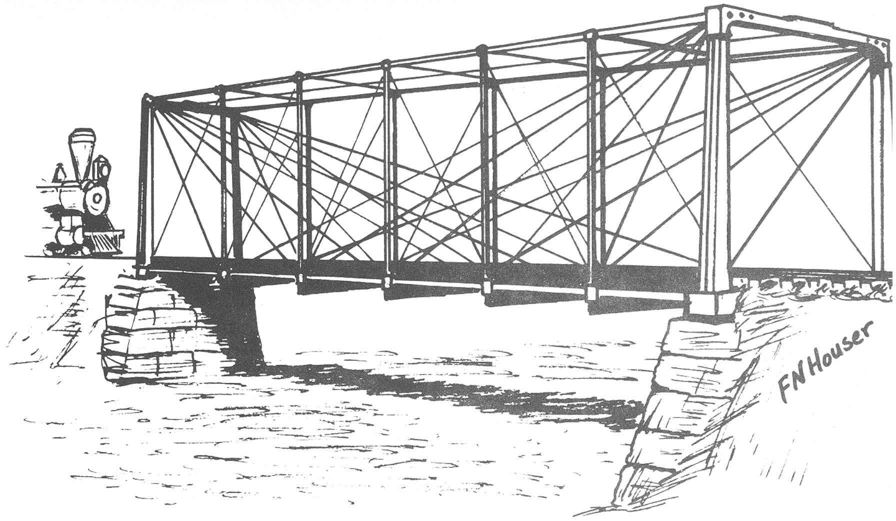
For more than 2000 years, the stone arch was the main structure-type for major bridges, and many examples can be found in Europe dating back to the Roman Empire and earlier. Stone arches are usually strong, durable, and picturesque, but they do have some limitations--the most obvious being impracticality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

The world's first iron bridge was built over the Severn River in England in 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.



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 third of the 19th century. (Drawing by Frederick N. Houser, Jr.)



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. Referring to politicians, columist George Will once quipped: "All of our problems are caused by their solutions." Whereas there are many differences between researchers and politicians, it is true that applications of research findings often lead to new problems. There is, in fact, a cycle that proceeds from research to new information to applications to new questions to additional research needs.

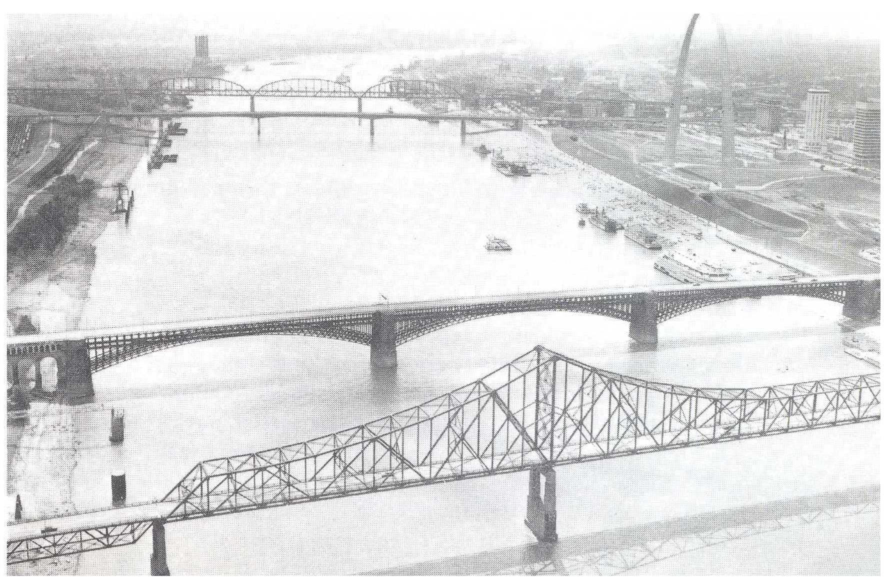
TECHNOLOGY AND PROGRESS

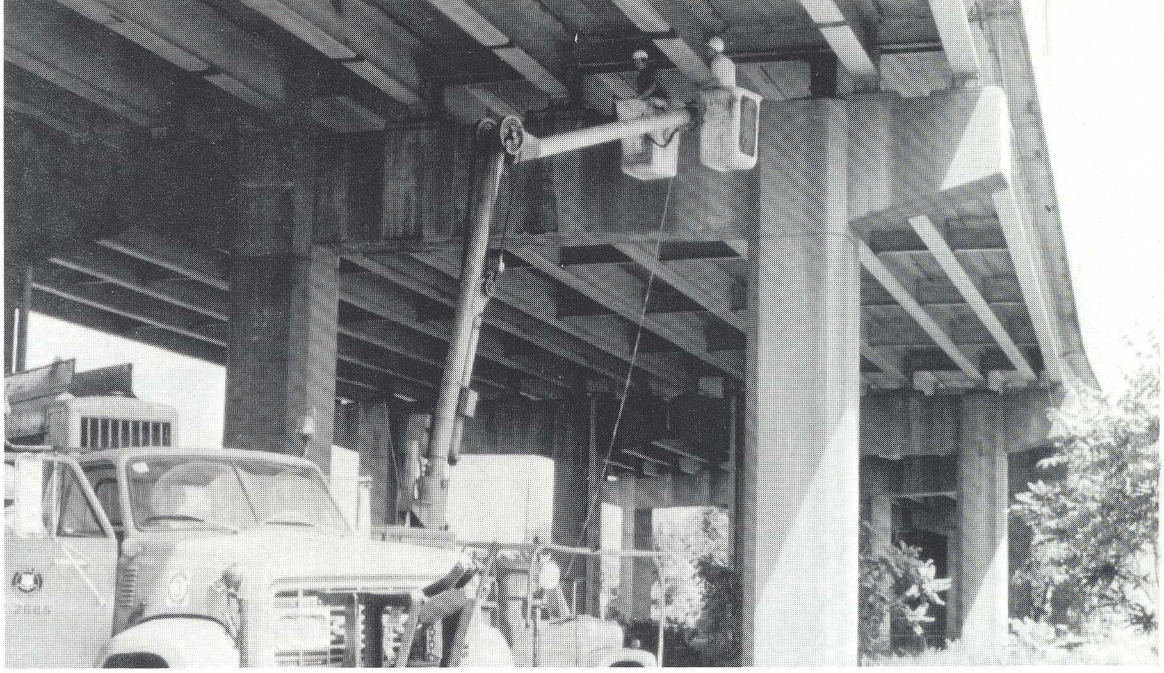
"The rich gifts of nature must first be rendered subservient to man before he can hope to comprehend her true spirit. In this sense the advancement of the sciences and various arts of life may well be hailed as the harbingers of good; its laborers are our friends, not our enemies. The works of industry will be sown broadcast over the surface of the earth, and want will disappear.

Among the various branches of modern industry, perhaps none has produced riper and better fruits than the art of making and improving iron and steel. By the agency of steam, through the instrumentality of iron and steel, the physical powers of man have already been multiplied. And yet the great field has only been commenced to be broken; vast tracts remain yet untouched."

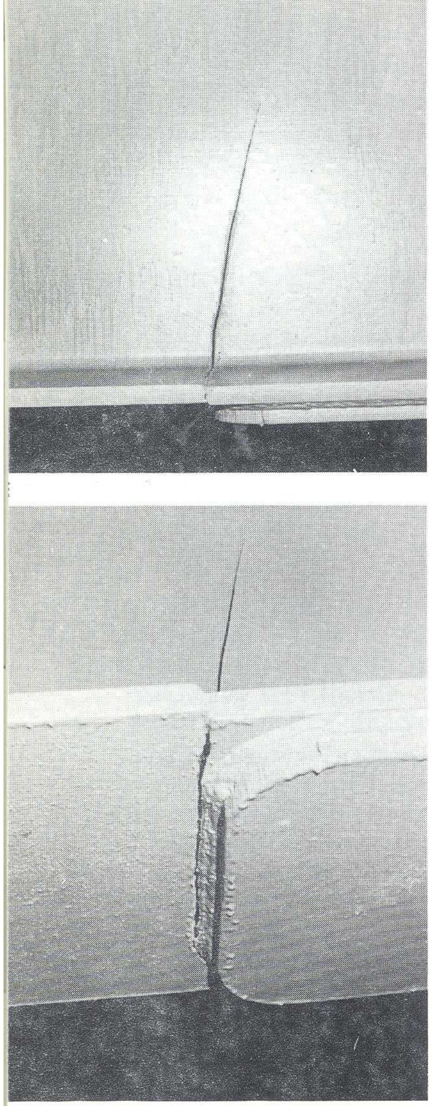
—*John A. Roebling*
Report to the President and Board of Directors, Covington and Cincinnati Bridge Company, April 1, 1867

The Eads Bridge (second from camera), oldest and most graceful of the four bridges across the Mississippi River at St. Louis, was completed in 1874; it was the first bridge to make extensive use of structural steel. Also shown is the Poplar Street Bridge (third from camera). Built in the mid-1960s, it is the longest box girder span in the United States and the first major bridge in this country to use welded orthotropic construction. Many thousands of welded steel bridges were built following the availability of weldable steel in the late 1950s. (Photograph courtesy of J. Way man Williams)





The crack shown to the left 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.



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 though 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 photograph).

This cycle is not a justification for the self-perpetuation of research nor does it merely return the engineer to the same place he started; it is the mechanism by which advancements are made in all fields of technology.

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.

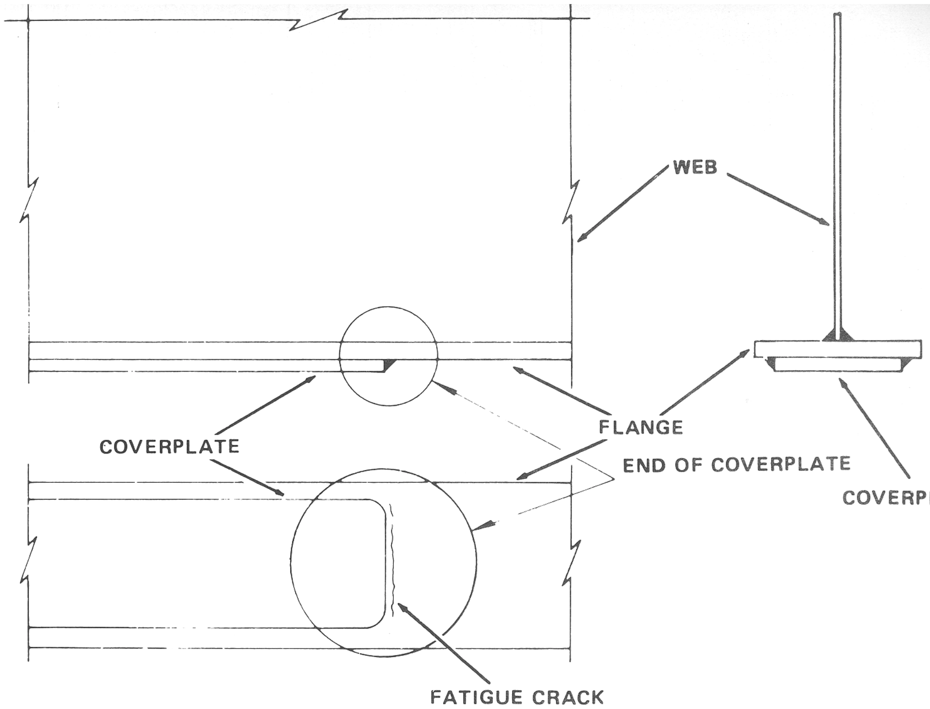
Battling Fatigue

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.

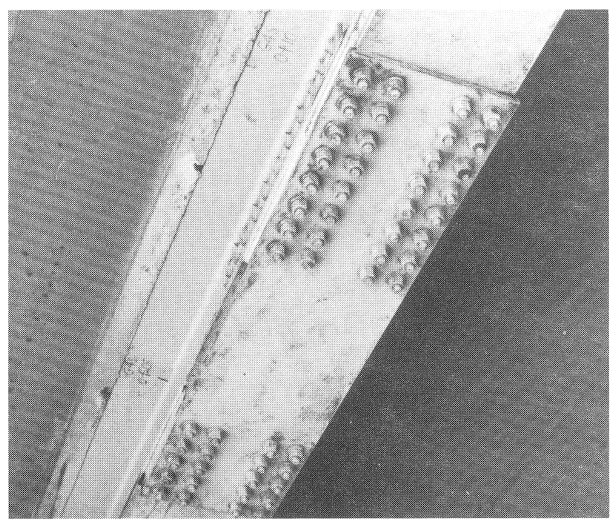
One problem has been that the welding process inevitably results in residual stresses and small discontinuities that are of little consequence when the size and number of stress cycles are within acceptable levels. However, many repetitions of loading at even a moderate level can cause fatigue cracks 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 frac-

The location of a fatigue crack in the girder flange along the toe of the fillet weld at the end of a cover plate is shown. 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 the photograph on the facing page.



Bolted splice used to repair beams with severe fatigue cracking. This method was used to repair several cracked beams, at a cost of approximately $2,000 each, in the Yellow Mill Pond Bridge.



ture 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 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.

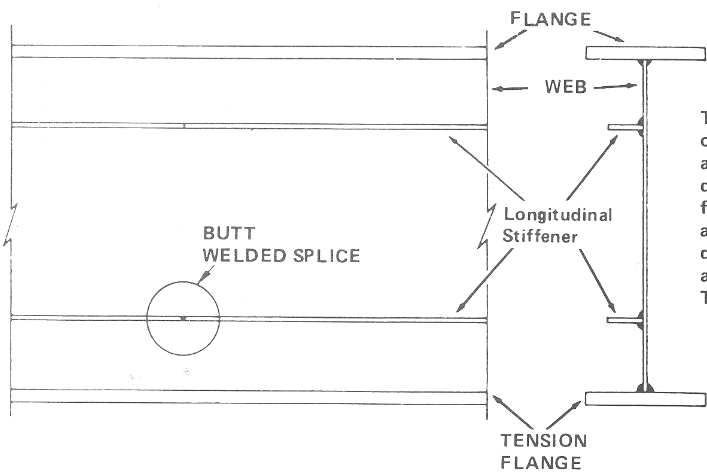
Research at Lehigh University has shown that air-hammer peening along the weld toe at the end of a cover plate can extend significantly the fatigue life of a bridge beam. At a cost of about $50/joint, peening was used to retrofit some 700 cover plate ends in the Yellow Mill Pond Bridge, thus avoiding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

Future Returns on Investment

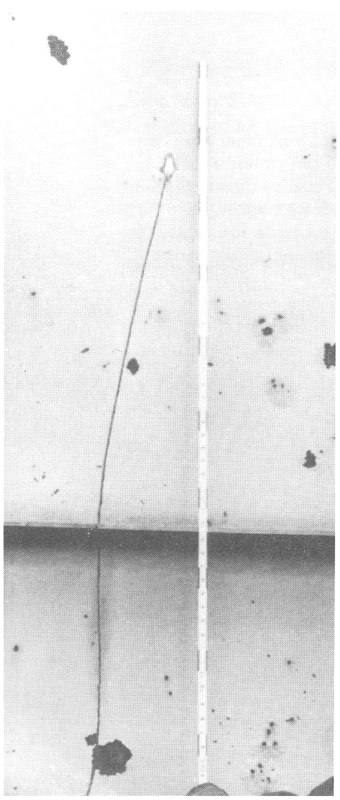
The conditions that led to fatigue problems in these bridges are present in many others in the United States, and it is highly probable that similar fatigue cracking could occur in those bridges. The techniques developed at Lehigh University provide economical alternatives to removal and replacement 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, cablestayed 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.

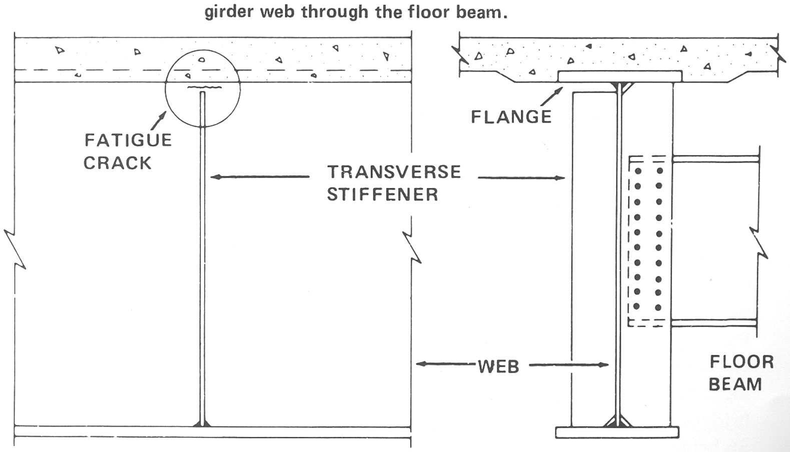


The location of a butt welded splice in the longitudinal stiffener of a plate girder is shown. Many such stiffeners are used only for aesthetic purposes and have no structural function; therefore, quality control and nondestructive inspection of these welds frequently have not been as rigorous as for 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.



A fatigue crack in the girder web, starting at a defective groove weld in the longitudinal stiffener (center of photograph) and extending upward and downward in the web. 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 can be 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 $5,000 each.

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 transmitted into the girder web through the floor beam.



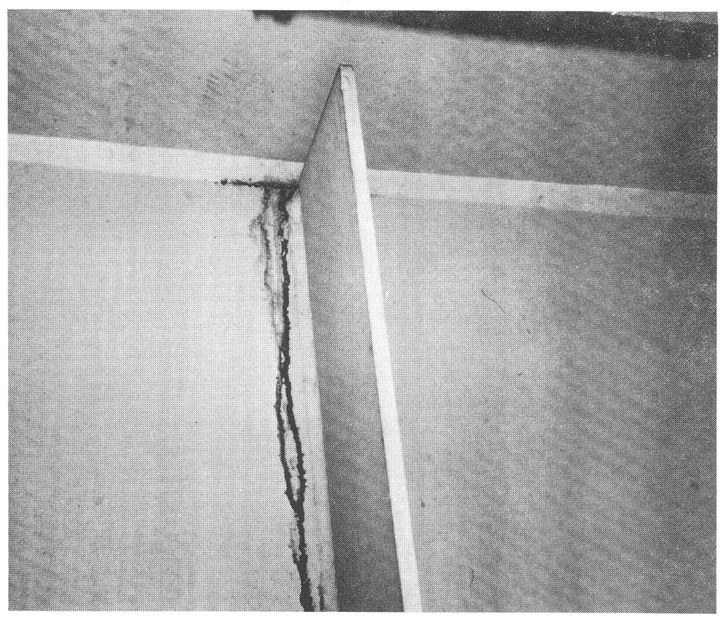
FATIGUE AND BRITTLE FRACTURE

"... 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.

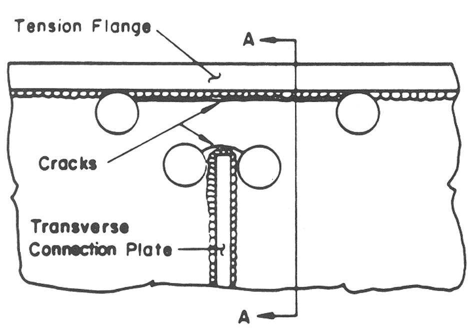
It is currently believed that suspension bridges are exposed to great vibrations, and that these vibrations have a tendency to *crystallize,* or to *granulate* (as some prefer) the wire, and that by this process its strength will be gradually destroyed. Now, the fact that the strength of iron, or any 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 torsion.

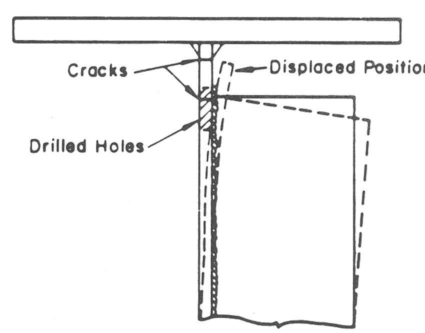
But while the fact is acknowledged, that iron may be fractured when exposed to great vibration, tension and torsion, another fact is equally well understood; the same material, when exposed to a *moderate* tension, with very slight or no vibration, will endure and be safe *an indefinite length of time.* 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*

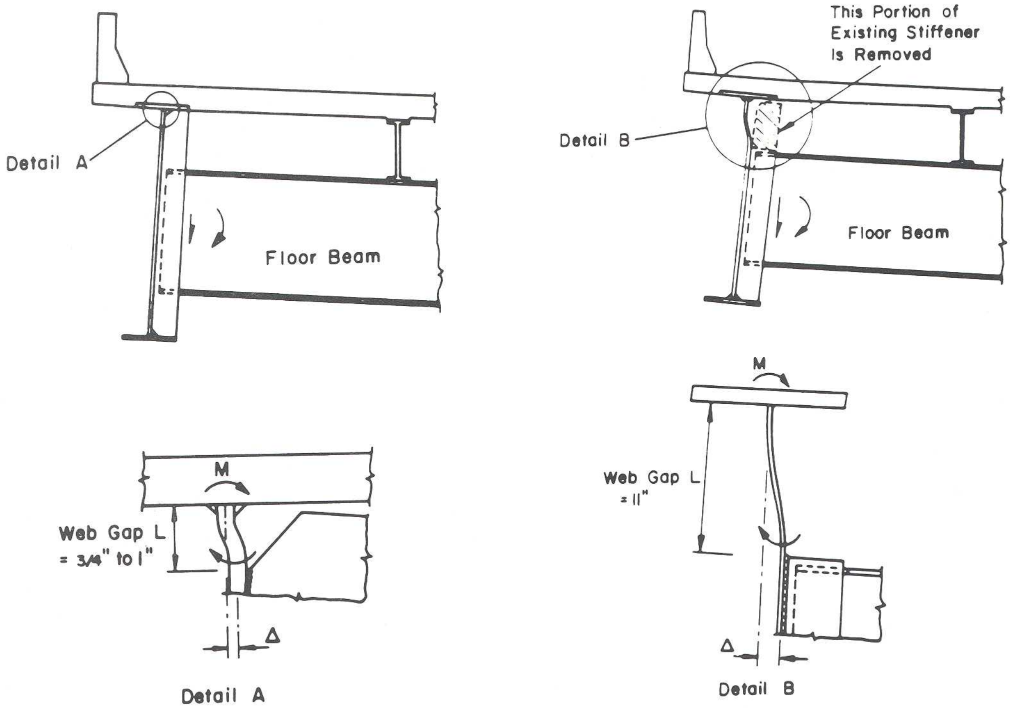
Cracking can be seen along the flange-web weld near the top of the transverse stiffener, with rust stains running down the web. A retrofit technique developed by John Fisher of Lehigh University has been used to arrest the growth of fatigue cracks and to reduce the severity of out-of-plane deformations 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.



Cracks, retrofit holes, and resulting displacement at the end of a transverse stiffener.







Through the removal of a portion of the connection plate (stiffener) adjacent to the web gap, 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 ensures that cracks do not reinitiate from the holes drilled at the crack tips.

STEEL INDUSTRY

"Iron and steel are the materials which pre-eminently stand foremost as elements of civilization. That nation which attains to the highest perfection in its skillful production and application to the various arts of life will rank also highest in the scale of social advancement and political power. This proposition wants to be more fully comprehended in our country. If the government of a nation refuses to protect these branches of industry, which more than any others are calculated to give it power and wealth, and to make it independent, such nation will find itself rapidly outstripped by other people who have better comprehended this fact. The material forms the basis of the mental and the spiritual; without it the mind may conceive, but cannot execute."

—*John A. Roebling*