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## **Nondestructive Methods of Fatigue Crack Detection in Steel Bridge Members**

*An NCHRP staff digest of the essential findings from an interim report on NCHRP Project 12-15, "Detection and Repair of Fatigue Cracking in Highway Bridges," by Alan W. Pense, Lehigh University, Bethlehem, Pennsylvania*

### THE PROBLEM AND ITS SOLUTION

There are many thousands of steel bridges throughout the nation's transportation system. Over the years some of these structures will experience fatigue damage as they are subject to an increasing accumulation of loading cycles. Fatigue cracks will need to be detected and repaired on a routine basis. The study summarized herein reviews the state-of-the-art in nondestructive inspection methods and evaluates their reliability and adaptability for the detection of fatigue cracks in welded highway bridges.

*Because this Research Results Digest is also the full text of the agency interim report, the statement above concerning loans of the uncorrected draft does not apply.*

Lehigh University started work on NCHRP Project 12-15 in October 1972. A final report is expected to be available early in 1975. The primary effort in this study is being directed at the evaluation of methods for improving fatigue life and arresting the progress of fatigue damage that occurs at severe notch-producing details. An additional objective was the production of two state-of-the-art reports. This Digest comprises the report on methods of nondestructive inspection. Its purpose is to call immediate attention to the findings and recommendations of this part of the study. Research Results Digest 59, "Classification of Welded Bridge Details for Fatigue Loading," a review of typical welded bridge details and an evaluation of those most susceptible to fatigue crack growth, was published in March 1974.

## FINDINGS

In any review of the state-of-the-art in nondestructive testing techniques, one is immediately impressed with the wide variety of methods that can be used to determine the presence or absence of flaws and discontinuities in materials, the development and rate of growth of flaws in service, and even the metallurgical state of the material in terms of grain size and heat treatment. However, many of the numerous surveys that have been produced on this topic in the past five years have included material not pertinent to the purposes of this review. For example, they are often concerned with flaws in semi-finished products or in small-scale parts that can easily be cleaned or examined in detail. The type of nondestructive examination considered here is quite different.

In the first place, this review is concerned with fatigue crack detection in weldments rather than general examination of unwelded rolled or forged products and, in particular, crack detection in the more common structural steel grades. Because of the emphasis on weldments, the area to be inspected is much more limited than a generalized material examination but may be one that involves examination of the more difficult geometries that characterize weldments.

Emphasis in this review is on in situ testing. There are many types of tests that can readily be run in a laboratory but not so easily done in position on a large structure, especially if the position is 65 feet above ground underneath a bridge. The limitations that this testing requirement places on the method may be more significant than those of any other single requirement.

Finally, the emphasis in this review is on fatigue crack detection, especially old fatigue cracks on existing structures. Unlike other defects, which are volumetric in their dimensions, these cracks can be extremely tight and covered with corrosion product. The most significant requirement is the ability of the method to define these cracks accurately in terms of length and depth. The focus of this review is to assess the capability of nondestructive testing techniques to do this job effectively.

An important aspect of this review is to realize the underlying concept of fatigue failure prevention that is employed. This concept is as follows: fatigue "failure" in large structural members initiates at fabrication flaws and proceeds by the growth of these flaws until a final failure mode, such as brittle fracture or buckling, terminates the useful life of the structure. The life of the structure, therefore, consists of the growth of the flaws, slowly at first and then more rapidly, to a critical size. The initial fabrication flaws may be large or small. In many instances they will be too small to be detected by current nondestructive test methods. It is not the main purpose of this review to examine all known methods for finding fabrication flaws; rather, it is to discuss the methods that are applicable to detecting the fatigue cracks growing from the flaws and to assess their ability to give an accurate estimate of the size of those cracks. With this information in hand, the remaining life of the fatigued structure may also be estimated and the necessary corrective steps taken.

The ability of any given method to detect fatigue cracks is aided by the fact that the critical points for fatigue cracking in a given bridge structure are at least predictable. The design of the structure dictates where live-load stress concentrations are most likely to be, and thus the areas needing examination can be reduced in number. Moreover, it is known that in many cases the critical areas will lie at the toes of welds located in specific regions in that structure. The

inspection technique can then be specifically applied to detect cracks at these regions, and to define their exact size and shape. When the crack grows at the external toe of a fillet weld, the external geometry of the joint will be a significant factor to be considered. If cracking occurs at the internal root of a weld, there will be even more severe requirements placed on the nondestructive test techniques. Thus an important part of the evaluation will be how well the method performs in a real-life on-line situation involving the typical weld geometry in a large structure, but one in which the probable location of cracks is known.

### REVIEW OF NONDESTRUCTIVE TECHNIQUES

All of the techniques of nondestructive examination that could be used for field detection of fatigue cracks are not reviewed in detail in this Digest. The potential methods of nondestructive examination in general are numerous; however, only a few have been attempted in the field on this type of problem. Therefore, this review is limited to only five methods that either have been attempted for fatigue crack detection or have such potential that their immediate application is promising. Other possible methods not considered because of their present state of development include such techniques as acoustic emission, acoustic spectroscopy, acoustic holography, infrared, etc. This limits the consideration of nondestructive examination to basically five methods: X-ray, ultrasonic, dye penetrant, magnetic particle, and eddy current. A review of the characteristics of these five methods and their potential for various types of applications is shown in Figure 1(1). Before detailed consideration of Figure 1, it is necessary to give a brief explanation of the principle underlying each method. For a more detailed explanation of each method, its principles and its practice, other sources are recommended (2, 3, 4).

#### X-Ray Examination

Nondestructive examination by use of X-rays depends on the fact that X-radiation, produced either by a commercial X-ray machine or by radioactive decay of a radioisotope, will be absorbed by a material in proportion to the thickness of the part examined and the atomic number. Thus, if a defective piece of material is examined by this method, the X-ray absorption at the region of the defect will be different (usually less) than sound material next to this region. The X-radiation coming through the part is recorded on a film or a fluorescent screen; the image is usually darker in the area where the defect is located. The X-ray image on film provides a permanent record of the defect, and also shows the size and shape of the defect in two dimensions. It does not show its position in depth in the part.

It follows from this description that defects such as slag inclusions or porosity in welds or castings are easily detected by this method. Planar defects such as cracks are also detectable; but only if oriented approximately parallel to the axis of the X-ray beam. Cracks or planar defects perpendicular to the X-ray beam axis will not change the X-ray absorption significantly and thus will be undetected. Intermediate orientations will produce varying degrees of defect detectability.

Advantages of this method of nondestructive examination are the permanent record that normally results, the ability to determine internal defect size and shape (and thus defect nature), and its almost universal acceptance in codes and by the engineering profession in general. The prime disadvantages to this method are its inability to locate the depth of the defect, its inability to locate poorly oriented planar defects, and the need to use, in general, large or hazardous equipment. It may also be difficult to apply in some field locations. One special con-

sideration with this method which makes it particularly attractive is the fact that the resulting film is, in fact, a photograph of the part, and thus is immediately geometrically relatable to the part examined. No secondary analysis of the data is necessary.

### Ultrasonic Examination

Ultrasonic testing relies on the wave properties of sound in materials to detect internal flaws. High-frequency sound waves in the form of mechanical vibrations are applied to the part to be tested and the waves, passing through the material, strike either a defect or, eventually, an external surface. The sound vibrations are then reflected and the nature of the return signal indicates the location and type of reflecting surface. Normal instrumentation includes a sound wave generator and pick-up device (usually combined in one unit) and a display screen on which the initial and reflected pulse is displayed. Display instrumentation permits an estimation of the position (in depth) of the defect, the nature of the defect and, by moving the detection portion of the unit (called the search unit) along the part to be examined, the size of the defect. The test sensitivity is influenced by a great number of testing variables, such as sound frequency, design of the search unit, instrumentation, electronic processing of the return signal, and the skill of the operator. Normal results of the examination are a form prepared by the operator based on his observations of the display screen.

The major advantages of this system of nondestructive examination are its portability, sensitivity and ability to detect the location of cracks or defects in depth. On the other hand, the major fault of the system is that, until very recent times, no permanent record of the defect was produced. It is, of course, now possible to make photographic records of the display, but this method has not been too popular. Another characteristic of the system often cited as a difficulty is the sensitivity of the method. It is possible to see too much; i.e., grain size in metals and minor defects not observable by other methods. The system cannot detect surface defects very well. The dependency of the method on operator skill must also be considered an unfavorable factor.

More research has been undertaken to modify this method and make it more widely applicable than most of the others, so advances in technology are more likely in this field.

### Dye Penetrant Examination

The dye penetrant method of inspection is probably the most commonly employed shop and field method of defect detection. Although it is limited entirely to defects that penetrate the surface of the structure, it is inexpensive, easily applied, and easily interpreted. The method itself is simple. The surface of the part to be examined is cleaned, usually mechanically and/or with a chemical degreasing agent. A fluid is placed on the surface to be examined, often with an aerosol spray, and allowed to penetrate cracks or surface defects by capillary attraction or other surface wetting phenomena. After a period of time, usually minutes, the penetrant is removed and a second solution is sprayed on the surface. The second coating, called a developer, usually dries to a chalky powder and remains unchanged in the regions where no defect exists. In the location of a crack, the penetrant seeps from the crack where it is trapped and stains the developer. For this reason bright-colored (often red) penetrants are used. The red penetrant stains on the white chalky developer indicate the presence of a crack or other defect when visually inspected by the examiner. Modifications of the system in-

clude penetrants of different viscosity to detect different size cracks, wet rather than dry developers, and penetrants that fluoresce under ultraviolet light. These penetrants, used in conjunction with ultraviolet light examination, make smaller defects visible.

The principal advantages of the method are the ease with which the tests are conducted, the minimal skills required, and the low cost. Tests are not time consuming and may be made frequently during other operations (for example, to determine if a defect being removed by grinding is completely eliminated). It must be considered the most portable of all methods.

The principal disadvantage is that only surface defects can be detected. This places a limitation of the usefulness of the method for the defect depth determination and "code" approval of most structures. However, from the practical shop viewpoint, many defects that occur during construction (for example, weld cracks) are detectable if dye penetrant is used at intermediate stages in the construction. Thus, defects that are later buried can be detected and repaired before they are hidden from view. Use of dye penetrant during fabrication may prevent later rejection when ultrasonic or X-ray examination is used. The more sophisticated dye penetrant methods, using ultraviolet light, are rarely used in field applications.

#### Magnetic Particle Examination

This method of inspection, like the dye penetrant one, is limited to surface or near-surface defects. An additional limitation placed on the process is the fact that only magnetic materials may be examined. In the shop application of the method, the part to be examined is placed in a magnetic field and fine powdered iron is sprayed (in suspension) or blown on it. If the magnetic field is undisturbed by any surface or subsurface discontinuities, the iron powder aligns itself with the field in a uniform film. If a discontinuity (such as a crack) disturbs the field, a concentration of magnetic lines of force will occur, and thus a concentration of iron powder. This concentration will show the presence of the crack during visual inspection. In order to detect the crack, it must be aligned transverse or nearly transverse to the magnetic field. For this reason, the magnetic field must either be aligned perpendicular to the expected direction of defect formation or must be varied in direction. For shop tests, this is usually accomplished by sequentially magnetizing the part in a large circular coil to produce a longitudinal magnetic field and passing current through the part to produce a circular magnetic field.

In field applications, the part is locally magnetized by use of two current-carrying copper prods that are placed on the surface of the part. These prods produce a circular magnetic field about each contact point when current flows between them and surface defects transverse to the field are detected by use of iron powder. If the prods are moved about the part or structure to be examined, defects at any orientation may be detected.

The advantages to this method are its relative portability, the minimal skills required to operate it, and its ability to detect even tight cracks. Of course, it is limited in the materials that it may be applied to, and the type of defects it may detect. Again, in some applications, it has the additional limitation that it leaves the part in the magnetized condition. Although this is not normally a problem, it may interfere with some subsequent operations, such as welding. It is possible to demagnetize the area examined by this method, but this is time consuming and adds to the cost.

### Eddy Current Examination

This method operates very similarly to magnetic particle inspection but the defect is detected by a perturbation in the electrical, not magnetic, field in the material examined. In this technique, a coil carrying alternating current produces eddy currents in a conductor nearby. The conductor eddy currents, in turn, create impedance in the exciting or, if desired, a separate search coil. The impedance produced depends on the nature of the conductor and the exciting coil, the magnitude and frequency of the current, and the presence or absence of discontinuities in the conductor. The method is therefore instrumented such that a coil is scanned over the surface of the area to be examined and defects produce a characteristic change in impedance as read from a dial or meter (output can be put on a chart if desired).

This method has been given only limited application for several reasons, most important of which has been that generally only simple geometries can be examined. Complex geometries change the impedance readings in themselves, and thus limit the usefulness of the procedure. Again, as with magnetic particle examination, only conductors can be examined.

There is some real potential for this method. Defects in depth can be detected, or, with suitable frequency control, examination may be limited to the surface. Defect size can also be estimated from the response of the area examined. It is insensitive to many surface conditions (for example, paint) which limit other methods. This method appears to need further development, however, to be generally applicable. Certainly the geometry sensitivity of the method is a real disadvantage.

### COMPARISON OF NONDESTRUCTIVE EXAMINATION METHODS

A general summary of the processes discussed in the foregoing, including their over all capabilities, is contained in Figure 1. This review is reproduced, with some deletions, from an article published in 1969 and so requires some modifications, as indicated later. However, examination of Figure 1 does reveal some useful information on these processes. There is no process that is good for all kinds of defects, either in general, or specifically, in welds. Radiography, which is so widely used for internal voids and for defects in welds, is none the less not very satisfactory from the standpoint of surface cracks, and is specifically listed as being poor in detection capabilities for fatigue cracks in service. Even though there have been recent developments in the field of radiography, the inherent problem of poor surface crack detectability has not been solved. The more recent work on X-ray examination has included development of high-energy X-ray units that are capable of examining steel bridge sections up to 2 in. in thickness in a single high-energy short-term pulse (2). Although this greatly enhances the over all usefulness of the technique for general inspection of internal defects because it decreases the time required, it does not improve fatigue crack detection capability. It should be noted from the chart that crack detection is related to orientation in this process, and thus fatigue cracks, which would normally be parallel to the X-ray beam axis in inspecting girders, for example, would be expected to be more detectable than cracks in other orientations. The fact remains that, in the opinion of the researchers, this method is not ideal for fatigue crack detection.

The ultrasonic test method is also not completely ideal for detection of fatigue cracks in all its operating modes. Once again, it is quite good for inspection of internal voids. If the right testing procedure is employed (i.e., the angle-beam method with contact pulse-reflection), crack detection both for internal

voids and for fatigue cracks is listed as good. One real advantage this process has over the others listed as good for surface crack detection, is that it can be used to determine crack depth. However, for minute surface cracks, often the precursor of fatigue, there are better methods.

This chart suggests that the best methods for surface crack detection are magnetic particle and dye penetrant examination. Of these two, magnetic particle inspection probably is best. Its advantages over penetrants are that even very tight cracks are detectable, and, although surface condition is a factor, surface cleanliness is not as important with magnetic particle examination as with dye penetrants. For minute surface cracks, neither method is superior. If wet magnetic particle methods or fluorescent dyes were used, both would be good for small cracks. However, current practice is not to use either of these methods extensively in field applications. The real limitations on these two processes (magnetic particle and dye penetrant) come in their inability to detect the depth as well as the length of surface cracks. Most fatigue cracks start at surfaces such as weld toes and geometrical discontinuities. After a period of growth, they can be irregular in shape. Some regions may be deep, others shallow, but these methods cannot detect this variation. This can be a fairly critical problem, especially when a decision must be made on the best method to be used to undertake repair of a fatigue-cracked structure.

It is appropriate to consider at this point which type of nondestructive examination system would be most effective to use for fatigue crack detection if only one could be used. In the opinion of the researchers, this method would surely be ultrasonic examination. Not only is it the most suitable because it can detect both surface and internal defects, but also because it is capable of defining the shape and depth of the crack. One feature of the practical application of ultrasonics to fatigue cracks, particularly cracks at weld toes, is that, using the angle-beam method, the search unit does not need to go directly over the crack to be examined. This is a decided advantage because fatigue cracks at weld toes are difficult to expose due to the normal geometrical discontinuity produced by the weld reinforcement. Examination by methods that require exposure of the crack by grinding are less satisfactory. Using the angle-beam method, the ultrasonic beam is directed toward the crack at an angle to the plate surface, usually 70°. This means that the search unit approaches the crack from the side and thus, except for very small cracks, is separated from the weld toe geometry by a finite distance. Assuming that the crack is not small, the ultrasonic method then has a decided advantage.

Of course, it is not entirely necessary to select only one nondestructive examination method. In some respects a combination of magnetic particle and ultrasonics would be a superior detection method. With such a system both surface and buried cracks could be detected and defined. In this case, however, careful cleaning of the area to be examined would be necessary. The end result would, however, be a more accurate crack evaluation.

#### CURRENT CAPABILITIES OF NONDESTRUCTIVE EXAMINATION METHODS

It is interesting to note that, with the large body of literature on nondestructive testing available, little is devoted to the actual capabilities of the various methods to detect cracks. It may be that a great deal of information is available in company and agency files, but little has been published specifically on this topic in the past ten years. There has been a great deal of effort on the part of the nondestructive test industry to develop standards and test specimens for

more uniform testing, but none of these contain natural cracks. Indeed, fabrication of a fatigue-cracked weld specimen standard would be quite expensive because, after making a measurement of fatigue crack depth on a practical weld detail, the only way to determine the accuracy of the measurement is to destructively section the weld. Relatively few investigations of this type have been undertaken. Based on whatever data are available, however, some estimates of the capacity of various methods to detect fatigue cracks may be made.

#### X-Ray Examination

Good radiography, done under controlled conditions, should reveal defects between 0.5% and 1.0% of the thickness examined in depth. Defects 2% of the thickness in depth are probably reasonable for field condition tests, and indeed meet the requirements of many government and industrial standards. The accuracy of crack detection by this technique is obviously dependent on the size of the section examined. Although this standard of crack detection couched in terms of section thickness is quite suitable for some industrial applications, it is not particularly helpful for fatigue cracks in which actual sizes need to be estimated. In a typical 5/8-in. to 1-in. thick steel section this means a crack about 20 mils deep. This minimum crack detection estimate must be considered an optimistic one in many cases. Take, for example, the case of a fatigue crack starting at the end of a cover plate in a girder. X-radiation would detect a 20-mil crack in this location provided it is not directly over the web section. Unfortunately, over the web section (where the crack is most likely to start), the X-rays will pass through the web section and be absorbed, and thus cannot effectively detect a crack in this location. Discounting this problem, crack detection under good conditions is quite satisfactory by this method, and cracks on the order of 0.05 in. deep and 0.1 in. long should be detectable.

#### Ultrasonic Examination

Based on findings from this project and others, the minimum crack depth or crack depth range that appears detectable at the present time by this method is about 30 to 50 mils. There is no doubt that it is possible to detect smaller cracks than this, but reproducible field condition tests are probably not going to exceed this sensitivity. In an investigation of fatigue cracks in fillet welded beam and T joints (<sup>7</sup>), the average deviation of the actual fatigue crack depth from the measured value was 35 mils. Deviation in crack length from the measured value (for cracks up to 45 in. in length) was much greater. The authors of this paper suggested that some of the inaccuracies are due to the tightness of the cracks and branching or plastic deformation of the crack tip. Recent work on ultrasonics may improve this level of performance. One research paper (<sup>8</sup>) suggests that computer processing of the raw pulse-echo data can greatly improve accuracy and resolution of the process. If so, this method will have improved usefulness, although field application of computer-processed ultrasonics appears to be in the distant future. Current best capability would be detection of cracks 0.05 in. deep and about 0.1 in. long.

#### Other Methods

Examination of the current literature did not reveal any quantitative estimates of the accuracy of the magnetic particle, dye penetrant, or eddy current methods of inspection. In any case, they do not detect crack depth and thus cannot have the same criteria applied to them. Lacking any concrete experimental data, the author, in his limited shop experience with dye-penetrant examination would estimate that the smallest crack shallow that it can reveal by visual examination is 100 mils.

Considering this to be a fatigue crack of semi-elliptical shape, the minimum detectable crack depth is then about 50 mils, or comparable to ultrasonic test capabilities.

### Realistic Capability of Detection Systems

Upon reading the literature in the field of crack detection and considering the optimum crack detection capabilities of various systems, one finds that the crack detection limit is quite good (on the order of 0.1 in. or less). Somehow, between the laboratory and the field, this level of capability is almost never achieved. Although it is understandable that some loss in capability will occur, the magnitude is sometimes greater than would normally be anticipated based on the differences between the laboratory and field conditions of testing. The optimistic estimates indicated in this section must therefore be balanced by field experience with several systems. These kinds of data are difficult to obtain; however, some recent work sponsored by the Federal Highway Administration permits experience with a practical system to be evaluated and gives a realistic picture of present capabilities in the field. This experience is discussed in the next section.

### PRACTICAL FIELD CRACK DETECTION

In spite of the relatively good crack detection capabilities shown by a variety of nondestructive examination techniques, the question still remains as to what level of performance may be expected under field conditions. The estimates of crack detection capability indicated in the foregoing were almost exclusively for laboratory conditions where the surface condition of the structure, the orientation of the defect, and the operating conditions of the equipment were either quite favorable or at least well under control. To balance this somewhat optimistic set of conditions, nondestructive examination of a real structure under field conditions needs to be described. To make this transfer of nondestructive examination technology from the laboratory to the field, some compromises must usually be made. For example, sensitivity may be sacrificed in behalf of greater coverage, or ease of operation, or portability. Again, some of the information that might be obtained may be lost because of limited operator skill, or operator discomfort, or surface conditions of the structure.

In spite of these problems, however, attempts have been made to develop a non-destructive examination system that, although a compromise from the ideal, will still perform effectively in the field. Examination of the performance of this system can serve as a realistic measure of the state-of-the-art in field examination. Discussed next is this recently developed system utilizing both the Acoustic Crack Detector (ACD) and the Magnetic Crack Definer (MCD).

### The ACD, MCD System and Its Potential

The two-instrument system (ACD and MCD) developed by the Southwest Research Institute for the Federal Highway Administration (2) was specifically designed to detect fatigue cracks on existing structures using semi-skilled personnel. The system consists of portable one-man units used in concert to first detect (ACD) and then define the length (MCD) of the crack. Each unit consists of a hand-held probe and a back pack. The Acoustic Crack Detector is basically a 2.25-MHz 70°-wedge ultrasonic probe that is coupled to the surface of the area to be inspected with glycerine. When pulses are returned to the detector from a defect or a metal surface, the echo is electronically processed and the distance from the probe to the defect is displayed digitally at the probe. In addition, the coupling effectiveness of the probe to the surface is indicated by a light on the probe. The presence of a defect

is also audibly indicated in an earphone. The varying path length differences from the probe to defects are electronically compensated. The instrument is first calibrated for surface condition of the structure to be inspected and the maximum working distance at which inspection may be done is determined. The unit operates effectively at from 3 ft to 10 ft from the region to be inspected, depending on the surface conditions. The expected sensitivity at those distances was to be able to detect a crack  $3/4$  in. or more long (perhaps less at close distances).

The back pack power and electronic unit should operate for 8 hr without recharging, and is intended to be used with the probe to scan structures for the presence of cracks rapidly and under field conditions.

Once a crack or defect has been detected, the length of the crack is determined by the Magnetic Crack Definer. This hand-held probe and back pack unit operates on AC magnetic field disturbance principles. An iron core electromagnet operating on low-frequency (106 Hz) AC current creates an AC magnetic field and AC current in the specimen examined. Two differential coil pickups oriented selectively with respect to the driving magnet detect disturbances in the magnetic field when a crack is present. When a crack is detected, a light appears on the probe and an audible tone is heard in an earphone. By following the crack with the probe unit, the extent of the crack may be mapped. The intended sensitivity of the unit was to determine crack lengths (as long as the crack comes to the surface) to within  $1/4$  in. This unit operates about 1 hr without recharging, but is normally used only after the ACD has indicated that a crack is present. The unit operates well even on heavily scaled or old painted surfaces.

The Federal Highway Administration, with the cooperation of ten states, is presently evaluating these instruments under field and laboratory use, and a comprehensive evaluation of the units' capabilities will be made in the near future.

Early experience with the FHA units, both in the laboratory and in the field, was satisfactory. Cracks in beams, stiffeners, bolted joints, and eye bars were detected in the size range of 0.15 to 1.8 in. by semiskilled personnel. The units were subsequently field tested in Texas, Arkansas, Idaho, and Connecticut. In the tests in Texas, Arkansas and Idaho, in only one case were defects, in this case preexisting weld defects, found - and these were volume defects, not cracks. In these tests rivet and bolt holes in the structures were readily detected.

The field tests in Connecticut were performed under different conditions; fatigue cracks were known to be present and the test was to see if the system could accurately detect and define the cracks. The bridges examined were the Yellow Mill Pond Bridge in Bridgeport and the Quinnipiac River Bridge in New Haven. In the former bridge the emphasis was on the detection of cracks by the ACD; in the latter, the effectiveness of the MCD in finding the tip of a known crack was assessed.

In the opinion of the researchers, the results of these tests were not entirely promising. In the case of the Yellow Mill Pond Bridge, the ACD unit could detect cracks 1 in. long and through the thickness of the beam flanges at the toes of transversely welded cover plates. Confirmation of these cracks and definition of their length with the MCD was only partially effective. Shorter cracks that were found visually using a 10X magnifying glass were either missed entirely by the MCD or identified only after being found visually. The Quinnipiac River Bridge had an existing fatigue crack growing from a stiffener butt weld into the web and flange of a fascia girder. The MCD was employed to define the ends of the crack in the flange so that holes could be drilled at the crack tips and the crack arrested. Holes

drilled on the basis of the MCD crack length determination proved to be not at the crack tips, and the crack was found to extend at least 1/2 in. beyond the MCD indication.

This experience would indicate that large cracks, at least, could be found by the FHWA units, but cracks smaller than the minimum rated sensitivity could also be missed. Because some cracks missed by the MCD unit could be found by an experienced investigator with a 10X field lens, it is clear that knowing just where to look is a significant factor in crack detection. In general, however, inspection of bridges and large structures can not be undertaken by highly skilled personnel, thus at present the crack sizes that are detectable by field crews must be assumed to be at least 1 in. long and about 1/2 in. deep; smaller sizes than this are likely to be missed. It will be seen that these crack sizes are at least an order of magnitude larger than the minimum sizes detectable under laboratory conditions, so there is a great deal of room for improvement; however, the ACD and MCD units are a step in the right direction.

#### The Problem of Detectability and Reliability

A note of caution must be sounded when estimates of the minimum crack size that can be detected by a given process are listed. The fact that these cracks can be detected does not always assure that they will be. Papers published by nondestructive examination experts are often more optimistic than realistic about the capabilities of these systems. Recent emphasis on "zero defects" in construction and fabrication has not presented a true picture of real components and structures produced and tested by real people. In this regard, an interesting paper (10) describing the results of round-robin testing of defective nuclear reactor plates should be noted. Although not exactly the same as tests of bridge construction, the tests provide a comparison of the performance of 10 teams of nondestructive examination experts, 5 using X-rays and 5 using ultrasonics on the same components. The tests were performed under shop conditions using the ASME Boiler and Pressure Vessel Code (Nuclear Section III) as the standard. Identical calibration and test procedures were to be followed by each team, and the parts examined were of simple geometry (plates). The result was that the ultrasonic test method was consistently more sensitive than the radiographic method. More startling was the fact that no team found all the flaws, although their presence was subsequently verified by sectioning of the plate. Accuracy scores on ultrasonic examination ranged from 50% flaw detection to 90%; however, the team that found 90% of the flaws, also found 20% false indications from non-existent flaws. The radiographic detection score ranged from 30% to about 50%; that is, half the flaws were undetected. All of the flaws were found by the 10 teams as a whole, however.

Because these tests were run under relatively controlled conditions, and with set standards, it is hard to see why flaws were missed. The reasons were human ones. Teams did not follow instructions, did not record flaws properly, and, most of all, did not pay attention to detail. From private talks with the sponsors of these tests, it was learned that before the reported tests, the teams had been given a practice run in which even more flaws were missed.

The results of these tests need not be overly discouraging, but they do place the problem of crack detection in a more realistic light. Minimum-size cracks may be detected by a variety of methods. Evidence indicates that a finite portion of them will be missed. In the case of fatigue cracks, inspection at a later time may reveal them as they grow larger. The minimum crack sizes detectable under ideal conditions are encouraging because tentative findings from NCHRP Project 12-15 at

Lehigh University indicate that cracks this size can be treated by several methods to prolong the fatigue life of a member. But practical detectable crack sizes greatly exceed this level. Even at best, therefore, it must be understood that in most instances tight fatigue cracks will inevitably be missed at this size and grow to a size where they can no longer easily be repaired. Design of bridge structures must take this eventuality into account.

#### SUMMARY

A variety of nondestructive examination methods is available today for detection of fatigue cracks in bridge structures. X-ray, ultrasonic, magnetic particle, dye penetrant, and eddy current inspection methods will all provide means to detect cracks, but in terms of the field identification and characterization of fatigue cracks, ultrasonic examination appears to be the most desirable of the methods available. Minimum crack sizes detectable by this method are about 0.1 in. long, but practical detectable sizes in the field are on the order of 1 in. Because of the continuing research work on this method and others, there is promise of better detection capability in the future. In spite of its capabilities, it must be remembered that no method is better than the operator, and this method, like many others, cannot be considered 100% reliable in crack detection.

#### APPLICATIONS

The findings from this study should be of immediate value to structural engineers and others involved in the design, construction, and maintenance of welded steel bridges. As is evident in the foregoing, the study is reported in clearly understandable terms and does not require additional effort by the user to interpret the findings before being able to relate them to his particular circumstances. It would appear that enough evidence exists relative to all the nondestructive inspection methods investigated for the potential user to make immediate judgments as to their suitability for use.

#### REFERENCES

1. Anon., "Field Day for Nondestructive Testing." Welding Design and Fabrication (Feb. 1969) pp. 53-60.
2. McMasters, R. C., ed., Nondestructive Testing Handbook, Vol. I and II. Society for Nondestructive Testing (1963).
3. Barton, J. R., and Kusenberger, F. N., "Fatigue Damage Detection." ASTM Spec. Tech. Publ. No. 495, pp. 123-227.
4. Biskup, J. T., "Welding Inspection." ASCE-IABSE Conference Reprint Reports, Vol. 1b-9 (Internat. Conference on Planning and Design of Tall Buildings, Aug. 1972, Lehigh University), pp. 77-92.
5. Rhoten, M. L., Galis, M. J., Hudec, R., and Hayes, P. K., "Nondestructive Tests for Welds in Highway Bridges." EES-261 No. 28, Ohio State University, Ohio Dept. of Highways, Bureau of Public Roads.

<div>G = good F = fair P = poor □ = unsuitable</div> <div>1 — Fluoroscopy suitable only for thin sections. 2 — If beam is parallel to cracks. 3 — Special thickness gages available. 4 — Size of defect found depends on thickness of section. 5 — Defects must be open to a surface to be located with penetrants.</div> <div>Our thanks to Krautkramer Ultrasonics, Inc., and Magnaflux Corp. for their help in revising this chart.</div>		NONDESTRUCTIVE EXAMINATION TEST COMPARISON																					
		GENERAL								SHEET AND PLATE			WELDS				PROCESSING		IN SERVICE				
													WITH BEAD		WITHOUT BEAD								
				MINUTE SURFACE CRACKS	DEEPER SURFACE CRACKS	INTERNAL CRACKS	INTERNAL Voids	THICKNESS	METALLURGICAL VARIATIONS	THICKNESS	LAMINATIONS	HOLES	INTERNAL CRACKS LACK OF FUSION AND PENETRATION	SLAG INCLUSION/POROSITY	INTERNAL CRACKS LACK OF FUSION AND PENETRATION	SLAG INCLUSIONS/POROSITY	SURFACE CRACKS	HEAT TREAT CRACKS	GRINDING CRACKS	FATIGUE CRACKS, HEAT CRACKS	STRESS CORROSION	BLISTERING	THINNING
PENETRATING RADIATION*	X-RAY		F <sup>2</sup>	F <sup>2</sup>	G	F	F	G <sup>3</sup>		G	G <sup>2</sup>	G	G <sup>2</sup>	G	P	P		P	F	P	F	G	
	FLUOROSCOPY <sup>1</sup>				P	F				G	F <sup>2</sup>	F	F <sup>2</sup>	F							P	P	
	RADIUM AND RADIOISOTOPE		F <sup>2</sup>	F <sup>2</sup>	G	F	F	G <sup>3</sup>		G	G <sup>2</sup>	G	G <sup>2</sup>	G	P				P	P	P	F	P
ULTRASONIC AND SONIC	CONTACT PULSE REFLECTION	OVER NORM. TO SURF. 1/2"			G	G	G	F	G	G				G				G		G	G	P	
		SEND AND RECEIVE			G	G	G	P			G				G				G	G	G	G	G
		ANGLE BEAM	P	G	G	G		P		F	F	G	P	G	F	P	F	P	G				P
		SURFACE WAVE	G	G												P	F	G	F	F			
	IMMERSION PULSE REFLECTION	NORM. TO SURF.			G	G	G	F	G	G	G				F								
		ANGLE BEAM	P	G	G	G				F	F	F	F	G	F	G	F	P	G				
	THROUGH TRANSMISSION				F	G		F		G		F	F								F		
	RESONANCE				P	P	G	P	G	G											G	G	P
	METER THICKNESS GAGE (under 3")						G		G	G											G	G	F
	SONIC and MECHANICAL VIBRATION			P				G															
MAGNETIC PARTICLE	A.C.	WET	G	G						F		F		F		G	G	G	G	G			
		DRY	F	G							F		F		F		G	G	G	G	F		P
	D.C.	WET	G	G	P					G		F		F		G	G	G	G	G			
		DRY	F	G	F	P				G		G	G	G	G	G	G	G	G	F			P
ELECTRO-MAGNETICS	EDDY CURRENT		F	G			F	G	P			P		P	F	G	F					F	
	MAGNETIC PROPERTY ANALYSIS		P	F	P	P	F	G	F			P		P	P	G	F	F				P	
	LEAKAGE FIELD PICKUP		F	G	F						P		F		F	G	G	F	G				
	D.C. CONDUCTION		F	F	P	P	F	P	F	P	P					F	F	F	F	F		F	
PENETRANTS*	VISIBLE DYE PENETRANT		F	G						F	P					G	G	G	G	G			F
	FLUORESCENT DYE PENETRANT		G	G						F	P					G	G	G	G	G			F

Figure 1. Comparison of Nondestructive Examination Test.

6. Dick, P., "Introduction to Nondestructive Testing." ASM Metals Engineering Inst. (1972).
7. DeGiacomo, G., Crisci, J. R., and Goldspiel, S., "An Ultrasonic Method for Measuring Crack Depth in Structural Weldments." Materials Evaluation (Sept. 1970) pp. 189-193, 204.
8. Frederick, S. R., and Seydel, J. A., "Improved Discontinuity Detection Using Computer-Aided Ultrasonic Pulse-Echo Techniques." Bull. No. 185 Welding Research Council (July 1973).
9. Barton, J. R., Kusenberger, F. N., and Birchak, J. R., "Development of a New System for Detecting Fatigue Cracks in Steel Bridges." FHA Final Report, FHWA-RD-73.
10. Anon., "Nondestructive Examination of PVRC Plate-Weld Specimen 201." Welding Jour. Res. Suppl. (Dec. 1971) pp. 529s-538s.

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