Detection of Flaws in Bars and Cables in Concrete Bridge Structures

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This paper presents the results of a study of a nondestructive evaluation technique, the Magnetic Field Disturbance (MFD) system, for detection of flaws in the reinforcing and prestressing steels of prestressed concrete bridges. This work included development of an improved MFD signal processing technique, a series of laboratory experiments, and tests of prestressed bridge beams in the field. A description of the principles of the MFD system and of various signal processing and interpretation techniques is provided. It was found that when a flawed bar or cable is within 6 in. of the surface of the concrete beam, it is possible to detect and locate flaws with a minimum size equivalent to a 5 percent loss of a cross-sectional area of the steel.

Many existing structures, including highway bridges, have been designed by using the prestressing or post-tensioning concept. High-strength bars and cables are normally used as the primary structural components in these structures. The safe load-carrying capability of such structural elements depends primarily on the integrity of these prestressing bars and cables. Because of the nature and type of construction, deterioration and eventual failure of one or more of these prestressing bars or cables could result in catastrophic failure of part or all of the structure.

As existing prestressed and post-tensioned concrete structures become older, it becomes more important to be able to evaluate the condition of their prestressing steel elements. Periodic visual inspections of prestressed concrete bridges throughout the world have demonstrated the growing problem of deterioration of the prestressing steel as a result of corrosion.

No reliable and practical nondestructive evaluation technique has been available for assessing the condition of the steel within concrete bridge members. Past research sponsored by the U.S. Department of Transportation, Federal Highway Administration (FHWA), resulted in the development of a prototype instrument (see Figure 1), the Magnetic Field Disturbance (MFD) system, for detecting flaws in the steel embedded in concrete (*1*). Other previous reports are described elsewhere (*2–4*). The system is based on applying a steady magnetic field near a member and scanning the member's surface to detect perturbations in the magnetic field caused by the presence of flaws in the prestressing or reinforcing steel.

This paper discusses the results of a study conducted at the University of Wisconsin-Milwaukee to evaluate the performance of the MFD system, to enhance the data acquisition and signal processing techniques, and to create a database from a series of characterized MFD signals. The principles of the MFD and related signals are discussed first. The signal analysis methods employed during this study are next described. Results from the laboratory experiments and field tests of prestressed bridge beams are presented last.

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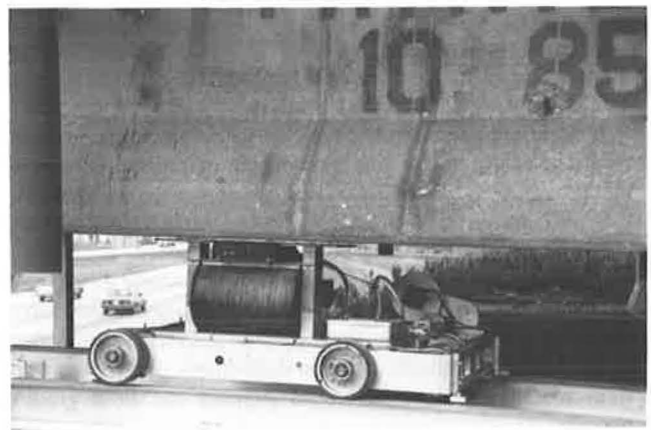

FIGURE 1 The prototype MFD instrument.

PRINCIPLES OF MFD

The present MFD system consists of an electromagnet, detecting devices, and data acquisition and processing hardware and software. The detecting devices consist of an array of four Hall Effect sensors to detect perturbations of the applied magnetic field. The sensors are horizontally oriented between the electromagnet poles, as shown in Figure 2, to measure the changes in the vertical component of the magnetic field. The entire magnet and sensor assembly scans the bottom surface of a member along its length. The steel becomes magnetized, and the vertical component of the field is measured simultaneously by all sensors at closely spaced points, normally at 0.2-in. intervals, along the length of the member. Any disturbances of the field detected by the probes may be attributed to the presence of flaws, stirrups, or steel artifacts (i.e., chairs, scrap metals, etc.).

In the presence of a magnetic field, the atomic dipoles of the steel will become aligned with the external field, resulting in the development of a large flux within the steel (*5*). The degree of alignment depends on the strength of the magne-

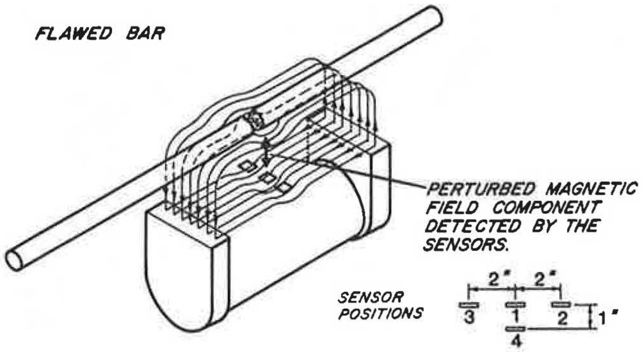

FIGURE 2 Assembly of the electromagnet and sensors.

tizing field as well as the properties of the steel. When the strength of the applied field is relatively large, complete alignment of the atomic dipoles will result; this is known as saturation of the steel. A change in the cross-sectional area of steel due to the presence of a discontinuity results in a change in the magnetic permeability or in perturbations of the magnetic field that may be detected by sensitive probes. Figure 3 shows the flux leakage or fringing due to the presence of a flaw in a magnetized steel rod. The magnitude of the perturbation, or the vertical components of the flux, will depend on several factors. The most important ones are the strength of the magnetizing field, the size of the flaw, and the distance between the magnet-sensor assembly and the flawed bar. A plot of the vertical component of the flux, or the Hall voltage, as a function of longitudinal position along the length of the beam is termed the MFD signal.

In prestressed concrete bridge beams, three sources that produce MFD signals may be identified:

1. Flaws in the longitudinal steel,
2. Stirrups, and
3. Steel chairs and other metallic artifacts.

Recorded MFD signals for steel chairs and other near-surface artifacts are easily distinguished from the signals generated because of the presence of stirrups and of flaws in cables and bars. These signals have reversed polarity and larger amplitudes with shorter durations.

The MFD signals may be interpreted easily when the steel reinforcement layout is simple. In real structures, when many adjacent cables or bars are present, the signal analysis becomes complicated. The analysis is complicated because of the superposition of the MFD signals from individual steel cables and bars.

SIGNAL ANALYSIS PROCEDURES

Signal differencing, correlation, and magnetic field profile (MFP) techniques as well as signal frequency analysis were used in this study.

From the initial evaluation of the MFD signals in the frequency domain, it was found that there were no distinct frequency components of the signals that could be related to flaws, stirrups, or steel artifacts. Previous studies concur with these findings. Therefore, no further signal interpretation in the frequency domain was performed. In the differencing technique, the data from sensor 4 are subtracted from those of sensor 1 to reduce the effects of the stirrup-related signals. In the correlation method of analysis the recorded signals are compared to an ideal flaw signal, defined by a mathematical model, to determine the degree of similarity in terms of a correlation coefficient. An illustration of the procedure is shown in Figure 4. The correlation values are then plotted as a function of position along the length of the member, resulting in a correlation curve. The correlation values for the analysis can range between +1 and −1, where a value of +1 indicates a perfect match with the ideal flaw and −1 indicates a signal that is the exact opposite of the algorithm. A correlation coefficient greater than 0.9 indicates the high probability of the presence of a flaw. Since sensor 4 is directly positioned below sensor 1, the subtraction procedure can substantially reduce the effect in the data of the presence of the stirrups, leaving primarily the flaw-related signals. The stirrup effects in the data can be reduced further by normalizing the amplitudes of signals from channel 4 with respect to channel 1 prior to the subtraction.

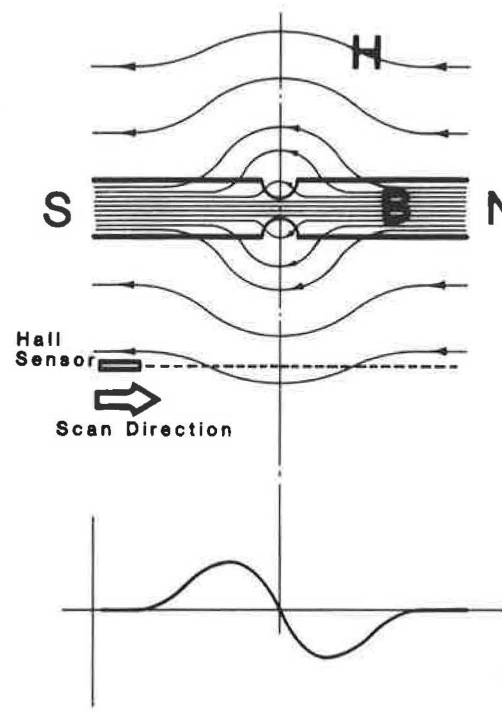

FIGURE 3 Fringing of the magnetic field and resulted flaw signal.

An additional signal processing technique, the magnetic field profile (MFP) method, was developed during this study. In the MFP method the three-dimensional properties of the MFD signals are investigated by also evaluating the variation of the signal amplitudes in the transverse direction. In this method, a positive peak in the signals for both the longitudinal and transverse directions followed by a negative peak indicates a flaw. The MFP method analyzes data acquired from an array of six sensors spaced horizontally and in a transverse direction at 1-in. intervals. Transverse profiles of the vertical components of the magnetic field are constructed as a function of position along the length of a specimen. These profiles are

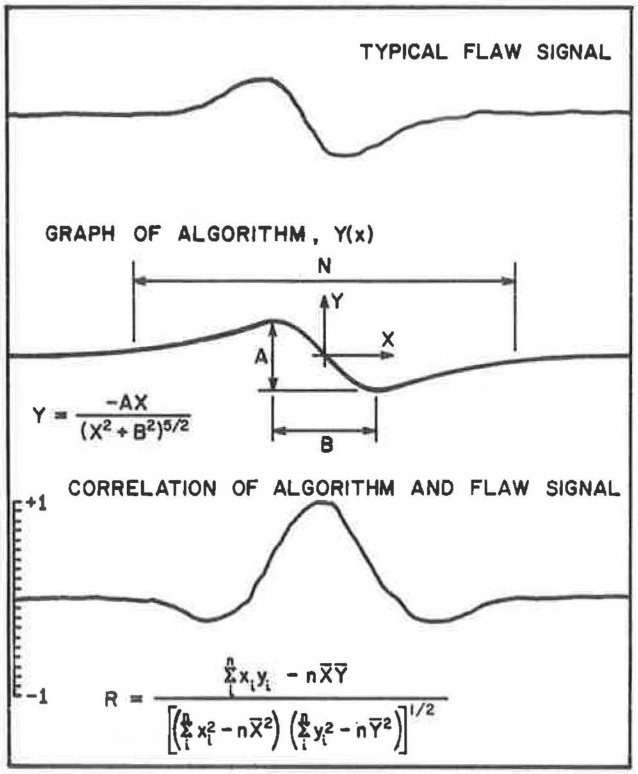

FIGURE 4 Plot of the correlation values, *R*, with respect to position.

then examined for peak values that exceed a predetermined threshold level indicating flaws.

EXPERIMENTAL PROGRAM

Bar and cable specimens containing mechanically produced flaws were studied in the laboratory. The objectives were to evaluate the effectiveness of the MFD system in locating flaws under various known conditions and to develop a database for further development of the signal processing methods. Various test parameters were considered to determine their effects on the MFD signals. Those parameters are as follows:

1. Size of flaw,
2. Type of flaw,
3. Flaw depth,
4. Flaw orientation,
5. Effects of stirrups and steel artifacts,
6. Effect of prestressing forces, and
7. Presence of adjacent longitudinal steel.

A concrete beam containing two types of stirrups placed in separate halves of the beam was constructed (see Figures 5 and 6). The stirrups were cast at a spacing of 15 in. throughout the length of the beam. PVC tubes were cast into the lower region of the beam to make it possible to vary the location of the flawed specimens and the density of any adjacent longitudinal reinforcement. In addition, steel chairs were cast into the beam at known locations near the bottom surface to study the signals produced and their effects on the signals from the flawed cables and bars.

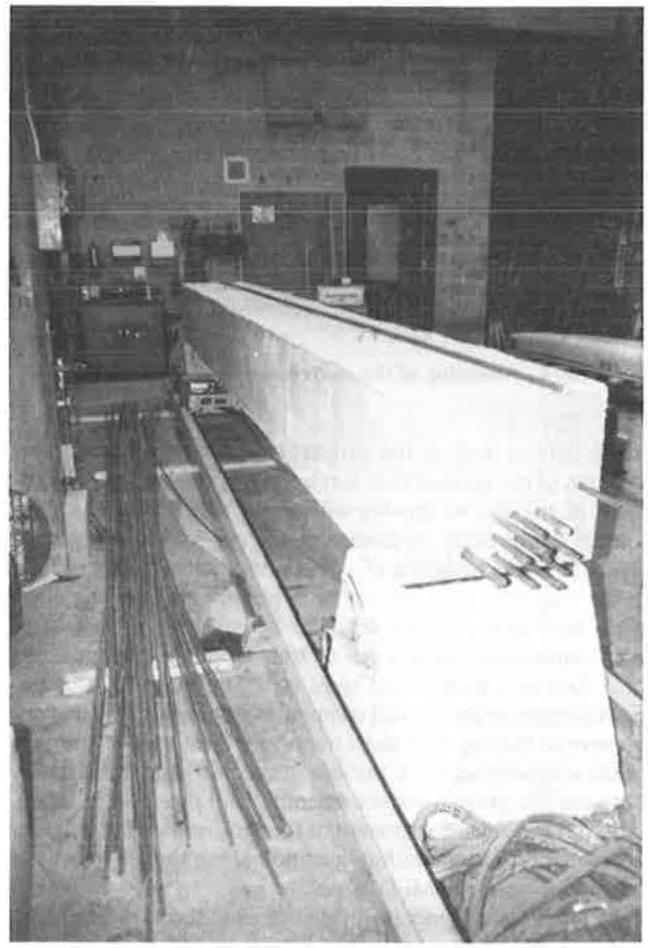

FIGURE 5 Concrete beam for tests of flawed steel bar and cable specimens.

Field tests were conducted to evaluate the MFD system's performance in locating flaws in situ. These tests were conducted at two different locations. The first test consisted of the evaluation of two Texas-type, "C" I-beams, which had been rejected because of local honeycombing. Figure 7 shows the system during evaluation of one of the beams. Unflawed and mechanically flawed cables of the beams were scanned, and the relevant data were examined. The second test was conducted at the site of a 30-year-old, three-span, in-service bridge in Lake County, Illinois. The members inspected were standard, 42-in., Texas-type, "C" I-beams, as shown in Figure 8, containing ½-in., pretensioned seven-wire strands.

RESULTS AND DISCUSSION

Correct data interpretation of MFD signals depends on a knowledge of the signal characteristics from the influence of various possible parameters. Correct interpretation was achieved in this study through an experimental program described earlier. Therefore, an extensive effort was devoted to this part of the study.

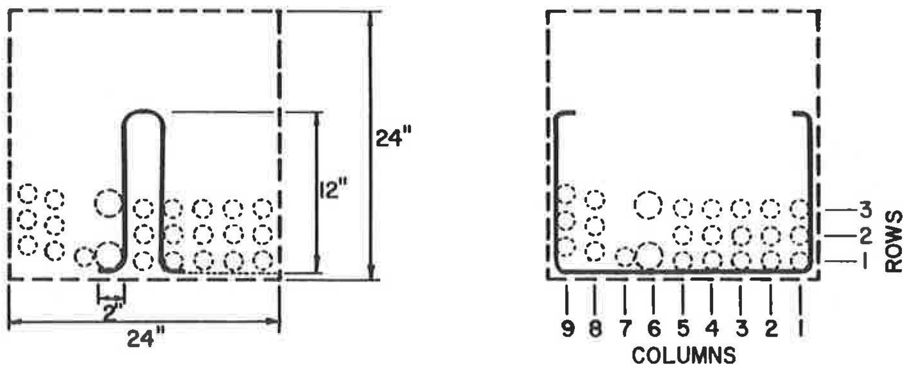

FIGURE 6 Concrete test beam sections showing U-type and rectangular-type stirrups.

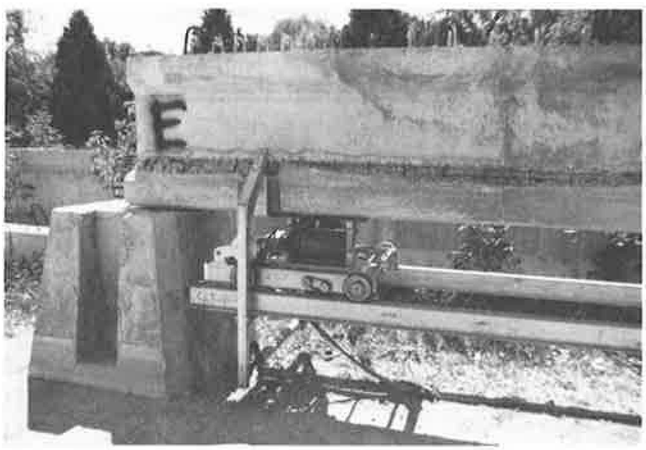

FIGURE 7 The MFD instrument during test of a rejected bridge beam.

Flaw Characteristics

The effect of section loss on the signal amplitudes produced for three different bar flaw types is shown in Figure 9, which also shows the different bar types. The tests were performed in the lowest position in the test beam, with eight adjacent longitudinal bars. Significant variation of signal amplitudes is observed for the various flaw types; it is a function of the amount of steel removed at the position of the defects. Tests were also conducted for the hacksaw and notch flaw types with the flaw oriented both upward and downward to study the effect of flaw orientation on the MFD signals. No significant difference was observed, however. For the tests performed in the stirrup region, where flaws were positioned midway between two adjacent, rectangular-type stirrups, a rather uniform reduction in signal amplitudes for all three flaw types was observed. This amplitude reduction is due to the superposition of signals from flaws and from stirrups that have similar wave-shapes but different phases.

It has been observed that flaw signals with an amplitude of less than 0.1 volts cannot be detected reliably. These signals correspond to section losses of approximately 5 percent for flaws located outside the influence of stirrups, and of approximately 40 percent to 50 percent for flaws located midway between stirrups spaced 15 in. apart, for a test specimen containing uniform flaws at a concrete depth of 2 in.

Signal amplitudes are significantly reduced when depth of concrete cover is increased. Figure 10 shows the effect of depth of concrete cover and section loss on the amplitudes of the signals obtained for the uniform flaw bar specimen with no adjacent steel or stirrups. Similar results were obtained for bar specimens of the other two flaw types, although no signals were obtained in the case of the hacksaw flaws for a concrete depth of 6.5 in.

An increase in the amount of adjacent longitudinal steel will cause a reduction in the signal amplitude. Figure 11a shows such an effect for the uniform flaw bar specimen, while Figures 11b through 11e depict the various layouts for the flawed and adjacent bars. This is attributed to the redistribution of magnetic flux to the surrounding steel, so that a smaller amount of flux passes through the flawed specimen. As a result, less fringing and smaller perturbations of the magnetic field will occur, which will produce smaller flaw signals.

Figure 12 is a graphical representation of the values of the correlation coefficients for the data corresponding to Figure 11. All correlation values were obtained using the differenced data that were normalized only when a flawed bar was located in a stirrup region. As the figure indicates, higher, or better, correlation values were obtained when there were no stirrups in the vicinity of the flaw. Noting that a high degree of reliability in identifying a flaw corresponds to a minimum correlation coefficient of 0.9, only section losses exceeding about 40 percent may be identified for flaws in the stirrup region even with a concrete cover of only 2 in.

Depth of concrete cover and fracture separation gap size significantly affect the signal amplitudes. Figure 13 shows such effects for the complete fracture of a no. 6 bar and a ½-in., 7-wire strand. The tests were taken in the presence of eight adjacent unflawed bars or cables. It is interesting to note that for both the bar and the cable specimens, the signal amplitude increased to a maximum value and subsequently decreased. This response is attributed to the fact that, at a certain gap size, the vertical dispersion of the flux in the medium surrounding the flaw reaches its maximum value. The subsequent reduction of the signal amplitude is a result of the passage of less flux through the flawed specimen.

The effect of the prestressing force on the MFD signals was investigated. A comparison of the signal amplitudes obtained

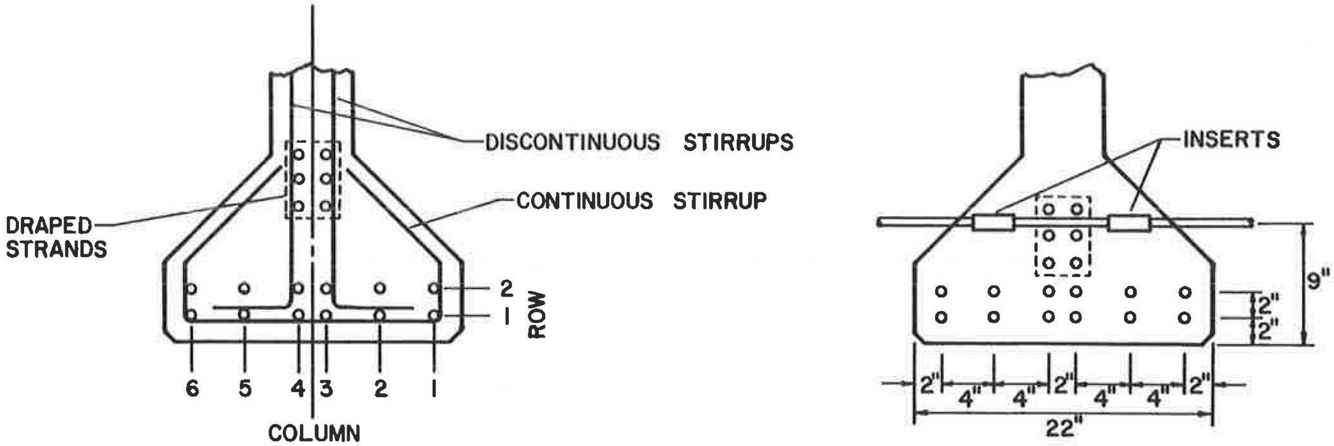

FIGURE 8 Typical cross sections of the in-service bridge beams showing details for reinforcing and diaphragm inserts.

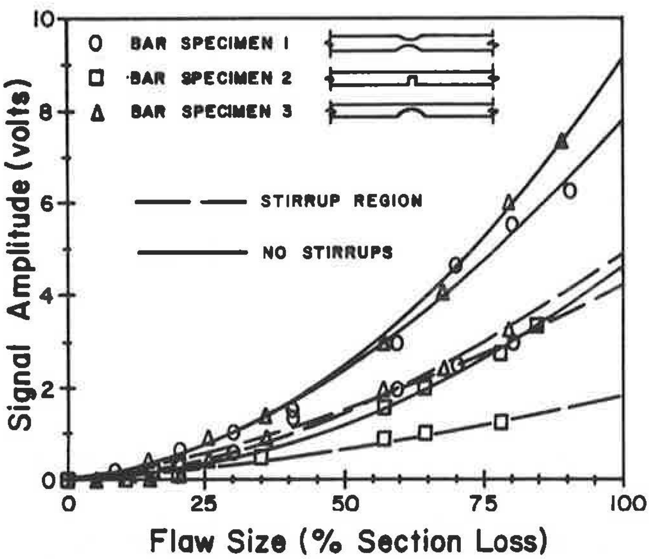

FIGURE 9 Magnitude of signal amplitude with flaw sizes.

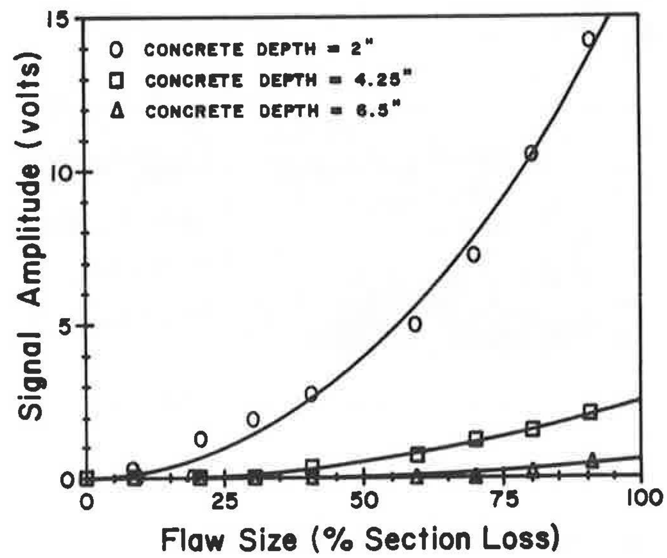

FIGURE 10 Magnitude of signal amplitude with depth of concrete cover.

for the complete fracture of a ½-in., 7-wire strand is shown in Figure 14 for both a stressed cable and an unstressed one. The signal amplitudes for the stressed cable remain consistently higher than those obtained for the unstressed cable; this will have a positive effect on the performance of the MFD system with real prestressed structures. This is due to the fact that the prestressing force is in the same direction as the lines of magnetic flux. The stress physically aids the alignment of the atomic dipoles of the reinforcement (*6*); this effect is known as the magnetostriction phenomenon. The result is an increase in the amount of flux passing through the reinforcement; therefore, larger perturbations are caused by flaws. The corresponding correlation coefficients for stressed cables were found to be higher than those for unstressed cables.

Correlation and Profile Analysis Data

A no. 6 steel bar containing five complete fractures at different positions and with various gap sizes was used, and related MFD signals were analyzed. Figure 15 shows the signals that were recorded from sensors 1 and 4, along with an unnormalized differenced plot and the plot of the correlation coefficient values. The figure also shows the steel bar with positions of the complete fractures. The test was conducted with the bar located 2 in. above the sensors. As can be seen from the figure, a distinct peak has been obtained on the graph of the correlation values at the position of each of the flaws. Each peak corresponds to a correlation value greater than 0.9, which indicates a flaw with a high degree of reliability.

The value of the peak separation, *B* (shown in Figure 4), which is to be used in the algorithm of the correlation analysis procedure, has been found to vary with the many parameters considered in this study. It was generally found, however, to increase primarily with increasing flaw depth. Optimum values of *B* were found to be about 16 for the first row of reinforcement, at approximately 2 in. from the sensors, and 24 for deeper flaws, regardless of the size or type of the flaw. This is due to the fact that, for deeper flaws, the resulting signals will have longer durations, which corresponds to a

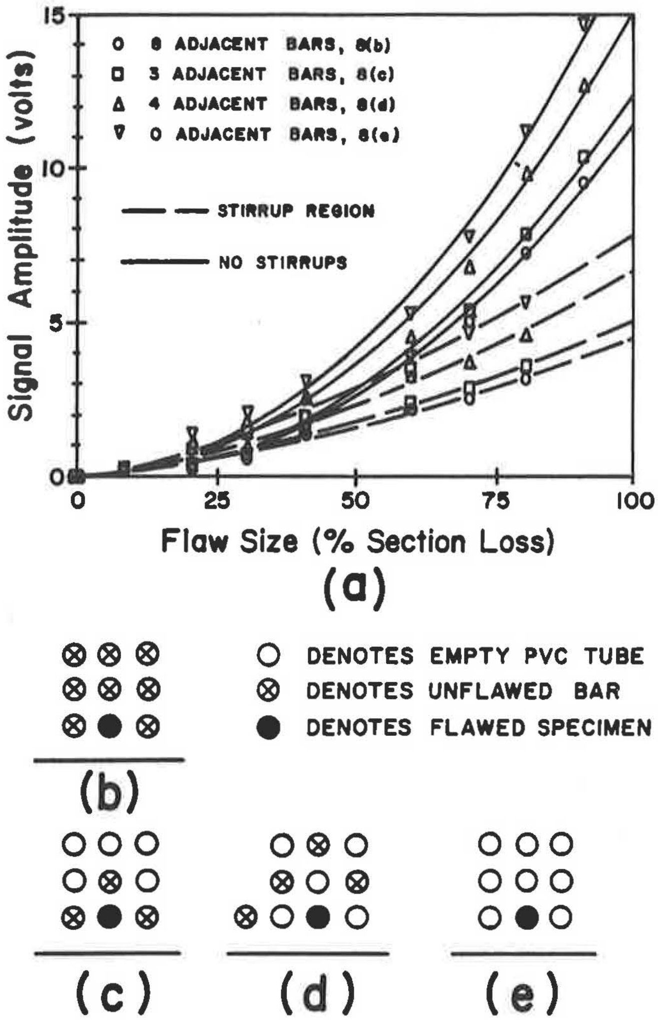

FIGURE 11 Effect of the amount of adjacent steel on the signal amplitude.

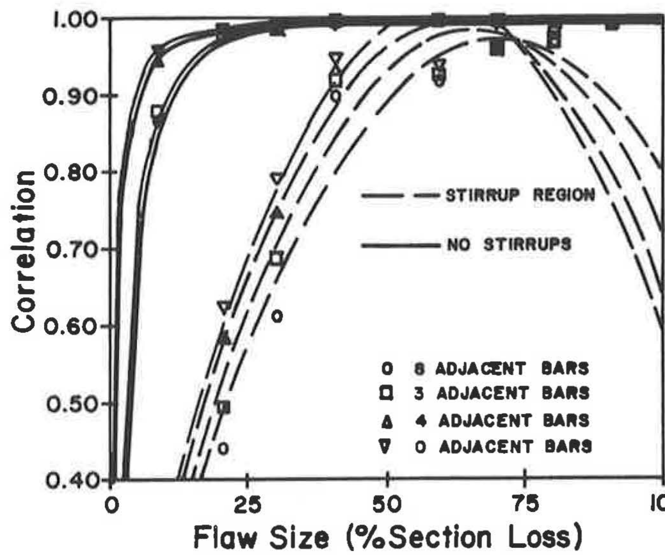

FIGURE 12 Correlation values with respect to amount of adjacent steel.

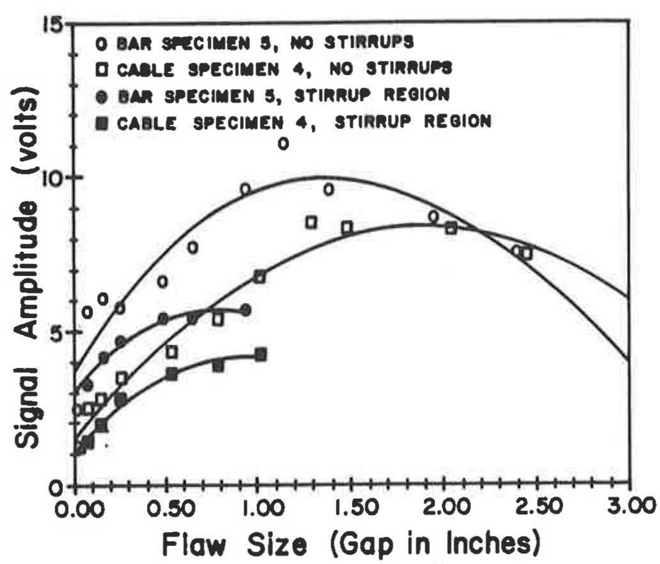

FIGURE 13 Effect of fracture separation for bars and cables on amplitude of the MFD signals.

larger value of B. These results are in agreement with those of previous studies.

The correlation method is sensitive to small flaw signals since it is less dependent on signal amplitude than on signal shape. It is evident from the data, however, that the correlation method of analysis may not always yield reliable results. The presence of stirrups and other steel artifacts can mask the presence of even relatively large flaws, such as complete fracture, when the correlation method of analysis is used. In addition, relatively strong indications of the existence of flaws were erroneously obtained in regions between stirrups in some cases.

Attempts to resolve the difficulties associated with the correlation method resulted in the development of the MFP technique described earlier. The same data that were used in Figure 15 are presented again in Figure 16, but from an array of six sensors that were spaced 1 in. apart. An investigation of the transverse profiles at each point along the length of the specimens can indicate the presence of a flaw, stirrup, or other steel artifacts. Figure 16 also shows transverse profiles for a flaw and for a stirrup. Preliminary analyses using this method have been encouraging. In a number of cases, the MFP method of analysis indicated the presence of a complete fracture where the correlation analysis had failed, in the region of stirrups. While the correlation method of analysis is a powerful technique for identifying flaws in many situations, the MFP analysis can enhance MFD signal interpretation significantly in a few important cases where the correlation method has not been effective.

Field Test Findings

A number of important findings were made as a result of the field tests that were conducted on an in-service bridge described earlier. Results of the profile analysis were found to improve

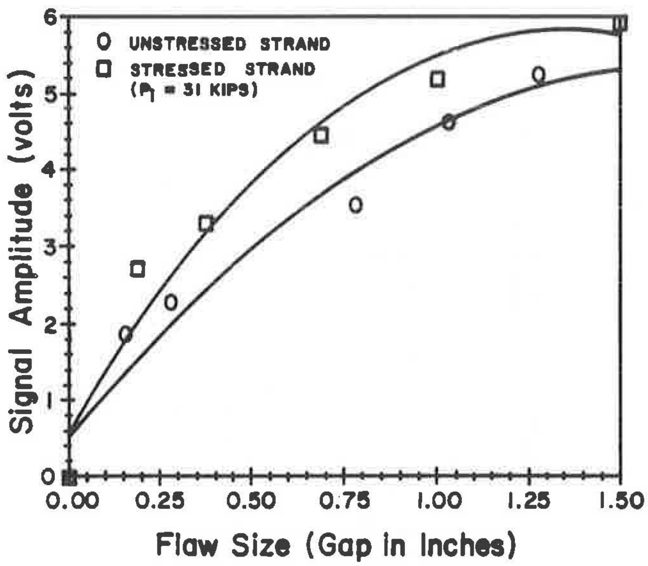

FIGURE 14 Effect of prestressing on signal amplitude.

interpretation of the correlation analysis for the data obtained, although the two methods were not in agreement for all cases. In a number of cases, correlation values greater than the flaw indication threshold of 0.9 were obtained in locations where flaws were determined not to exist. The profile method was helpful in identifying some of these false flaw indications.

A knowledge of the structural details for a member under test is of significant importance when the MFD system is used. For example, during this field test, a flawlike signal was recorded that strongly indicated the presence of a flaw by both the correlation and the profile methods. The signal was located at the midspan of the beam, however, where the bridge plans indicated the presence of an anchor insert for the diaphragm (see Figure 8).

CONCLUSIONS

Evaluation of the MFD technique during this study indicated that the system is the most promising nondestructive method for identifying flaws in prestressed concrete structures.

The most significant parameters that influenced the amplitude and shape of the MFD signals were found to be the distance between the flaws and the probes, the flaw size, and the presence of additional longitudinal steel as well as the stirrups and steel artifacts.

A single method of signal analysis (i.e., the correlation method or the profile method) was found to be incapable of yielding reliable results in all cases. The most reliable results may be obtained from an MFD test by using both methods and having a thorough knowledge of the related structural details.

While the present MFD technique is the most suitable and available method for assessing the status of steel within prestressed concrete bridge members, it is also associated with some shortcomings. The difficulties encountered during field testing are its primary weakness; these are due to excessive weight of the system (approximately 250 lb.) and the inefficient design of devices used for attaching the instrumentation to the bridge beams.

RECOMMENDATIONS

The results of this study indicate that it is possible to make major improvements in the MFD system. Significant weight reduction, updating the present instrumentation, and enhancement of signal analysis procedures to overcome the system's present shortcomings are all possible. Weight reduction and improved efficiency may be achieved by use of a permanent magnet system with probes of greater sensitivity. An updated electronic design and an expanded sensor array with addi-

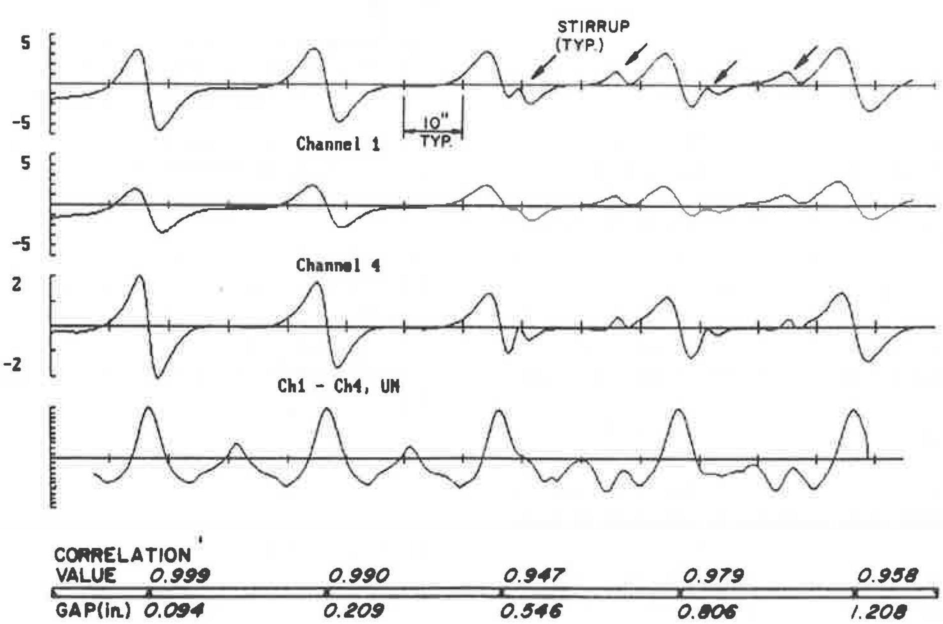

FIGURE 15 Typical data plots for sensors 1 and 4 and the differenced data. The result of the correlation analysis is shown below.

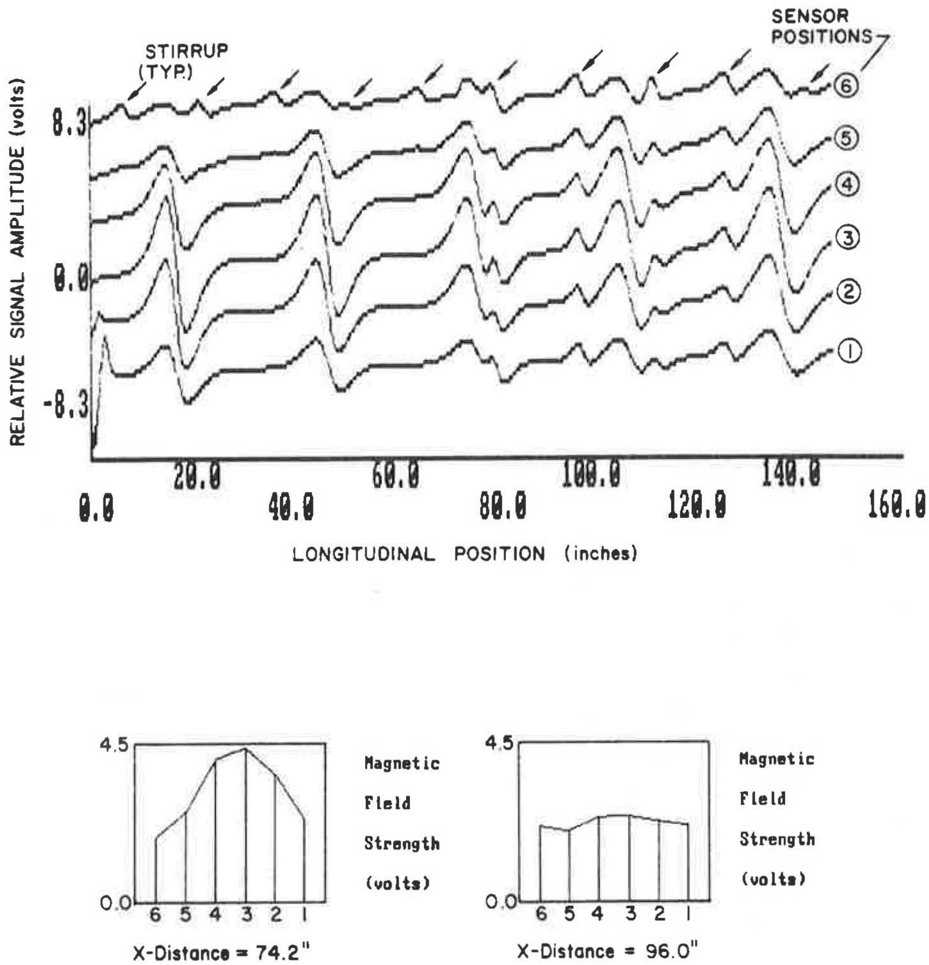

FIGURE 16 Data plot from the six-sensor array used in the profile analysis. Typical flaw and stirrup profiles are shown below.

tional development of signal analysis procedures will enhance the system's current ability to identify flaws.

ACKNOWLEDGMENTS

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