NCHRP
National Cooperative Highway Research Program

RESEARCH RESULTS DIGEST

August 1992 Number 188

Areas of Interest: 25 Structures Design and Performance, 34 General Materials, 40 Maintenance, III Materials, Construction, Maintenance (Highway Transportation, Public Transit)

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Ultrasonic Nondestructive Testing for Deterioration of High-Strength Steel Components Embedded in Concrete

An NCHRP digest of the essential findings from the agency final report on NCHRP Project 10-30(3), "Nondestructive Methods for Field Inspection of Embedded or Encased High-Strength Steel Rods and Cables," conducted by the Corrosion and Protection Centre Industrial Services (CAPSIS), University of Manchester Institute of Science and Technology, U.K. The digest was prepared by Lloyd R. Crowther, Consultant.

THE PROBLEM AND ITS SOLUTION

The ability to detect the possible corrosion, deterioration, and structural integrity of steel tendons or rods used in segmentally constructed or prestressed concrete bridges would allow engineers to make informed decisions about the maintenance and rehabilitation of bridge members. NCHRP Project 10-30(3) was initiated to develop a nondestructive testing method suitable for field inspection of bridges to detect serious deterioration of high-strength steel tendons or rods embedded in concrete. The case of posttensioned, prestressed concrete structures, with seven-wire strand steel tendons inside metal ducts, was regarded as a critical case to be addressed.

The research agency had reviewed different nondestructive testing methods, and their capabilities and limitations for detecting the condition of embedded or encased steel rods and cables in an earlier phase of this project (NCHRP Project 10-30(1), 1987). It had concluded that magnetic- and radiographic-based methods could give some information about the presence and condition of embedded steel components, but there were severe limitations — mainly the depth of penetration and the cost inherent in these techniques, particularly for the case of posttensioned cables in metal ducts. This preliminary work did, however, indicate a potential for ultrasonic pulsing to give information about embedded steel components. (Ultrasonic designates the frequency of mechanical vibrations above the range audible to the human ear, i.e., above 20,000 vibrations per second.) Some effort was also initiated to investigate an acoustical emissions technique for detecting changes in the behavior of steel tendons or rods over time; however, this technique was eventually abandoned. Therefore, the study focused primarily on the ultrasonic-testing technique beginning with the theoretical basis. Modeling analyses were necessary to develop the signal-processing and experimental techniques to enable a prototype system to be configured. The final phase of this program was originally intended to involve practical prototype system field trials on examples of prestressed concrete bridges. A prototype system was developed, but not to the degree whereby field trials would have provided any worthwhile information.

FINDINGS

An extensive literature search was made to uncover the reported developments and progress in the application of ultrasound to the examination of reinforced concrete structures. The ultrasound systems forming the basis of these literature searches were:

- The Impact Echo Method
- Acoustic Emission
- Acoustic Pulsing
- Radar/Microwave System
- Stress waves generated by Moderate Speed Gun or Schmidt Hammer
- Electromagnet Impact Driving Method

The state of the art, as indicated by these literature reviews, suggests that progress toward solutions of the problems posed here has been slow and difficult. None of the techniques reviewed are capable of providing a simple mobile system that can be operated by nonexpert personnel. The remaining findings, therefore, represent work that is unique in the field of experimentation and detail significant progress towards a viable solution.

The research was based on the following principles: (1) the detected signal from an ultrasonic pulse transmitted through concrete reinforced with steel can be analyzed and (2) at least some of the various characteristics of the detected signal will contain information regarding the internal composition of the concrete and the condition of the reinforcing components.

During project execution, great emphasis was placed on theoretical analysis and signal processing to be able to identify the signal content relevant to the embedded components and their condition. The experimental results consistently showed differences in the first part of the ultrasonic signal received, known as the prewave signal, when embedded steel was present. However, analysis of the overall signal content in either the time domain or the frequency domain did not prove sufficiently informative.

Extensive experimental trials were carried out using probes of different frequencies in the range of 50 to 500 Mhz. These probes were tested on single wires and rods and on seven-wire strands with different defective conditions present while the subjects were immersed in a water tank, or embedded in mortar or concrete blocks. A prestressed concrete beam was constructed that included examples of voids, corrosion, and broken wires. Concrete samples with ducts containing simulated broken wires and voids were also constructed and tested. Because of the inherent scatter and attenuation (signal weakening) problems with ultrasonic signals in concrete, *conventional ultrasonic* testing methods were not successful in giving readily interpretable results about the condition of the components embedded in concrete.

To eliminate the scatter and attenuation, an initial prototype system was constructed. The prototype consisted of a central transmitting probe surrounded by four receiving transducers so that the signals received by corresponding pairs of transducers could be compared to show the difference between intact and damaged components. This prototype was not successful with *conventional ultrasonic time domain analysis* because the signal content of interest was buried within the lower-frequency higher-power constituents that suffered less attenuation.

The next stage was to alter the transducer design to transmit discrete frequencies. Attempts to construct transducers that restricted the ringing time to very short periods and to give a prescribed frequency response were not successful in improving the signal content. This result led to the conclusion that the high-frequency signal containing the information about the condition of the embedded components was becoming so attenuated that it was always swamped by lower frequencies.

The above conclusion led to an attempted solution by improving the signal-processing techniques. Signal-processing and filtering techniques to separate different frequency bands from signals of broad-band transducers were successfully introduced. An advanced signal-processing technique was developed in which the signal received at a transducer is transformed to the frequency domain to give the complete frequency spectrum. Block-filtering techniques were then applied to the frequency spectrum to select the signal content lying within narrow frequency bands of about 50 Khz. The signal from these restricted bands was then inversely transformed back to the time domain enabling the high-frequency content material to be examined.

This advanced signal-processing technique has been combined with the use of rolling transducers in a second prototype system for scanning concrete beams containing embedded steel components. It was initially demonstrated that this second prototype is capable of detecting voids and defective regions in small samples. Subsequent work has shown that the present system is capable of identifying voids of the order of 30 mm (1 1/8+") at depths of the order of 100 mm (4") from the surface. It is also capable of identifying major breaks in cables involving a total separation of not less than 30 mm at a depth of approximately 70 mm (2 3/4"). The system is also sensitive to regions affected significantly by chloride contamination over similar depths. The system has been unable to detect single breaks in multiwire strand. Tests on fusion-bonded epoxy-coated steel bars have also been carried out, but the system has not been proven capable of detecting minor corrosion in these cases.

CONCLUSIONS

It was recognized at an early stage that success required ultrasonic signals to be identified at much higher frequencies than those used for conventional testing of concrete. The 'State-of-the-Art' literature survey showed that progress in the identification of prestressing components in concrete structures has been slow and difficult due to the involved technical problems. No existing techniques were capable of providing a simple, mobile, user-friendly inspection system.

Ultrasonic signals can be propagated along long lengths of steel rods or cables in air. Once the steel is embedded in concrete, the signals become severely attenuated reducing the propagation distance to no more than one or two meters.

The propagation of ultrasonic signals in concrete is subject to scatter and attenuation dependent on the relative size of aggregate to the wavelength. Stochastic (random) scattering occurs where the aggregate diameter is approximately the same as the wavelength; its signal loss is proportional to the square of the frequency. Rayleigh scattering (Rayleigh waves are surface waves present in a solid having uniform properties) occurs where the aggregate diameter is much less than the wavelength; its signal loss is proportional to the fourth power of the frequency. High-frequency signals are consequently much more severely attenuated than low-frequency signals.

To detect the presence of, and gather information about, the condition of concrete-embedded steel rods and tendons, the wavelength of the ultrasound must be of the same order as the embedded component's dimension of interest. This requirement mandates that information be collected from the high-frequency components having the shorter wavelength.

The central hypothesis of the developed methodology in signal processing is that different wavelengths -- that is, different frequencies -- will be reflected with different energies depending on the size, geometry, and acoustical impedance of the defect encountered. By partitioning the reflected signal into discrete frequency bands and by comparing the magnitudes of their energies, it is possible to derive information relating to the position, size, and nature of the defect.

The development of techniques capable of locating major faults under shallow concrete covers in embedded prestressing steel components was accomplished. However, the capabilities are limited and the development did not reach the stage of a robust field prototype system. Nonetheless, the research is well documented and represents significant progress in the design of future ultrasonic testing systems capable of revealing the condition of components embedded in concrete.

FINAL REPORT

The agency final report, entitled "Non-Destructive Methods for Field Inspection of Embedded or Encased High-Strength Steel Rods and Cables," gives a detailed account of the research, the findings, the theoretical considerations and justifications, and the conclusions. Figures, tables, plates, and seven appendices including a comprehensive bibliography are included. The report has been distributed to NCHRP sponsores (i.e., the state transportation departments) and is available for loan or purchase ($15.00) to others on request to the National Cooperative Highway Research Program, Transportation Research Board, 2101 Constitution Avenue, N.W., Washington, D.C. 20418.

ACKNOWLEDGMENTS

The research project summarized herein was performed under NCHRP Project 10-30(3) by the Corrosion & Protection Centre Industrial Services, University of Manchester Institute of Science & Technology, U.K. Professor F.M. Burdekin was Principal Investigator and Project Director; Dr. D.G. John was Principal Investigator and Project Manager.

Professor P.A. Payne and Mr. T.A. Smith, Senior Consultants; Dr. K. Hladky, Senior Project Officer; Dr. P. Gaydecki, Project Officer; and Mr. P. Nedwell, Experimental Officer, all contributed to the work. The research team was ably supported by Dr. Walid Damaj in the experimental and theoretical work; Mr. Martin Doyle and Mr. John Wall in organizing the preparation of concrete samples; Mr. Lee Sherwood, Mr. Robert Kean, Dr. Morph Jafar, and Mr. Harvey Turner in assisting with potential measurements and force-corrosion experiments; Mr. Ding in investigating the possibility of using pseudo-random code generation techniques; and Mr. Peter Aylott in assisting and advising on computer-related aspects of the project.

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