Radar and Acoustic Emission Applied to Study of Bridge Decks, Suspension Cables, and Masonry Tunnel

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Studies have been conducted that suggest that it is feasible to use acoustic-emission and radar techniques for the nondestructive testing of masonry and of bridge cables. The examination of the condition of a brick railroad tunnel was carried out by using both techniques. Radar was used to determine the conditions of several reinforced concrete roadways and bridge decks. Acoustic emission was used in a novel way involving the application of small stresses to bridge cables, and the resultant emission pattern was correlated with the condition of the cables. The equipment used is discussed in some detail, as are the uses of special techniques for obtaining and analyzing the data. Several means of loading the bridge cables to obtain the acoustic emission were used; the use of an air hammer is the most effective technique found thus far. Several photographic techniques were developed to correlate the mass of data obtained from radar studies of roadways. These photographic techniques and the advantages of each are discussed in some detail. It is concluded that radar and acoustic emission are potentially useful tools for nondestructive testing of masonry and bridge cables.

This paper describes progress in the state of the art of adapting acoustic-emission and radar techniques to the study of the condition of suspension-bridge cables, concrete bridge decks, and brick tunnels.

The research is motivated by the continuing need to maintain the structural integrity of our bridges and tunnels, which represent very substantial capital investments. This maintenance is complicated by complex construction features: for example, the main structural support of the George Washington Bridge is the four main cables, which are made up of 105 896 wires. At the New York and New Jersey landfalls, each cable splits into 61 strands, each of which is terminated at a turning shoe and anchored in a concrete block through an eye bar. Although these areas are inspected, a better, nondestructive technique of quantitatively evaluating the condition is desirable.

The George Washington Bridge, together with several other bridges, is part of a major arterial system through and around New York City. The decks of these bridges are constructed of reinforced concrete on steel beams. Although the designs vary, they generally consist of a 20-cm (8-in) thick structural portion and up to a 7.5-cm (3-in) asphalt riding surface.

Another part of our transportation net is an old brick railroad tunnel built before 1900. The walls are 0.76 m (2.5 ft) thick and consist of several courses of brick and mortar and a boiler-plate outer skin.

The research techniques that we are attempting to adapt to the study of these structures are acoustic emission and downward-looking radar. (In this paper, we are condensing two papers into one: In general, we have tried to discuss one technique and its use and then the other technique and its details.)

Acoustic emission is a technique that has been in use for about 10 years. It is generally defined as the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from a localized source or sources within a material. In a popular sense, it could be described as listening to a stressed material talk (1).

Some applications of the use of acoustic emission are checking of pressure vessels for flaws or leaks, checking of welds for defects as the weld is fabricated, and detecting hidden active corrosion locations and created stress flaws. In all cases, the material is stressed, and the acoustic-emission counts are monitored (2).

Radar has been used for years, but this downward-looking high-precision technique has only recently evolved as a detector for nonmetallic mines. It has since been used experimentally to nondestructively check the condition of a concrete road and to check for voids under a concrete runway. The radar signal is directed into the material under test, and the patterns created by the reflected waves are observed. In the final interpretation, the results can be considered similar to those produced by an x-ray scan of the material.

We are attempting two unusual applications of acoustic emission. The first is to attempt to determine the condition of the George Washington Bridge cable without stressing it to the 10 percent overload generally associated with acoustic-emission testing (3). The second is an attempt, for the first time, to apply the acoustic-emission technique to the study of the condition of masonry—in this case, a brick railroad tunnel. Both applications seem promising, and we intend to continue developing these areas.

In addition to the use of acoustic emission in the tunnel, radar was also tested for this application. At this juncture, radar seems to be the more promising technique.

Our major experience with radar has been for bridge-deck evaluation. It has been used to nondestructively examine more than 45 km (28 miles) of riding surface, and the results are promising. Our latest data analysis suggests that we have developed a technique that has a reasonable confidence level for identifying good or deteriorating concrete.

EQUIPMENT DESCRIPTION

Radar

Ground-penetrating radar uses a single antenna for both transmitting and receiving (see Figure 1). Its special design allows high-frequency, short-pulse signals to be directed into the earth, concrete, masonry, or other nonmetallic materials. There is an initial return at the surface and additional returns at each interface or change in medium. It is these returns that provide the peaks in the observed signal and have allowed field detection of nonmetallic mines and apparently may allow evaluation of road and tunnel conditions.

The return signal or trace was viewed on a single-channel oscilloscope. For viewing in the laboratory, the radar signal was recorded on a three-channel tape recorder. The signal trace was recorded on one channel, the synch pulse on a second, and voice location annotations and comments on a third. The power was supplied

Figure 1. Horn and transmitting and receiving antenna with antenna hookup to rear of van.

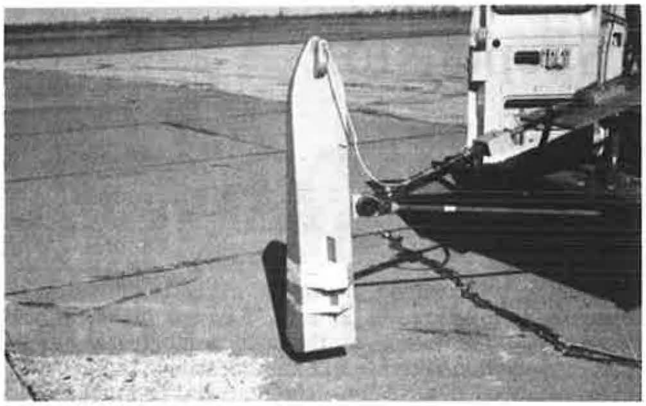
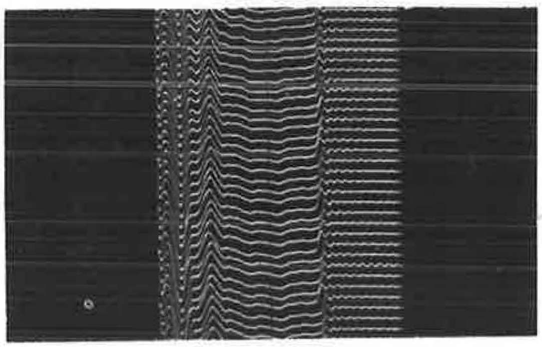
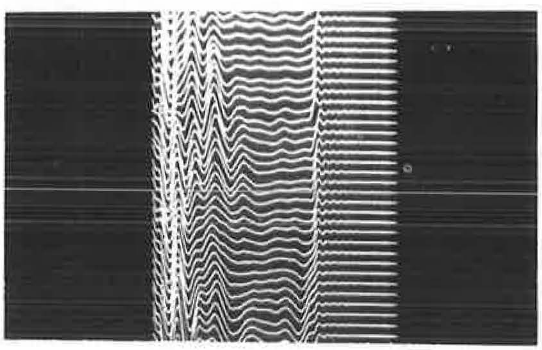


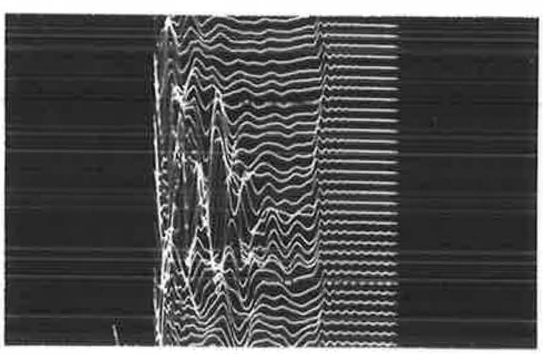
Figure 2. Typical topographic traces.



Stationary

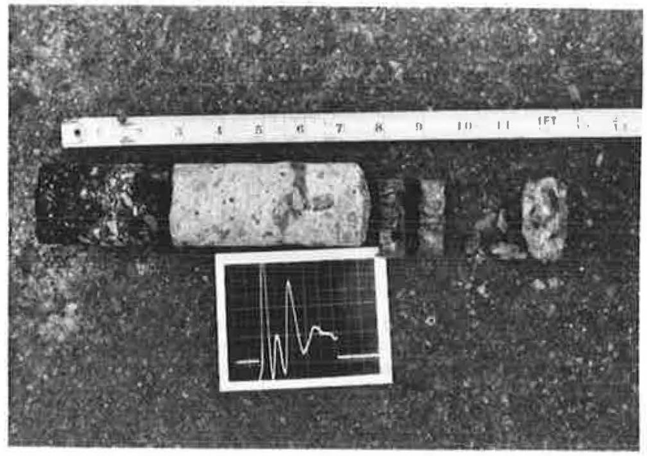


Normal Movement



Disturbed Area

Figure 3. Comparison of core and radar trace.



by two 12-V aircraft batteries for the radar and a 110-V gas-operated generator or a 110-V line for the auxiliaries. A high-speed streak (shutterless) camera was used to obtain a continuous 35-mm film reproduction of the oscilloscope traces. By adjusting the film speed, each trace can be displayed at a fixed distance from the preceding trace and, when the film is viewed, takes on a topographic appearance (Figure 2).

A polaroid scope camera was used to assist in analyzing the data and appears to be the most promising method of display for data interpretation developed thus far.

Acoustic Emission

Acoustic-emission counts are the number of times the acoustic-emission amplitude exceeds a preset threshold during any selected portion of a test (4). The equipment used provided a running digital display of the counts and a voltage output that was also displayed on a recorder. To induce local stress, either a variable-force, variable-frequency vibrator was used to provide stress by vibration or an air hammer was used to provide stress by hammer blows.

PROCEDURE

Radar: Bridges

A van was outfitted with the radar equipment, an oscilloscope, a 110-V gasoline-driven generator, and a tape recorder. The radar and its support equipment were operated on three bridges—Outerbridge Crossing, Bayonne Bridge, and George Washington Bridge.

The van was driven across the bridge in traffic at about 8-12 km/h (5-7 mph). The transmitter pulse-repetition rate was such that at this speed every 7.5 cm (3 in) of roadway was documented as a trace. The radar pulse was directed into the concrete roadway, and the reflections were observed on the cathode ray tube. An example of a trace is shown in Figure 3. At the Outerbridge Crossing, measurements were made in the right wheel track, the left wheel track, and between the tracks in each of the four lanes. On the Bayonne Bridge, measurements were recorded only in the wheel tracks and, on the George Washington Bridge, measurements were made only of the right wheel track of one lane. The Bayonne Bridge is more than 1.6 km (1 mile) long and was surveyed in a single afternoon. This was equivalent to more than 13 km (8 miles) of reading and approximately equivalent to taking a reading every 7.6 cm.

Viewing the taped data displayed on the oscilloscope indicated that a consecutive view of the traces in hard copy might be the best way to show changes taking place. Therefore, all of the tapes were photographed onto 61 m (200-ft) rolls of 35-mm film that show a topographic-like indication of the road as seen by radar. This film can be read on a modified motor-operated light table combined with a microfilm reader, which provides the observer both macro and micro viewing capabilities.

The latest and most promising technique has been to photograph (superimpose) approximately 5 s of continuous run (150 individual traces) onto one polaroid film. This has the effects of creating an envelope of traces and of showing deviations, if any, from the normal.

Radar: Tunnel

The dismounted radar equipment was used to examine the 0.76-m thick brick tunnel wall. The cross-sectional curvature of the elliptical tunnel walls seemed to affect the signal to a small extent, in that it changed as the radar horn was rotated angularly. This seemed to be true also for the distance the horn was held from the wall, which was restricted to 2.5 cm (1 in). Neither the angularity or the distance seemed a problem on the roadways and bridge decks. Not all of the tunnel radar data were tape recorded. Those that were not were filmed on polaroid from the oscilloscope display.

For both the bridge and the tunnel studies, the radar unit was standardized by measuring a shift in the position of the trace when the radar was reflected from a flat metal target at various distances from it in free air.

Acoustic Emission: Tunnel

The first laboratory-feasibility evaluation of masonry conditions by using acoustic emission was made on a string of bricks mortared end to end and established that there was signal transmission through brick. Subsequently, several bricks were mortared together and stressed in a compression test machine. The acoustic emissions were monitored by a transducer on the brick surface from a few counts as the load was applied to an avalanche of counts as failure approached.

Based on these results, acoustic-emission testing was next undertaken in the brick tunnel. After an initial series of tests to determine the field parameters (signal speed, distance, and depth of penetration) to be expected, a simple jacking-screw loading device was designed. Because large stresses in the wall were considered undesirable, the loads that were applied were extremely small.

Acoustic-emission signals were measured at several test points in the tunnel. The load was applied in 45.4-kg (100-lb) increments. Readings were made on the following day in some locations to check for relaxation effects.

Acoustic Emission: Bridge Cables

At the George Washington Bridge, the acoustic-emission technique was used on some of the strands of the 61 that make up a main cable. Tests were made on two of the main cables and were conducted in both the New York and the New Jersey anchorages. Because direct stressing is not desirable, very light stresses were applied by hammer blows and the acoustic emissions were recorded.

The first series of tests were those in the New York anchorage; a hand-held plastic-head mallet was used for hammering on the strands. The results were generally repeatable, but the mallet was difficult to use under the existing conditions. Next, a manually operated drop hammer was used to stimulate the cables with a controlled force. However, this technique was also inadequate for satisfactory results. A vibrator was then obtained, which vibrated the cable sufficiently to obtain acoustic emission but, again, the results were erratic. The use of a variable-speed, variable-force vibrator also gave erratic results.

Finally, an air hammer was obtained: This was used with a metal striking plate held between the hammer and the cable to protect the strands (see Figure 4), and gave the most repeatable and encouraging results.

Generally, a series of 8 to 10 blows were recorded and averaged to determine the rank order of the strands tested.

DISCUSSION OF DATA

Radar: Data Reduction

Generation of a trace every 7.5 cm for approximately 45 km creates a volume of data that is almost unmanageable. Reconstituting the data on an oscilloscope showed many variations that could not be coped with visually. The 35-mm shutterless streak camera seemed an appropriate technique with which to manage the visual information.

This technique gave a strip of film that was topographic in nature and appeared to indicate structural changes (see Figure 2). A more recent photographic technique being developed makes use of a time exposure that superimposes many traces, one upon another, which outlines the normally encountered envelope of variability

Figure 4. Arrangement for acoustic-emission test of George Washington Bridge strands.

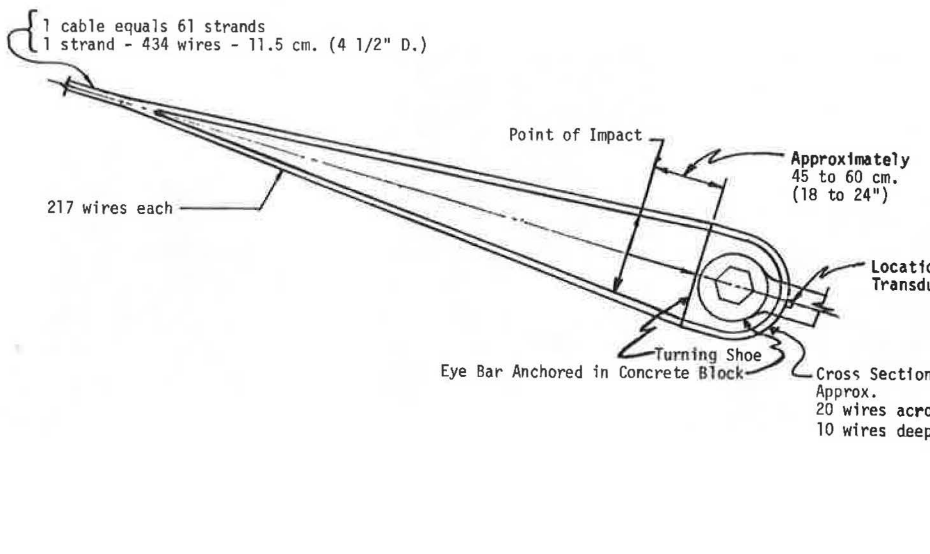
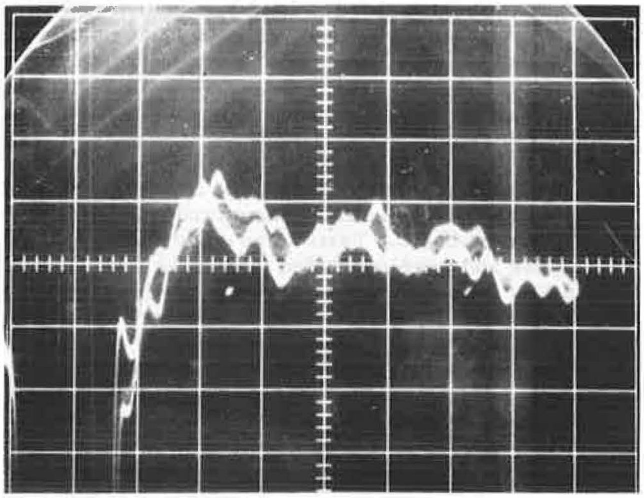


Figure 5. Time exposure of envelope of radar traces.



(see Figure 5). Major structural variations seem to be more readily identifiable with this technique.

Although this may be a workable system, we are also investigating computerized mathematical procedures that could approach real-time analysis.

Radar: Tunnel

At the present time, the radar data can be evaluated in only qualitative terms. The entire trace for a location or a series of traces for an area must be considered to determine the condition of the structure being viewed. In general, with assumed sound structures, the traces fall into a family of traces that has few, if any, variations. As can be seen from Figures 2 and 5, the envelope of traces falls within a relatively close pattern. Unfortunately, because of the presence of large metal drainage pipe in this tunnel that interfered with the radar signal at the location where acoustic-emission data had been taken, it was not possible to precisely compare the acoustic-emission and the radar data.

Radar: Roadway

By far our most voluminous set of data is that for the bridge roadways, 4800 m (15 750 ft) of tape that have been reduced to 1700 m (5800 ft) of 35-mm film (see Figure 2 for typical examples of this film). All that has been said about the radar data taken in the tunnel is applicable to the roadway data with two additional comments: first, the ratio between disturbed and quiet areas seems to be what might normally be expected in the field and, second, visible structures such as joints are clearly discernible in the data. Figure 3 shows a core and its previously taken radar signature. The first left-hand peak represents the interface between asphalt and concrete and the third peak shows the deterioration of the bottom of the core.

The latest procedure consists of superimposing a series of approximately 120 individual consecutive radar traces in about a 5-s period on a single polaroid picture. When the picture has all the traces superimposed on each other, they give the appearance of a single trace and cores taken from the area represented by the picture are sound. On the other hand, when many separate traces are visible or the picture has a ragged appearance, cores taken from the area represented by the data may be of poor quality (see Figures 6 and 7).

Acoustic Emission: Tunnel

The acoustic-emission data are shown in Figure 8. In addition, monitoring positions A5 to A9 when there were trains in an adjacent tunnel showed good agreement between counts observed under stress and counts observed when trains were passing.

Monitoring Position	Train	Highest Index
A5	371	300
A6	163	150
A7	1212	2000
A8	98	150
A9	1065	700

The data would seem to be consistent within themselves and may show the normal limits of variation in the structure. It was also interesting that the area giving the highest index (A7) was one that had a noticeable hollow sound when tapped. The Kaiser effect (5) (the absence of detectable acoustic emissions until previously applied stress levels are exceeded) is clear in some cases (such as A2, A4, A6, and A8), but in others, the second loading cycle produced early emissions.

Figure 6. Nonsuperimposed trace characteristic of deteriorated concrete.

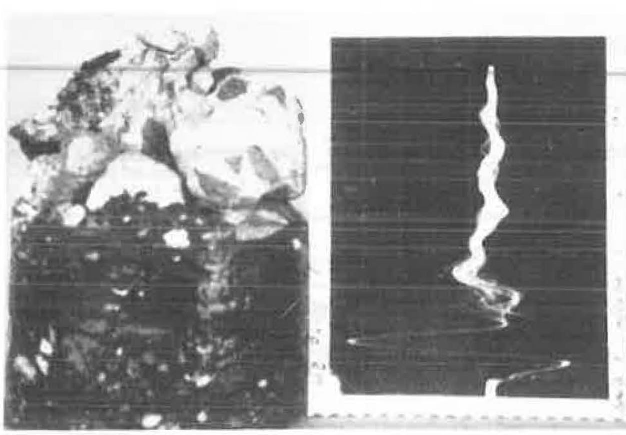


Figure 7. Tight envelope of traces indicating sound concrete.

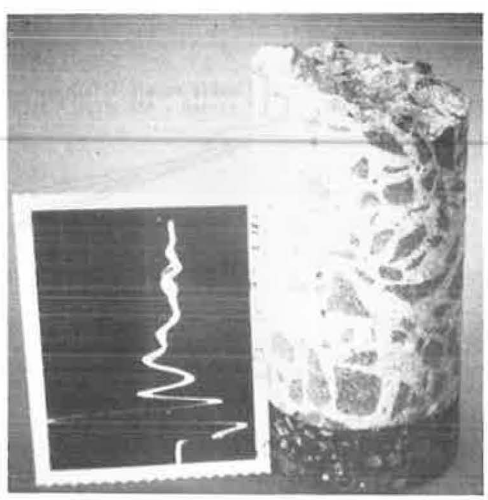
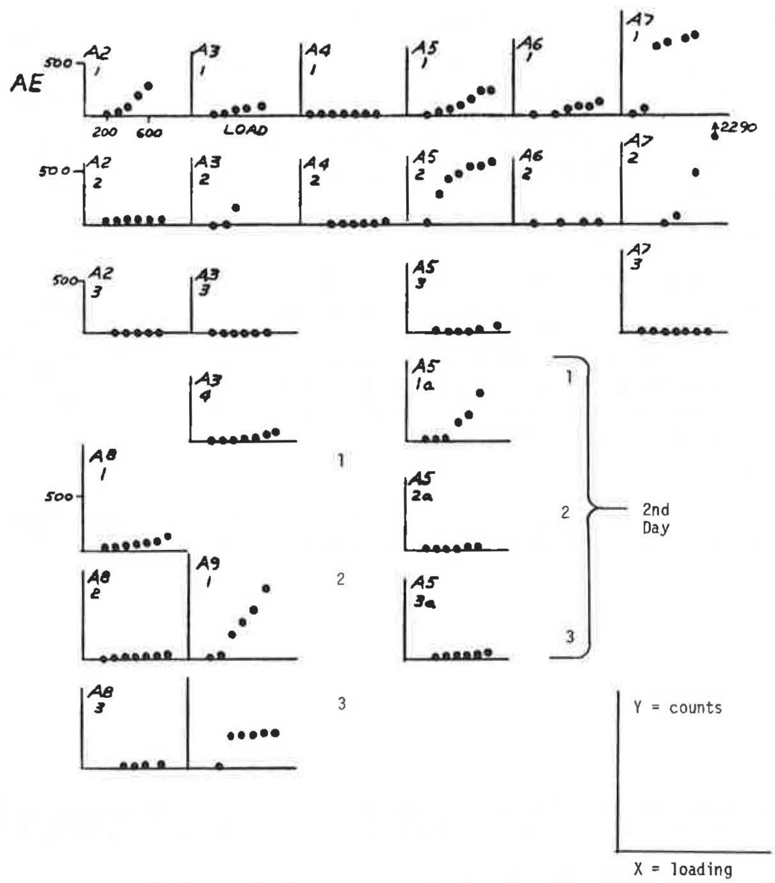


Figure 8. Acoustic-emission reading from brick tunnel.



Acoustic Emission: Bridge Cables

Of the thirty strands examined (see Table 1), the strand condition indicated by the acoustic-emission index seemed to be reasonably consistent with the conditions indicated by other inspection procedures. For reasons that are not understood at present, the emission from the upper strands was greater than that from the lower strands. Blows on the shoe provided greatest index of acoustic emission, which may be attributable to the transmission medium, solid steel.

CONCLUSIONS

Based on our experiences in the state of the art of radar and acoustic-emission techniques, we feel that both have considerable potential for rapidly, economically, accurately, and nondestructively evaluating bridge decks, roadways, runways, masonry, and steel suspender cables. Both should be pursued and developed further.

This conclusion is based on the successful identification of both good and disturbed concrete by using superimposed polaroid trace images for radar and on the prospect of rapid data reduction and evaluation via some algorithm or computer procedure that would result in a digital display.

Acoustic emission detected different levels of emission in the tunnel and perhaps some differentiation in emission in the bridge-cable strands.

Furthermore, acoustic emission appears to have potential for determining the condition of inaccessible wires of a multiwire cable or strand. One of the difficulties that still exists is that of developing the best technique for introducing the minimum acceptable level of stress to the strands. Acoustic emission is probably a feasible method of nondestructively determining masonry condition. There are, however, two major disadvantages: (a) It is cumbersome to use in a tunnel and (b) it requires that the area be stressed. We have,

Table 1. Main cable index numbers.

Strand No.	Lower Strand	Upper Strand	Shoe
43	1	12	38
41	3	12	72
37	3	21	54
56	5	17	49
60	5	16	69
61	5	20	53
39	6	5	36
12	6	46	60
45	7	12	75
42	8	16	95
46	8	21	152
20	8	23	66
49	8	26	55
16	9	12	65
55	9	30	40
47	10	12	80
53	10	30	51
50	11	18	98
48	11	22	79
36	11	22	101
40	18	22	113
89	18	41	54
44	24	24	81
54	24	50	101
8	25	14	189
58	28	21	130
51	29	29	138
57	29	35	86
4	32	44	73
52	35	41	171
Max	35	50	189
Min	1	5	36

therefore, decided to temporarily defer its use in tunnels in favor of radar.

In our opinion, radar shows qualitative distinctions in the conditions of the brick tunnel. However, because the brick tunnel is a more complex system than the roadway in terms of the data, we have decided to direct our present efforts to the interpretation of the bridge-deck and roadway data.

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Abridgment

Dynamic Properties of Skewed Beam-Slab Highway Bridges

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The dynamic response and vibrational characteristics of railroad and highway bridges are of concern to bridge designers. This is due to the fact that, through the prediction of the dynamic response, the amplification of the static live-load stresses and deformations can be estimated and this, in turn, may require the redimensioning of the superstructure. It has been shown that the amplification of the static response through the use of an impact factor can lead to erroneous results (1, 2). The vibrational characteristics (more specifically, the periods of vibration) of the bridges are usually used in conjunction with the definition of sensitivity to earthquake forces and the human perception of the vibration of the superstructure.

The natural periods of vibration of highway bridges can be used in the discrimination of the dynamic characteristics. The development of simple empirical formulas that can predict the natural periods of vibration would be the optimal solution. Analytical studies have resulted in sufficient information on the natural periods of vibration of simple-span beam-slab highway bridges that have reinforced concrete decks and prestressed concrete I-beams and may or may not have skew (1, 3, 4, 5, 6). This paper summarizes the results of research carried out to predict the natural periods of vibration of these types of bridges that have skew.

DESIGN AND ANALYSIS OF BRIDGES

The paper focuses attention on simple-span beam-slab bridges that have prestressed concrete I-beams. To be representative of the variety of bridges encountered in the field, 33 right bridges were designed by using current engineering practices (7). Their span lengths, curb-to-curb widths, and beam spacings varied from 12.20 to 27.44 m (40 to 90 ft), 7.32 to 18.30 m (24 to 60 ft), and 1.46 to 2.61 m (4 ft 9 in to 8 ft 7 in) respectively: A detailed description of the bridges is available elsewhere (3, 5). The configurations considered cover a wide range of variation in the design parameters.

In the definition of the dynamic characteristics of the bridges, the superstructures were simulated by using the finite-element method. The deck slab was modeled via plate-bending elements and the beams as beam-bending elements. The analysis was performed by using the computer program SAP IV (8). The first three fundamental periods of vibration of the superstructures, both those that had and those that did not have skew, are available elsewhere (3, 5). The empirical formulas for the prediction of the periods of vibration of right bridges that have not already been computed are also available (5). The analysis assumed that no vehicle is on the bridge. The differences between these unloaded and loaded periods have been presented previously (1).

SKEWED BRIDGES

In the parametric study, the design parameters of the 33 right bridges were retained intact, but the geometries of the bridges were changed for skew angles of 60° and 45° (90° skew being the right bridge). The inclusion of the new bridges has resulted in the consideration of a total of 99 bridges. Through the application of the finite-