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The impact-echo response of concrete plates containing delaminations: numerical, experimental and field studies

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This paper describes the use of the impact-echo technique – a non-destructive testing technique based on the use of transient stress waves – for detecting delaminations in concrete plate-like structures such as bridge decks, slabs, and walls. Results obtained from numerical (finite element) analysis and controlled-flaw laboratory studies are presented and used to explain the elastic impact response of delaminated plates. Current impact-echo instrumentation is described, and results obtained from concrete bridge decks containing delaminations caused by corrosion of reinforcing steel are presented. These results provide a better understanding of the impact response of delaminated plates.

1. INTRODUCTION

A common problem in repair and rehabilitation of concrete structures is to determine the extent of cracking within a structure. In plate-like structures such as bridge decks, slabs and infill walls in frames, cracking often occurs in the form of delaminations in the plane of the reinforcing bars. For example, in reinforced concrete bridge decks, chloride-induced corrosion of reinforcing bars leads to bursting forces which produce cracks around the bars. These cracks propagate in the plane of the bars due to the larger bursting forces caused by continued corrosion and forces caused by expansion of water which penetrates the cracks and undergoes freezing and thawing [1]. In reinforced concrete infill (or shear) walls in frame structures, cracking around bars leading to delaminations can be caused by cyclic loading in an earthquake [2].

Previous laboratory work by Sansalone and Carino [3] showed that the impact-echo method could be used for detecting delaminations in plate-like structures. However, this earlier work did not fully explain the impact response of delaminated plates. This paper presents a more complete explanation of the impact-echo response of a delaminated plate using three-dimensional, dynamic finite-element models and laboratory specimens containing delaminations of known size and depth. In addition, with the development of field impact-echo instrumentation [4], field studies on concrete bridge decks could be performed to verify the results obtained from numerical and laboratory studies.

This paper begins with a brief introduction to the impact-echo method (testing technique and signal processing) and a discussion of the important equations and parameters in impact-echo testing of plate structures. Impact-echo instrumentation is then described. Next, information on the numerical models used to study transient wave propagation in concrete plates containing flaws and details of controlled-flaw laboratory specimens is presented. Numerical and experimental results are used to explain the impact response of concrete plates containing delaminations. Then, results obtained from impact-echo tests performed on concrete bridge decks are presented.

2. MATERIALS AND METHODS

2.1 The impact-echo method

In the impact-echo method, a transient stress pulse is introduced into a structure by mechanical impact at a point on the surface. This pulse travels into the plate as dilatational (P-) and distortional (S-) waves and along the surface as a Rayleigh (R-) wave. The P- and S-waves propagate into the structure along spherical wavefronts and are reflected by internal cracks or voids or interfaces and by the external boundaries of the structure. A displacement transducer located close to the impact point is used to monitor the surface displacements caused by the arrival of these reflected waves. These waves are, in turn, reflected at the free surface, and they propagate back into the test object to be reflected again by internal interfaces or boundaries. Therefore, a transient resonance condition is set up by multiple reflections of the waves between the free surface and internal defects or external boundaries. P-waves are of primary importance in impact-echo testing of plate structures, because the displacements caused by P-waves are much larger than those caused by S-waves at points located close to the impact point [5]. The frequency of P-wave arrivals at the transducer is determined by transforming the recorded time-domain signal into the frequency domain using the fast Fourier transform technique. The frequencies associated with the peaks in the resulting amplitude spectrum represent the dominant frequencies in the waveform. Knowing the P-wave speed in the test object, C_p, the depth, d, to an internal void or crack or

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an external boundary can be calculated as

$$d = C_p/2f \quad (1)$$

where f is the frequency of P-wave reflections from the internal interface or bottom plate surface. Equation 1 is valid for calculating the frequency of reflections from interfaces where the material at the interface is acoustically less stiff (has a lower acoustic impedance) than the concrete [6]. For example, when waves are incident upon a concrete–air boundary (the bottom of a bridge deck or an air-filled crack), nearly 100% of the incident wave is reflected. For a wave incident on a concrete–water boundary, about 70% of the incident wave is reflected.

2.2 Instrumentation

An impact-echo test system is composed of three components: impactors; a receiving transducer; and a portable computer with a data-acquisition card. The following paragraphs describe these components.

The choice of an impact source is very important. In current impact-echo research and field work, hardened steel spheres on spring-steel rods are used as impact sources. The force–time history of the elastic impact of a sphere can be approximated as a half-cycle sine curve [5]. The duration (or contact time, t_c) of the impact determines the frequency content of the stress pulse that is generated [5,7]. The durations of the impacts produced by current impact-echo sources range from about 10 to 80 μs. Most of the energy in the pulse can be considered to be contained in frequencies less than about $1.5/t_c$. A shorter duration of impact produces a broader range of frequencies in the waves; however, the amplitude of each component frequency is lower. The impact duration determines the size of the defect which can be detected by impact-echo testing. As the duration decreases, the pulse contains higher frequency (shorter wavelength) components, and smaller defects or interfaces can be detected. Shorter-duration impacts are also needed to locate shallower defects. However, waves produced by shorter-duration impacts will have limited penetrating ability in concrete. Thus, the impact duration should be chosen so that the pulse that is generated contains waves with wavelengths approximately equal to or somewhat less than the following parameters: (i) the lateral dimensions of the defect or interface to be detected, and (ii) twice the depth ($2d$) of the defect to be detected.

The receiver is a broad-band displacement transducer consisting of a small, conically-shaped, piezoelectric element cemented to a brass cylinder [8]. The signal produced by this transducer is proportional to normal surface displacement. A thin sheet of lead is used between the conical element and the concrete surface to complete the transducer circuit and to couple the transducer to the rough concrete surface. In current test systems, the impactors and transducers are housed in a hand-held unit which can be used to test horizontal, vertical or overhead surfaces [4,9].

A portable computer-based data-acquisition system is used to capture the output of the transducer, store the digitized waveforms, and perform signal processing and analysis. For all the experimental results presented in this paper, displacement waveforms contain 1024 points recorded at a sampling interval of 2 μs. The resulting digital amplitude spectra have a resolution of 0.488 kHz.

2.3 Numerical methods

Because theoretical solutions for the transient impact response of bounded structures containing flaws do not exist, an explicit, three-dimensional finite-element code, DYNA3D [10] was used by the authors to study the impact response of plates containing delaminations. In each of the analyses, eight-noded solid (linear) elements were used to represent the continuum, and numerical integration of the equations of motion was accomplished using the central difference method. An input generator, INGRID [11], was used to create the finite element models for DYNA3D. An interactive graphic post-processor, TAURUS [12], was used to obtain deformed shapes and contour plots of stresses at selected times and displacement waveforms at points (nodes) on the surface near the point of impact. These waveforms simulate the impact-echo response measured by a transducer. The impact of a sphere on a plate was simulated by applying a pressure loading with a force–time history of a half-cycle sine curve over a small number of elements [5]. Different duration impacts were obtained by changing the period of the sine curve. In the analyses, the concrete plates were unsupported to avoid exciting structural modes of vibration caused by rigid restraints.

The material model used to represent the behaviour of concrete was a linear elastic, isotropic model. The model is valid for concrete at the low strain levels produced by the low-frequency stress waves produced by elastic impact. The values of density, modulus of elasticity and Poisson's ratio used to define the material model for concrete were 2300 kg m^{-3}, 33 100 MPa and 0.2, respectively.

2.4 Controlled-flaw laboratory specimens

Controlled-flaw specimens are used to study signals from flaws in structures where the structural dimensions and the flaw size and location are all known. These specimens also offer a means of verifying results obtained from the numerical models. The laboratory results discussed in the paper were obtained from two specimens: a 2.4 m long, 1.4 m wide, 0.2 m thick reinforced concrete plate and a 3 m long, 1.5 m wide, 0.4 m thick plain concrete specimen. In the reinforced plate, concrete cover over the top layer of 25.4 mm diameter reinforcing bars was 40 mm. Cracks were simulated using thin, flexible foam sheets. The uncompressed thickness of the sheets was 5 mm. The concrete was made using a normal-strength Portland cement mixture and limestone aggregate. The aggregate had a 13 mm maximum size.

3. NUMERICAL AND EXPERIMENTAL STUDIES

In the following sections, numerical and experimental results will be used to explain the impact response of a solid plate and plates containing delaminations. The effect of delamination depth and size will be shown. The effect of changing the location of the impact point over the delamination will also be discussed. Subsequently, results obtained from an impact-echo study on a concrete bridge deck will be summarized.

3.1 Solid plates

The impact-echo response of a solid plate is dominated by multiple reflections of the P-wave through the thickness of the plate. This is true as long as the lateral dimensions of the plate are approximately six times larger than the plate thickness. These reflections produce a surface displacement response which when transformed into the frequency domain is characterized by a single dominant peak at a frequency defined by Equation 1. This frequency is called the 'thickness' frequency.

A typical solid plate response obtained from an impact-echo test on the 0.2 m thick concrete plate described earlier is shown in Fig. 1. Fig. 1a shows the test configuration. The impact duration was 40 μs. The P-wave speed in the concrete was 4000 m s^{-1}, so the expected thickness frequency is $f = 4000/(2 \times 0.2) = 10$ kHz. Fig. 1b shows the waveform and Fig. 1c shows the amplitude spectrum. Arrows on the waveform indicate successive arrivals of the P-wave, with 2P, 4P, 6P designations indicating respectively a wave that has been reflected two, four, six times through the plate thickness. The spectrum exhibits a single large amplitude peak at 9.8 kHz which is the closest digital point to the calculated value. Thus Fig. 1 shows the basic solid response which will be used for comparison with the numerical, laboratory and field responses obtained from concrete plates.

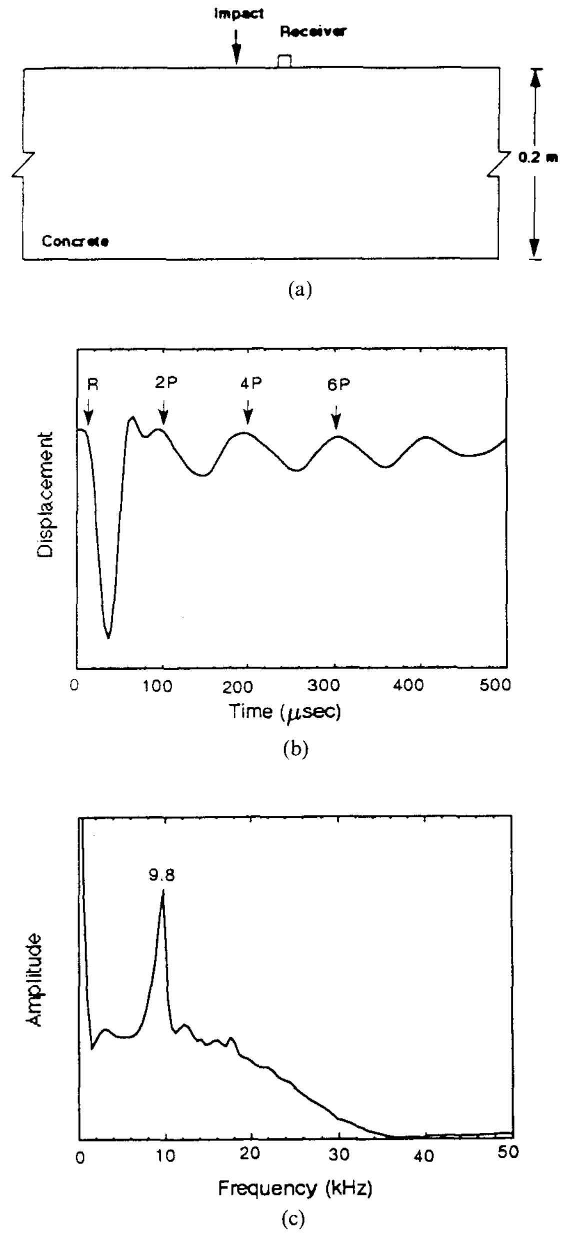

Fig. 1 Impact response of a solid plate: (a) model cross-section, (b) waveform, (c) amplitude spectrum.

3.2 Plates containing deep delaminations

The response of a plate containing a crack or delimination depends upon the size and depth of the delamination. The impact-echo response of a plate containing a deep delamination is the simpler case. Take for example the plate shown in Fig. 2a. The plate thickness was 0.4 m, and the depth of the 0.4 m circular delamination was 0.3 m. The P-wave speed in the concrete was 3910 m s^{-1}, and the thickness frequency of the solid plate was 4.9 kHz. When an impact-echo test is carried out over the delamination, reflections from the surface of the delamination dominate the response. The waveform (Fig. 2b) shows periodic displacements produced by P-wave reflections from the delamination. The spectrum (Fig. 2c) exhibits one large amplitude peak at a frequency of 6.84 kHz. Using Equation 1, this frequency gives a calculated depth of $3910/(2 \times 6840) =$ 0.29 m, which compares well with the known depth of 0.3 m. This response is very typical of the responses obtained from large, deep delaminations.

3.3 Plates containing shallow delaminations

The impact response of a concrete plate containing a shallow delamination is fundamentally different from the response obtained from a plate containing a deeper delamination, because the waves generated by the impact excite one or more flexural modes of vibration of the concrete section above the shallow delamination. When subjected to impact, the delaminated section vibrates as a plate restrained on its edges. These modes of vibration correspond to the hollow or 'drummy' sounds one hears when sounding a concrete structure containing a shallow

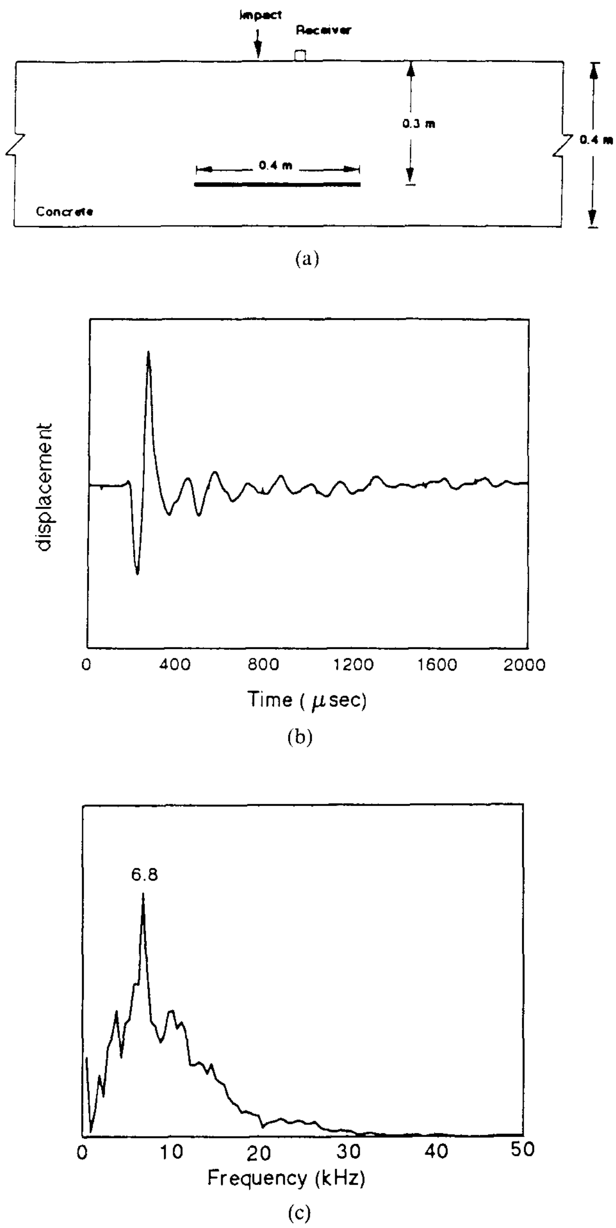

Fig. 2 Impact response of a plate containing a deep delamination: (a) specimen cross-section; (b) waveform, (c) amplitude spectrum.

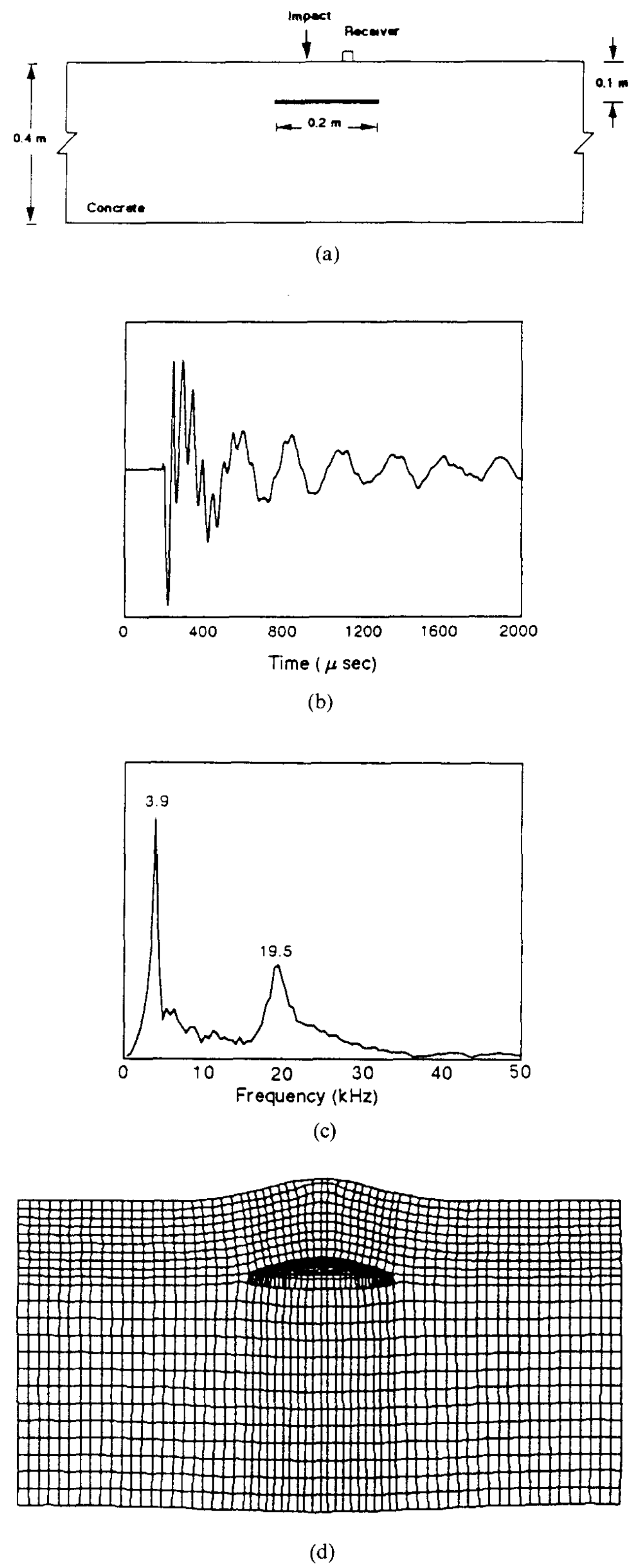

Fig. 3 Impact response of a plate containing a 0.1 m deep delamination: (a) specimen cross-section, (b) waveform, (c) amplitude spectrum, (d) finite-element model showing the fundamental flexural mode of vibration.

delamination. As will be shown in the following paragraphs, the frequencies associated with these flexural modes of vibration depend upon the lateral dimensions and the depth of the delamination. In addition, the modes which are excited depend upon the location of the impact point.

Fig. 3 gives an example of a typical response obtained over a shallow delamination. The delamination is 0.2 m in diameter, and it is located 0.1 m below the top surface of the 0.4 m thick laboratory slab (Fig. 3a). Using the known P-wave speed of 3910 m s^{-1}, the frequency corresponding to reflections from the delamination is $3910/(2 \times 0.1\ \text{m}) = 19.6$ kHz. Fig. 3b and c shows respectively the waveform and spectrum obtained from an impact-echo test where the impact point was located over the centre of the delamination. The impact duration was 30 μs. The waveform exhibits higher-frequency, smaller-amplitude oscillations (P-wave reflections from the delamination) superimposed upon a much larger, lower-frequency oscillation. The spectrum exhibits two significant peaks. There is a lower-amplitude, higher-frequency peak at 20 kHz which is the peak produced by reflections from the delamination. There is a very large-amplitude peak at 3.9 kHz which is the peak produced by fundamental flexural vibration of the section of the plate above the delamination. It is this vibration which produced the large-amplitude, low-frequency oscillations in the waveform. Note that the frequency of this vibration is lower than the 4.9 kHz thickness frequency of the solid plate.

Fig. 3d shows the deformed shape of a finite-element model of the 0.4 m thick laboratory slab shown in Fig. 3a. The numerical model has been subjected to a force–time function which is a sine curve with a frequency of 3.9 kHz. This loading has been applied over two elements at the surface of the plate directly over the centre of the delamination. This technique, called resonant analysis, allows the authors to excite the numerical model in its various modes of vibration and visualize the deformed shapes. If the force–time function has a frequency which corresponds to one of the modes of vibration of the structure (in this case, the fundamental flexural frequency), the mode is excited, and mode shapes can be clearly seen.

3.4 Influence of the impact position

An important parameter in determining the measured impact-echo response is the position of the impact relative to the plane of the delamination. To illustrate the effect of changing the impact position, a series of results obtained from over a 0.14 m wide by 0.90 m long delamination, located about 0.05 m deep in a 0.2 m thick laboratory slab, are shown in Fig. 4. Fig. 4a shows a cross-section of the slab containing the artificial delamination which was formed over a reinforcing bar. Notice that the depth of the delamination over the reinforcing bar is about 0.04 m. The P-wave speed in the concrete was 3910 m s^{-1}. The thickness frequency for the solid plate was 9.8 kHz.

If the impact point is located at or near the centre of the delamination (the case shown above in Fig. 3), the fundamental flexural frequency will be dominant, and the impact-echo response will be characterized by a very large-amplitude, flexural vibration. The amplitude of this flexural vibration becomes larger as the depth of the delamination becomes shallower and as the lateral dimensions of the delamination become larger. This makes it more difficult to detect the much smaller-amplitude, higher-frequency reflections from the top surface of the delamination. For example, Fig. 4b shows a spectrum obtained over the centre of the delamination shown in Fig. 4a. The large-amplitude peak at 3.4 kHz is the fundamental flexural frequency, and the small bump centred around 46 kHz corresponds to reflections from the delamination over the top of the reinforcing bar.

If, however, the impact point is located half-way between the centre and the edge of a delamination, the first antisymmetric flexural frequency will be excited also. Fig. 4c is a spectrum obtained for this test configuration (impact point No. 2 in Fig. 4a). Now there are two high-amplitude peaks present. The peak at 3.4 kHz is the fundamental frequency, and the peak at 6.8 kHz is the second flexural frequency. The smaller-amplitude but distinct peak at 39 kHz corresponds to reflections from the delamination, which is at a depth of about 0.05 m under impact point No. 2. Fig. 4d shows the deformed shape of a finite-element model of the laboratory slab shown in Fig. 4a. The numerical model has been subjected to a force–time function with a frequency of 6.8 kHz. The forcing function was applied at impact point No. 2. The deformed mesh has the shape of the first antisymmetric flexural mode. (Note that this mode does not always have a frequency that is twice the fundamental mode. The frequency of higher modes depends on the geometry of the delamination. More explanation about how the geometry of delaminations affects the impact response will be given subsequently.)

As the impact point approaches the edge of a delamination, higher-frequency peaks appear in the spectral response in addition to the flexural vibrations. These peaks correspond to waves which have diffracted around the edge of the crack and been reflected from the bottom of the plate, and reflections from the edge of the crack. For example, Fig. 4e shows a spectrum obtained from impact point No. 3 (see Fig. 4a) which is very close to the edge of the delamination. A distinct peak appears at 9.3 kHz, which is one digital point lower than the solid thickness frequency of the plate. As the impact point moves off the edge of the delamination (impact point No. 4), this peak at 9.3 kHz becomes the dominant peak, and the peaks corresponding to the flexural frequencies diminish in amplitude until they eventually disappear. The secondary peak at about 18 kHz corresponds to twice the plate thickness frequency [5].

Often, secondary peaks are observed in spectra at frequencies which have higher values than the fundamental frequency, but which are much lower in amplitude than the fundamental or first antisymmetric flexural modes. For example, note the presence of secondary peaks in Fig. 4b. These peaks correspond to other modes of vibration excited by impact over rectangular delaminations, and their frequencies depend on the geometry. For example, a spectrum from a numerical analysis of a 0.2 m thick plate containing a 0.14×0.9 m delamination at a depth of 0.053 m is shown in Fig. 5a. (This case is similar to that shown in Fig. 4b except that the P-wave speed in the numerical model is 4000 instead of 3910 m s^{-1}.) The spectrum exhibits a large-amplitude peak at 3.9 kHz which is the fundamental flexural frequency, a small-amplitude peak at 38 kHz which corresponds to reflections from the top surface of the delamination, and secondary peaks at 4.9 and 5.9 kHz which are produced by the higher flexural modes in the long (0.9 m) dimension of the delamination. These modes are illustrated in the series of deformed shapes shown in Fig. 5b, c and d. These shapes were obtained using resonant analysis with sinusoidal force–time functions

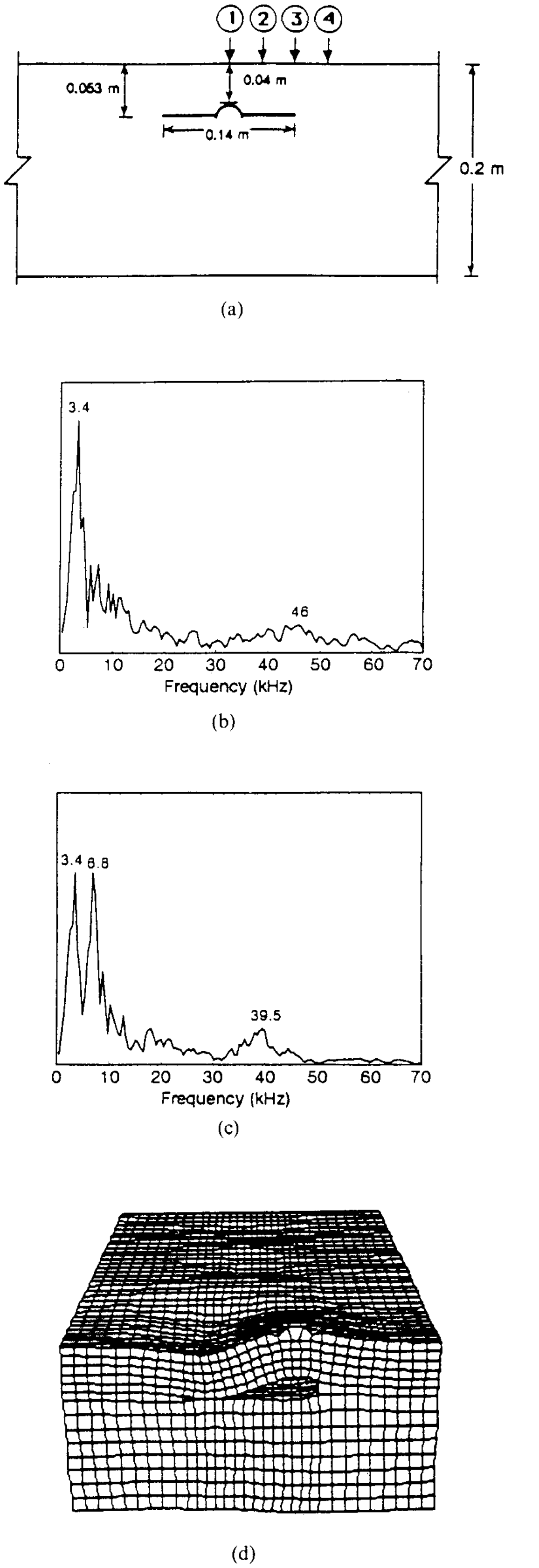

Fig. 4 Impact responses from a plate containing a shallow delamination: (a) specimen cross-section showing locations of impact, (b) spectrum obtained from an impact-echo test over the centre of the delamination (point No. 1), (c) spectrum obtained from impact point No. 2, (d) finite-element model showing the second flexural mode of vibration.

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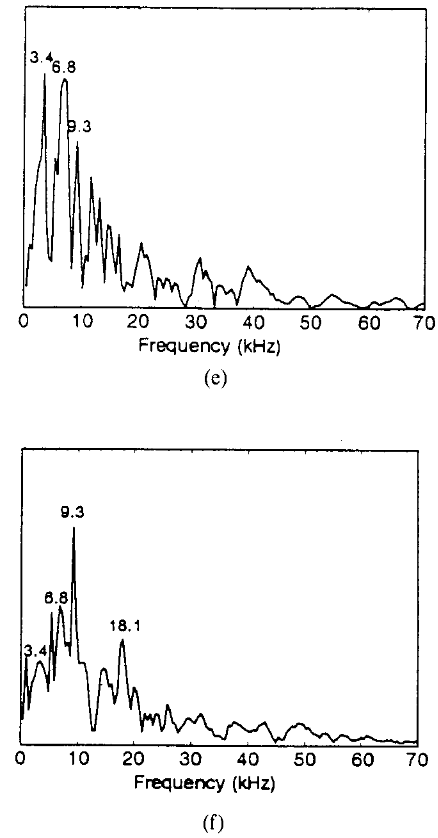


Fig. 4 *continued* (e) spectrum obtained close to the edge of the delamination (point No. 3), (f) spectrum obtained from a point just off the edge of the delamination (point No. 4).

having frequencies of 3.9, 4.9 and 5.9 kHz, respectively. The small (0.14 m) dimension vibrates in the fundamental mode, while the 4.9 and 5.9 kHz excitations excite the second and third symmetric modes, respectively, in the long dimension of the delamination.

3.5 Influence of the dimensions of the delamination

The frequencies of the flexural modes which are excited by impact on a delaminated plate are a function of the depth and lateral dimensions of a delamination. First consider the effect of changing lateral dimensions. Fig. 6a shows the cross-sectional geometry of the 0.2 m thick laboratory slab containing a 0.10 m wide delamination. The depth of the delamination is the same as in the previous case shown in Fig. 4. In this example, spectra representing three delamination geometries will be shown. In all these cases, the impact point was located over the centre of the delamination. Fig. 6b, c and d show spectra obtained over 0.1 m × 0.1 m, 0.1 m × 0.3 m and 0.1 m × 0.9 m delaminations, respectively. The spectral response in all cases is dominated by a very large-amplitude frequency peak produced by the fundamental flexural vibration of the delaminated section. The frequency of the flexural vibration is 7.3 kHz for the 0.1 m × 0.1 m case. As the dimensions of the

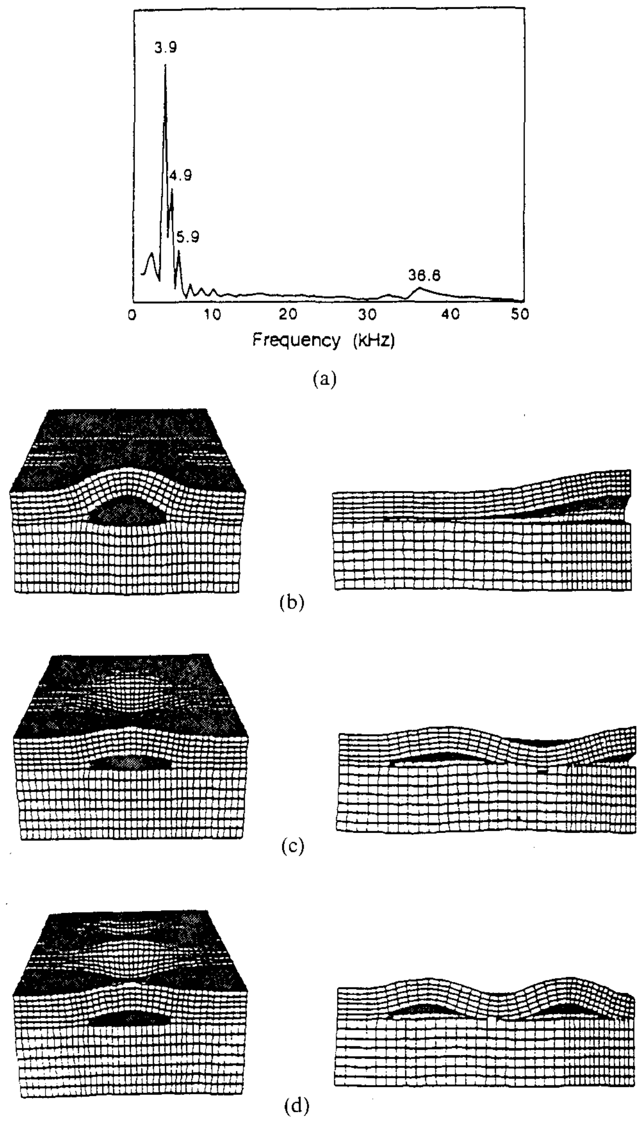


Fig. 5 Modes of vibration of a shallow (0.05 m deep) rectangular (0.1 m by 0.9 m) delamination: (a) spectrum obtained from impact over the centre of the delamination, (b–d) finite-element model showing the first and higher flexural modes of vibration.

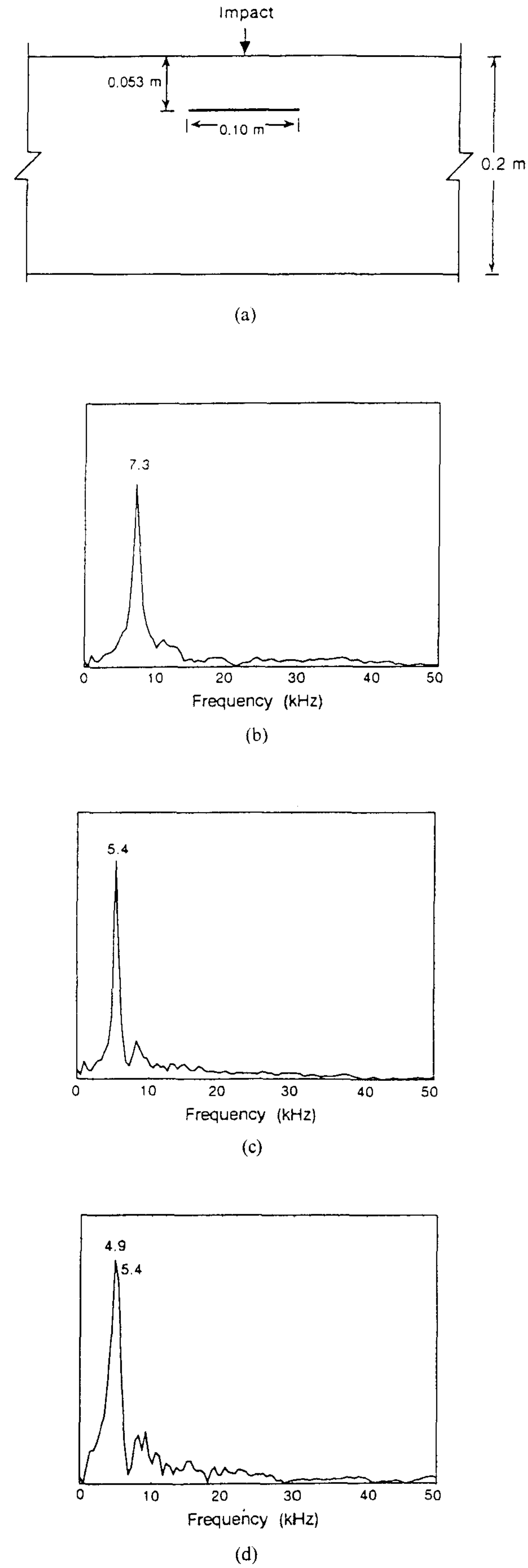
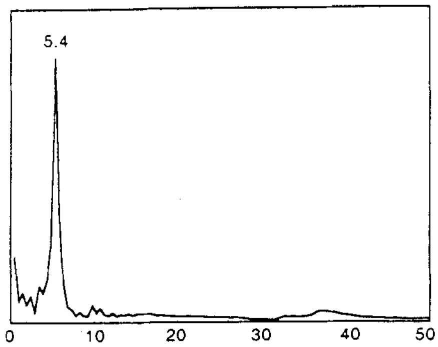


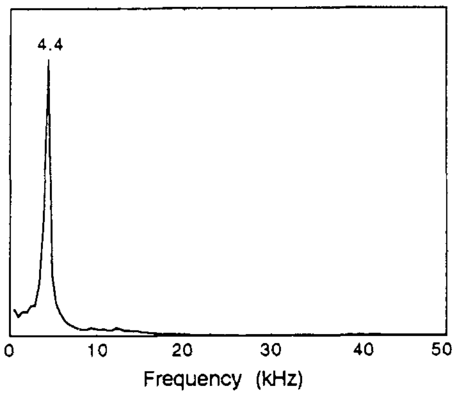
Fig. 6 Spectra obtained from plates with shallow (0.05 m deep) rectangular delaminations having dimensions of (b) 0.1 m × 0.1 m, (c) 0.1 m × 0.3 m, (d) 0.1 m × 0.9 m where the specimen cross-section is as shown in (a).

delamination increase, the section of plate above the delamination becomes more flexible, and thus the frequency of the flexural vibration shifts to a lower value – 5.4 kHz for the 0.1 m × 0.3 m case. As the long dimension of the delamination becomes larger, the shift in frequency gradually diminishes and levels off. In this example, as the long dimension increases from 0.3 to 0.9 m there is only a slight decrease in the frequency, as shown in Fig. 6c. In the 0.1 m × 0.9 m case, the peak frequency occurs at 4.9 to 5.4 kHz. Another example of this decrease in stiffness is seen by comparing the 0.1 m × 0.9 m case with the 0.14 m × 0.9 m example shown previously in Fig. 4b. In this comparison the short dimension increases from 0.1 to 0.14 m, and the fundamental flexural frequency occurred at 3.4 instead of 4.9 kHz.

As the depth of a delamination decreases, the section above the delamination becomes more flexible, and again



(a)



(b)

Fig. 7 Spectra obtained from plates with square (0.15 m × 0.15 m) delaminations having depths of (a) 0.05 m, (b) 0.025 m.

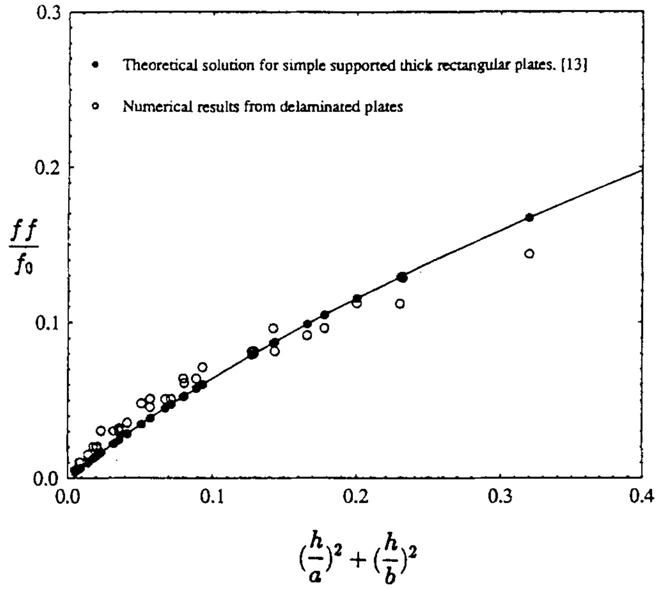


Fig. 8 Plot showing flexural frequencies obtained from numerical analyses of plates containing delaminations and from the theoretical solution of Mindlin *et al.* [13] for the flexural vibration of simply-supported, rectangular plates.

the frequency of the fundamental flexural mode will shift to a lower value. The 'hollow' sound one hears when impacting over a shallow delamination is accentuated (the frequency becomes lower and has a higher amplitude) as the depth of the delamination decreases. Figs. 7a and b show the spectra obtained from numerical analyses of a model where impact was applied over the centre of a 0.15 m × 0.15 m delamination located at depths of 0.05 and 0.0254 m, respectively. The fundamental flexural frequency shifts from 5.4 to 4.4 kHz as the depth decreases from 0.05 to 0.0254 m.

Many numerical analyses were carried out as part of this study of the impact-echo response of delaminated plates. No theoretical solutions exist for the response of plates containing delaminations; however, the results of the numerical analyses were compared with the theoretical solution for the vibrations of a thick rectangular plate with simple supports on all four edges [13]. The following paragraphs summarize the key results of this study.

It was found that four parameters affect the fundamental flexural frequency of rectangular delaminations in plates. These parameters include the two lateral dimensions of the rectangular delamination (a and b), the depth of delamination (h), and the material properties of the plate which can be best expressed in terms of the shear-wave speed in the material. The first three parameters are related to the geometry of the delamination and the fourth one is a function of the elastic constants (modulus of elasticity and Poisson's ratio) and density of the concrete. Numerical models with delaminations having shorter dimensions ranging from 0.15 to 0.6 m and aspect ratios (long to short lateral dimension) ranging from 1 to 3 were studied. The depth of each delamination was varied from 0.025 to 0.08 m. The elastic constants of the plate were also varied to represent a range of different concretes.

The results of all of these analyses are shown as open circles in the plot shown in Fig. 8. The results are expressed in terms of the fundamental frequency (ff) normalized by dividing by f_0, which is the ratio of shear-wave speed (C_s) divided by the depth (h) of the delamination, versus a geometric parameter, λ, which is equal to $[(h/a)^2 + (h/b)^2]$. This particular representation of the results was chosen to facilitate comparison with an existing theoretical solution for the flexural vibration of thick plates with simply supported edges [13]. The relevant equations for the theoretical solution are given in the Appendix. Results obtained for various plate geometries and material properties are shown as filled circles in Fig. 8.

The comparison of the numerical and theoretical results shows that the fundamental frequency of a shallow delaminated section in a plate is slightly higher than the flexural frequency calculated using the theoretical solution for the corresponding plate. This result is expected, given that the boundaries of the delaminated section are more rigid than the simply-supported condition in the theoretical solution. The numerical results parallel the theoretical results for λ less than about

0.13. However, as λ increases (which means the thickness of delamination increases), the numerical results obtained for delaminated plates begin to diverge from the theoretical solution. That is, the numerical result gives a frequency that is much less than the theoretical solution for a plate. This is because the frequency of the flexural vibration does not continue to increase as the depth of the delamination increases, and in fact, the behaviour of thicker delaminated sections is no longer accurately modelled by the concept of flexural vibrations in a plate.

As delaminations become deeper than about 0.08 m, the frequency peak corresponding to reflections between the top plate surface and the top surface of the delamination are distinct and easy to identify (recall Fig. 3). The peak(s) in the spectrum corresponding to the flexural vibrations no longer completely dominate the spectrum, and the depth of a delamination can be easily determined using Equation 1. Eventually as the depth of a delamination increases, the cracked section above the delamination becomes too stiff and flexural vibrations are not excited.

The numerical results are valid for delaminations with lateral dimensions in the range of $0.15\,m \leq a$ or $b \leq 0.6$ m. When the lateral dimensions of a delamination are larger than 0.6 m, the fundamental flexural frequency is very low and difficult to determine accurately. In addition, if the larger lateral dimension of the delamination is less than 0.15 m, displacements caused by reflections from waves which propagate around the flaw and reflect from the bottom surface of the plate are superimposed upon the displacements caused by the flexural vibration of the delaminated section. The observed frequency peak(s) in the amplitude spectrum are a result of both of these effects and are thus dependent upon the thickness of the plate. The results of the numerical analyses also showed that as the lateral dimensions of rectangular delaminations increase beyond an aspect ratio of about 3 (long dimension/short dimension), the frequency of the flexural vibrations does not change significantly. This effect of lateral dimensions can be explained by the theoretical solution. As shown in Equation 4 of the Appendix, if either a or b is large, the geometric parameter λ becomes mainly a function of the smaller dimension. An example of this was shown by the results presented in Fig. 6 where λ decreased by 44% as the aspect ratio increased from 1 to 3, but only decreased another 10% as the aspect ratio further increased to 9. Because the fundamental frequency is related to the square root of λ, there is only a very small change in the corresponding fundamental frequency for the latter case.

In real structures, delaminations are not often well-defined geometric shapes such as rectangles, squares or circles. However, the knowledge gained from these numerical and laboratory studies has provided a much greater understanding of the impact-echo response of delaminated plates, and it has made interpretation of field results from actual concrete structures easier. This understanding has also allowed the interpretation of field results obtained from plate-like structures containing delaminations to be automated using an artificial intelligence technique called a neural network [4,9,14]. In the following section, results obtained from a concrete bridge deck are discussed.

4. FIELD STUDY ON A BRIDGE DECK

With the development of portable and rapid impact-echo field instrumentation and signal analysis software in the early 1990s [9,14], it is now feasible to test large concrete structures. During 1991, a series of field studies on concrete bridge decks was carried out by the authors in conjunction with the New York State Department of Transportation (NYSDOT). In these studies, the authors performed impact-echo testing and presented a summary of their results to NYSDOT engineers. The engineers then used destructive (coring) and non-destructive (sounding) methods to verify the impact-echo results. In the following paragraphs results from one field study are presented. Typical results obtained from solid and delaminated sections of 0.22 m thick, concrete bridge deck are shown, as well as a summary of all the results obtained from one 6.7 m wide lane of a 58 m long deck.

The bridge was a two-span composite highway structure consisting of a 0.22 m thick concrete deck poured on a metal pan form and supported by steel beams. The steel reinforcing bars were 13 mm in diameter, and the cover over the bars was approximately 50 mm. Bars were placed in two layers in both directions and were spaced about 0.45 m in the transverse direction and 1.2 m in the longitudinal direction. At the time this study was performed the bridge was 19 years old, and sections of the deck were known to contain delaminations at the top layer of reinforcing steel.

The P-wave speed in the concrete was calculated based on the deck thickness specified in the design drawings and impact-echo results obtained from tests performed over solid sections of the bridge deck. Prior to performing initial impact-echo tests, the P-wave speed was estimated and a thickness frequency calculated. Subsequently, tests were performed until the solid response was identified. Then the measured thickness frequency was used to calculate an accurate P-wave speed using Equation 1. Fig. 9 shows a typical waveform and amplitude spectrum obtained from a test over a solid section of the deck. The waveform shows the periodic displacements caused by the multiple P-wave reflections through the thickness of the plate, and the spectrum exhibits a single dominant peak at a frequency corresponding to these P-wave reflections (recall Fig. 1). The thickness frequency at 8.3 kHz gives a calculated P-wave speed, $C_p = 2(0.22\ \mathrm{m} \times 8300\ \mathrm{Hz}) = 3650\ \mathrm{m\ s^{-1}}$. (Cores drilled later verified the specified thickness of the deck.)

For comparison, Fig. 10 shows two impact-echo responses obtained from delaminated areas of the deck. Fig. 10a was obtained near the middle of a large delamination. The waveform exhibits a very large-amplitude flexural frequency with much

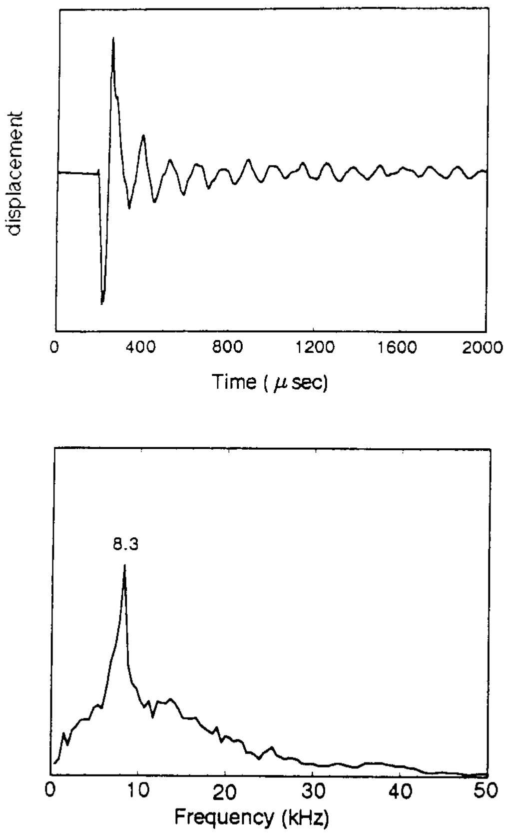


Fig. 9 Waveform and spectrum obtained from solid section of a concrete bridge deck.

smaller-amplitude higher-frequency oscillations superimposed on the very large lower-frequency flexural oscillations. The spectrum exhibits one large-amplitude peak at 3.9 kHz which corresponds to the fundamental flexural mode of vibration. The flexural vibration is very large relative to reflections from the delamination; thus the frequency response produced by reflections from the delamination (expected at about 36 kHz) is not noticeable. Fig. 10b shows a waveform and spectrum obtained near the edge of the delamination. The amplitude of displacements in the waveform is much less than in the previous case, and as expected, the spectrum shows multiple lower-frequency peaks (less than 8.3 kHz thickness frequency) which are produced by the fundamental and higher flexural modes of vibration and a somewhat lower-amplitude peak at a value shifted just below the solid thickness frequency of the plate.

In a final series of tests on this bridge deck, a 0.9 m × 0.9 m test grid was marked out along one lane of the deck. An impact-echo test was performed at each grid point. It took approximately 1.5 h to perform all the tests. Delaminated areas of the lane are shown in Fig. 11. NYSDOT engineers independently sounded the same lane of the bridge deck using a hammer, and they also marked areas of delamination. A comparison of the sounding results with the impact-echo results is shown in Fig. 12. The agreement is excellent.

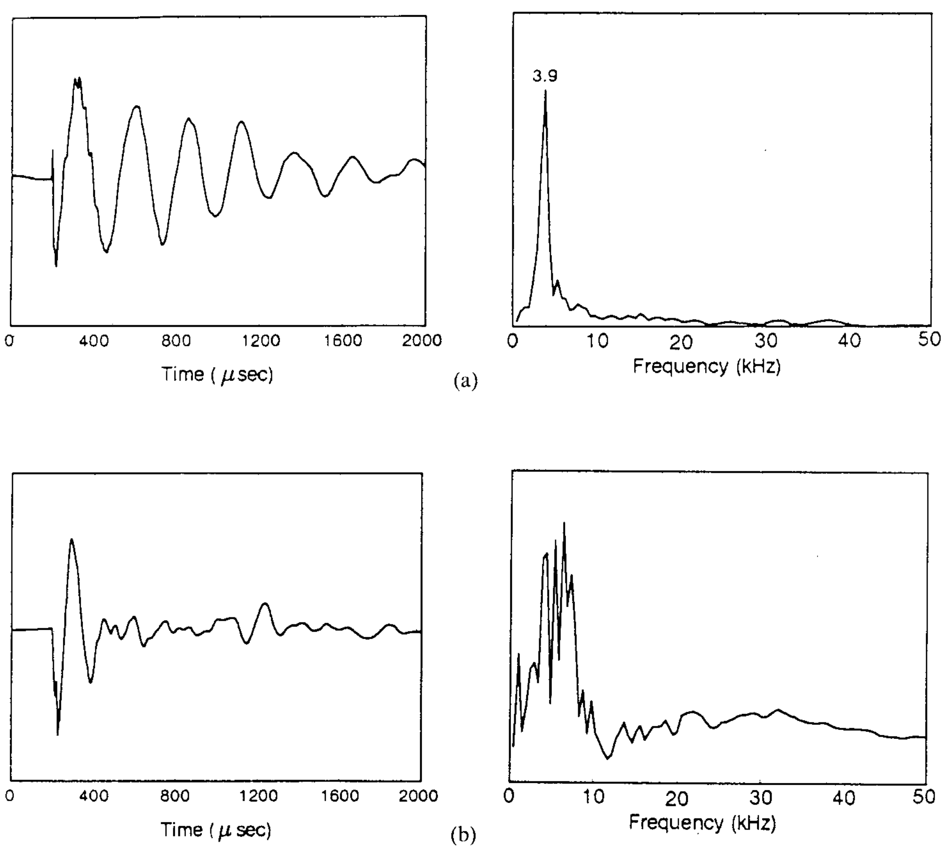


Fig. 10 Waveforms and spectra obtained from delamination sections of a concrete bridge deck: (a) impact at centre of delamination, (b) impact near edge of delamination.

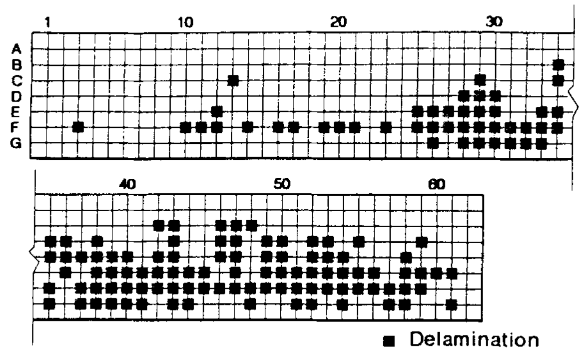


Fig. 11 Summary of impact-echo results showing locations of delaminations as obtained from a series of tests carried out on a 0.9 m × 0.9 m grid across one lane of a bridge deck.

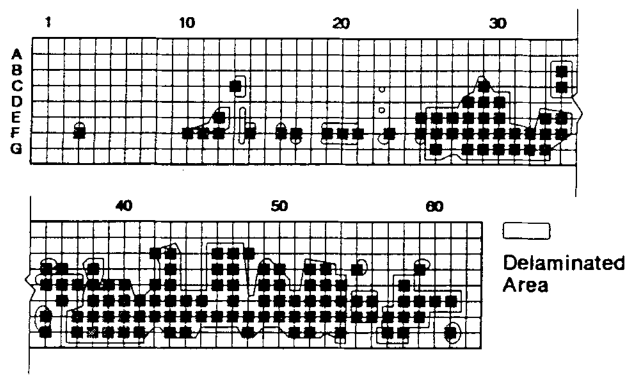


Fig. 12 Comparison of impact-echo results from bridge deck with locations of shallow delaminations as obtained by sounding.

A valid question which may be asked after seeing this comparison is: 'Why use the more complicated impact-echo method on a concrete bridge deck, if sounding gives the same results?' The series of field studies carried out with the NYSDOT showed the following: (i) impact-echo measurements are not affected by traffic noise while sounding is difficult in heavy traffic areas; (ii) the impact-echo techniques can detect deep delaminations while sounding can only be used to detect shallow delaminations; (iii) the results do not depend on the subjective interpretation of the operator; and (iv) the impact-echo field test system is faster than sounding.

5. CONCLUSIONS

It has been shown that the impact response of concrete plates containing shallow cracks or delaminations is fundamentally different from the response obtained from plates containing deeper cracks, because the waves generated by the impact excite one or more flexural modes of vibration of the concrete section above the shallow delamination. Numerical models and laboratory specimens containing flaws at known locations were used to explain and quantify the response of plates with shallow delaminations. The impact response of plates containing delaminations was shown to depend upon the depth of the delamination, the lateral dimensions of the delamination, the location of the impact point over the delamination, and the elastic properties of the concrete. Field studies on a concrete bridge deck containing shallow delaminations were used to confirm the results of the numerical and laboratory studies.

Although real delaminations are generally not well-defined geometric shapes, the knowledge gained from the numerical and laboratory studies summarized in this paper has provided a much greater understanding of the impact-echo response of delaminated plates, and it has made interpretation of field results from concrete plate-like structures, such as the bridge deck discussed in this paper, easier. This understanding also made possible the use of artificial intelligence techniques to automate the interpretation of results obtained from plates containing delaminations.

This study has been part of an ongoing research programme aimed at developing the theoretical and experimental basis for the impact-echo technique for non-destructive testing of concrete structures. Begun in 1983, the work has led to the development of the impact-echo technique for testing plates, beams and columns [15], and most recently, hollow cylindrical structures such as pipes [16]. The work discussed in this paper forms the second phase of a three-year study aimed at understanding impact-echo signals from reinforced concrete plates containing delaminations. The first phase involved studying the interaction of stress waves and reinforcing bars in concrete [17] and determining the effects on impact-echo signals as cracks form and propagate to form delaminations. The third phase has as its goal determining the minimum crack width (crack-opening displacement) in concrete that will cause reflection of stress waves generated by impact. Detailed results of this study which involved numerical and experimental fracture and wave propagation studies will be published in a subsequent paper. It is worth mentioning here, however, that a crack with a width of about 0.1 mm or larger will not transmit stress waves generated by short-duration impacts and the response of the crack section will be as described in this paper. Together the three phases of this work form the essence of the first author's PhD thesis research.

APPENDIX

The theoretical fundamental flexural frequency of a simply supported rectangular thick concrete plate is given [13] by

$$ff = f_1 \times f_0 \tag{2}$$

$$f_0 = \frac{C_s}{h} \tag{3}$$

$$f_1 = \frac{1}{2}\left(\frac{1 + 3.36\lambda - \Omega}{2}\right)^{1/2} \tag{4}$$

$$\lambda = \left(\frac{h}{a}\right)^2 + \left(\frac{h}{b}\right)^2 \tag{5}$$

$$\Omega = [(1 + 3.36\lambda)^2 - 8.6\lambda^2]^{1/2} \qquad (6)$$

where ff = fundamental flexural frequency, a, b = lateral dimensions of the thick plate, h = thickness of the plate and C_s = shear-wave speed of concrete. The value for Poisson's ratio, ν, and κ^2 in the theoretical analysis were $\nu = 0.2$ and $\kappa^2 = 0.86$ [18]; κ^2 is used in the calculation of Ω.

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RESUME

Réponse impact-écho de plaques de béton présentant des clivages: études numérique, expérimentale et *in situ*

On décrit ici l'utilisation de la technique impact-écho – méthode d'essai non destructive basée sur l'utilisation d'ondes de pression acoustique transitoires – pour détecter les clivages dans des plaques de béton, telles que tabliers de pont, poutres et murs. On présente les résultats fournis par les méthodes numériques (élément fini) et l'étude en laboratoire sur éprouvette fissurée témoin, qui sont utilisées pour expliquer la réponse élastique à l'impact des plaques détériorées. On décrit l'appareillage courant et l'on expose les résultats obtenus sur des tabliers de ponts en béton qui présentent des clivages dus à la corrosion de l'armature. Ces résultats contribuent à mieux faire comprendre la réponse à l'impact de plaques détériorées.