SONIC/ULTRASONIC MEASUREMENTS FOR BRIDGE DECK EVALUATIONS

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ABSTRACT

NDT Engineering, Inc and the Massachusetts Highway Department developed an automated sonic/ultrasonic bridge deck evaluation system for evaluating the condition of bridge decks with and without wearing surfaces. This system makes nondestructive measurements to determine the mechanical properties of concrete by measuring (at the surface) the compressional and shear wave velocities of a transmitted stress wave generated by a projectile impact energy source. The deck slab in the thickness direction is evaluated using continuous reflected (resonant frequency) compressional waves. These measurements determine the presence of vertical cracking as well as major and minor delamination. In addition, the seriousness of the delamination or vertical cracking is evaluated further by measuring the average deck concrete strengths through a developed empirical relationship between the measured stress wave compressional and shear wave velocity values and the concrete unconfined compressive strength. In addition to the empirical strengths, the velocity values are used to calculate the moduli values, Young's, bulk and shear as well as Poisson's Ratio.

Several bridge deck testing projects are presented where the sonic/ultrasonic testing system was used and the results were successfully compared with known flaws or post survey repairs. The comparison indicates that the sonic/ultrasonic testing will detect cracking, vertical or horizontal (partial or full deck) and delamination that are not visible and detected by traditional inspection methods.

INTRODUCTION

Sonic/ultrasonic testing is the most definitive NDT testing technique for the assessment of concrete. These nondestructive measurements determine the mechanical properties of concrete by measuring (at the surface) the compressional and shear wave velocities of a transmitted stress wave generated by a projectile impact energy source. The deck slab in the thickness direction is evaluated using continuous reflected (resonant frequency) compressional waves.

The concrete strength characteristic and localized anomalous conditions are determined by direct compressional and shear wave velocity measurements. The transmission velocity values determine the elastic deformational characteristics of the concrete, including Young's, bulk, and shear moduli, as well as Poisson's ratio, and provide information to calculate strength values. High compressional and shear wave velocity values are associated with massive, unfractured, high strength concrete. The sonic/ultrasonic wave velocities are affected by cracking at both the micro and macro level, and therefore become a predictor of future deterioration because microcracks under continual loading-unloading and freezing- thawing coalesce to form macro cracks and finally delamination and spalls. Continuous reflected signals set up a resonance at a frequency that is related to the concrete thickness and compressional velocity which allow an assessment of the concrete in the thickness direction and identification of delamination.

The testing presented was done with an automated “roll along” bridge deck testing device (ATD) developed under contract to the Massachusetts Highway Department. This system uses a projectile impact energy source and an “L” shaped array of 4 sensors mounted on wheels so that the whole system can roll along acquiring data at one-foot intervals. At each energy input position, this device measures along a 2.5 foot line transverse to the bridge axis and simultaneously along a line 1.3 foot long in the axial direction covering a rectangular area 3.25 sq. ft. Measurements are at 1 foot along the bridge axis so that there is overlap of the area covered.

SONIC/ULTRASONIC WAVE MEASUREMENTS

The sonic/ultrasonic measurements are made using systems designed and built by NDT Engineering specifically for testing concrete. These systems are comprised of an energy source, a linear array of sensors, signal conditioning (amplification and filtering) analog to digital conversion and a P.C. to archive and display data and provide quality assurance.

The sonic/ultrasonic measurements made to determine the integrity and engineering characteristics of concrete are generated by a single, wide band, impulse projectile energy source. This energy source is effective on bare concrete, as well as concrete covered by asphalt wearing surfaces. This source has a wide band response that is sufficient to maximize the resolution, have sufficient penetration to examine the concrete being tested and excite the fundamental frequencies being sought.

The transmitted energy is in the form of three principal wave types, compressional (contraction and expansion particle motion), shear (transverse motion), and surface waves. Each boundary that has a density and or velocity contrast will reflect and/or refract these waves; the compressional and shear waves velocity values determine the Young's, shear, and bulk moduli values as well as the density and Poisson's Ratio of the materials being tested. In turn, the velocity values can be used to calculate the moduli values and Poisson's Ratio given that a reasonable estimate of the density is known. The moduli values measured are the dynamic moduli values at low strain. In general, the difference between the dynamic values and the static values is almost entirely controlled by the crack density of the concrete and the orientation of the cracks. Strength determined with sample cracks perpendicular to the axis of the core will not differ greatly from uncracked concrete in static compressive testing. Whereas cracking at 45 degrees to the axis will produce a much lower static strength. Crack densities can be determined by comparing the uncracked to the in-situ condition of the concrete; crack orientation can be determined by measurements in different directions.

The measurements made by NDT Engineering to assess concrete involve multi-measurements from the same test points; the velocity is measured directly from the energy point of impact to a linear array(s) of sensors spaced at distances that are in excess of the thickness of the concrete being tested; reflectors are measured individually or more often by examining the resonant frequency content of the time domain recordings. Each reflecting surface produces a multi-path reflection in the layer it bounds. For example, the generated wave will travel to a delaminated surface and then reflect back to the surface of the concrete in multi-reflections. These become apparent in the frequency domain where processing enhances their presence (along with higher modes). These reverberations (echoes) are particularly diagnostic of delaminations, cracked concrete, and decomposed inclusions, voids, etc. by the particular frequency band generated by the mechanical discontinuity. In addition, where severe damage has occurred, there is a drum head (low frequency) effect due to near total delamination in the host material which causes resonance in a relatively narrow band usually in the human hearing range; however, the resulting amplitude may or may not allow the resonance to be heard without amplification. This is the basis of the "chain drag" sounding using the human ear to recognize frequency differences; the ear is limited in its perception and will distinguish only those situations in the hearing range which constitutes a relatively small population of the potential problems.

One of the advantages of the sonic/ultrasonic method is its ability to "look through" overlying coatings or wearing surfaces. This is done using refracted wave measurements and resonant frequency analysis. A critically refracted wave for an asphalt overlay on concrete travels through layer 1 as a direct wave and at a distance dependent on layer 1 thickness and velocity, the wave is refracted because the velocity of the concrete is higher than that of the asphalt. The wave is bent (similar to the appearance of a stick in water) toward, and travels along the boundary between the asphalt and the concrete. The higher velocity of the concrete assures that the refracted wave (2) will overtake the direct wave (1) at some critical distance designated as X_c. Further away from the source than X_c, the refracted wave in the concrete will constitute a first time arrival and the velocity measured between the sensors for this refracted wave is the true velocity of the concrete.

The measured travel time for the critical refraction (which divided into the distance is the velocity) is given by:

$$T = \frac{1}{V_2}\left(X_c - 2Z \tan q \right) + \frac{1}{V_1}\frac{2Z}{\cos q}$$

where Z is the thickness, X_c is the horizontal distance after which the refracted arrivals become the first arrivals, ∅ is the incident angle controlled by Snell's law ($\sin\varnothing = V_1/V_2$), and V is the velocity of the material. If there is no overlay then the velocity is simply the distance divided by the time.

Resonant Frequency / Reflections

The resonant frequencies, which are repeated reflections (echoes), are determined by the thickness and the velocity of the material. Since the velocity is measured as described above then the thickness can be determined directly. The resonance of a simple beam is given by:

$$f = \frac{nV}{2}Z$$

for a free-free or fixed-fixed condition, n = 1,2,3,4-

$$f = \frac{nV}{4}Z$$

for a fixed-free beam, n = 1,3,5,7-----

Where f is the frequency, n is the mode, V is the velocity and Z is the thickness. For more than one

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

layer the reciprocal frequency of the composite is the additive reciprocals of the individual layers. Since the frequency and velocity are measured, the thickness can be determined. This thickness can be the thickness of the concrete slab, floor, deck, etc., being measured or it can be the thickness of material overlying a delamination. The computation of the dimensions of an included body, cracked and deteriorated concrete or delamination can be determined in a similar fashion from the measured frequency and velocity.

Refracted waves are dependent only on a contrast in velocity, while a reflection can take place where there is a change in velocity or density or both. The impedance, which causes a wave to be reflected, is given by:

$$I = \frac{r_2V_2 - r_1V_1}{r_2V_2 + r_1V_1}$$

where p is the density and V is the velocity of the top or underlying material. This impedance determines the strength of the reflector. The contrast between an air filled void at the back of or within, the concrete is significant, the velocity in air is 1,000 ft/sec and the velocity in concrete is 13,000 ft/sec. The density difference is very large. The same difference exists for a water filled void where the velocity in water is 5,000 ft/sec and concrete is nearly 2.5 times denser. Voiding behind a liner or under a slab is usually well distinguished by a distinct resonant frequency.

Moduli Values and Strength

The moduli values as stated above are determined from the velocity values using an assumed or measured density. The density is usually the best known or best-estimated value for the concrete; its variance generally does not affect the calculations significantly. Damage need not be visible to affect velocity measurements and strength calculations; there can be a 20% reduction in strength of the concrete from micro cracking that is below the visual level with the naked eye. In fact the process of deterioration of most concrete starts at the micro level and with continued stress the micro cracks coalesce into macro cracks and finally to major (visible) cracking and spalling. The ability to measure at the micro level well in advance of future needed repair provides a management tool for establishing priorities for different structures as well as the repairs needed for an individual structure.

CASE STUDIES

To evaluate the effectiveness of the sonic/ultrasonic nondestructive testing method to assess internal bridge deck conditions on bare concrete decks and decks with asphalt wearing surfaces, data were acquired on several bridges that were to be cored or repaired. Below is a discussion of the results for bridges that comparison data were obtained from cores or repairs.

I-95 over Union Street Norwood, MA MHD Bridge # N-25-28 Southbound

Sonic/ultrasonic nondestructive testing data were acquired on the center lane, which was blocked from traffic by Jersey Barriers. The bridge is a three span 107 foot long steel stringer bridge with an 8 inch thick reinforced concrete deck and a 2 to 3 inch thick asphalt wearing surface. Four parallel lines of NDT data were acquired for 100% NDT survey coverage of the area.

NDT survey results obtained through the asphalt-wearing surface identified upper deck deterioration/ partial deck repairs in all the areas subsequently repaired. Repair areas were identified by traditional chain dragging methods after the asphalt wearing surface was removed. NDT results identified approximately 242 square feet for partial deck repair and 12.5 square feet of debonded asphalt (no penetration and result for concrete). Approximately 200 square feet of the area tested was partial deck repaired. Three areas identified by sonic/ultrasonic results with fracturing but not repaired (based on traditional chain dragging inspection) were partial deck excavated to further evaluate the NDT results. Visual inspection of the excavation indicate no delamination at the upper rebar set, however an inspection of the bottom of deck prior to excavation and after a heavy rain indicated water seeping through vertical crack at these locations. It is concluded that the sonic/ultrasonic data had identified areas of full deck vertical cracking .

Pell Bridge, Newport, Rhode Island for Parsons Brinkerhoff

Nondestructive sonic/ultrasonic-testing was performed to evaluate the condition of the bare concrete bridge deck and identify areas of cracked and decomposed deck concrete. Approximately 8,238 linear feet on the EBL and 9,520 linear feet on the WBL of sonic/ultrasonic data were acquired on two survey lines in the right hand travel lanes. The testing was done with an automated “roll along” bridge deck testing device (ATD) developed under contract to the Massachusetts Highway Department. At each energy input position, this device measures along a 2.5 foot line transverse to the bridge axis and simultaneously along a line 1.3 foot long in the axial direction effectively covering a rectangular area 3.25 sq ft. Measurement intervals are at 1 foot along the bridge axis so that there is overlap of the rectangular area covered. The nondestructive data were acquired along a line (axial) of near the center of the east and westbound slow speed lanes. The results of this investigation were used to classify the bridge deck concrete conditions into five categories:

1) Good, 3000 + psi with no significant cracking, vertical or horizontal (delamination) or decomposition;
2) Delaminations at the upper rebar level;
3) Delamination and or fracturing at the lower rebar level;
4) Low average strength concrete associated with visible cracks and patches;
5) Micro cracked (not visible to naked eye) weakened surface.

Areas of the bridge characterized as Category 1 have compressional and shear wave velocity values of 13,000+ ft/sec and shear wave velocity values of 6,500+ ft/sec and a resonant frequency in the range of 7.5 to 10 kHz. The compressional wave velocity of 13,500 ft/sec with a shear wave velocity of 6,500 ft/sec equates to 4,000-psi concrete with little fracturing and deterioration. The 7.5 to 10 kHz resonant frequencies equate to a full deck resonance of 7 to 10 inches (compressional wave velocity of 13,000ft/sec.). Survey lines located over the support beams where the concrete thickness is 10 inches are distinguished from the 7inch-slab thickness by a lower resonant frequency

Category 2 locations have compressional and shear wave velocity values similar to category 1 with resonant frequency values of 17 to 20 kHz and no well defined full deck resonance (7 to 10 kHz). The 17 to 20kHz frequencies are indicative of delamination at a depth of approximately 4 to 4.5 inches (upper part of deck concrete). For the most part category 2 are single events and considered minor delamination. Category 2 condition was detected on consecutive measurements generally confined to axial distances of 3 to 5 feet (or less) indicating that delamination is not occurring over large areas.

Category 3 are locations with compressional and shear wave velocity values similar to category 1 but resonant frequency values of 13 to 17 kHz. The 13 to 17 kHz frequencies indicates a delamination at a depth no shallower then 5 to 6 inches (approximate depth of the lower reinforcing set).

Category 4 is locations of visible transverse cracks or patched areas with low compressional and shear wave velocities and no well-defined resonant frequencies. These results indicate significant horizontal and vertical cracking. Many of the locations in category 4 are previous patches. These measurements indicate that the patches have mechanical properties much different from the host concrete or that they may not be well bonded due to micro cracking at the patch edge as a result of jack hammering associated with repairing.

The sonic/ultrasonic data for Category 5 are similar to Category 4 except there is no visible cracking, patching. It is believed that these locations have a high concentration of near surface vertical and horizontal micro cracks with high potential for future damage.

Several locations where NDT results indicate category 2 conditions were cored and delamination detected. The survey results demonstrated the effectiveness of sonic/ultrasonic testing to isolate and identify very specific locations and types of deck deterioration. Areas where the shear velocity value drops to zero are indicative of vertical cracks with no shear strength across their boundaries under normal loads. These cracks can provide avenues for water permeation into the concrete with the potential for deterioration.

Federal Highway Administration Deck Pads

As part of a test of the sonic/ultrasonic technique, twelve pads at the Federal Highway Administration facility in McLean, Virginia were tested by nondestructive sonic/ultrasonic measurements. The purpose of the testing was to determine the variation in data quality as well as the ability of the method to identify the condition of the pads. Seven of the pads were bare concrete and five were asphalt covered. Ten of the pads were cut from existing bridges and transported to the facility; two pads were poured at the facility.

The pads are generally 11 to 12 feet long and about 6 feet wide; this is too small for the use of the automated device. A 2.5 foot linear array of sensors was used which reasonably represents the automated device. Data were acquired in the longitudinal and transverse directions along a one-foot grid with this array.

The results from the nondestructive testing identified the internal conditions of both the bare and asphalt covered concrete pads. The bare decks results are higher resolution and easier to evaluate. The presence of asphalt lowers the effective frequency band and amplitude of the outgoing signal because it absorbs more energy being a less rigid material than concrete.

SUMMARY

Sonic/ultrasonic nondestructive testing provides an accurate detailed assessment of internal bridge deck concrete conditions as well as a direct measurement of the in-situ strength condition of the bridge deck concrete. High quality data are acquired efficiently on bridges with and without wearing surface, with no special conditions or preparation, under normal traffic conditions with traffic control. Comparison of sonic/ultrasonic results to coring and repair results indicate that sonic/ultrasonic results identify vertical cracking and incipient delamination that would be missed by traditional chain dragging, hammer tapping, or visual inspections as well as more severe delamination and deterioration conditions that are identified by traditional methods.

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