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Measuring thickness in concrete plates

ABSTRACT

Determining the thickness of concrete plates by an analysis of the interference of transmitted and reflected longitudinal waves. Stationary vibration variant of the testing method and the impact-echo method. The use of the phase velocity method for the assessing of material properties and for checking geometric characteristics. The application of the method during tests of a floor structure made from steel fibre reinforced concrete in an industrial enterprise.

1. INTRODUCTION

Concrete floors are subjected to considerable load actions in industrial enterprises. Requirements for the serviceability, especially on deflections, result from the production process. Demands on the properties of the floor structure increase proportionate to the significance of the trouble-free service. Consequently, interest is focused on checking the quality.

One of the essential conditions of the proper manufacturing of a plate is to maintain the thickness. The unevenness of the subgrade and the concrete surface is prescribed in the technical standards or required by the users. To achieve the designed mechanical properties is equally important for floor structures, where progressive materials, such as fibre-reinforced concrete or self-compacting concrete, are applied. Determining the geometric and mechanical characteristics of floor structures is an actual task nowadays. It is evident that destructive methods could be used only to a limited extent. The taking of cores is time-consuming and expensive, and it impairs the integrity of the structure. Non-destructive testing techniques seem to be most appropriate for solving this problem.

An overview of suitable methods, their advantages and a mutual comparison is presented below. The application of a dynamic diagnostic technique for testing the floor structure in a machine industry enterprise is described.

2. PRINCIPLE OF THE METHODS

An analysis of mechanical vibration could be used advantageously for the measuring of thickness in floor structures. Longitudinal, distortional and surface (Rayleigh) waves propagate from a vibrator acting on the accessible surface of the plate (Fig. 1). It is useful,
therefore, to locate the receiver close to the place, where the sinusoidal harmonic vibration is excited. The amplitudes of longitudinal waves are then much greater than those of the distortional waves.

If the spherical wavefronts reach the boundary between the concrete and the subgrade, which is characterized by a change in the density, they are reflected back to the free surface. Interference between the transmitted and reflected waves occurs in the structure. The change in the exciting frequency will affect the amplitudes of the measured displacement. If the subgrade exhibits a lower density than the material of the floor, the standing wave motion will arise, and hence the maximum amplitude will be reached when the wavelength \( \lambda \) will be twice the thickness \( h \) of the plate. At the known velocity of the longitudinal waves \( c_L \) (m.s\(^{-1}\)), the thickness could be calculated according to the expression

\[
H = \frac{c_L \cdot T}{2} = \frac{c_L}{2f} \quad (m)
\]

where \( T (s) \) is the time period of the vibration and \( f \) (Hz) is its frequency. With regard to the dimensions of the plate perpendicular to the direction of the wave motion in comparison with the wavelength, we can qualify the medium as three-dimensional, and the velocity could be then expressed as

\[
c_{L1} = c_L \sqrt{\frac{1-v}{1+2v(1-2v)}} \quad (ms^{-1})
\]

where \( c_{L1} \) is the velocity of the longitudinal waves in a one-dimensional medium and \( v \) (-) is the dynamic coefficient of the lateral strain. The velocity \( c_{L1} \) could be expressed again by the means of the elasticity modulus of the material of the plate in compression and tension \( E \) (Pa) and density \( \rho \) (kg.m\(^{-3}\)) in the form

\[
c_{L1} = \frac{E}{\sqrt{\rho}} \quad (ms^{-1})
\]

The described technique of testing is based on stationary exciting vibration. Similarly, pulse methods could be used, described, e.g., in (Carino and Sansalone, 1992), (Moczko, A. and Moczko, M., 2001) or (ASTM C 1383-98) and called the impact-echo method. The transient force (Fig. 2), caused by the mechanical impact (e.g., by tapping a steel ball), will produce a spectrum of vibrations with different frequencies. The propagated waves are reflected from the boundary, and their interference occurs. The displacement on the accessible surface is registered by the receiver, which is placed close to the impact point. If the density in the subgrade is smaller than in the concrete, the maximum amplitude will correspond again to the vibration with a wavelength equal to twice the thickness of the plate. The dependence of the amplitudes on the frequencies could be received by the fast Fourier transformation (FFT) of the time course of the displacements. The thickness of the plate is expressed in the same way as with the stationary vibration variant of the method from Eq. (1).

![Fig. 1 Principle of the method using stationary vibration](image)

![Fig. 2 Principle of the impact-echo method](image)
(Martinček, 1975), (Martinček, 1983) and (Martinček, 1994) seems to be advantageous. Because both methods use the stationary excited vibration, they could be applied at the same installation of the measuring equipment. The PVM is based on measuring the velocity of flexural waves, by which the mechanical properties of the structure are characterised. The variant of PVM with a constant measuring basis and a varying exciting frequency (Martinček and Pokorný) is advantageous for the automation of measurements. A description of the testing technique and a procedure for evaluating the measurements is in (Pokorný, Gašparík and Jerga, 2000).

The equivalent thickness of the plate $h_{eq}$ received from the PVM could be used for the verification of the results according to Eq. (1). For isotropic plates the $h_{eq}$ corresponds to the thickness $h$ according to Eq. (1). The calculated parameter $c_{L1}$ together with the density of the material allow the assessment of the dynamic modulus of elasticity from Eq. (3). The dynamic stiffness of the unit strip of the plate could be calculated finally according to the expression

$$E I = \frac{c_{L1}^2 h_{eq}^3}{12 \rho}$$

where $I$ is the moment of inertia of the unit strip.

Another method for determining the vibration velocity of the material of the plate is the use of the ultrasonic pulse method. If the density is growing from the surface to the inside of the structure, we can determine the velocity of pulses at different depths by measuring the transit time from the transmitter to the various positions of the receiver on the surface of the plate.

The reinforcement in concrete also reflects mechanical waves, as reported for the impact-echo method in (Carino and Sansalone, 1992). Contrary to the usual boundary between concrete and the subgrade, the steel of the reinforcing bar has a greater density; and hence, the vibration will reflect with change of phase equal to one half of the time period $T$. The standing wave motion will arise at the frequency of the stationary exciting with maximum amplitudes on the free surface. While crossing through the whole depth of the plate (Fig. 3a), the vibration loops will occur on both surfaces and the node inside of the plate (if the subgrade has a lower density than the material of the plate); upon reflection from the steel, the vibration loop will be on the surface of the plate and the node on the surface of the reinforcing bar (Fig. 3b). The frequency $f_a$, when reflecting without the change in phase from the boundary between the plate and the subgrade, could be derived from Eq. (1) as

$$f_a = \frac{c_{L1}}{2h}$$

Upon the reflection from the steel reinforcement, the frequency $f_b$ of the standing wave motion could be expressed by the ratio

$$f_b = \frac{c_L}{4h}$$

The frequency $f_a$ upon the reflection from the bottom surface of the plate is therefore twice the frequency $f_b$ if the vibration is reflected from the steel bar at the same depth. The thickness of the layer from the surface of the plate up to the surface of the reinforcing bar is expressed by the equation

$$h = \frac{\lambda}{4}$$

where $\lambda$ is the wavelength.

3. IN SITU MEASUREMENTS

A non-destructive method for determining thickness by an analysis of the interference of the transmitted and reflected longitudinal waves using the stationary exciting was applied during tests of the floor plate structure from steel-fibre reinforced concrete in an industrial enterprise.

An ESE 211 electrodynamic vibrator modified for action into the body with an exciting frequency up to 25 kHz was used, as was the KD 41 piezo-electric accelerometer for measuring the mechanical vibration. A total of 197 thickness magnitudes were assessed. The concrete cores were drilled for determining the actual thickness and the velocity of the wave motion. This was also verified on the cylinders by using the USME 6 ultrasonic pulse testing apparatus with the exciting frequency equal to 46 kHz. The velocity $c_L$ equal to about 4500 m.s$^{-1}$ was used for calculating the thickness $h$ according to Eq. (1).

The histogram of the experimental plate’s thickness is plotted in Fig. 4. The minimum value is 173.1 mm and the maximum one 208.7 mm. The average is equal to 191.6 mm; the standard deviation is 7.45 mm; and the skewness is –0.3046. A probability density curve of three-parametric lognormal distribution was used for the
approximation of the experimental results. It was derived from the normal distribution of the function
\[ u = \ln|\bar{h} - h_0| \] (8)
where \( h_0 \) is equal to 266.8 mm.

As is evident from Eq. (1), the reliability of the results is affected by the accuracy of the frequency measurements, just as by the dispersion of the magnitude of the velocities of the longitudinal wave motion. This is dependent according to Eq. (2) and (3) on the dynamic coefficient of the lateral strain, on the modulus of elasticity and on the density of the material. The scattering of these parameters is affected by the technology of the manufacturing of the floor structure.

4. CONCLUSIONS

The experimental measurements confirmed the propriety of the method of determining thickness by use of the interference of transmitted and reflected longitudinal mechanical waves. It is convenient to apply the phase velocity method for setting the wave motion velocity when using a variant of the method with stationary exciting for determining thickness. The actual quality of the subgrade must be known for truthful interpretation of the measurements.

Some anomalies in the course of the frequencies could be caused by the reflection of waves from voids and reinforcing bars.

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