POSSIBILITIES OF NON-DESTRUCTIVE TESTING METHODS FOR MATERIAL PROPERTIES DETERMINATION

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Abstract

This article focuses on the possibilities of using the pulse-echo method for determining material characteristics of concrete in structures. The subject of the performed experiment is to verify whether it is possible to estimate the elastic modulus on structures accessible from only one side , where the commonly used through-transmission method cannot be applied, and to compare it with this method. Additionally, it verifies how much the results differ between general and precise values for each tested location.

Keywords

Modulus of elasticity, concrete, pulse-echo, non-destructive testing

1 INTRODUCTION

The ultrasonic testing method has been considered very reliable in material diagnostics for a relatively long time, capable of providing a wide range of important information in a non-destructive manner. It can determine dynamic elastic moduli, verify uniformity, and indicate the presence of defects. Typically, two probes are used - a transmitter and a receiver, between which the ultrasonic wave travels through the examined material. This method therefore requires a structure accessible from two sides. When a structure is exposed only from one side, the reflection method, or pulse-echo method, become an option. This method has already proven useful for detecting flaws and defects. However, replacing the through-transmission method with pulse-echo method, for example for estimating the elastic modulus in poorly accessible structures is still not very common.

During 2024, the construction of a certain bridge structure was underway. Already during the concreting process, doubts arose about the quality of the supplied concrete, and following subsequent expert assessment, a decision was made to completely demolish the structure already built. The structure was cut into several-ton segments, visible in Fig. 1 and removed. This created unique specimens for verifying the capabilities of pulse-echo testing on an actual structure with the possibility of collecting desired number of samples, as shown in Fig. 2.

Fig. 1 Segments on the dump.

Fig. 2 Core drilling samples from segment A.

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2 METHODOLOGY

Two instruments for structural diagnostics were used during the experiment - the Pundit 250 Array with a matrix probe, shown in Fig. 3, which is used for the pulse-echo method. This device has a total of 24 transducers/sensors that record shear waves travelling through the material. The second device was the Pundit PL-200 used for the through-transmission method. This device records longitudinal waves travelling through the material.

Fig. 3 Matrix probe of Pundit 250 Array.

Fig. 4 Sample during load testing.

A location for calibrating both instruments to simulate real measurements on a structure was first selected, i.e., a spot accessible from both sides. At this location, with a thickness of 0.75 m, the travel velocity of longitudinal waves and shear waves was determined from a total of 36 measurements. The average value was 4,475 ms^{-1} for the longitudinal wave v_p, and 2,388 ms^{-1}, for the shear wave v_s, the ratio of these values was 0.53. When the structure was inaccessible from the second side, this ratio could be estimated using formula (1) and an estimate of Poisson's ratio (μ). Using the common value for concrete of 0.2, the ratio would be 0.54 [1].

$$\frac{v_s}{v_p} = \sqrt{\frac{1-2\mu}{2(1+\mu)}} \tag{1}$$

$$\mu = \frac{1-2\frac{v_s^2}{v_p^2}}{2-2\frac{v_s^2}{v_p^2}} \tag{2}$$

$$E_{cu} = \rho v_p^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \tag{3}$$

The examined structure had a constant thickness of 0.75 m in all parts. Not all segments were easily accessible; those were selected for performing the measurements with both instruments, taking core samples, and where varying concrete quality was expected. Selected segments were measured, and 9 locations were identified for conducting the experiment. Three locations where high-quality concrete was expected, three where average-quality concrete was expected, and three where poor-quality concrete was expected. These locations were thoroughly examined using both the through-transmission method and the pulse-echo method. Subsequently, core samples with a diameter of 75 mm were extracted.

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In the laboratory, the core samples were cut into test specimens with 2:1 and 1:1 aspect ratio. The bulk density was determined on these specimens. The longitudinal wave velocities in the specimens were measured again for further comparison.

The following part of the experiment involved evaluating the elastic modulus from the shear wave velocities obtained by the pulse-echo method. The equation (3) from the valid Czech standard ČSN 73 1371 was used for the calculation, where the dynamic elastic modulus E_{cu} was calculated using the material bulk density ρ, longitudinal wave velocity v_p, and Poisson's ratio μ. It would not be possible to determine the bulk density in purely non-destructive testing, however, if the extraction of a few test specimens is allowed, or if the comparative specimens are available, at least an approximate value can be obtained. The average value determined from all samples was used for the E_{cu1} calculation, which was 2,227 kg/m^3. The longitudinal wave velocity v_p used in ČSN 73 1371 was calculated from the shear wave velocity v_s and the ratio determined during the calibration measurement (0.53). Poisson's ratio was also calculated from the calibration measurement using equation (2) from the ratio of longitudinal and shear wave velocities [2]. The value of Poisson's ratio was determined to be 0.30.

The dynamic elastic moduli E_{cu2} were calculated according to the same relationship using the longitudinal wave velocity determined at the given location with the Pundit PL-200 device. The constant value of bulk density and Poisson's ratio was maintained.

The dynamic elastic moduli E_{cu3} were calculated according to the same relationship but using specific values that would not be possible to determine during in-situ measurements for comparison. The values determined for the specific location from the sample taken in the laboratory was used for bulk density ρ. The value measured on the already prepared test specimens was used for longitudinal wave velocity v_p,. The ratio of the shear wave determined in-situ, and the longitudinal wave determined on the prepared test specimen was used for Poisson's ratio μ.

Static elastic moduli were determined on the prepared 2:1 specimen that can be seen in Fig. 4. Cyclic loading was performed with three loading cycles up to a level of ⅓ of the anticipated failure force. The sample was unloaded to a basic force of 2.5 kN, as shown in Fig. 5 after stabilization and reading of the relative deformations. Immediately after performing the cyclic loading, the compressive strength was determined, and the correctness of the procedure was verified. Due to the focus on practical application of the method, a regression curve was also created between the longitudinal wave velocity and the compressive strength of specimens, as described by the ČSN EN 13791 standard. A regression relationship was established between both types of waves and the elastic modulus.

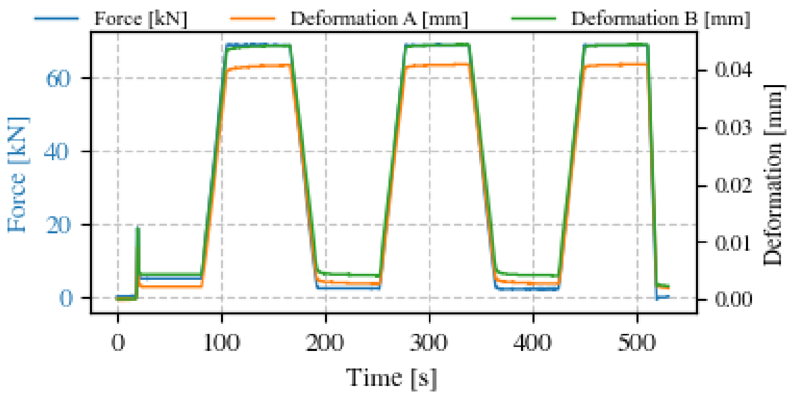

Fig. 5 Process of cyclic sample testing for determination of static modulus of elasticity.

Elastic moduli determined by ultrasound typically provide higher values than static moduli; according to the standard ČSN 73 2011, a reduction coefficient κ_u is used to convert to static elastic modulus. However, the values specified by the standard do not reflect contemporary materials. A reduction coefficient κ_u was applied as recommended by Cikrle and Kocáb [3] for the conversion of dynamic elastic modulus to static elastic modulus. Their research on contemporary concrete materials indicates that for concrete aged more than 3 weeks, the actual

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value of this coefficient is approximately 0.8, which differs from older values specified in standards. The resulting converted static elastic moduli are designated as E_{c1}, E_{c2}, and E_{c3}.

3 RESULTS

Tab. 1 summarizes the most significant values of the experiment. P-wave velocity measured by the Pundit PL-200 device, S-wave velocity measured by the Pundit 250-Array device, dynamic elastic modulus E_{cu1}, calculated from the shear wave velocities and values obtained during calibration (simulation of real measurement), dynamic elastic modulus E_{cu2}, calculated from the longitudinal wave velocity and values obtained during calibration (for comparison with the through-transmission method), dynamic elastic modulus E_{cu3}, calculated from the shear wave velocity and characteristics of the extracted sample, and static elastic modulus E_c, determined by cyclic loading.

Tab. 1 Measured P-wave and S-wave velocities and calculated elastic moduli.

	P-wave velocity (m/s)	**S-wave velocity (m/s)**	**Dynamic E_{cu1} (GPa)**	**Dynamic E_{cu2} (GPa)**	**Dynamic E_{cu3} (GPa)**	**Static E_c (GPa)**
V1	4,012	2,175	27.7	26.5	25.2	20.4
V2	4,228	2,371	32.9	29.4	30.9	21.0
V3	4,106	2,349	32.3	27.7	30.0	23.0
V4	4,402	2,661	41.4	31.8	37.4	25.7
V5	4,475	2,356	32.5	32.9	32.6	26.8
V6	4,543	2,580	38.9	33.9	37.6	27.8
V7	4,516	2,610	39.9	33.5	38.7	33.0
V8	4,645	2,321	31.5	35.5	33.9	35.2
V9	4,622	2,577	38.9	35.1	40.0	36.2

Fig. 6 displays the differences between the calculated dynamic elastic moduli and the measured static modulus. The average deviation of E_{cu1} from the static elastic modulus is 7.43 GPa, for E_{cu2} 4.13 GPa, and for E_{cu3} 6.36 GPa. The average deviation of E_{c1} is 0.41 GPa, E_{c2} -2.23 GPa, and E_{c3} -0.45 GPa after converting the dynamic elastic moduli to static moduli using the reduction coefficient κ_u,

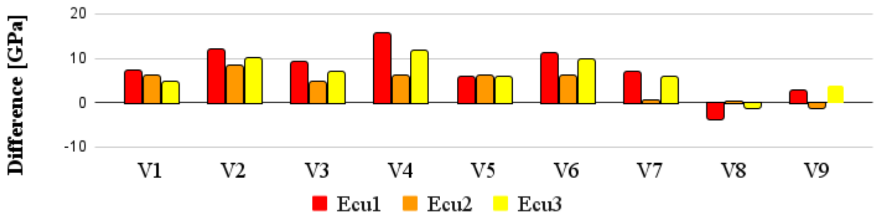

Fig. 6 Differences between measured static E_c and calculated dynamic elastic moduli.

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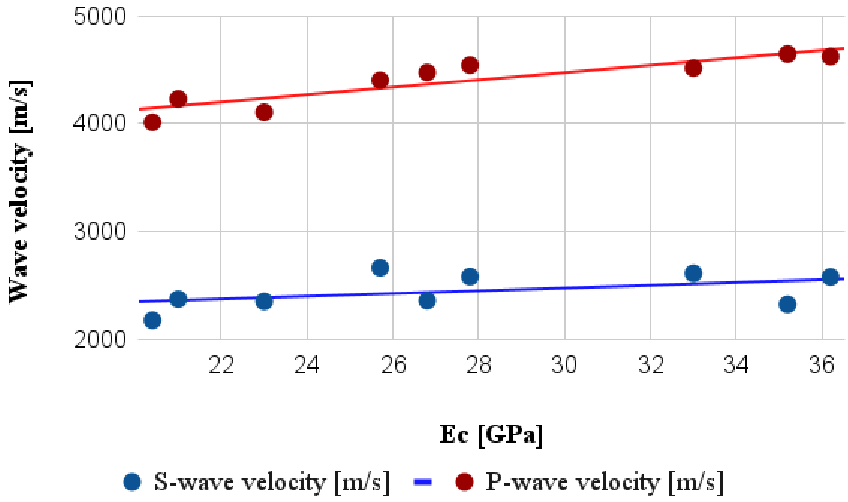

Fig. 7 Correlation between wave velocities and static elastic moduli.

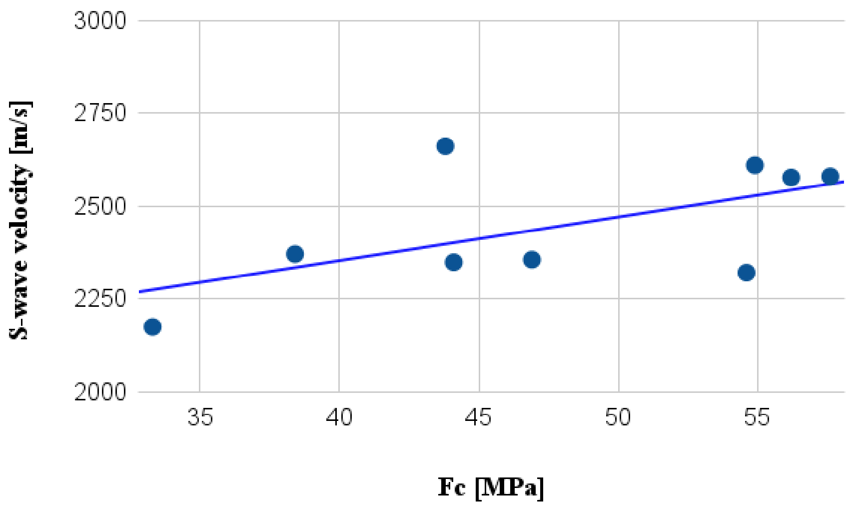

Fig. 8. Correlation between shear wave velocity and compressive strength.

Linear regression analysis was performed to establish relationships between wave velocities and material properties. For compressive strength versus shear wave velocity, the regression equation is $F_c = 0.031 \times v_s - 29.230$ ($R^2 = 0.369$). For static elastic modulus versus shear wave velocity, the regression equation is $E_c = 0.017 \times v_s - 12.757$ ($R^2 = 0.214$). For static elastic modulus versus longitudinal wave velocity, the regression equation is $E_c = 0.023 \times v_p - 74.449$ ($R^2 = 0.796$). None of the samples showed standardized residuals exceeding two standard deviations from the mean in any of the regression models (F_c vs. v_s max -1.79, E_c vs. v_s max 1.88, E_c vs. v_p max 1.29. This suggests there are no atypical values that would significantly distort regression results.

4 DISCUSSION

The concrete used for the experiment was rejected at the construction site as defective and inhomogeneous. The results show a significant dispersion of static elastic moduli. At the same time, this was part of an actual structure; the samples contained reinforcing steel, prestressing tendons, spacers, and minor defects. Despite these

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obstacles, when estimating the elastic modulus in-situ with calibration on only approximately 0.5 m long section, the pulse-echo method showed values differing on average by only 0.41 GPa.

The results shown in Fig. 6 seem interesting, namely the decreasing difference between the calculated dynamic elastic moduli and the static elastic modulus. Their difference decreases at higher values, which also corresponds with higher compressive strengths and bulk density [4]. This phenomenon, which is reflected for example in the value of the reduction coefficient κ_u in the standard ČSN 73 2011, can be observed precisely due to the non-uniformity of the concrete.

Pearson correlation coefficients were calculated to quantify the relationship between the different measurement methods. The through-transmission method (E_{c2}) demonstrated a strong correlation with the directly measured static elastic modulus ($r = 0.899$, $p < 0.001$), explaining 80.8% of the variance ($r^2 = 0.808$). The precisely calibrated measurements (E_{c3}) showed a moderate correlation ($r = 0.756$, $r^2 = 0.572$), while the pulse-echo method (E_{c1}) showed a weaker positive correlation ($r = 0.458$, $r^2 = 0.210$), explaining 14.9% of the variance ($r^2 = 0.149$), corresponding to recent findings by Ivanchev [5], who also found that pulse-echo methods (UPEM) demonstrated higher relative errors compared to through-transmission approaches when estimating elastic modulus. Similarly, Lee et al. [6] observed that dynamic moduli from different measurement techniques correlate differently with static modulus, with shear-wave based measurements showing consistently different relationships than P-wave or resonance methods. This variation in measurement accuracy aligns with Popovics [7], who demonstrated that different dynamic testing methods provide varying Ed values for the same concrete samples, and that the relationship between static and dynamic moduli depends significantly on which method was used to obtain Ed.

After applying the reduction coefficient $\kappa_u = 0.8$, the mean absolute error between the pulse-echo method (E_{c1}) and the static elastic modulus was reduced to 4.18 GPa, compared to 2.97 GPa for the through-transmission method (E_{c2}) and 2.94 GPa for the precisely calibrated measurements (E_{c3}). These findings indicate that while the pulse-echo method provides estimates of elastic modulus with reasonable average accuracy (as shown by the average deviation of 0.41 GPa reported earlier), the relatively weaker correlation suggests greater variability in individual measurements compared to the through-transmission method. This highlights the importance of site-specific calibration when using the pulse-echo method in practical applications.

Another limitation that should be acknowledged is that while the rejected bridge segments provided a unique opportunity to test actual structural concrete, they represent only one specific concrete mix design and construction approach, such as prestressing, that can affect measured velocities [8]. Different concrete compositions, particularly those with varying aggregate sizes or air entrainment, might provide different relationships between dynamic and static moduli.

5 CONCLUSION

The aim of the experiment was to verify whether the pulse-echo method could be used to estimate the elastic modulus in-situ on a real structure accessible only from one side only. Based on the results, it can be stated that:

- The pulse-echo method can be used to estimate the elastic modulus in-situ,
- While the average difference after applying the reduction coefficient was only 0.41 GPa, correlation analysis revealed a relatively weak relationship,
- Site-specific calibration substantially improves results, as evidenced by the increased correlation when using precise calibration values,
- A significant parameter is the value of the coefficient κ_u.

An interesting point is the reduction coefficient used in the ČSN 73 2011 standard and its determination. Without its use, the through-transmission method achieved more accurate results, while the reflection method differed by an average of 7.43 GPa. After its application, the static moduli from the reflection method differed by only 0.41 GPa, which is a very good result. On the other hand, the magnitude of the coefficient depends solely on the tester's estimation.

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