APPLICATION OF THE ULTRASONIC PHASE SPECTROSCOPY ON CONSTRUCTION MATERIALS

ANWENDUNG DER ULTRASCHALLPHASENSPEKTROSKOPIE AUF WERKSTOFFE IM BAUWESEN

APPLICATION DE LA PHASE D'ULTRA-SON SPECTROSCOPIE A DES MATERIAUX DE CONSTRUCTION

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SUMMARY

There are different techniques for the evaluation of the quality and internal structure of a specimen. The most usual nondestructiv methods at the IWB are the acoustic emission technique, the ultrasonic-transmission measurement and the impact-echo method. A more recent test method on construction materials is the ultrasonic phase spectroscopy. By transmitting continuous waves of varying frequency through a specimen, a phase-vs-frequency relation can be measured. Out of this relation one can determine the velocity, the acoustic impedance and the elastic constants of the specimen. Also one can measure the increasing damage during a compression test.

ZUSAMMENFASSUNG

Zur Bewertung der Qualität und inneren Struktur eines Prüfkörpers gibt es unterschiedliche Techniken. Die an unserem Institut am gebräuchlichsten eingesetzten zerstörungsfreie Prüfmethoden sind die Schallemissionsanalyse, die Ultraschall-Transmissionsmessung und das Impakt-Echo Verfahren. Ein neueres Werkstoffen stellt die Ultraschall-Prüfsystem an im Bauwesen Phasenspektroskopie (UPS) dar. Bei diesem Verfahren wird die Phase des Ausgangssignals mit der Phase eines durch den Prüfkörper transmittierten Signals verglichen. Trägt man diesen Phasenverlauf über die Frequenz auf, kann die Wellengeschwindigkeit in der Probe bestimmt werden, woraus sich die akustische Impedanz, sowie die elastischen Konstanten ermitteln lassen. Die Methode eignet sich auch dazu, Daten während eines Druckversuchs aufzuzeichnen und so den Schädigungsverlauf zu verfolgen.

RESUME

Il y a différentes techniques pour l'évaluation de la qualité et de la structure interne d'un spécimen. Les méthodes de nondestructiv les plus habituelles à l'IWB sont la technique acoustique d'émission, la mesure d'ultrasoniquetransmission et la méthode d'impact-écho. Une méthode plus récente d'essai sur des matériaux de construction est la spectroscopie ultrasonique de phase. En transmettant les vagues continues de la fréquence variable par un spécimen, une relation de phase-contre-fréquence peut être mesurée. Hors de cette relation on peut déterminer la vitesse, l'impédance acoustique et les constantes élastiques du spécimen. En outre on peut mesurer les dommages croissants pendant un essai de compressibilité. compression test.

Keywords: ultrasonic phase spectroscopy, wave velocity, uniaxial compression test

INTRODUCTION

The wave velocity in materials can be determined by several measurement methods. One of them is the ultrasonic phase spectroscopy (UPS) also known as the π -phase-comperison method. At the beginning of the 70's the method was described by Lynnworth et al. [1]. Their experimentel equipment existed out a frequency oscillator, frequency counter, wideband amplifier and an oscilloscope. With such a lot of instruments the calibration was a delicate thing and take a long time. Today modern networkanalyzers allow a very simple measurement procedure [2] and enables an automatically calibration of the equipment. So the method can be used to follow the increasing damage during an uniaxial compression test [3].

This article describes basics of the UPS and also the analysing methods of the detected data. Also UPS be compared with results of the ultrasonic pulse spectroscopy and acoustic emission tests.

ULTRASONIC PHASE SPECTROSCOPY

The equipment used for UPS is very compact. In addition to the networkanalyzer [4] one needs two ultrasonic sensors with a broadband frequency spectrum and a linear run of the phase curve. Now a wave with the frequency ftransmitted through a specimen with the length L be compared with the input signal. Because the specimen has the same function as a "velocity-resistor", a runtime difference between the input and output signal occurs.



Fig.1: The experimental setup and on the right side the measuring window of UPAS.

An increasing of the frequency is finally leading to continuous phase shift $\Delta \Phi$. If the phase plotted against the frequency, one can determine the velocity V out the gradient of the curve [5]:

$$V = -2\pi L \left(\frac{df}{d\Delta\Phi}\right). \tag{1}$$

The programme UPAS [3] was developed to automate the data acquisition which controls the network analyzer Advantest R3754A. The program, which was written under LabVIEW 6i, calibrates the ultrasonic sensors to get a linear amplitude distribution against the frequency. Also it stores the results in the ASCII format which allows a data analysis in the most commonly used programmes.

During a compression test more than 200 individual events can arise. This is called an additional expenditure in the analysis time and data evaluation. Therefore a software was programmed, in order to determine the gradient of the curve automatically.

An other problem is the coupling of the sonsor on the specimen and so the choice of a suitable ultrasonic couplant [6]. It must have a high bandwith and a low damping factor. The following figure 2 demonstrates the different damping of some coupling agents, as wax, medical ultrasonic gel, Butyl seal tape and

hot-melt adhesive. The frequency quality and the low damping caused by the thin liquid layer of ultrasonic gel be opposed to the less adhesive property on materials like concrete or stone. These materials comparable with a sponge absorb the liquid part of the gel and make the coupling time-dependent. in the beginning hot-melt adhesive is liquid and enables a thin film between the coupling layers. The hardened glue has a high acoustic impedance what allows a good acoustic adaptation. It is the preferred couplant for rough surfaces. The hot glue clings very good on different materials, but it is so good that it is very difficult to separate the face to face together-glued sensors after the calibration because the coupling layer is too big. Wax is equal to hot-melting adhesive but it is softer in hardened condition, thus the separation-procedure of the sensors is less complex. Also the run of the curve in higher frequency areas is better. The handling of wax is uncomfortable because it hardened very fast. A compromise between these couplants agents is Butyl seal tape. Because Butyl is kneadable, its handling is simple and the adhesion characteristic is good, which can be improved by Butyl primers. To avoid the loss of the time dependent adhesive, one must provide a constant contact pressure.



Fig. 2: Damping curves of different coupling agents. The illustration on the right side shows a test specimen, which is coupled according to the new method with liquid plastic and ultrasonic gel.

There are many different coupling agents with different qualities. The correct choice of the agent depends on the specimen surface quality and the sensor type. Especially for concrete there exists a new coupling method. The specimen surface be pretreated with clear varnish or liquid plastic. Thereby a flat dust-free layer on which one can couple with ultrasonic gel results. The sensors must be fastened by a holder.

ANALYSIS METHODS

During a compression test the network analyzer scans every 10 seconds a frequency range and recorded both the phase and linear amplitude over the frequency. All data result from a uniaxial compression test on a concrete cube with side length 15 cm, an aggregate corn of 1,2/2 mm, a steel fiber (Dramix ZP 305) fraction of 0,4vol.-% and a water/cement ratio of 0,4. Out of these data a programme calculates the wave velocity out of the gradient of the phase curve (Figure 3 left). Therefor is only used the linear increasing part of the curve. The corners of the linear part signifies highest and lowest transmitted frequency. How one can see both the velocity and the maximum transmitted frequency decrease with increasing damage. The frequency range depends in the lower part on damping-effects of the specimen like interferences, side-wall reflections and complexe modes, in the higher part on the bandwidth of the sensors [7]. If the slope $df/d\Delta\Phi$ is constant, as in the frequency range of this experiment, dispersion is not significant.



Fig. 3: Phase as a function of the frequency and the velocity as a function of the deformation. The data are a result of an uniaxial compression test at a steel fiber reinforced concrete cube.

The right side of figur 3 represents a result of the velocity analysis for a compression test. In the beginning the speed decreases slowly, until the cracks gain strongly. At this point the microcracks are connected. Because there is now

no direct way for the waves from sensor to sensor the velocity decreases strongly.

Also one can analyse the frequency spectrum over the time and the damage increasing. The network analyzer scans every 10 seconds a frequency range. This is like a fourier-spectrum of the transmitted signal. All spectra side by side form a flow chart and also a intensity diagramm by top view how figure 4 on the left side shows. Dark colours are low amplitude value. The specimen has a length L and a material dependent wave velocity. Thus frequencies, which correspond to one of the multiples half wavelength, are preferred. They form standing waves which transmit more energy to the other side. This effect shows the 3D graphic on the right side in picture 4. Like in the mountains there are peaks and valleys whereby the standing waves correlate with the peaks.



Fig. 4: Frequency spectrum as a function of time. On the right side a zoomed 3D-graphic where the mountain structure clearly stand out.

Higher frequencies are more strongly absorbed with increasing damage, since they are already disturbed by smallest cracks. This can be observed also at the transmitted amplitude of the signal. The picture on the left presents the change in amplitude versus the deformation for whole and different frequency ranges. The amplitudes react sensitiver to damages than the velocitiy. With a special developed programme one can separate special frequency ranges and calculate the amplitudes. As expected amplitudes of higher frequencies decrease faster with increasing deformation.



Fig 5.: Amplitude versus deformation for the whole frequency range and special frequency ranges normed on the left side.

ULTRASONIC PHASE SPECTROSCOPY AND ULTRASONIC PULSE SPECTROSCOPY

With the ultrasonic pulse spectroscopy (UIS) one can determine the amplitude, frequency spectrum and the velocity of a specimen during a compression test too. But in contrast to the ultrasonic phase spectroscopy (UPS) a calibration is impossible. The advantage of the UIS is the high energy of the input signal so specimens with a bigger thickness can be measured. The frequency range be limited by the bandwidth of the sensor and the pulse length of the input signal. In this study the sensors (Vallen VS 30) mainly dictated this range (10-60 kHz). In this study both measurement methods applied at the same time to one specimen. A result of the good coupling of the UPS sensors with liquid plastik and ultrasonic gel as well as the insensibility of the UPS equipment against external interferences. For the UIS experimental setup (figure 6) an ultrasonic emitter and four receivers (for a better area cover) are used. The setup of UPS is the same as in the chapter before. Additionally there are two position encoders on the sides of the UPS sensors. Thus the specimen surface leaves no more place.

A problem is the detection of the amplitude of the transmitted pulse waves because they are with other oscillations superimpose. From there the onset time must be determined, so that the first vibration in the signal can be separated and the amplitude can be extracted. The peak of this amplitude corresponds with the longitudinal wave considered for the analysis [8].



Fig. 6: Experimental setup and specimen fit with components.

To define the onset time of 1000 and more signals, a programme was developed that calculates that point of time automatically via the Hinkley-criterion with a dynamic threshold-control [9]. This algorithem makes a good job when the transmitted signals are low-noise. In the reality the detected signals are superimposed with noise from the measurement equipment and external interferences. Additionally the calculated onset times are filtered by a smoothprogramme. With the smoothed dataset the point of time is searched in the original data when the longitudinal wave arrives. A comparison with the energy, the square of the signal amplitude, and the maximal transmitted amplitude (figure 7) shows that specimen intern activities during the compression have high influence on the results. It seem that in compressed areas the signal energy increases. If the internal structure finally gives way, the energy or maximally transmitted amplitude makes a jump downward, until it comes again to a compression. In contrast thereto the first amplitude of the longitudinal wave decrease constantly.

The next picture shows a comparison between the velocity determination by UPS and UIS. At the beginning both curves have the same gradient. The velocity of the UPS measurement has a higher value due to the not exact definition of the onset time and associated failure in the determination. With about 0,18 millimeters the UPS curve breaks in, because the absorption in the test specimen becomes too large due to internal damages.



Fig. 7.: a)Automatic onset-time determination and smoothing of the onset times, b) amplitude of the first longitudinal amplitude versus deformation, c) the square of the signal integral (proportional energy) versus deformation, d) maximal amplitude versus deformation.

The input signal of the UIS has sufficient energy, in order to cross smaller cracks. Therefore also a more homogeneous form. On the right side of figure 8 the frequency spectrum is pictured. The bandwidth of the sensors lies between 5 and 60 kHz. Because no calibration was made, the resonance frequencies of the sensors at 10 and 50 kHz are clearly identifiable. Between this range the resonances of the specimen are visible as with the UPS method but in the lower frequency range.



Fig. 8.: Velocity versus deformation determine with the pulse spectroscopy (black) and the UPS (grey). Right the frequency spectrum result from the IPS data.

ULTRASONIC PHASE SPECTROSCOPY AND ACOUSTIC EMISSION

Acoustic Emission Analysis (AEA) is another non-destructive testing method [10]. AE occurs if a crack growth or crack borders rub against . Therefor the test object must be compressed or stressed. The method detects the acoustic events and can identify, locate, and display the damage to the tested object [11]. In this study a concrete cube (aggregate 1,2/2 mm, steel fiber fraction 1,3 Vol.-%, w/z 0,4) was chosen on which a localisation of the acoustic events was realized. To create acoustic emissions the cube underwent an uniaxial compression test with different load levels. To determine the velocity and the maximal transmitted frequency the cube was scanned by the UPS after every test and the acoustic events were located. For the localization are used the velocityresults from the UPS analysis. The next picture shows the experimental setup of AE. Eight sensors recorded the emission signals, two sensors triggered the events. Additionally two position encoders were mounted. At first the specimen was scanned by UPS then loaded from 0 to 400 kN. AE measurements were taken during the loading. With the data the localization for the several events were calculated. Now the load was enlarged by 100 kN and the specimen was loaded again.

Figure 9 shows the damage development with increasing loading. The maximal transmitted frequency reacts sensitiver to little changes in structure. But it is sensitive with regard to the coupling too.



Fig. 8: Experimental setup of acoustic emission test. On the left one can see the transient recorder system, the three preamplifiers and on the right background the prepaired test specimen.

So the interpretation of the results is not easy and needs good experiences. The results of both measurements methods harmonize very good. The test specimen breaks at the right side, which at the lightening color distribution in the speed and frequency diagram becomes evident. This be emphasized by the increase of the acoustic emission on the right side. The white areas in the velocity and frequency diagram stand for a impossible measurement of transmission. A more exact examination of the specimen yielded that the cube was sloping.







Load level 0-850 kN



Fig. 9: Result from the UPS, velocity c and maximal transmitted frequency f, and from AEA in y-z direction of the specimen.

CONCLUSION

A new non-destructive measurement method, the ultrasonic phase spectroscopy, was tested on construction materials. The experimental setup today is very simple with networkanalyzers which enables a calibration of the measurement equipment and an automatically operational sequence of the measurement by programs. The increasing damage can be observed during the compression test and several data can be calculated. So the velocity, the amplitude for the whole frequency range and special ranges, the maximal transmitted frequency and additionally the resonance frequencies of the specimen. The comparison with the ultrasonic pulse spectroscopy and the acoustic emission analysis yielded good agreements. So the measurement method can be adapted on all materials for non-destructive testining so long as the damping threshold is not reached. In the future improving of the coupling and a more exact deformation determination is planned.

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