Prediction Method of Crack Depth of Concrete Building Components Based on Ultrasonic Signal

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Abstract. Cracks in concrete components have a serious impact on the safety of building structures. On the one hand, with the increase of service life, cracks will reduce the safety of building structures, and with the deepening of cracks, the service life of building structures will be reduced. Therefore, it is very necessary to predict cracks in concrete components. In the crack prediction of concrete building components, the predicted results deviate from the actual value due to the deviation of the measured strain value of concrete. Based on ultrasonic signal, a method for predicting crack depth of concrete building components is proposed. In the process of concrete ultrasonic transmission, the number and length of micro cracks will increase and expand due to stress concentration. According to this phenomenon, the finite element simulation of concrete building components is carried out to obtain the damage model. The characteristics of concrete cracks are extracted based on ultrasonic signals, and the law of acoustic frequency changing with time can also reflect the state of medium stress. The extracted crack signal features of concrete building components are input into CNN model for prediction and recognition. The test results show that the prediction method of crack depth of concrete building components based on ultrasonic signal can improve the accuracy of prediction results and has high engineering application value.

Keywords: Ultrasonic signal · Concrete · Building components · Crack analysis · Crack depth · Depth prediction

1 Introduction

With the rapid growth of concrete infrastructure construction in China, more and more attention has been paid to the health prediction and maintenance of later facilities. Cracks will inevitably appear in the construction or long-term use of concrete structures. If cracks are not found and repaired in time, it will not only affect the appearance, but also affect the normal use of concrete structures. Therefore, it is very important to predict concrete cracks.

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Concrete is one of the most widely used building materials in infrastructure construction, which is widely used in infrastructure construction such as roads, bridges, tunnels, dams and houses. Cracks are inevitable in the construction process or long-term use of concrete structures. The main reasons for cracks are as follows: cracks are caused by uneven stress due to low tensile strength of concrete structures and excessive load for a long time; Because the concrete structure is often exposed to the outside, it is easy to deform under the influence of external temperature changes, and it is often eroded by rain to cause cracks; The quality of construction materials and the level of construction technology directly affect the quality and service life of concrete structures [1].

If the cracks in the concrete structure can not be found and repaired in time, the damage to the structure will be aggravated. When the depth and width of the crack exceed the critical value borne by the concrete structure, it will not only affect the external beauty, but also affect the normal use of the concrete structure, and may even lead to major safety accidents and unnecessary losses. Therefore, the prediction and prevention of concrete cracks are of great significance for maintaining the stability of concrete structures and extending the service life.

The method in reference [2] proposes a concrete crack prediction method based on the improved convolutional neural network, which uses the entropy threshold method to process the image, improves the traditional convolutional neural network from three aspects, and uses the improved convolutional neural network to train the sample image, so as to complete the prediction of concrete cracks. Reference [3] proposes a concrete crack prediction method based on laser ultrasonic technology, establishes a plane strain finite element model, and studies the interaction law between laser-excited surface waves and concrete surface cracks. Analyze the scattering echo characteristics of surface wave and crack front (the longitudinal edge where the wave and crack first act), discuss the influence of crack depth on the time difference of scattering echo characteristic points, and complete the prediction of concrete cracks. Reference [4] proposes a concrete crack prediction method based on the array ultrasonic imaging method. According to the principle and calculation method of the array ultrasonic imaging method to predict the crack depth, the imaging prediction is carried out across a single crack and the whole specimen, and the prediction results of concrete cracks are obtained. Although the above method can complete the prediction of concrete cracks, there are problems such as insufficient prediction accuracy and low data recall.

Ultrasonic nondestructive testing technology is widely used in the field of civil engineering in recent years because of its convenient, fast and accurate operation. The frequency of the acoustic wave method used in the ultrasonic method is far lower than that of the electromagnetic wave, which can achieve nondestructive testing in a large depth range in concrete. Moreover, the price of ultrasonic equipment is low and the detection algorithm is flexible. Therefore, this paper proposes a method for predicting the crack depth of concrete building components based on ultrasonic signals. The overall research technical route of this method is as follows: through ultrasonic technology, the number and length data of concrete cracks are collected, and the finite element simulation of concrete components is carried out according to the collected data. Based on the finite simulation results, the damage model of components is established. The ultrasonic frequency is calculated to extract the characteristics of concrete cracks and the stress state of concrete structures. The extracted crack features are input into the CNN model to complete the prediction of concrete cracks.

2 Prediction Method of Crack Depth of Concrete Building Components Based on Ultrasonic Signal

2.1 Ultrasonic Conduction Mode of Concrete

At the meso material level, concrete is a multiphase composite composed of mortar, aggregate, interface transition zone and various defects such as pores and inclusions. The failure process of concrete structure is a progressive process of damage, damage accumulation, macro crack occurrence and macro crack propagation. Under the action of no external load, there are a certain amount of micro cracks in it. When the crack length and stress concentration of concrete are low, the number of cracks will increase. The conduction mode of ultrasonic wave in concrete building components is shown in Fig. 1.

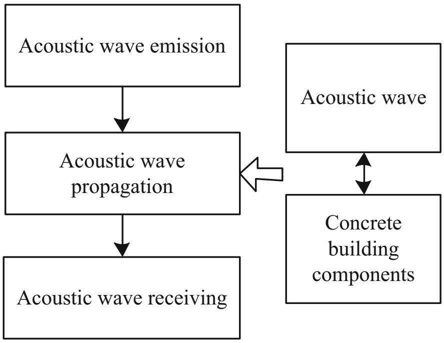


Fig. 1. Ultrasonic conduction mode

Assuming that the crack inside the concrete is a narrow cut, the inhomogeneity of the medium will cause slight differences in the sound pressure and density at each particle, which is expressed as additional sound pressure and additional density. When the displacement vector of a particle caused by a wave such as an elastic wave is small, any product of higher-order vectors can be ignored. Therefore, for any point in the inhomogeneous medium, its sound pressure and density are expressed as:

$$\begin{cases} A = A_0 + A_1(t) \\ B = B_0 + B_1(t) \end{cases} \tag{1}$$

In formula (1), A_0 represents the average sound pressure, B_0 represents the average density, A and B respectively represent the sound pressure and density at any point in the concrete building component; A_1 and B_1 represent additional sound pressure and additional density; t represents the propagation time of ultrasonic wave.

According to the law of conservation of mass and momentum, it can be proved that the spatial and temporal distribution of sound pressure in medium is closely related to the spatial distribution of density. For the damage equation of concrete crack, it is considered that when the concrete is subjected to stress, the crack volume changes accordingly, resulting in the displacement of particles in the material. For any point in the non-uniform subspace, the sound field propagating to the particle satisfies the free boundary Green's function, and the calculation formula is as follows:

$$W(r_1) = \frac{\alpha t \beta}{4\pi \| r - r_1 \|} \tag{2}$$

In formula (2), W represents the sound field at the particle; α represents scattering operator; β represents wave velocity; r and r_1 represent any point and particle respectively.

The second-order amplitude generated by ultrasonic propagation is directly proportional to the square of wave propagation distance, frequency and intensity. The total additional scattered sound field can be obtained by integrating the fields of all points in space at the particle. When the ultrasonic ranging is certain, the higher the intensity and frequency of the input wave, the more obvious the second-order amplitude. However, the amplitude of the input wave is limited. The second-order harmonic of ultrasonic is often detected by inputting a higher frequency. Therefore, concrete has randomness at the meso material level, and its density, elastic modulus and other mechanical parameters are random quantities related to spatial location. However, the higher the ultrasonic frequency, the corresponding signal attenuation will increase. Because the wavelength of ultrasonic wave in concrete is equivalent to the size of coarse aggregate, the propagation of ultrasonic wave will be affected by the non-uniformity of concrete medium (interference), resulting in the randomness of the measured ultrasonic signal.

2.2 Finite Element Simulation of Concrete Building Components

In the process of using ultrasonic method to detect concrete structure, the received signal often carries complex information inside the structure. Through fast Fourier transform, we can explore the law of ultrasonic propagation inside the structure. Concrete, rock and other materials are structural analysis based on the assumption of continuous medium and the concepts of stress and strain. ABAQUS is a set of highly functional finite element software, which can solve all engineering linear problems to nonlinear problems. The specific flow chart of finite element analysis is as follows (Fig. 2):

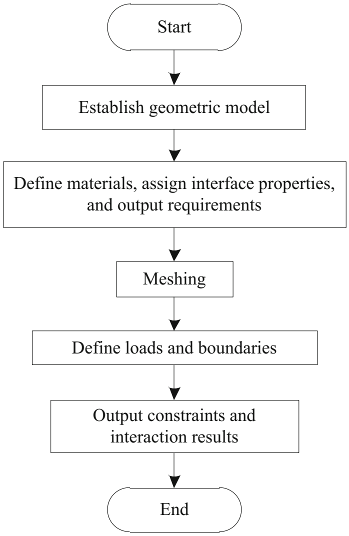


Fig. 2. Finite element analysis process

When establishing the constitutive model of damage, the study of damage variables is often the most important content. For the definition of damage variables, we can study a representative volume element in solid materials from a macro point of view and use the method of continuum mechanics to investigate the changes of macro mechanical property parameters caused by damage. In the step of establishing the geometric model, the aggregate of concrete building components is randomly generated according to the two-dimensional circle, and the coordinates of the corresponding aggregate are read in MATLAB. The corresponding geometric model is directly established in ABAQUS, and three material properties are defined, including aggregate, mortar and interface. As long as the external load does not continue to increase, the cracks in the concrete will not continue to increase and expand, and new cracks will appear, and a few cracks will be closed during unloading. When defining the analysis step, the time length needs to meet the following constraints:

$$\Delta\tau = \frac{1}{20\varphi_{\max}} \tag{3}$$

In formula (3), $\Delta\tau$ represents the length of time; $\varphi_{\max}$ represents the maximum frequency of time domain excitation.

The integrity of concrete materials has not changed, and the constitutive relationship of concrete at this stage can also be approximately regarded as linear. Since the shear wave velocity is smaller than the longitudinal wave velocity, that is, the transverse wave length is smaller than the longitudinal wave wavelength, the minimum wavelength of the shear wave (generally 10 nodes) is used to control the grid size. In fact, at this stage of crack formation, the number and length of mortar cracks and interface cracks are very small and can be ignored. In grid division, except that the grid size close to aggregate and mortar is 0.8 mm, the other grid sizes are LMM. If the aggregate in concrete is not easy to be damaged, its density is defined as high. From the physical level, the ultrasonic nonlinear coefficient is a quantitative index that can characterize the degree of waveform distortion when ultrasonic waves pass through concrete materials. The strength of cement slurry and interface materials is relatively low and easy to be damaged, so the concrete damage model is used to describe the nonlinearity of loaded concrete in the finite element software simulation. Ultrasonic nonlinear coefficient can not only reflect the damage degree of material, but also reflect the growth rate of damage variable with strain. In traditional linear ultrasonic testing, the value of ultrasonic wave velocity will be directly affected by the elastic modulus of materials. In the stress field, referring to the concrete damage plasticity (CDP) model in ABAQUS, it mainly uses the damage factor to express the stiffness degradation of materials. The elastic modulus at any time can be expressed as:

$$P = P_0(1 - \chi)^2 \tag{4}$$

In formula (4), P and P_0 represent the elastic modulus and initial modulus of any node; χ represents the damage factor.

Under the action of long-term continuous load, while the concrete material is creep, the hydration reaction also continues. The hydration reaction makes the concrete material more dense and the elastic modulus increases gradually. In the sound field, in order to simulate the propagation of ultrasonic wave in concrete, the signal modulated by harm window function is used as the excitation signal in this paper. Considering the frequency resolution and spectrum leakage, Hanning window is adopted this time [5]. The corresponding function form is:

$$\gamma(t) = \frac{1}{2}\left[1 - \cos\left(\frac{2\pi\eta t}{m}\right)\right] \tag{5}$$

In formula (5), $\gamma(t)$ represents Hanning window function; η represents frequency; m indicates the number of windows.

Ultrasonic signal is constrained by subjective factors (human operation) and external conditions (instrument and environment), so it is very necessary to verify or predict with the help of relevant finite element calculation software.

2.3 Extraction of Concrete Crack Characteristics Based on Ultrasonic Signal

As a measurement signal, ultrasonic itself has a certain degree of uncertainty. The measurement error caused by the accuracy of the acquisition instrument and the standard deviation of the amplitude are analyzed. In addition, the measurement error of the amplitude of the waveform will also be caused by the ambient temperature and humidity, ambient noise and coupling system. The crack propagation and extension will occur when the concrete is under the stress that is not higher than the critical stress of failure for a long time, which is about 70% - 90% of the stress level. At this time, the cracks will expand to the mortar, resulting in the increase of mortar cracks, and the cracks will be connected with each other to form relatively large cracks. Therefore, the interior of the concrete will be affected and the integrity will be weakened, and the stress–strain relationship is also nonlinear [6]. However, as long as the load remains unchanged or unloaded, the crack propagation will tend to stop. The primary goal of ultrasonic coda test is to improve the stability of waveform and control the quality of coda data, which is conducive to analyzing the load relationship between stress amplitude matrix and characteristic vector. For an acoustic acquisition signal, from the perspective of the field of digital signal processing, the signal is the equal spacing sampling of the real analog signal, and the sampling frequency determines the accuracy of the digital signal [7]. In each frequency position combination, it should also be noted that several pairs of identical signals will be generated during the transmission and reception of ultrasonic signals. This is determined by acoustic reciprocity, so only one signal needs to be taken for analysis. Using MATLAB to carry out fast Fourier transform FFT on the discrete acoustic signal data, the complex set of the acoustic signal about the number of sampling points can be obtained.

The calculation formula of amplitude $\mu(s)$ corresponding to the s-th frequency is as follows:

$$\mu(s) = \vartheta(t)e^{-\frac{2\pi st}{n}} \tag{6}$$

In formula (6), $\vartheta(t)$ represents the amplitude sequence corresponding to the discrete time of the continuous signal $\phi(t)$, n represents the number of sampling points; e is the natural constant. In order to facilitate observation, in the subgraph corresponding to each frequency position combination, the balance position of each signal is shifted upward by a certain value relative to the balance position of the previous signal to avoid overlap [8], and the complex part is expressed by the triangular function through the Euler formula.

$\mu(s)$ is a conjugate complex set symmetrical about s, that is, the digital signals at these sampling points can obtain $\frac{n}{2} + 1$ frequency amplitude information including zero frequency. The arrival time of ultrasonic signals collected at the same location is almost the same even if the frequency is different; Even at the same distance from the excitation source and the same frequency, the amplitude of the ultrasonic signal has great variability; Within the measurement frequency range, the waveform consistency is better with the increase of frequency [9]. At this time, the expression of the continuous signal with respect to the time variable t can be deduced from the complex set obtained by the FFT processing of any waveform $\vartheta(t)$ with respect to the discrete time series. The calculation formula is as follows:

$$\vartheta(t) = |\mu(s)|\cos\left(\frac{2\pi st}{n} + \lambda_0\right) \tag{7}$$

In Eq. (7), λ_0 represents the initial phase, which is the angle between $\vartheta(t)$ and the real axis on the complex plane.

The discrete Fourier transform of ultrasonic sampling data can fully display the frequency domain information. On the premise that the total number of samples remains unchanged, its relationship with the time-domain signal is that the higher the sampling frequency is, the higher the resolution of the time-domain signal is and the lower the resolution of the frequency-domain signal is. The speed of sound is equal to the ratio of the propagation distance to the arrival time of the wave. The propagation distance of wave is known information, that is, the distance between the transducer collecting the signal and the excitation transducer. In order to determine the arrival time of the wave, this paper uses the threshold method, that is, the maximum value of time-domain noise is defined as the threshold, and the time corresponding to the first sampling point exceeding the threshold is the arrival time of the wave. In practical engineering, the receiving frequency of ultrasonic detection signal is often concentrated in one frequency band. When analyzing the signal in frequency domain, it is necessary to conditionally amplify the resolution of useful frequency band and reduce the resolution of useless frequency band (such as noise) [10]. Finally, the variation law of acoustic frequency with time can also reflect the stress state of the medium, highlighting the time-domain characteristics of ultrasonic signal at the cracks of concrete building components.

2.4 The Prediction Model of Crack Depth of Building Components is Established

Based on the signal characteristics of cracks in concrete building components, a crack depth prediction model is established. The extracted crack features of concrete building components are input into CNN model for classification and recognition. In this paper, inception V3 neural network is used for training and recognition. Inception V3 is a CNN model proposed by Google. The biggest feature of the network model is the mixed layer, which is a multi-layer network and network nested structure, that is, the original node is also a network. Compared with V2 version, the biggest change of V3 version is to divide the convolution kernel of 7*7 into two one-dimensional convolution kernels of 7*1 and 1*7. Splitting one convolution kernel into two convolution kernels can not only accelerate the calculation speed, but also further deepen the network, so as to strengthen the nonlinear characteristics of the network. When training CNN model, it is necessary to select an appropriate target loss function to evaluate the consistency between the crack prediction results and the real label. Cross entropy loss function is one of the most widely used loss functions in deep learning. The cross entropy loss function is still used in this paper. The formula of cross entropy function is shown in Eq. (8).

$$F = z \log z' + (1 - z) \log\left(1 - z'\right) \tag{8}$$

In formula (8), F represents the cross entropy function; z represents the crack value of the real mark; z' is the predicted value of the model.

The high-order harmonic signal is sensitive to the cracks in the damage area, and the cracks are randomly generated and uncontrollable in the signal propagation path, resulting in faster energy attenuation of the high-order harmonic signal. In addition, the human operation error is easy to cause the dispersion of the test result data. This can also explain the so-called "filtering function of concrete", that is, high-order signal waves are filtered with the increase of structural damage. After determining the loss function, the function is optimized by small batch gradient descent. Each gradient update selects a small number of samples randomly from the training samples for learning, which reduces the oscillation of the convergence process. If the learning rate is set too small, the convergence speed of the model will be very slow. If the learning rate is set too large, the model will oscillate around the minimum or even deviate. In order to solve the problem that the model oscillates back and forth at the local minimum, the gradient descent method with momentum is generated. Suppose that after a neural network model is trained on the data set, the full connection layer at the top of the model is removed, that is, the layer that outputs the set category probability is removed, and the rest is fixed as a feature extractor, Then train a linear classifier on a new data set according to the classification set by yourself. The commonly used linear classifier is softmax classifier, which is connected with the feature extractor to customize its own task. So far, the design of crack depth prediction method of concrete building components based on ultrasonic signal has been completed.

3 Experimental Study

3.1 Experiment Preparation

The section of the concrete cube specimen in this experiment is designed to be 1000 mm * 1000 mm * 2000 mm, and a small amount of reinforcement is arranged to prevent temperature cracks. The experimental system is composed of signal generator, signal amplifier, transducer, oscilloscope and computer. After the electrical signal emitted by the signal generator is amplified, it is transmitted into the concrete through the transmitting transducer (the electrical signal is converted into acoustic signal), and then the receiving transducer (the acoustic signal is converted into electrical signal) feeds back the signal carrying the damage information of concrete material to the oscillograph, and then Fourier transform the time-domain signal to obtain the spectral characteristics of the signal. The standard value of the compressive strength of the concrete used in the experiment is 30 MPa. When pouring the concrete, it shall be fully vibrated to discharge the bubbles. The concrete pouring is in summer, and the ambient humidity and temperature are relatively stable. Therefore, under natural conditions, the test piece is covered with gunny bags and watered for 28 days to ensure that the test piece has no visible cracks and hidden cracks as far as possible. The particle size of coarse aggregate for concrete is 5 mm to 25 mm. The size of smart aggregate (SA) is equivalent to that of coarse aggregate, so it will not interfere with the mechanical properties of concrete. The water cement ratio of concrete material is 0.47. Ubuntu16.04 LTS 64 bit operating system is used as the working platform, Python is used as the main programming language, and the whole network model is built by using Pytorch version 1.4.0 deep learning framework.

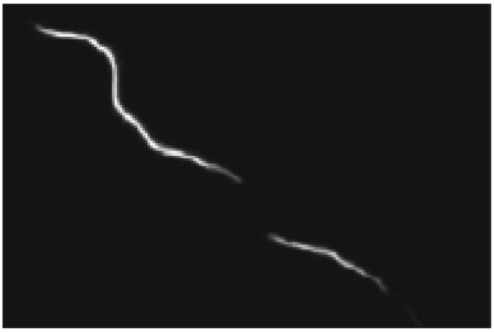
3.2 Results and Analysis

The cracks of concrete building components are selected as the research objects, and the methods of this paper, reference [2] and reference [3] are used to carry out the experiment of crack prediction effect. The cracks of concrete building components are shown in Fig. 3.

Fig. 3. Cracks in concrete building components

(a) Methods in this paper

(b) Reference [2] method



(c) Reference [3] method

Fig. 4. Crack prediction results of concrete building components with different methods

The fracture prediction results of the three methods are shown in Fig. 4.

From the crack prediction results of concrete buildings shown in Fig. 4, it can be seen that the crack prediction results of the method in this paper are closest to the real crack results, while the crack prediction results of the methods in reference [2] and reference [3] are poor, intermittent and incoherent, which can not guarantee the safety of concrete buildings.

In order to further verify the performance of the crack depth prediction method of concrete building components based on ultrasonic signals proposed in this paper, the method in this paper is compared with the method in reference [2] and the method in reference [3]. The accuracy, precision, recall and F1 value are selected as the evaluation indicators, and the test results are shown in Table 1–4.

Table 1. Comparison results of accuracy (%)

Number of tests	Prediction method of crack depth of concrete building components based on ultrasonic signal	Reference [2] method	Reference [3] method
1	92.43	85.47	78.46
2	94.85	84.79	72.57
3	93.56	85.56	79.58
4	95.62	86.25	81.25
5	94.57	82.61	82.66
6	92.19	83.24	83.32
7	91.58	84.38	82.03
8	92.26	82.56	82.22
9	93.35	83.23	79.55
10	94.12	86.02	80.92

According to the results in Table 1, the accuracy of the crack depth prediction method of concrete building components based on ultrasonic signals is 93.45%, which is 9.04% and 13.19% higher than the methods in reference [2] and reference [3].

Table 2. Comparison results of precision rate (%)

Number of tests	Prediction method of crack depth of concrete building components based on ultrasonic signal	Reference [2] method	Reference [3] method
1	96.43	77.46	81.71
2	95.87	79.83	82.94
3	96.56	78.69	80.58
4	94.21	79.25	82.85
5	95.55	72.52	86.66
6	96.32	76.91	85.22
7	95.56	75.34	85.33
8	94.29	78.58	82.52
9	93.60	76.25	84.01
10	95.26	77.62	83.42

According to the results in Table 2, the accuracy rate of the crack depth prediction method of concrete building components based on ultrasonic signals is 95.37%, which is 18.12% and 11.85% higher than the methods in reference [2] and reference [3].

Table 3. Comparison results of recall rate (%)

Number of tests	Prediction method of crack depth of concrete building components based on ultrasonic signal	Reference [2] method	Reference [3] method
1	85.09	77.49	72.43
2	91.56	75.88	76.87
3	90.62	74.51	75.94
4	88.23	76.62	73.65
5	87.07	75.25	72.26
6	85.16	75.36	75.52
7	86.52	75.60	76.33
8	84.25	74.23	71.22
9	85.84	78.18	72.51
10	86.41	76.51	70.18

According to the results in Table 3, the recall rate of the crack depth prediction method of concrete building components based on ultrasonic signals is 87.08%, which is 11.12% and 13.39% higher than the methods in reference [2] and reference [3].

Table 4. Comparison results of F1 value (%)

Number of tests	Prediction method of crack depth of concrete building components based on ultrasonic signal	Reference [2] method	Reference [3] method
1	90.41	77.48	76.79
2	93.67	77.80	79.79
3	93.50	76.54	78.19
4	91.12	77.91	77.98
5	91.11	73.86	78.81
6	90.40	76.13	80.08
7	90.82	75.47	80.58
8	88.99	76.34	76.45
9	89.55	77.20	77.84
10	90.62	77.06	76.23

According to the results in Table 4, the F1 value of the method for predicting the crack depth of concrete building components based on ultrasonic signals is 91.02%, which is 14.44% and 12.75% higher than the methods in reference [2] and reference [3].

Based on the above results, the method proposed in this paper can obtain the signal characteristics of cracks. The samples used for training and testing can well show the difference between positive and negative samples, and show the signal characteristics of cracks in the way of training. Therefore, it shows better prediction performance of crack depth, so as to provide support for crack detection and health assessment of concrete building components.

4 Concluding Remarks

Cracks are one of the main diseases of concrete structures. Timely and effective detection of these cracks is of great significance to maintain the sustainable use of concrete structures. In this paper, a method for predicting the crack depth of concrete building components based on ultrasonic signal is proposed. This method can improve the accuracy of prediction, is convenient and reliable, and has great engineering practical value. In the actual concrete ultrasonic testing work, the changes inside the structure may be more complex. If you want to improve the reliability of acoustic testing technology, more improvements are needed. In terms of signal processing, there will be occasional abnormalities in the waveform measured in the test, but if the error is not obvious, it can not be found in time, which will have a certain impact on the follow-up analysis work.

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