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Nondestructive Testing of Concrete Strength Based on Consolidation Wave Speed Measurement

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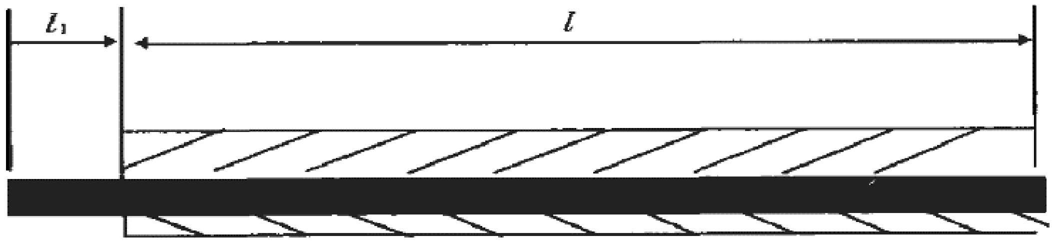
Consolidation wave speed measurement is used to identify the quality of concrete structures, and to inspect defective concrete specimens. Experiments and numerical analysis were used to establish a nondestructive testing technique for concrete structures in the paper, based on consolidation stress wave speed measurement for anchoring segments of reinforced concrete. The results showed that the shock pulse on reinforcing bars by exciter could effectively detect defects of concrete specimens, and could reveal inner concrete structures in a comprehensive and precise manner.

1. Introduction

During concrete construction, it is a must to strengthen quality inspection and control, which serves as one of the critical links of assuring the quality of buildings. Nondestructive testing technology was applied to concrete testing in the field of architectural engineering in China in the middle 1950s. Since the 1970s, as domestic engineers have stepped up efforts to popularize it, this technology has maturated towards normalization and standardization. The concept of nondestructive testing techniques for concrete structures is that the inner concrete structure remains intact, one uses monitoring equipment to inspect the physical quantity associated with concrete and rebars, and further identifies conditions of the reinforced concrete, such as strength, homogeneity, continuity, durability, and existing defects. Currently, the main nondestructive testing techniques for concrete structures in China include resonant frequency methods, the ultrasonic pulse velocity method, radioactive methods and the vertical reflection method. However, any of the above methods has limitations such that only one parameter can be measured each time under particular conditions. Given this, by testing the consolidation wave speed of stress waves from exciters in anchoring segments of reinforced concrete, the paper proposed a new real-time, nondestructive approach to deduce concrete strength.

2. Test principle

Assuming that there was a variable impedance surface in the internal structure of the reinforcing bar, which is shown in Figure 1.



l_1—free section length; l—anchoring section length

Figure 1: Sketch map of the structure

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The wave impedance of the upper medium was expressed as $Z_1=\rho_1V_1a_1$, and the waveimp dance of the lower medium as $Z_2=\rho_2V_2a_2$. Under transient impact force, the rebar end propagated the vibration to the other end in the form of stress wave. During the propagation, projection and refraction occurred at the time when the stress wave ran into the variable impedance surface. Thus, according to momentum conservation law, the corresponding reflection coefficient R and the refraction coefficient T could be obtained as:

$$R=\frac{Z_2-Z_1}{Z_2+Z_1}=\frac{\rho_2V_2a_2-\rho_1V_1a_1}{\rho_2V_2a+\rho_1V_1a_1} \tag{1}$$

$$T=\frac{2Z_2}{Z_2+Z_1}=\frac{2\rho_2V_2a_2}{\rho_2V_2a_2+\rho_1V_1a_1} \tag{2}$$

Where ρ_1—density of the upper medium; ρ_2—density of the lower medium;v_1—propagation velocity of the stress wave in the upper medium;v_2—propagation velocity of the stress wave in the lower medium;a_1—area of the upper part of the variable impedance surface;a_2—area of the lower part of the variable impedance surface. The reinforcing bar of the anchoring section was analyzed. It was approximately regarded that the generalized axial wave impedance of the rebar in the variable impedance surface increased namely $R>0$; in contrast, the wave impedance of the lower part of the variable impedance surface in the anchoring section could be deemed to be gradually decreasing, namely $R<0$. Reflection occurred when the stress wave ran into the upper part of the variable impedance surface. At the same time, wave impedance surged, and the reflective angle and the incident angle were in-phase. However, total reflection would emerge when the reflected wave was propagated to the rebar end, on which occasion the stress wave and the initial stress wave were inverted (Li, et al., 2004; Wang, et al., 2004). If the propagation velocity of the stress wave in the rebar was tested through ultrasound as$v$, the reflective time of the anchoring sectionwas supposed to be $t=2l_1/v$.

3. Test methods

The propagation velocity of the stress wave in the internal structure of the reinforced concrete can reflect concrete quality directly. In general, the reinforced steel bars anchored at the construction site are under various influences. The vibration pattern of rebars will be prominently affected by the concrete as they have different stiffness and damping from those of the rebar (Kimet al., 2008; Kwak et al., 2008). In actual cases, despite highly complexity, the rebar vibration can be calculated briefly under the following assumptions:

Since the exciting force derived from low strain dynamic testing is tiny, the following conditions can be satisfied: the rebar is under self-excited oscillation, and the Hooke's Law of elasticity is applicable to calculate the relationship between displacement, stress, and strain of each particle in the internal structure of the vibrated rebar.

In the low strain dynamic testing, the rebar texture is evenly and isotropically distributed.

If the length l and the diameter d meet the conditions of $l/d\geq10$, the following requirements will be satisfied: when the rebar is under impact vibration, the cross-section of the rebar remains at the same plane state, meanwhile the displacement, direction, and size of mass points in the cross section are uniform (Li et al., 2000; Liu et al., 2000).

A small part of control volume was extracted from the anchoring section, which is shown below.

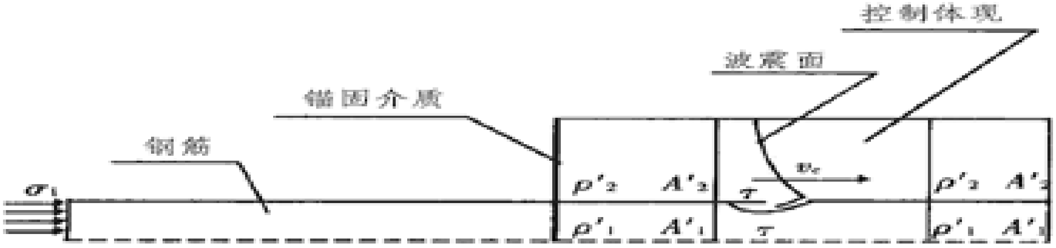


Figure 2: The control volume of the anchoring section

First, the paper postulated that the bonding strength between the rebar surface and the concrete surface was great enough. Under the low stress conditions, a pulse excitation was imposed on the rebar end, followed by the propagation of a stable elastic stress wave from this end to the other end according to the S.T.Venat principle. When the stress wave reached the anchoring section of the reinforced steel bar, dynamic shear stress emerged on the distorted, bended surface (Li, et al., 2008; Zhang, et al., 2008; Wang, et al., 2008). The shear stress field could be considered as limited, and the certain area near the left wave shock surface was quasi-static. The surface shear stress was basically zero. Thus, the continuity equations concerning the rebar and the concrete were expressed as follows:

$$\rho'_1 A'_1 \,(VC\text{-}V) = \rho_1 A_1 V_C \tag{3}$$

$$\rho'_1 2A'_2 \,(VC\text{-}V) = \rho_2 A_2 V_C \tag{4}$$

Where: ρ_1—density of the rebar in the control volume;ρ_2—density of the concrete in the control volume;A_1—CSA of the rebar in the control volume;A_2—CSA of the concrete in the control volume;ρ'_1—density of the rebar in the quasi-static area;ρ'_2—density of the concrete in the quasi-static area;A'_1—CSA of the rebar in the quasi-static area;A'_2—CSA of the concrete in the quasi-static area; v—displacement velocity of the particle.
The positive strain$\varepsilon_x$and the elongationε were equal to each other in the stress wave-free area in front of the wave shock surface. According to the conditions of Love kinetics:

$$\varepsilon_{x1}=\varepsilon_{x2}=\varepsilon=\varepsilon_{x=-}\frac{V}{V_C} \tag{5}$$

whereε_{x1}——positive strain of the rebar; ε_{x2}——positive strain of the concrete.
In the quasi-static strain area that was to the left of the control volume, the relationship between material stress and strain was given as:

$$\sigma_{x1}= C_1\varepsilon_{x1} \tag{6}$$

$$\sigma_{x2}= C_2\varepsilon_{x2} \tag{7}$$

whereσ_{x1}—uniaxial stress of the rebar; C_1—stiffness coefficient of the rebar; σ_{x2}—uniaxial stress of the concrete; C_2—stiffness coefficient of the concrete. C_1 and C_2 could be determined by constraint equations according to actual conditions.
The equation of mean stress could be obtained from equation (6) and equation (7):

$$\sigma_{ave} =\sigma_{x1} V_1+\sigma_{x2} V_2 =(V_1 C_1+ V_2 C_2)\, \varepsilon_x \tag{8}$$

Where: σ_{ave}——mean stress; V_1——rebar volume percentage; V_2——concrete volumepercentage
As an internal stress, shear stress exerted no effect on the integral momentum balance. The equation of the integral momentum balance was expressed as:

$$\sigma_{x1} A'_1+\sigma_{x2} A'_2=-VCV\,(\rho_1 A_1+\rho_2 A_2) \tag{9}$$

During low strain testing, supposing that$A'_1/A_1= A'_2/A_2=1$, and equation (5)-(8) could be integrated. Thus the velocity of wave shock surface was estimated as:

$$V_C^2=\frac{A_1C_1+ A_2C_2}{A_1\rho_1+ A_2\rho_2} \tag{10}$$

Where: $A_1C_1+ A_2C_2$—mean strength, which was related to the contact conditions and its size between the rebar and the concrete. The obtained value of mean strength was different from that under the mixture law; $A_1\rho_1+ A_2\rho_2$—mean density.
In equation (10), if$\alpha=A_1/A_2$, when$\alpha\to 0$, the stress wave velocity in the concrete approximated consolidation wave speed v_c; whereas, when$\alpha\to\infty$, the stress wave velocity in the rebar approached to consolidation wave speed v_c. Therefore, it could be deducted that the consolidation wave speed in the anchoring section was distributed between the stress wave velocity in the rebar and the stress wave velocity in the concrete (Malik, et al., 1992).

4. Experiment research

4.1 specimen fabrication

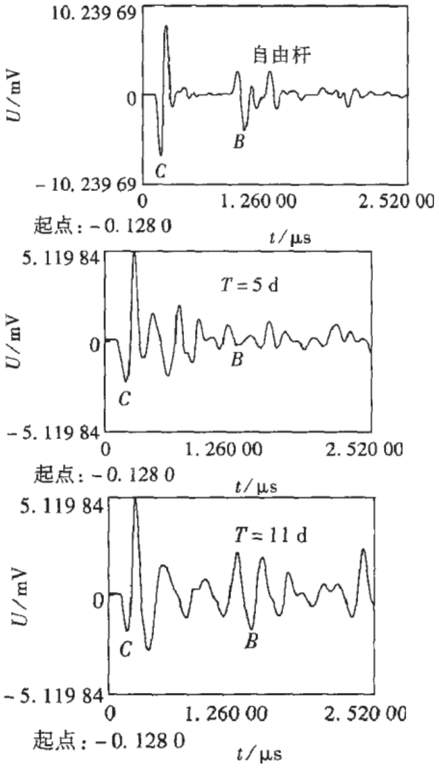
Plain round steel (or deformed steel bar) acted as the major material of the rebar specimen, with the reservation of rebar end at the free sectionl_1($l_1 < l/10$).C30 concrete was used in the experiment. The anchoring agent was cement mortar, for which the proportion of cement to fine sand was set as 1:1.5, and the water-binder ratio was 1:0.5. Table 1 is the sample parameters, and Figure 1 is the structure of the specimen.

Table 1: Parameters of the specimen

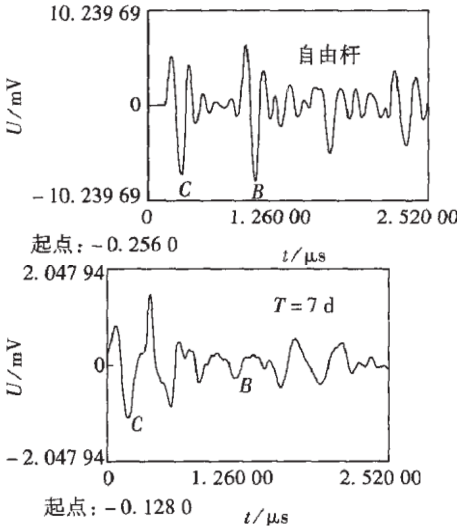
Specimen	material	l_1/cm	l/cm	d/mm
$1^{\#}$	Plain round steel	12	198	16
$2^{\#}$	Deformed steel bar	4	176	17
$3^{\#}$	Plain round steel	8	392	16

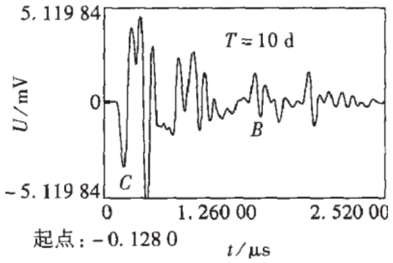
4.2 full-length anchoring rebar test

The experimental apparatus contained dynamic data acquisition machine, acceleration sensor, and needle exciter with springs. The acceleration sensor was installed on the exposed rebar end, and shock pulse was imposed on the rebar by needle exciter. Figure 3 shows the acceleration response curves of different specimens at different curing time. Figure 4 is the relationship between consolidation wave speed and curing time.

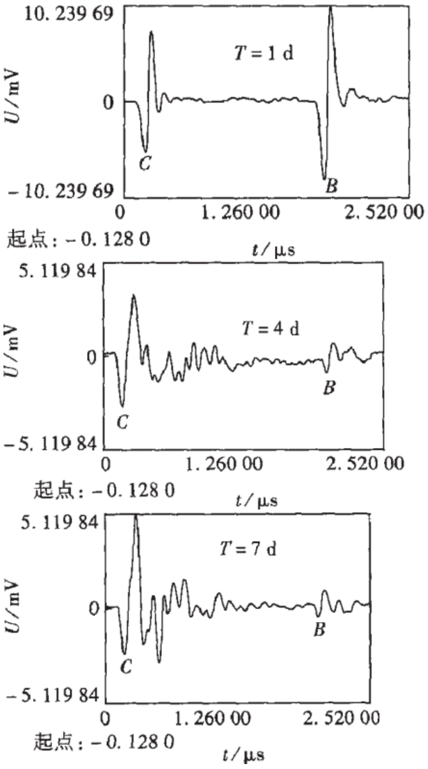


a. The acceleration response curves of the $1^{\#}$ specimen at different curing time





b. The acceleration response curves of the 2# specimen at different curing time



c. The acceleration response curves of the 3# specimen at different curing time

Figure 3: The acceleration response curves of different specimens at different curing time

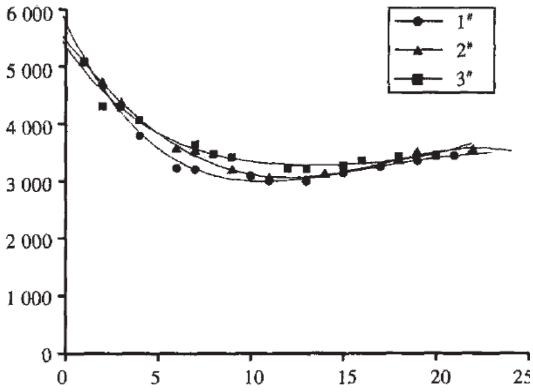


Figure 4: The relationship between consolidation wave speed and curing time

The collected signals were analyzed by certain software for the reflection time t_2 at the bottom of the anchoring rebar. Thus, the consolidation wave speed was obtained as:

$$V_C=\frac{2L}{t2-2L1/V} \tag{11}$$

Where v_1——elastic stress wave velocity in the rebar rod (The measured value for this specimen is v_1=5070m/s)

4.3 Analysis of experimental results

1) It can be seen from Figure 3 and Figure 4, during initial curing time, that the consolidation wave speed and the stress wave velocity are similar to each other in the free section of the rebar rod. As the curing period prolongs gradually, the consolidation wave speed decreases. The reason is that the initial concrete strength has not formed, thus exerting little bond stress on the rod body; however, the concrete strength increases as the concrete continues to be cured, leading to a prolonged reflection of stress wave at the bottom of the anchoring bar(Zhou, et al., 1985).

2) When the curing time falls into the interval of 10-14d, the consolidation wave speed and the stress wave velocity are in close proximity to each other in the concrete, and there is small change of the reflection time of the stress wave at the bottom of the anchoring bar.

3) When the curing time exceeds 14d, the consolidation wave speed begins to climb slowly, with small changing amplitude. The reflection time of the stress wave at the bottom of the anchoring bar tends to edge down.

5. Conclusion

Both the theoretical analysis and the experiment results show that the consolidation wave speed in the concrete structures is able to change. The paper suggests that, revealing its changing law such as the consolidation wave velocity is able to measure the quality of reinforced concrete. In this way, a new nondestructive testing method of concrete quality is proposed in the paper. In fact, as there is no discussion of quantitative relations between consolidation wave speed and the quality of concrete structures in the paper, this issue needs to be further studied.

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