CHEMICAL ENGINEERING TRANSACTIONS
VOL. 62, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Fei Song, Haibo Wang, Fang He

ISBN 978-88-95608- 60-0; **ISSN** 2283-9216

DOI: 10.3303/CET1762154

Experimental Study of the Working Stress State of Concrete Frame Structures through Ultrasonic Testing

Yan Zhao, Wenxiu Hao*, Xiao Xu

Agricultural University of Hebei, Baoding 071000, China
hwxansys@126.com

This paper studies the impact of different locations including frame columns, frame beams and nodes to ultrasonic velocity through performing ultrasonic testing of single-layer and single-span reinforced concrete frame structures; and analyzes the change rule of stress state of test pieces and ultrasonic velocity under different stress processes. This paper also establishes the baseline stress test curve of the concrete frame structures based on test data. The study shows that the change of velocity of tensile zone of the simple bending sections of the frame beams is larger than that of the compressive zone when the structures reach ultimate stress; the drop of ultrasonic velocity of locations in shear-bending sections is relatively smaller. As for frame columns, the velocity change of locations that are near the nodes is the largest; and for the frame, nodes have the most obvious impact to the ultrasonic velocity and the drop of ultrasonic velocity is the largest.

1. Introduction

Concrete structure is the main structural form in modern construction engineering. The stress level of concrete in buildings is the most direct and reliable index that reflects the safety performance of buildings; therefore, it is of critical importance to accurately obtain the precise working stress value of structures in service for inspection and safety assessment. The ultrasonic method, as a relatively mature nondestructive testing technology, is extensively applied in engineering study, since instrument involved are portable and easy to be operated. In recent years, scholars both at home and abroad have carried out study on the strength and damage of concrete materials with ultrasonic inspection technology from many aspects. After the propose of ultrasonic inspection technology of concrete (Jones, 1963), foreign scholars performed ultrasonic inspection of reactive powder concrete and bituminous concrete, and corresponding results showed that the ultrasonic inspection technology is feasible (Sansalone and Carino, 1986; Glenn et al., 2014; Mesut et al., 2004; Van et al., 2011; Fasnakis et al., 2016; Ogunbode et al., 2017; Ondrejka et al., 2017); they also compared compressive strength and elasticity static modulus based on ultrasonic testing, so as to confirm the possibility to inspect recycled concrete with ultrasonic (Pani and Francesconi, 2014). Domestic scholars also conducted ultrasonic inspection of different concrete materials under different stress states, and established the relation between ultrasonic with damage and compressive strength (Zhu et al., 1998; Yan et al., 2002; Li et al., 2006; Li et al., 2007); then tested concrete test pieces with different steel fiber contents and strength, to obtain the change rule of velocity under different stresses, and established a mathematical model for the strength of concrete and velocity (Zhu et al., 2010; Liu and Zhang, 2011). Moreover, they also carried out ultrasonic inspection of concrete test pieces with reinforcement on two sides, to study the impact of rebar in concrete members to ultrasonic velocity; and proposed the formula on relation between working stress and ultrasonic velocity of concrete based on experiments (Gao et al., 2017). However, the study on inspection of the working stress of concrete structures in service with ultrasonic is basically blank both at home and abroad at the current stage. Thus, the inspection of stress level of reinforced concrete members under stress with ultrasonic and the establishment of baseline stress test curves of concrete structures under different stress states can provide a new assessment index for quality assessment of concrete buildings, and also provide new assessment theories and a non-destructive testing method to evaluate the level of strength loss of concrete architectural structures in service.

Please cite this article as: Yan Zhao, Wenxiu Hao, Xiao Xu, 2017, Experimental study of the working stress state of concrete frame structures through ultrasonic testing, Chemical Engineering Transactions, 62, 919-924 DOI:10.3303/CET1762154

This paper compares the impact of frame beams, frame columns and nodes to ultrasonic velocity through experimental study of concrete frame structures, analyzes the change rule of ultrasonic velocity of concrete structures under different stresses, and establish baseline stress test curve of concrete frame structures based on experiments.

2. Overview of the test

2.1 Design and manufacturing of the test pieces

The experimenters fabricate a single-layer and single-span reinforced concrete frame structure for the test, adopt rebar of grade HRB400 for longitudinal steel bar for frame beams, frame columns and mudsills, and use rebar of grade HPB300 with a diameter of 6mm for stirrups, with the interval being 150mm, strength of concrete being C40 and thickness of protective layer being 20mm. Please refer to Table 1 for the parameters of frame structures and Figure 1 for detailed size of test pieces and information about reinforcing bars.

Table 1: Parameters of reinforced concrete frame

Location	Size of section	Concrete strength grade	Cube compressive strength / MPa	Stirrup	Diameter of longitudinal bar	Longitudinal bar
Frame beam	150mm×250mm	C40	44.57	HPB300	12mm	HRB400
Frame column	200mm×200mm	C40	44.57	HPB300	14mm	HRB400
Mudsill	150mm×200mm	C40	44.57	HPB300	12mm	HRB400

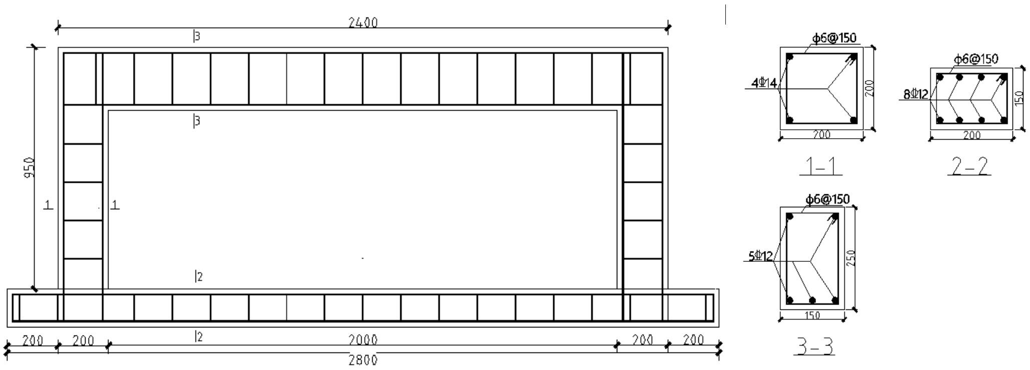


Figure 1: Diagram of the size of test pieces and reinforcing bars

The concrete frame is fabricated in the field of the laboratory of Hebei Agricultural University, and formwork is made of wood by workers in the field after rebar is bound according to the design scheme. Detailed procedures are as follow: firstly, pour concrete, sand, stone and water into agitator kettle in sequence and stir well; then place the mixed concrete into the wooden formwork, and finally vibrate the concrete with vibrating rod until the concrete fills up the inner space of the formwork. Cover the test piece with plastic film after pouring, water for curing every day, remove the formwork seven days later and use it in the experiment after 30 days of natural curing.

2.2 Loading scheme and layout of measuring points

Prior to the commencement of the experiment, the experimenters applied vaseline of proper amount to the contact surface between the test piece and distributive girder, so as to reduce the impact of “confinement effect” caused by frictional drag to the concrete member. They carried out ultrasonic inspection test for the concrete member with level-to-level loading method; set the dwell time of loading of each level to be 10min, determined the loading value and loading speed in accordance with the *Standard for Test Method of Concrete Structures* (GB50152-2012T), and then performed ultrasonic test and data collection. The loading instrument used in the test is electro-hydraulic servo multichannel pseudo-dynamic loading system, and ultrasonic detecting instrument is ZBL-U520 nonmetal ultrasonic detecting instrument.

3. Test phenomena and analysis of results

3.1 Test phenomena

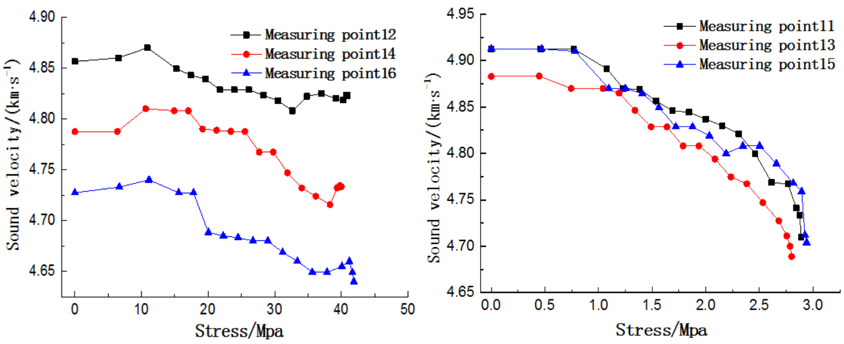
After the concrete structure enters into loading stage, the dwell time of each level is 10min, and corresponding measuring points are tested with ultrasonic detecting instrument afterwards. The appearance of frame does not show any obvious change at earlier stage of loading, but when the load reaches 80%, microfractures appear firstly on the nodes of the frame structure, then spread to the top of frame columns and simple bending sections of frame beams with the increase of load, and the microfractures on nodes enlarge as well; when the ultimate bearing capacity is reached, the microfractures on frame beams and frame columns all develop, with microfractures on nodes developing the most quickly and the longest one being 150mm long and 3mm wide. Figure 2 presents the failure mode of the test piece.

Figure 2: Failure mode of the test piece

3.2 Analysis of test results

(1) Change rule of ultrasonic velocity of concrete frame beams

Figure 3 shows the changing trend of ultrasonic velocity of simple bending sections of concrete frame beams. It can be seen from Figure a that the compactness of concrete in the compressive zone is intensified when the load is started to be applied, leading to the increasing trend of ultrasonic velocity; and the ultrasonic velocity starts to show a very slight decreasing trend with the increase of load until the component is broken, drops by 2% from 4.727Km/s to 4.64Km/s.



(a) Comprehensive zone of frame beams (b) Tensile zone of frame beams

Figure 3: Diagram on the changing trend of ultrasonic velocity of simple bending section of the frame beams

It can be seen from Figure b that the internal damage of concrete on measuring point No. 13 and No. 15 develops faster compared with measuring point No. 13 when a load of 30% of the ultimate stress starts to be applied, which causes an earlier decrease of the ultrasonic velocity at measuring point No.11 and No. 15, and makes the ultrasonic velocity value at measuring point No. 13 basically remain unchanged; and the ultrasonic velocity value at measuring point No. 11 and No. 15 decreases soon afterwards instead of from the beginning. When a load of 80% of the ultimate stress is applied, the damage of concrete within tensile zones of the frame beams deteriorates with continuous application of load, and the fractures develop further, resulting in the decrease of ultrasonic velocity at the same rate at the three measuring points. When the load reaches the ultimate stress, the internal damage of concrete further deteriorates and the development of microfractures expedites at later stage of structural damage, which increases the falling speed of ultrasonic velocity compared with the previous two stages. However, node failure happens to the frame structure ultimately, the damage of tensile zones of the frame beams is only at its medium stage when the structure fails, and the drop of ultrasonic velocity at the three measuring points is only 5% from 4.912Km/s to 4.704Km/s finally, which is very small.

(2) Change rule of the ultrasonic velocity in concrete frame columns

Figure 4 is the changing trend diagram of ultrasonic velocity in main broken locations of the concrete frame columns. The initial ultrasonic velocity of the two measuring points is different due to uneven compactness of the concrete component, which is caused by the difference in construction process. When a load of 30% of the ultimate stress starts to be applied, the compactness of the concrete at measuring point No. 24 on the concrete frame is enhanced under load, resulting in the increase of ultrasonic velocity accordingly. When a load of 80% of the ultimate is applied, internal microfractures start to develop with the further increase of load and the interaction of coarse aggregate and cementing material of the frame columns; and the fractures near the frame nodes make ultrasonic velocity decrease quickly. When the load reaches the ultimate stress, fractures develop on the frame columns near the nodes, spread gradually and become visible; and finally the ultrasonic velocity drops by 7% from 4.687Km/s to 4.399Km/s.

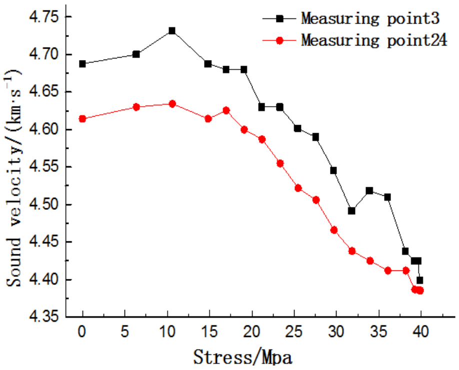


Figure 4: Diagram on the changing trend of ultrasonic velocity of main broken locations of frame columns

(3) Changing trend of the ultrasonic velocity in the concrete frame nodes

Figure 5 is the changing trend diagram of ultrasonic velocity in nodes of the concrete frame. As shown in the Figure, the initial ultrasonic velocity of the left and right nodes is different due to uneven compactness of the concrete component which is caused by the difference in construction process. When a load of 25% of the ultimate stress starts to be applied, the internal damage of concrete at this stage is not serious enough to change the ultrasonic velocity value of the two measuring points, because frame nodes are designed reinforcement zones, which are capable of bearing higher loads. When a load of 80% of the ultimate stress is applied, the internal fractures of concrete in the locations of nodes grow gradually with the increase of load and make the route of ultrasonic prolonged when it crosses the concrete member; but the ultrasonic velocity remains unchanged in the process, which causes the falling trend of ultrasonic velocity. When the load reaches the ultimate stress, microfractures connect with each other to form macrofractures in the frame with the accumulation and further development of damage. The longest macrofractures can have a length of 150mm and a width of 3mm, and make the ultrasonic velocity of the two measuring points decline at a higher speed by 12% from 4.702Km/s to 4.166Km/s finally.

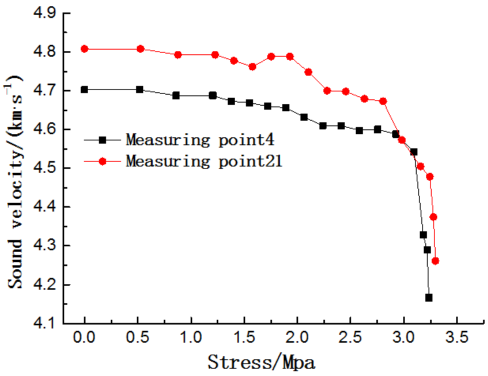


Figure 5: Diagram on the changing trend of ultrasonic velocity of the frame nodes

4. Baseline stress test curve

The baseline stress test curve of the concrete frame structure is fitted based on the experimental data of 30d, the data are normalized due to different initial sound velocities with analysis software as shown in Formula (1). The coefficients of concrete frame test piece are shown in Table 2.

$$\sigma = \sigma_M \left(1 - A_1 e^{A_2 \frac{v}{v_0}}\right) \quad (1)$$

In the formula: σ is the working stress of test locations of the concrete member, N/mm^2; v is the ultrasonic velocity, Km/s; v_0 is the initial ultrasonic velocity, and its value is 4.848 Km / s; σ_M is the ultimate stress of the concrete, N/mm^2; and its value is provided in Table 2 as well; $A_1 A_2$ is the coefficient, and its value is provided in Table 2.

Table 2: Coefficients of reinforced concrete frame

Location	σ_M	A_1	A_2
frame columns	40.0	1.3.×10-3	5.8.
frame beams	3.0	1.2×10-4	7.5.
nodes	3.0	1.5×10-4	8.0

The initial sound velocity is mainly affected by the strength of concrete in the table. The strength curves established by Yao and Chen (2000) are close to the experimental data. However, due to the difference of concrete materials, the measured sound velocity will deviate. Curve is improved to obtain the strength curve: f_{cu}^{c}=0.1986k $v^{3.5041}$, k is the influence coefficient, take 0.8, so this paper use strength curve to deduce the initial sound velocity in the actual construction concrete strength.

Figure 6 is the fitting chart on the relation between the working stress ratio and ultrasonic velocity ratio in the concrete frame structure. It can be seen from the Figure that the baseline stress test curve of the concrete frame is divided into three stages, and corresponding working stress of concrete at each stage is as follow:

Stage I: When a load of 20% of the ultimate stress starts to be applied, microfractures appear under the interaction of coarse aggregate and cementing material as the component is only under a low stress at the beginning of the stage. This low stress imposes certain impact to ultrasonic velocity value which exhibits a falling trend and matches well with the fitting curve at this preliminary stage, which is called adaption stage.

Stage II: When a load of 80% of the ultimate stress is applied, the stress is higher at this stage, long and thin fractures generate with the development of microfractures in concrete, the ultrasonic velocity value falls at a certain speed to 95% of the initial one finally. This stage is called fracture stage, because tiny fractures appear on the surface of the frame; and it is also called normal work stage since the component is still in normal service.

Stage III: When the load reaches the ultimate stress, the frame fails at this stage, the internal damage on main failure locations of the frame deteriorates with the further increase of stress, and microfractures connect with each other to form many visible fractures little by little, leading to a faster decrease in ultrasonic velocity to 85% of the initial ultrasonic velocity. This stage is called failure stage, since the yielding of rebar in the frame reaches the ultimate bearing capacity.

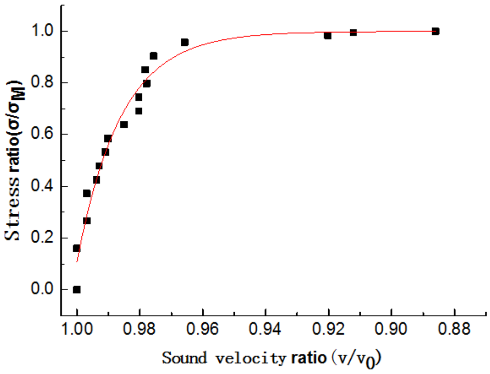


Figure 6: Fitting chart on the relation between the working stress ratio and ultrasonic velocity ratio of the frame

5. Conclusions

This paper studies the change rule of ultrasonic velocity in the structure under the influence of complex stress through experimental analysis of the concrete frame. The baseline stress test curve of frame structure is also drafted using the experimental data.

(1) The change rule of ultrasonic velocity in different locations of the concrete frame is basically identical: when a load of 20% of the ultimate stress starts to be applied, the ultrasonic velocity remains unchanged in general; when a load of 80% of the ultimate stress is applied, the ultrasonic velocity starts to fall; and when the load reaches the ultimate stress, the ultrasonic velocity decreases at a higher speed. The relative change of ultrasonic velocity for different location varies, with the nodes exhibiting the biggest change, which is followed by frame columns and frame beams in sequence.

(2) When the structure reaches the ultimate stress, the tensile zones in the simple bending sections of the frame beams have a bigger change in ultrasonic velocity than compressive zones. Compared with the initial ultrasonic velocity, tensile zones sustain a drop of 5% and the compressive zones sustain a drop of 2% only. The ultrasonic velocity in the shear-bending sections drops a little by 3%; the locations on frame columns near the nodes has a larger change with the drop of ultrasonic velocity being 7%; while the nodes sustain the largest change in ultrasonic velocity with a drop of 12%.

(3) The baseline stress test curve of the structure is drafted through fitting the relation between working stress and ultrasonic velocity; a coefficient table is provided for different locations of the concrete frame as well. In engineering practice, this curve can be used to preliminary check the stress of the structure, so as to provide a reference for test and evaluation.

Reference

Fasnakis D., Papanikolaou S., Tsouknidas A., Maropoulos S., 2016, Premature fracture during fatigue testing of reinforced-concrete steel bars, Academic Journal of Manufacturing Engineering, 14(4), 40-44.

Gao H., Hao W.X., Li L., Wang J.L., Sun J.H., 2017, Experimental study of concrete work stress using ultrasonic testing. Building Science, 33(3), 94-99, DOI: 10.13614/j.cnki.11-1962/tu.2017.03.016.

Jones R., 1963, The ultrasonic testing of concrete. Ultrasonics, 1(2), 78-82, DOI: 10.1016/0041-624X(63)90058-1.

Li F., Shen C.W., Li Y.X., Li H., 2006, Research on Damage of Asphalt Concrete by Ultrasonic inspection method. Journal of Wuhan University of Technology, 30(2), 293-296

Li L.J., Chen Z.Z, Xie W.F., 2007, Experimental study of compressive strength and ultrasonic velocity of high strength concrete filled with recycled rubber particles. Concrete, (6), 44-45.

Liu G.L., Zhang Z.P., 2011, Experimental Research of Concrete Compression Strength with Ultrasonic Non-destruction Detecting Method. Journal of Sichuan University of Science & Engineering, 24(3), 258-260.

Mesut T.S., Figen K.U., Yalcin K.., 2004, Application of ultrasonic method in asphalt concrete testing for fatigue life estimation. NDT & E International, (37), 597-602, DOI: 10.1016/j.ndteint.2004.03.006.

Ogunbode E.B., Egba E.I., Olaiju O.A., Elnafaty A.S., Kawuwa S.A., 2017, Microstructure and mechanical properties of green concrete composites containing coir fibre, Chemical Engineering Transactions, 61, 1879-1884, DOI: 10.3303/CET1761311

Ondrejka Harbulakova V., Estokova A., Kovalcikova M., 2017, Sustainable usage of slag in concrete for higher resistance in aggressive environment - mathematical evaluation, Chemical Engineering Transactions, 57, 481-486, DOI: 10.3303/CET1757081

Pani L., Francesconi L., 2014, Ultrasonic Test on Recycled Concrete: Relationship among Ultrasonic Waves Velocity, Compressive Strength and Elastic Modulus. Advanced Materials Research, 3031(894), 45-49.

Sansalone M., Carino NJ., 1986, Impact-echo: A method for flaw detection in concrete using transient stress waves, National Bureau of standards Report NBSR 86-3452, Gaithersburg, Maryland

Van Velsor J.K., Premkumar L., Chehab G., Rose J.L., 2011, Measuring the complex modulus of asphalt concrete using ultrasonic testing. Engineering Science and Technology Review, 4(2), 160-168.

Washer G., Fuchs P., Graybeal B.A., Hartmann J.L., 2014, Ultrasonic testing of reactive powder concrete transactions on ultrasonics. Ferroelectrics and Frequency Control, 51(2), 193-201.

Yan B.G., Yuan Y.M., Li Q.Z., 2002, A study on thickness detecting of concrete material by the ultrasonic method. Journal of Northwest University, 32(1), 20-22, DOI: 10.16152/j.cnki.xdxbzr.2002.01.008.

Yao J.J., Chen Z.X., 2000, Establishment of Ultrasonic Testing Strength Curve of Concrete Strength. Guangdong Architecture Civil Engineering, (1), 44-46.

Zhu J.Y., Chen L.Z., Yan X.S., 1998, Ultrasonic Pulses Behavior in Concrete During Compressive Loading. Engineering Mechanics, 13(3), 111-117.

Zhu Z.W., Zhu J., Qi J.L., Chen C.F., Lin F.L., 2010, Ultrasonic pulses behavior in steel fiber reinforced rubber high strength concrete during compressive loading. Concrete, (1), 12-14.