Advanced Materials Research Vols. 368-373 (2012) pp 2229-2234
Online available since 2011/Oct/24 at www.scientific.net

doi:10.4028/www.scientific.net/AMR.368-373.2229

Ultrasonic Detection Algorithm Research on the Damage Depth of Concrete after Fire

Jiangtao Yu[1,a], Yuan Liu[1,b], Zhoudao Lu[1,c], Peng Zhao[2,d]

[1]Research Institute of Structural Engineering and Disaster Reduction, Tongji University, Shanghai 20092, China;

[2]Suzhou Institute of Biomedical Engineering and Technology，Suzhou 215263，China

[a]yujiangtao@tongji.edu.cn, [b]liuyuan0811@126.com

[c]luzhoudao@163.com, [d]zhaopeng@sibet.ac.cn

Keywords: Concrete, Fire damage, Damage depth, Ultrasonic wave.

Abstract: To measure the depth of fire-damaged concrete by ultrasonic method, it was traditionally assumed that the concrete of the fire-damaged structural member could be simply classified into damaged layer and undamaged layer. Based on it, the damage depth can be calculated with a series of single-sided ultrasonic measured data. This method is simple and convenient but less accurate in the practical application. To improve the algorithm, hyperbola curves are adopted to simulate the varying of damage with depth in this paper. And parabolic curves are adopted to simulate the traces of ultrasonic wave in different measured distances. Therefore, the minimum propagation time can be obtained under different damage conditions. Through comparing the calculating results and measured data in different measured distances, the most likely damaged trend can be determined with least square method. At the end of this paper, examples are demonstrated to prove this algorithm feasible and more accurate than the traditional one.

Introduction

When exposed to fire, concrete undergoes a series of changes in its chemical composition and physical properties, which results in higher porosity, lower strength and lower elastic modulus, and has bad effects to bearing capacity and durability of concrete members [1-3]. Ultrasonic single side method and layer and layer method are the two main methods of detection of concrete damage [3,4]. Yang Yan-ke and Zheng Sheng-e did a series of experimental study on velocity of sound in concrete after fire by ultrasonic method and proved that there exists obvious relationship between strength of concrete after fire and velocity of sound in it, and ultrasonic method is effective for damage detection [5,6].

In order to facilitate the use of ultrasonic method, some assumptions were used to simplify the algorithm in code [4] and at the same time lead a coarser result. For example, according to code [4], the concrete element are divided into damaged layer and undamaged layer by a artificial boundary and the trace is assumed to be a trilinear model which is comprised of two oblique lines in damaged layer and a horizontal line in undamaged layer. Based on the assumption which is different from truth, the curve of measured distance and propagation time is double-linear9 (see Fig.1). In actual detection, it’s difficult to find the turning-point on the measured curve which leads the following analysis unsustainable.

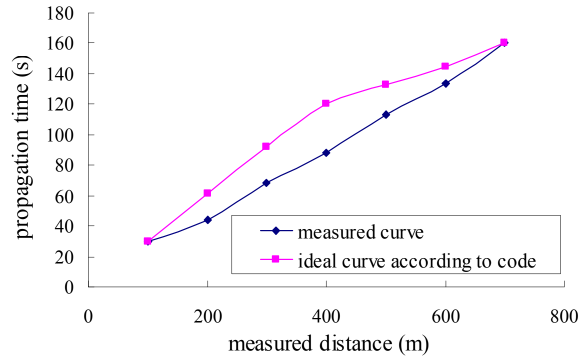

Fig. 1 Curves of measured distance and propagation time

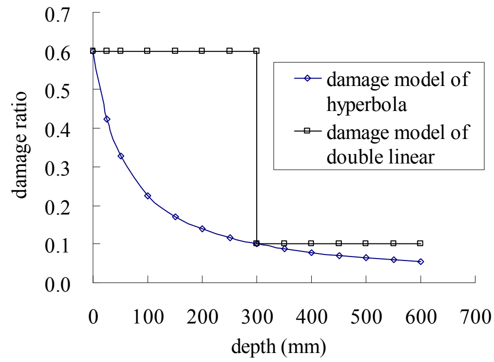

Fig. 2 Curves of fire damaged trends of concrete

Ultrasonic wave has infinite transmission paths in concrete and generally speaking, ultrasonic receive equipment gathers the propagation time of head wave. In undamaged concrete, head wave transmit by the nearly straight line path which is close to the surface. After fire, the surface layer damages which causes velocity of sound drops and when the measured distance is far, head wave may be transmit to the inner concrete which is damaged lightly. According to this theory, code[4] adopt the propagation times of head waves at different measured distances to calculate the damage depth which is not accurate enough because it import some assumptions to simplify. In order to modify the algorithm to get an ideal result, the following assumptions are adopted: 1) The concrete damage caused by fire is corresponding to temperature field ever experienced [3]. According to experimental and theoretical results from several research institutions, curves of temperature of concrete in fire and distance to exposed surface are smooth curves[1-3], so assume that velocity of sound in concrete distributed in hyperbolically pattern along depth(see Fig.2). 2) Ultrasonic wave's propagation path isn't a hyperbola [7,8]. 3) Concrete can seem to be undamaged if velocity of sound drops fewer than 10%. Relationship among mechanics property and temperature is linear when temperature is higher than 200˚C [3], and below 200℃ , the mechanics property drops little, fewer than 10%. So 10% is regarded as dividing line to distinguish the concrete damaged or not. These assumptions are more practical than those applied by code.

The principle and formulas algorithm

Based on assumption 1, concrete damage in direction of depth can be expressed as follow:

$$z = V_{max}[1.0 - m/(y+c)] \quad . \tag{1}$$

Where independent variables y stands for depth (unit mm); z stands for the corresponding velocity of sound; constant V_{max} is velocity of sound in undamaged concrete (unit m/s); m and c are coefficients need to be undetermined which have relationship with concrete damage. If m and c being determined, the concrete damage includes damage depth can be calculated.

In fire, parts where unaffected by fire exist in most structures, the value V_{max} can be get from these parts. If y=0, $z = V_{min} = V_{max}(1.0 - m/c)$, which stands for damage value of surface layer. In actual detection, a short distance (10mm) is adopted to detect the velocity of sound in most serious damaged concrete V_{min}, because at this time, the ultrasonic wave can be deemed to transmit along the surface. Therefore m and c have the relationship as follow:

$$m/c = 1 - V_{min}/V_{max} \quad . \tag{2}$$

In addition to Eq.2, some other conditions are needed to get m and c. According to the detection method provided by code, several distances are adopted (usually 6 distances with intervals of 100mm) to obtain the corresponding propagation times. A concrete member after fire has one pair of m and c which have relationship with damage degree. By giving the range of m and c, take all combinations step by step and calculate the propagation times at different measured distances.

Compared to the measured propagation times, the nearest set of date corresponds to the pair of m and c which is closest to the real damage coefficient. According to assumption 2, in a certain distance, the propagation path of ultrasonic wave can be expressed as follow:

$$y = k(x-a)(x+a), k \in (0,\infty). \tag{3}$$

where a stands for half of the measured distance (unit mm) and k is an impact factor which has relationship with propagation path. In a measured distance $2a$, the length of propagation path of ultrasonic wave is obtained by integral:

$$s = 2\int_0^a \sqrt{1+(y')^2}\,dx = 2\int_0^a \sqrt{1+4k^2x^2}\,dx. \tag{4}$$

Obviously, the smaller the k value, the smaller the total length of path. When k is close to 0, s=2a, and path is along concrete surface. Considering the damage, the velocity of sound in surface layer is slower, so the propagation time of head wave T (unit μs) is as follows:

$$T = \int_{-a}^{a} \frac{y}{z}dx = \frac{2k}{V_{\max}}\left[a\sqrt{a^2+\frac{1}{4k^2}} + \frac{1}{4k^2}\ln\left(2ka+\sqrt{1+4k^2a^2}\right)\right]$$

$$+\frac{2m}{V_{\max}}\left\{\frac{4}{a}\tan^{-1}\frac{\sqrt{1+4k^2a^2}-1}{2ka} + \ln\left|\frac{\frac{\sqrt{1+4k^2a^2}-1}{2ka}-\sqrt{4-\frac{4}{L}}}{\frac{\sqrt{1+4k^2a^2}-1}{2ka}+\sqrt{4-\frac{4}{L}}}\right|\right\}. \tag{5}$$

Eq.5 is derived by differentiating and order:

$$T'(k) = 0. \tag{6}$$

The minimum value T at any damage degree is obtained by solving Eq.6 and the expression is leaved out because the tediously long form. Combined with Eq.2, take m and c within modest bounds and get multiple minimum T corresponding to different measured distances. Find the T which is nearest to the measured data and then determine the m and c.

Numerical method

With the help of MATLAB, the author completed the programming UDFD - 2 which included numerical calculation, man-machine interface and graphics.

Numerical calculation principle and analytic method is consistent. In computing, often specify D a large scope, for example 0~60mm, in order to avoid omissions. So the calculation of the program includes triple nest of damage boundary depth D, measured distance 2a and depth coefficient of track k. The calculation process is as fig. 3.

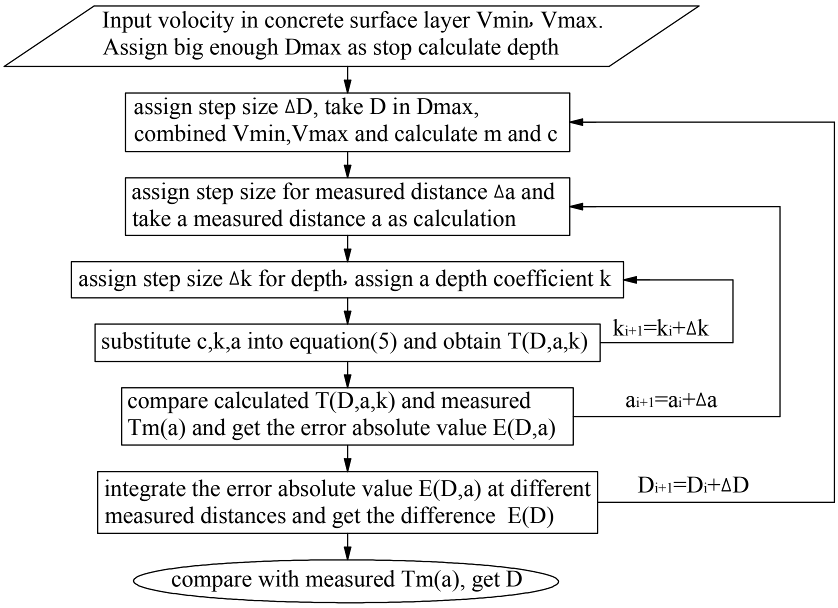

Fig.3 Flow diagram of numerical analysis program

Example analysis

In order to prove the rationality of this algorithm, a set of measured data of a concrete frame structure in a chemical factory and measured data from fire resistance lab of Tongji University by single-sided ultrasonic method was used. The method provided by code [4] was used to modify the effect of zero propagation time delay and the diameter of launch and receiver. The calculation results are as shown in table 1 and fig. 4~9. The curves of propagation and measured distance (fig. 5 and fig.8) are nearly straight, even fluctuate a little, the lines are not like double-linears. In this case the method provided by code to judge the break of the double–linear is difficult. As shown in fig. 5 and fig.8, the calculation curves and the measures curves are in good agreement.

Table 1 Comparison of detection data and matlab calculation results

single-sided ultrasonic measured data of a chemical factory			Calculation result by program		single-sided ultrasonic measured data from lab			Calculation result by program	
Measured distance (mm)	Propagation time by measure (us)	Modify velocity of sound (km/s)	Propagation time by calculation (us)	Velocity of sound by calculation (km/s)	Measured distance (mm)	Propagation time by measure (us)	Modify velocity of sound (km/s)	Propagation time by calculation (us)	Velocity of sound by calculation (km/s)
145	74.4	1.949	55.2	2.629	100	81.8	1.223	86.5	1.156
245	90.0	2.722	84.4	2.902	200	143.0	1.399	125.7	1.591
345	118.0	2.924	112.0	3.080	300	164.6	1.823	159.4	1.883
445	135.0	3.296	138.6	3.210	400	192.6	2.077	190.6	2.098
545	159.0	3.428	164.7	3.310	500	212.6	2.352	220.5	2.267
645	183.0	3.525	190.3	3.390	600	252.6	2.375	249.5	2.405

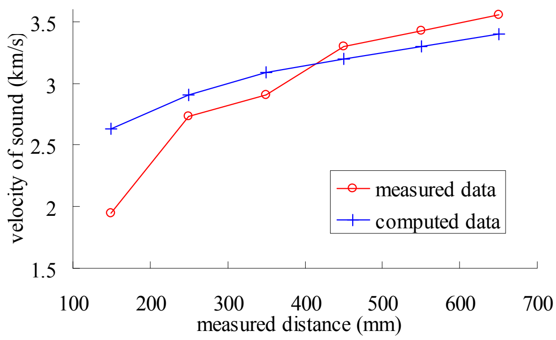

Fig.4 Curves of velocity of sound and measured distance (factory)

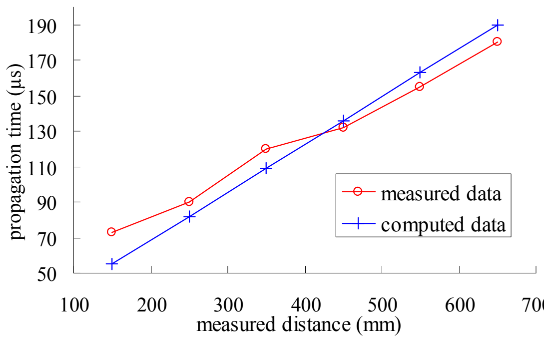

Fig.5 Curves of propagation time and measured distance (factory)

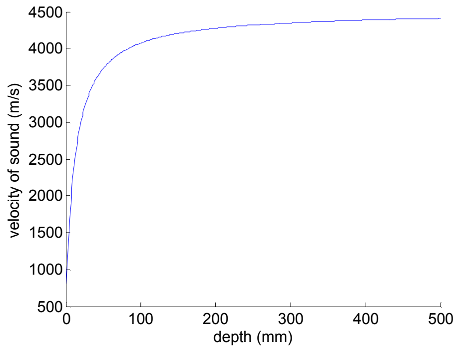

Fig. 6 Curve of fire damage trend of concrete (factory)

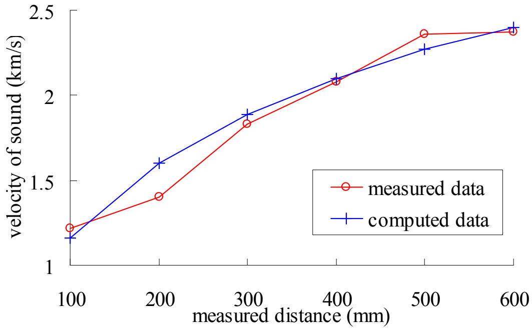

Fig.7 Curves of velocity of sound and measured distance (lab)

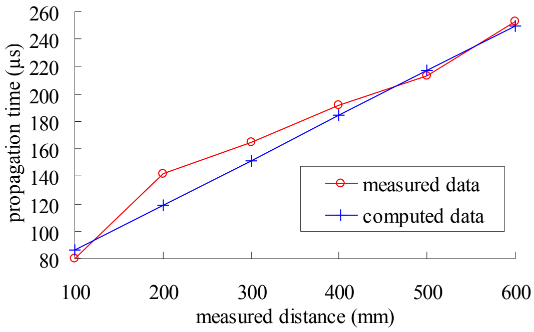

Fig.8 Curves of propagation time and measured distance (lab)

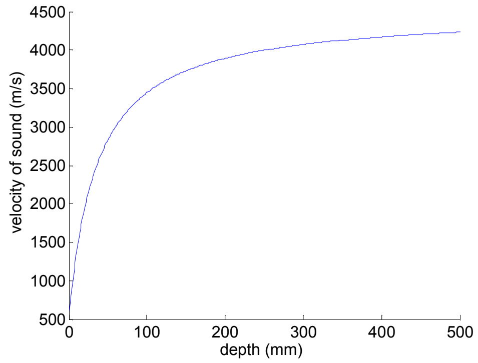

Fig. 9 Curve of fire damage trend of concrete (lab)

As is well-known, the velocity of sound in concrete measured by single-sided ultrasonic method will not change obviously with measured distance. From curves of velocity of sound and measured distance (fig.4 and fig.7), both measured velocity of sound and calculated velocity increase with depth which can be explain as follows: when measured distance is short, the head wave transmit in the part which damaged more serious and the velocity of sound is less than the velocity in undamaged concrete; with measured distance increasing, head wave transmits downward to the undamaged or slighter damaged concrete and the velocity of sound increasing. In contract, algorithm from code has double-linear only includes velocity of sound in damaged concrete and velocity in undamaged concrete, and is less accurate.

Curves of fire damage trends (calculating hyperbola) in fig. 6 and fig. 9 show the velocity of sound trend in direction of depth of concrete instead of thickness of damaged layer get by double-linear. Combining the velocity of sound in undamaged concrete, designers can calculate the removing depth and repairing depth. From fig. 6 and fig. 9, either strength of surface layer or damage depth get from lab is higher than that of concrete column of factory which agrees with rebound strength of surface layer get from scene.

Conclusions

Against the difficulty of detection of damage depth and damage trend of concrete structures after fire, single-sided ultrasonic algorithm used by code [4] is modified and formula deduction of the modified algorithm is done. Based on the algorithm, program and calculation are done by using MATLAB. Through analysis and comparison of two groups of measured date, the modified algorithm is more reasonable and more accurate on assessment of damage degree and damage trend of concrete after fire.

Acknowledgement

It is a project Supported by the National Natural Science Foundation of China (50778134).

References

[1] Zhenhai Guo, Xudong Shi. Behaviour of reinforcement concrete at elevated temperature and its calculation[M].Beijing: Tsinghua University Press, 2003

[2] Cancan Li. Experimental research of deterioration assessment for fire damaged concrete structures[D]. Shanghai: Tongji University, 2006.

[3] Jiangtao Yu. Experimental and theoretical research on damage assessment of reinforced concrete member after fire [D]. Shanghai: Tongji University, 2007.

[4] Technical specification for inspection of concrete defects by ultrasonic method (CECS 21: 2000) [S]. Beijing: China Engineering Construction Standardization Association, 2000

[5] Yanke Yang, Sheng'e Zhen. Evaluating temperature distribution of the section of fire damaged concrete elements by ultrasonic method[J].*Journal of Southwest Jiaotong University,* 1993,92(4) :78-83.

[6] Yanke Yang, Sheng'e Zhen. Fire damage inspection of concrete. [J].*Building Science Research of Sichuan*, 1991, (4):22-27

[7] Hongwei Ma, Jiatong Yang. Methods and advances of structural damage detection [J].*Advances in Mechanics*, 1999, 29(4):513-527.

[8] Bin Han, Tao Zhang. A study on the amplitude of elastic wave transmission in inhomogeneous media [J]. *Journal of Beijing Institute of Technology (Natural Science Edition),* 2006, 26(5):383-387

Advances in Civil Engineering and Architecture Innovation
10.4028/www.scientific.net/AMR.368-373

Ultrasonic Detection Algorithm Research on the Damage Depth of Concrete after Fire

10.4028/www.scientific.net/AMR.368-373.2229