Scientific paper

Ultrasonic Monitoring of Crack Propagation of Notched Concretes Using Embedded Piezo-electric Transducers

Shunquan Zhang¹, Wei Ma², Yuanliang Xiong³, Jinya Ma⁴, Chun Chen⁵, Yamei Zhang^{6*} and Zongjin Li⁷

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Abstract

The ultrasonic transmission method based on embedded piezoelectric transducers is employed to continuously monitor the cracking process of different strength notched concrete specimens under three-point bending. For comparison, the strain gauge technique is applied simultaneously. An ultrasonic damage index is employed to analyze the onset and propagation of cracking in concretes of three different strength levels. It is found that the damage process could be characterized by three typical stages, i.e., undamaged stage, progressive stage and failure stage, by this damage index. For estimating the onset of cracking, the embedded ultrasonic method is more accurate and sensitive than strain gauge technique. With the increase of strength level of concrete, the difference in initial cracking loads between the results obtained by the embedded ultrasonic method and strain gauge technique is reduced. An obvious decreasing trend in the duration of progressive damage stage with the increase of strength level is confirmed with embedded ultrasonic method.

1. Introduction

Nowadays concrete is still the most widely used building material across the world. Cracking caused by various factors is a key issue that influences the durability, service life and safety of concrete structures, it is therefore of great importance to monitor the damage process of concrete during its service period.

With regard to cracking monitoring, many nondestructive testing (NDT) techniques have been developed in recent years, among which the strain gauge technique is widely used for detecting concrete cracking (Chen *et al.* 2004; Badawi *et al.* 2005; Beppu *et al.* 2008). However, it requires a large amount of preparatory work and cannot continuously monitor the full damage process. Further-

more, the non-uniform strain field caused by roughness of concrete surface affects the test results extremely (Villalba *et al.* 2013). Visual inspection is also commonly used for estimating the state of a structure, but this method is not only time-consuming and costly, but also unreliable because it can only detect apparent macroscopic damage (Cruz *et al.* 2006; Goueygou *et al.* 2008). Acoustic emission (AE) technique has overwhelming advantages in detecting crack initiation, location and propagation over conventional methods based on the recording of transient signals, which correspond to newly initiated cracks or even propagation of existing cracks (Pei *et al.* 2015; Zhang *et al.* 2016). Dumoulin and Deraemaeker (2017b) pointed out that information may be lost and cannot be recovered if the AE monitoring system does not run during the cracking process in comparison with ultrasonic method. Therefore, the choice of defects identification in concrete between AE technique and ultrasonic method depends on instrument capability, serviceable range, condition and actual need. Radiographic techniques, namely X-rays, gamma-rays and neutron rays based techniques, are capable of detecting damage in concrete (McCann *et al.* 2001). However, they are in fact not only quite complicated and expensive, but are also required to meet strict safety provisions when applied. In addition, the resolution of these technologies is dependent on the size of testing objects. Generally speaking, the thinner the specimen, the smaller is the voxel size and the better the resolution (Olivier *et al.* 2016).

Ultrasonic transmission technique, known as one of the most reliable and convenient NDT methods, can be utilized to assess the concrete quality or damage by actively generated P-waves or S-waves (Aggelis and Shiotani 2007). Demirboğa *et al.* (2004) found a good correlation between ultrasonic pulse velocity and com-

¹Ph.D. student, School of Materials Science and Engineering, Jiangsu Key Laboratory of Construction Materials, Southeast University, Nanjing, 211189, China.

²Ph.D. student, Department of Infrastructure Engineering The University of Melbourne, Australia.

³Ph.D. student, School of Materials Science and Engineering, Jiangsu Key Laboratory of Construction Materials, Southeast University, Nanjing, 211189, China.

⁴Master course student, School of Materials Science and Engineering, Jiangsu Key Laboratory of Construction Materials, Southeast University, Nanjing, 211189, China.

⁵Professor, School of Materials Science and Engineering, Jiangsu Key Laboratory of Construction Materials, Southeast University, Nanjing, 211189, China.

⁶Professor, School of Materials Science and Engineering, Jiangsu Key Laboratory of Construction Materials, Southeast University, Nanjing, 211189, China.

*Corresponding author, E-mail: ymzhang@seu.edu.cn

⁷Professor, University of Macau, Macau, China.

pressive strength and elastic modulus based on empirical models for concretes. Grosse *et al.* (2006) and Kumar and Santhanam (2006) verified that the change of ultrasonic parameters like waveform, velocity and amplitude of initial wave etc., could provide a good qualitative or quantitative information on damage degree of concrete. However, the traditional commercially available PZT ultrasonic transducers are usually held in contact with concrete surfaces using coupling agent (gel or grease). Hence there will be inevitable matching problems between concrete and transducers, which are caused by irregular concrete surface or man-made operational mistakes (Xu *et al.* 2012; Kee *et al.* 2013). For in-situ application of the ultrasonic transmission technique, it has limitations in applicability in hard-to-access areas of concrete structures using external probes (Kee *et al.* 2013; Dumoulin *et al.* 2017a).

For the purpose of overcoming the aforementioned drawbacks, some researchers have developed embedded piezoelectric transducers that can be applied in concrete structures. These transducers, the so called 'smart aggregates', initially proposed at the University of Houston (Gu *et al.* 2006), can be flexibly distributed inside concrete structures and form a complete monitoring network. The preparation of embedded transducers can be classified into two types. The first type employs fragile piezoelectric ceramic patches or discs as core organs that are processed and packaged with multiple coating layers (Gu *et al.* 2006; Song *et al.* 2008; Dumoulin *et al.* 2012, 2014). This kind of transducer is inspired by a desire to reduce the cost by use of low-cost commercial piezoelectric patch or disc. The second type is comprised of cement-based piezoelectric composites with particles of piezoelectric materials (Li *et al.* 2002) or multiple piezoelectric plates (Dong and Li 2005), piezoelectric rods (Huang *et al.* 2015), etc. as sensing elements and cement based materials as binding material. These two types of transducers not only possess a superior piezoelectric property, a remarkable impedance matching with packaging cement based materials is achieved as well.

In this investigation, taking into account the complexity of manufacturing the second type of transducers, we choose the low-cost PZT piezoelectric ceramic disc directly both as the actuators and sensors and implement a special package technique. An ultrasonic monitoring system based on the embedded piezoelectric transducers is developed, which can continuously record signals at high rates and conduct post-process based on a damage indicator. The main advantage of this technique is the feasibility of monitoring online and real-time cracking process for concrete structures.

Early detection of initial cracking is essential to obtain such information about concrete structures and is thereafter helpful for taking necessary preventive or rehabilitative action to repair or maintain concrete structural members (Karaïskos *et al.* 2015; Shokouhi *et al.* 2012). In addition, strength grade, which is mainly determined by water to binder ratio, is a crucial factor that affects

concrete damage or fracture process (Wu *et al.* 2001). Due to the increase of brittleness, the crack propagation of high-strength concrete is different from that of normal concrete (Wittmann 2002). Therefore, compared with the traditional strain gauge technique, embedded transducers based ultrasonic monitoring system by introducing a damage index based on the computing of baseline value is employed to continuously investigate the damage process of different strength grade concrete specimens subjected to three-point bending load, the onset of cracking detected by both methods is compared as well.

2. Ultrasonic monitoring system

A schematic diagram of the active ultrasonic monitoring system using home-made embedded transducers can be referred in the work of Zhang *et al.* (2018), which is indeed similar as presented in the previous researches (Xu *et al.* 2012; Qin and Li 2008). The received signal at each damaged state corresponds to the appearance of cracks or microcracks in the concrete structure compared to the initial state. By analyzing the changes in the received signal, the damaged state of structure can be estimated. The working flow of the system is as follows: a short pulse excitation signal ($8 V_{p-p}$ with a pulse width of $4.984 \mu s$ and a frequency of 100 kHz) is generated by a KEYSIGHT 33500B signal generator, which has the ability to excite broadband frequencies in a very short period of time. In order to obtain high-voltage actuation, the pulse signal is amplified 50 times based on the TEGAM 2350 power amplifier. The amplified input signal with a voltage of $400 V_{p-p}$ drives the emission transducer, whose output compressive wave (P-wave) travels through the concrete and is acquired by a receiving transducer. The receiving signal is amplified by a low-noise STANFORD SR560 preamplifier and is then digitized and recorded every one second by the KEYSIGHT 3014A oscilloscope with a bandwidth of 100 MHz. The data acquisition system reaches up to one ultrasonic measurement per second, which is the minimum value in the system settings. The automatic computer program control of the entire system and the post-processing of recorded data implemented in PYTHON are both developed by the authors.

2.1 Preparation of embedded piezoelectric transducers

The PZT piezoelectric disc with a thickness of 0.75 mm, diameter of 20 mm and a resonance frequency of 100 kHz is selected for use as both the actuator and the sensor of embedded piezoelectric transducers. It works by applying voltage on the piezoelectric disc to produce mechanical vibrations (i.e. the ultrasonic P-waves) based on radial vibration mode and, conversely, generating electric charges when excited by stress.

In this study, the home-made piezoelectric transducer is composed of a piezoelectric disc, a matching layer, a packaging layer, a backing layer, a shielding layer, a

shielding wire, a wire, and etc. (**Fig. 1**). The detailed processing procedure of embedded piezoelectric transducers has been described by Zhang *et al.* (2018). The dimension of a finished transducer is 30 mm × 30 mm × 30 mm.

2.2 Performance of embedded piezoelectric transducers

In this investigation, the transducer pair is embedded in concrete specimens at a fixed distance based on a pitch-catch configuration, i.e., one emitter and one receiver (Gu *et al.* 2006). For crack monitoring of concrete, the distance between emission and receiving transducers should not be too long, otherwise the receiving signal may be too weak to identify. The onset point of initial wave can be clearly identified due to the high signal-to-noise ratio of receiving signal (Xu *et al.* 2012), which is highly essential for judging the propagation velocity or amplitude of receiving signal correctly. The acoustic impedance of transducer's matching layer, which can be calculated in term of the density and the elasticity modulus (Li *et al.* 2002), is quite near to that of hardened concrete matrix, which facilitates low energy loss and high efficiency transmission as the ultrasonic wave travels in these two different media (Lu *et al.* 2015).

Piezoelectric disc, which has the advantages of low cost, small size, light weight, fast response and etc., is more suitable for being used as a sensing element of embedded piezoelectric transducer (Kee *et al.* 2013; Dumoulin and Deraemaeker 2017a). However, the piezoelectric disc is extremely fragile and vulnerable to be damaged. In order to effectively encapsulate and protect the piezoelectric disc, the transducer should have sufficient strength. **Figure 2** shows the typical stress-strain curve of the embedded transducer under uniaxial compressive load. It can be observed that the elastic limit and ultimate strength of transducer are 69.25 MPa and 172.66 MPa respectively, indicating that the transducers have high toughness and high mechanical strength and can effectively protect the fragile piezoelectric disc in it. This

phenomenon can be attributed to the fact that the epoxy matrix incorporated with proper content of inorganic micron particles (which are cement powders in this study) performs a significant strengthening effect, as pointed out by Lee and Yee (2000). Moreover, the strength of transducer is comparable to or even higher than that of ordinary coarse aggregate. Therefore, the shrinkage strain effect ascribed to early hydration process of cement and the stress between transducers and aggregates caused by applied loading will have negligible effect on embedded piezoelectric transducers (Gu *et al.* 2006).

According to the experimental results of Gupta *et al.* (1985) for epoxy resin system, there was a slight decrease in tensile strength with the increase of temperature from 20°C to 80°C. However, the strength began to fall sharply as the ambient temperature grew from 80°C to 160°C. Hence, temperature increase is a key issue for transducers that are composed of epoxy resin, cement, etc. Gu *et al.* (2006) stated that the temperature inside concrete attributed to hydration heat is normally below 60 to 80°C. Therefore, it is necessary to take measures to reduce the temperature rise of interior concrete in the casting process in order to minimize its impact on embedded transducers. On the other hand, since the Curie temperature of the sensing element of transducer, namely the piezoelectric ceramic disc, is within the range of 200 to 350°C (Gu *et al.* 2006; Ochiai *et al.* 2008), the influence of temperature effect can therefore be neglected.

2.3 Ultrasonic damage index

For ultrasonic method, the value of velocity (or travel time, which can be calculated and according to l/v , where l is distance and v is ultrasonic velocity) and amplitude of initial wave are the two important parameters to evaluate the damage degree of concrete (Mirmiran and Wei 2001; Suaris and Fernando 1987). Shokouhi *et al.* (2012) stated that the variation of amplitude of receiving signal is more sensitive than the evolution of travel time for damage identification. The amplitude of initial reception wave can decrease when the concrete is damaged, as shown in

Fig. 1 The structure of a transducer.

Fig. 2 The typical stress-strain curve of the embedded transducer.

Table 1 Mix proportion of three types of concretes (kg/m³).

Strength Grade	Water/cement ratio	Cement	Water	Sand	Limestone	Super plasticizer
C40	0.53	377	200	754	1131	/
C60	0.35	457	160	686	1143	2.28
C80	0.26	538	140	646	968	8.60

Fig. 3 (a). In this investigation, ultrasonic damage index based on the variation of amplitude of receiving signal in the time window of the first half-period is chosen as an indicator to evaluate the damage of notched concrete. It should be noted that the first period of receiving signal accords with the shortest wave path, which is only influenced by the mechanical properties of concrete between emitter and receiver (Dumoulin and Deraemaeker 2017b; Dumoulin *et al.* 2014). The damage index which is similar to the estimation of the corrosion variation of reinforcing bar in concrete (Du *et al.* 2017), can be written as,

$$I_x = \frac{U_0 - U}{U_0} \quad (1)$$

where U is amplitude of a receiving signal at first half-period; the amplitude of undamaged initial receiving wave always fluctuates in a definitive range due to the interference of noise [Fig. 3 (b)], which may be attributed to the continuous vibration from the loading equipment. U_0 is a baseline value.

Since the distributed undamaged amplitudes are subject to Gauss distribution, Gaussian fitting is performed and fitting parameters can be obtained. The mean (or mathematical expectation) of fitting parameter can be regarded as a baseline value. The uniqueness of this damage index lies in developing a method that analyzes the noise on the basis of the computing of baseline value compared to the one presented by Dumoulin *et al.* (2014). According to equation (1), when the damage index is zero, it indicates that recorded signal is undamaged. When the index is equal to one, it implies that the damage amplitude is too weak to monitor.

3. Experiment

3.1 Raw materials and mix proportions of concrete

Portland cement 52.5 P·II with a specific surface area of 365 m²/kg and a density of 3150 kg/m³ was used as binding material of concrete. River sand with a fineness modulus of 2.6 was used as fine aggregate. Crushed limestone with particle size of 5 - 20 mm was employed as coarse aggregate. Polycarboxylate type superplasticizer with solid content of 30% was used to adjust the workability of concrete.

In order to investigate the effect of strength grade on the damage process of notched concrete under bending, three levels of water to binder ratio (0.53, 0.35 and 0.26) were considered. The detailed mix proportions are presented in Table 1.

3.2 Specimen preparation

For each strength grade, three cubic specimens (100 mm × 100 mm × 100 mm) were prepared for compression test and three cuboid specimens (100 mm × 100 mm × 400 mm) with notch for three-point bending test. The size of concrete notch is 100 mm (length) × 2 mm (width) × 35 mm (depth). Although the slump of these types of concretes was different (Table 2), vibration was conducted to assure the compaction of concrete. All the specimens were demolded 24 h after casting and then cured in standard curing room at 20±2°C and 95±2% relative humidity for 28 d. The compressive strength of the concretes is measured according to the Chinese National Standard (2016). The Young's modulus is calculated by embedded ultrasonic method in accordance with Carette *et al.* (2012). The mechanical properties of concretes are given in Table 2.

Fig. 3 (a) Time domain graph of the undamaged and damaged waves and (b) Evolution of amplitude of a notched concrete specimen.

Table 2 Slump and mechanical properties of three types of concretes.

Strength Grade	Slump (mm)	Density (kg/m ³)	Ultrasonic velocity (m/s)	Compressive strength (MPa)	Young's modulus (GPa)
C40	50	2414	4237	41.2	32.2
C60	60	2470	4336	61.8	34.5
C80	190	2596	4404	81.4	37.4

Before notched concrete casting, a couple of transducers were already pre-fixed in the plastic mold by Plexiglass plates, which were adhered to the back of transducers and had little effect on signal transmitting or receiving and the failure process of notched concretes. The surface-to-surface distance between the emission and receiving transducers is 150 mm. The surface-to-surface line between the outer edge of emission and receiving transducers is tangent to the notch tip. The arrangement of two embedded transducers in a notched concrete specimen is shown in Fig. 4. For direct transmission, i.e., when the transducer pairs are located on the two opposite faces in concrete, the transmission of ultrasonic longitudinal waves follows the principle of fastest travel path or shortest travel time (Karaïskos *et al.* 2015). The travel path of ultrasonic wave transmitted from an emitter displays a form of polyline when the concrete is undamaged, as shown in Fig. 4. Once cracks occur near the notch tip, the travel path will increase.

3.3 Three-point bending test

MTS 810 testing machine was used for three-point bending test of notched concrete specimens. The load speed was 0.02 mm/min. The crack mouth opening dis-

placement (CMOD) was measured by a clip gauge that was installed at bottom center of the notch. The damage process was monitored using embedded ultrasonic method, simultaneously strain gauge technique was applied during the loading process for comparison purpose. Crack will be initiated at the tip of the notch with the load increasing, which leads to the diffraction and refraction of waves by crack tip (Aggelis and Shiotani 2007).

The sensitive grid size, sensitivity coefficient and electrical resistance of strain gauges are 10 mm × 3 mm, 2.08 and 120 Ω, respectively. The half bridge method was adopted for recording the strain in concrete, for which one active gauge and one temperature compensation gauge were connected to a digital acquisition instrument.

Before the installation of strain gauges, the surface of concrete near the tip of the notch was polished to be even and smooth with a fine sand paper and then was cleaned using ethyl alcohol. After applying a thin layer of epoxy resin uniformly at the predetermined positions, two strain gauges were attached on each side of the notch symmetrically and lied on the tangent line of notch tip. This method can be referred from the work of Li *et al.* (2010). The arrangement of strain gauges is shown in Fig. 5.

Fig. 4 Configuration of a pair of embedded transducers in a notched concrete specimen.

Fig. 5 Configuration of strain gauges on the surface of a notched concrete specimen.

4. Results and discussion

4.1 The load-CMOD curves and fracture surface morphology of notched concretes

Figure 6 (a) shows the typical load-CMOD curves for C40, C60 and C80 notched concrete specimens under three-point bending test. As can be observed, the peak load of C40, C60 and C80 concrete specimen is 4009, 5227 and 6341 N, respectively, which indicates that the peak load increases with the increase of strength. The curve near the peak becomes sharper and the corresponding CMOD gets smaller at peak load for high strength concrete than that of low strength concrete. Compared with C40 and C60 concrete specimens, the load decreases more quickly after peak load for C80 concrete, indicating that C80 concrete shows a rapid fracture failure process. Therefore, high strength results in high brittleness of concrete (Chen and Liu 2004).

Figures 6 (b), (c) and (d) exhibit the fracture surface of C40, C60 and C80 notched concrete specimen, respectively. It can be observed that most coarse aggregates of C40 concrete are unfractured and consequently the fracture surface is of irregular and rough character; only part of coarse aggregates are fractured directly on the fracture surface of C60 concrete; the fracture surface of C80 concrete is flat and most of the coarse aggregates are fractured directly. Through the load-CMOD curves it is observed that the cracks in higher strength concrete develops quickly and can travel through either interfaces or aggregates; The zigzag growth paths of cracks in C40 and C60 concrete suggest that cracks mainly propagate

along the interfacial transition zone (ITZ) between coarse aggregate and mortar, which are the weakest zones in low and ordinary strength concrete, as pointed out by Chen and Liu (2004).

4.2 Damage process

Figures 7 to 9 demonstrate the evolution of the ultrasonic damage index and the evolution of load with the increase of CMOD of different strength concrete specimens. The ultrasonic damage index in the corresponding graph is shown in red color. Unfortunately, one parallel specimen of C40 concrete was defective, thus only the results of two parallel specimens are given. For all the specimens, the evolution of the ultrasonic damage index can be divided into three stages: undamaged stage, progressive stage and failure stage (Dumoulin *et al.* 2014). In the undamaged stage, the damage index grows slowly and fluctuates in a certain range attributed to noisy signals. In the progressive stage, break point can be clearly observed at the end of undamaged stage, indicating the beginning of the opening or propagation of cracks inside the concrete. Thereafter, the damage index starts to increase rapidly owing to the formation of large amounts of cracks that hinder the spread of ultrasonic wave. In the failure stage, the damage index approaches to 1, indicating the complete destruction of the concrete structures, because the receiving transducer cannot receive the ultrasonic wave anymore in this stage. It is worth noting that the damage index saturates while the load can still grow after the load drops to 50 to 60% of maximum value, indicating that the index has limitations in the

Fig. 6 (a) Load versus CMOD for notched concrete specimens with different strength levels; the fracture surface of (b) C40, (c) C60 and (d) C80 notched concrete specimens (The points denoted "A" correspond to completely fractured coarse aggregates, whereas those denoted "B" points represent unfractured coarse aggregates).

description of failure stage. If multiple pairs of transducers are employed along the depth above the notch, the information of damage evolution may become more complete.

Figures 7 to 9 show that the duration of progressive damage stages of C80, C60 and C40 concrete are 0.0792 - 0.1219 mm, 0.1782 - 0.2464 mm and 0.3069 - 0.5801 mm, respectively. With the increase of strength level, the duration of progressive damage stage is reduced evidently. The results show that with the strength increases, the damage of concrete structures is accelerated under concentrated load. Wu *et al.* (2001) pointed out that the higher the compressive strength, the higher the brittleness of concrete. According to Carpinteri and Brighenti (2010), the lower strength concrete has higher capacity of energy dissipation and exhibits a ductile behavior than higher strength concrete does during the fracture process. From the viewpoint of crack formation, Wittmann (2002) noted that high strength shows lower ductility than normal concrete. The duration of progressive damage stage for different strength grade concretes can be distinguished, indicating that the embedded ultrasonic transducer method is sensitive to the detection of difference in the duration of progressive damage stage between different strength grade concretes.

4.3 Initial cracking load

From Figs. 7 to 9, sudden jumps, which are representative of sudden cracking events at the end of undamaged stage, are observed. The load corresponding to the onset of cracking monitored by embedded ultrasonic method is regarded as initial cracking load. This method can therefore capture the initiation of damage, as well as the following progressive development of cracking until complete failure of concrete.

Figures 10 to 12 show the load-strain relation detected by strain gauges. If crack does not occur, the strain located on each side of concrete notch tip increases linearly, which is attributed the fact that elastic deformation takes place at the tip of the notch. Once crack forms due to stress concentration at the notch tip, a retraction phenomenon appears on load-strain curve because of the release of strain energy at the tip of the notch, after which the strain begins to decrease with increasing load. The load corresponding to the inflection point of strain in load-strain curve is defined as initial cracking load of one measuring point (Xu and Reinhardt 2000; Li *et al.* 2010). The lowest value of initial cracking load among several measuring points is selected as the initial cracking load (P_{ini}) of notched concrete specimen. In Figs. 10 to 12, point A is considered as the point of initial cracking load (P_{ini}), whereas point B is the peak point of maximum load (P_{max}). After the peak load, the strain decreases with the

Fig. 7 Evolution of the ultrasonic damage index and load of three parallel C80 concrete specimens; (a) C80-1, (b) C80-2 and (c) C80-3.

drop of load. Since the purpose of this investigation is to use the strain gauge technique to obtain the initial cracking load, close attention is paid to the retraction phenomenon in the curve because it is a key issue.

The initial cracking loads for all specimens measured by strain gauge technique and embedded ultrasonic method are summarized and illustrated in **Table 3** in detail. It can be seen that the initial cracking load obtained by strain gauge technique is higher than that by embedded ultrasonic method. The results can be attrib-

uted to the attaching approach and positions of strain gauges, as shown in **Fig. 5**. The cracking process starts from initiation and micro-cracking stage inside concrete, which can be detected by embedded ultrasonic method rather than strain gauge technique. Hence, the measured initial cracking loads from strain gauges are higher than the initial cracking loads detected by embedded ultrasonic method. Results from both methods reveal that the higher the strength, the higher the initial cracking load for notched concrete, because the bonding between

Fig. 8 Evolution of the ultrasonic damage index and load of three parallel C60 concrete specimens; (a) C60-1, (b) C60-2 and (c) C60-3.

Fig. 9 Evolution of the ultrasonic damage index and load of two parallel C40 concrete specimens; (a) C40-1 and (b) C40-2.

Table 3 Characteristic values obtained by strain gauge technique and embedded ultrasonic method.

(SGT: strain gauge technique; EUM: embedded ultrasonic method)								
No.	C80-1	C80-2	C80-3	C60-1	C60-2	C60-3	C40-1	C40-2
Peak load (KN)	6341	5876	5925	5475	5561	5227	4588	4009
Fracture energy (N·m ⁻¹)	270.1	255.8	266.7	233.0	242.7	230.4	205.5	198.7
Initial cracking load measured by SGT (KN)	4680	4285	4599	4117	3116	3947	3043	2003
Initial cracking load measured by EUM (KN)	4469	3966	4209	3595	2709	3382	2453	1578
EUM/SGT (%)	95.49	92.56	91.52	87.32	86.90	85.70	80.61	79.23

hardened mortar and coarse aggregate is enhanced when water to binder ratio is decreased (Beshr *et al.* 2003). Yan *et al.* (2001) pointed out that strength is an essential factor affecting the fracture energy that can be determined according to the RILEM recommendation on fracture mechanics of concrete (RILEM-TCS 1985), as given in the following equation:

$$G_F = \frac{W_0 + mg\delta_{\max}}{(h-a)t} \quad (2)$$

where W_0 is the work done by the concentrated load, namely, the area of close curve in load-deflection graph (N m); mg is the self-weight of the notch specimen (N); $\delta_{\max}$ is the maximum displacement at failure (m); h and t

are the height and width of the notched concrete specimen, respectively; a is the depth of the notch.

The calculated results are presented in **Table 3**. It can be seen that higher strength concrete has higher fracture energy, which means higher energy is needed for overcoming interfacial bond in concrete and consequently resulting in the higher initial cracking load for higher strength concrete (Wu *et al.* 2001). Carpinteri and Brighenti (2010) proved that concrete with high water to binder ratio possesses inferior fracture resistance.

For embedded ultrasonic method that is based on a pitch-catch configuration, the monitoring area is larger than that of strain gauge technique. Moreover, the transducers embedded in concrete can act as smart aggregates, the inside damage can be detected from the

Fig. 10 Load-strain curves of three parallel C80 concrete specimens; (a) C80-1, (b) C80-2 and (c) C80-3.

Fig. 11 Load-strain curves of three parallel C60 concrete specimens; (a) C60-1, (b) C60-2 and (c) C60-3.

Fig. 12 Load-strain curves of two parallel C40 concrete specimens; (a) C40-1 and (b) C40-2.

sudden increasing of ultrasonic damage index at the end of initial cracking stage. Therefore, compared with strain gauge technique, the embedded ultrasonic method can lead to earlier initial cracking load. In other words, the embedded ultrasonic method is more accurate and sensitive to the onset of initial cracking load than strain gauge technique is.

The ratio of initial cracking load detected by embedded ultrasonic method to that measured by strain gauge

technique for each concrete specimen is summarized in **Table 3** as well. The higher the ratio, the shorter is the period of crack propagation. The ratio ranges are 91.52 to 95.49%, 85.70 to 87.32% and 79.23 to 80.61% for C80, C60 and C40 concrete specimens, respectively. It can be seen that the ratio increases with the increase of strength, which indicates that cracks propagate rapidly from interior up to the surface in high strength notched concrete. As a quasi-brittle material, higher strength concrete

possesses higher brittleness (Wittmann 2002). According to Yan *et al.* (2001), for low water to cement ratio concrete, cracks usually pass through coarse aggregate directly, while for high water to cement ratio concrete, cracks propagate primarily around the aggregate. This phenomenon is proved in Fig. 6 as well. The results in Table 3 also demonstrate that the difference in the initial cracking load obtained from the two methods gets smaller when the strength grade of concrete becomes higher.

5. Conclusions

In this research, the cracking process of notched concrete specimens with different strength levels is detected by the use of an ultrasonic technique based on embedded piezoelectric transducers and traditional strain gauge technique. The following conclusions can be summarized:

- (1) The damage index is an excellent indicator in the detection of the onset of cracking in notched concrete specimens by the use of a pair of transducers. However, it has limitations in the description of damage evolution, especially at the failure stage.
- (2) The onset of cracking detected by embedded ultrasonic method is earlier than that by strain gauge technique, illustrating that embedded ultrasonic method has the better ability to capture the micro-cracking stage of concrete.
- (3) The difference in initial cracking loads between the value determined by embedded ultrasonic method and the result obtained by the strain gauge technique decreases with increasing strength level, indicating that cracks or damage propagate rapidly from interior up to the surface in high strength notched concrete.

Considering the limited monitoring area of one pair of transducers, it is necessary to embed more transducers in real structures in order to monitor the cracking at the most sensitive and weakest parts of practical engineering. Because of the low-cost of the transducers, it is possible to allow flexible configuration of transducer network. One important issue that needs further investigation is the optimization of transducer distribution in concrete structures. Besides, the damage index proposed in this investigation may be not applicable for multiple signals processing in case of multiple pairs of transducers. Further study of a damage index suitable for complex signal processing strategies should be meaningful.

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