23rd Australasian Conference on the Mechanics of Structures and Materials

2014

A novel method for tensile testing of very early-age concrete

Duy Nguyen
University of Queensland

Vinh Dao
University of Queensland

Publication details

Nguyen, D & Dao, V 2014, 'A novel method for tensile testing of very early-age concrete', in ST Smith (ed.), *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*, vol. I, Byron Bay, NSW, 9-12 December, Southern Cross University, Lismore, NSW, pp. 47-52. ISBN: 9780994152008.

A NOVEL METHOD FOR TENSILE TESTING OF VERY EARLY-AGE CONCRETE

Duy Nguyen
School of Civil Engineering, the University of Queensland
Brisbane St Lucia, QLD, 4072, Australia, d.nguyen14@uq.edu.au

Vinh Dao*
School of Civil Engineering, the University of Queensland
Brisbane St Lucia, QLD, 4072, Australia, v.dao@uq.edu.au (Corresponding Author)

ABSTRACT

Early-age cracking can seriously compromise the performance and aesthetics of concrete structures, and is thus an ongoing major concern to the concrete construction industry. More effective control of this form of cracking requires an improved knowledge of concrete properties. In this paper, currently available test methods for complete stress-strain curves of early-age concrete are first briefly reviewed. A new system specifically designed for early-age tensile testing of concrete is then described. The novel use of digital image correlation in this system enables the desired deformation to be reliably captured in a non-contact way – a significant improvement compared to previous studies. The more reliable data to be collected would result in improved knowledge of concrete at early ages, including the tensile strength, Young's modulus, strain at peak stress, and fracture mechanics characteristics, as well as their interrelationships and development with time. This improved understanding would form a solid basis for more effective control of early-age cracking in concrete.

KEYWORDS

Early-age concrete, direct tensile test, digital image correlation (DIC), pattern application.

INTRODUCTION

Early-age cracking can occur in concrete during the first few hours after casting. It can seriously compromise the serviceability, durability and aesthetics of concrete structures, and is thus a major concern to the concrete construction industry. Highway pavements, bridge decks, industrial and residential floors, wharves, podiums, and parking structures, to name a few, are all susceptible to this type of cracking. The current trend of increasing use of concrete mixes with lower water-binder ratios, lower bleed capacities, and higher contents of cement and fine materials such as silica fume, increases the susceptibility of concrete structures to early-age cracking. (In this paper, the term "early-age concrete" refers to concrete with ages of less than 8 hours after casting.)

In principle, cracking occurs when the tensile stresses arising in the concrete reach their tensile strength or, equivalently, when the restrained shrinkage strain reaches the strain at maximum tensile stress. Also, cracks can only grow if the energy required to break the material – the fracture energy – is supplied. Accordingly, knowledge of the complete tensile stress-strain curves of concrete at early ages is essential for the study of its behaviour, including early-age cracking.

Although this need for improved knowledge of complete stress-strain curves of early-age concrete has long been recognised, there is very limited literature available (Branch et al., 2002; Dao et al., 2009;

Hannant et al., 1999) due mainly to the considerable challenges in their measurements: Early-age concrete is quite fragile and has very low tensile strength.

In this paper, currently available test methods for complete stress-strain curves of early-age concrete are first briefly reviewed. On that basis, a novel tensile testing system that can reliably capture the complete stress-strain curves of early-age concrete is described. The to-be-collected data are expected to result in significantly improved knowledge of various very early-age tensile properties of concrete, including the tensile strength, Young's modulus, strain at peak stress, and fracture mechanics parameters, as well as their interrelationships and development with time.

REVIEW OF AVAILABLE TEST METHODS FOR COMPLETE STRESS-STRAIN CURVES OF EARLY-AGE CONCRETE

Available data on complete tensile stress-strain curves of concrete at very early ages are very limited (Branch et al., 2002; Dao et al., 2009; Hannant et al., 1999). Hannant et al. (1999) was the first group who applied the idea of an air-bearing bed with 10 round holes providing air-jets, supporting the specimen in order to minimize contact friction. The concrete specimen was cast into a steel mould with two removable "necks" and connected into a lightweight testing frame especially designed for the test. A displacement rate of 0.75mm/min was applied instead of loading rate to capture the descending part of tensile stress-strain curves. The strain measurement, however, relies on an LVDT attached on two posts precast into concrete specimen: The likely movement of the two posts in young concrete and the resulting disturbance seriously compromised the measurement accuracy. The applied displacement rate was also too fast in many cases to capture full stress-strain relationships.

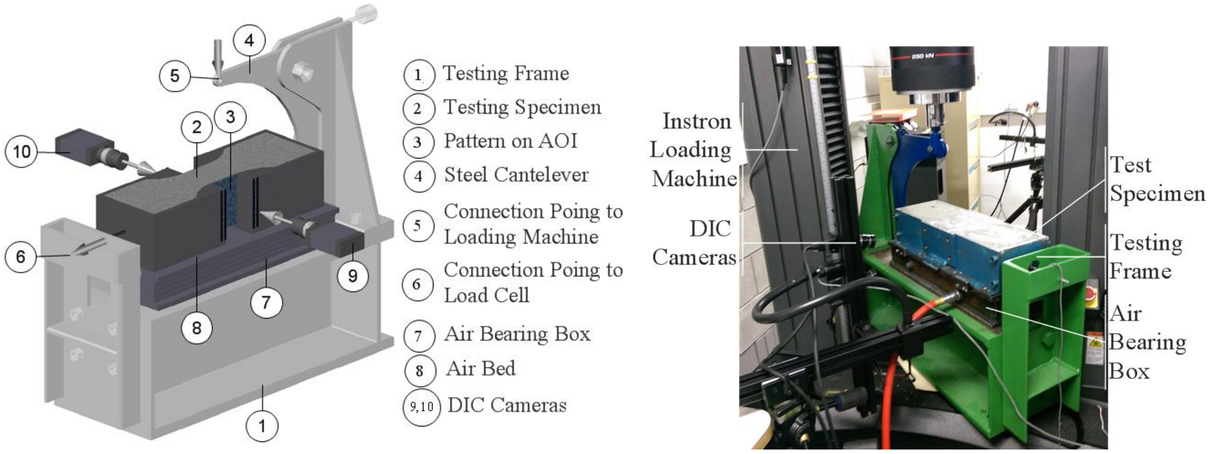
The air-bearing box system was also used in the new apparatus for the tensile testing of fresh concrete by Dao et al. (2009). Smaller displacement rate of 0.05mm/min was applied and full stress-strain curve of most test specimens was successfully captured. The total deformation of the whole specimen was recorded by a pair of LVDTs attached to the two specimen sides. Deformation over the central gauge-length was then estimated from the recorded total deformation using finite element analysis – However, the reliability of this estimation cannot be ascertained yet. The novel use of digital image correlation presented in the subsequent sections will help address this critical limitation by measuring the desired deformation over the central region in a non-contact way.

NOVEL TEST METHOD USING DIGITAL IMAGE CORRELATION AND AIR-BEARING BOX

The direct tensile test setup proposed in this paper is schematically shown in Figure 1a. Notable features of this test setup include: (a) the air bearing box to provide a uniform air cushion that virtually eliminates friction between the specimen and the supporting base, (b) the adoption of displacement-based test rate enabling full stress-strain curves to be captured, and *importantly* (c) the novel application of Digital Image Correlation (DIC) for displacement measurement to address the a critical limitation in earlier studies:

a) Two cameras (⑨ and ⑩ in Figure 1) are setup to capture the deformation of the exposed central region on both sides of the specimen. (The exposed central region is called the areas of interest – AOIs.) This setup for non-contact deformation measurement thus overcomes the limitations associated with the use of LVDTs on the posts precast in concrete (Hannant et al., 1999) or on the steel mould (Dao et al., 2009);
b) Two sides of the central regions are tracked simultaneously, enabling the successful capturing of the stress-strain relationship and the crack initiation-propagation process;

Although DIC has been successfully employed in testing of mature-age concrete (Destrebecq et al., 2011; Küntz et al., 2006; Skarżyński et al., 2013; Sutton, 2008), virtually no published research can be found on its application to concrete during its first day. In order to apply DIC, concrete surfaces need to be treated with appropriate materials to create a sufficiently contrast pattern for the cameras to recognize, while respecting its continuity and strength. Wet-, soft- and dark coloured surfaces of the specimen at early age make the pattern application a real challenge. More details on pattern application are included in the following sections.



(a) (b)

Figure 1. Schematic Illustration (a) and actual test setup (b) of Direct Tensile Apparatus

Digital Image Correlation (DIC) System

DIC is a particular trend of data extraction through image analysis, and has been one of the most effective ways for macroscopic displacement tracking, mechanical and structural testing both in 2D and 3D areas. Great achievements in computer technology and digital camera recently allow a widespread of DIC applications into surface measurement, displacement, interior deformation through volumetric scanning/imaging, and even in the dynamic testing (Sutton, 2008). In the field of concrete testing, DIC has been successfully applied in many situations, both full-scale structures (Destrebecq et al., 2011; Küntz et al., 2006) and small specimens (Helm, 2008; Sutton, 2008), both 3D DIC (Gencturk et al., 2014) and 2D DIC (Skarżyński et al., 2013), both site- and laboratory experiments.

Different from previous application, this study employs two 2D DIC systems, simultaneously tracking AOIs on the two sides of the specimen. These two systems although being separate, are synchronized during the test to obtain the stress-strain behaviour at each exact time- and load-step. What is achieved after those tests is a full-field data-rich source of displacement-stress-time relationship, from which further comprehensive investigations on mechanical and fracture properties can be considered.

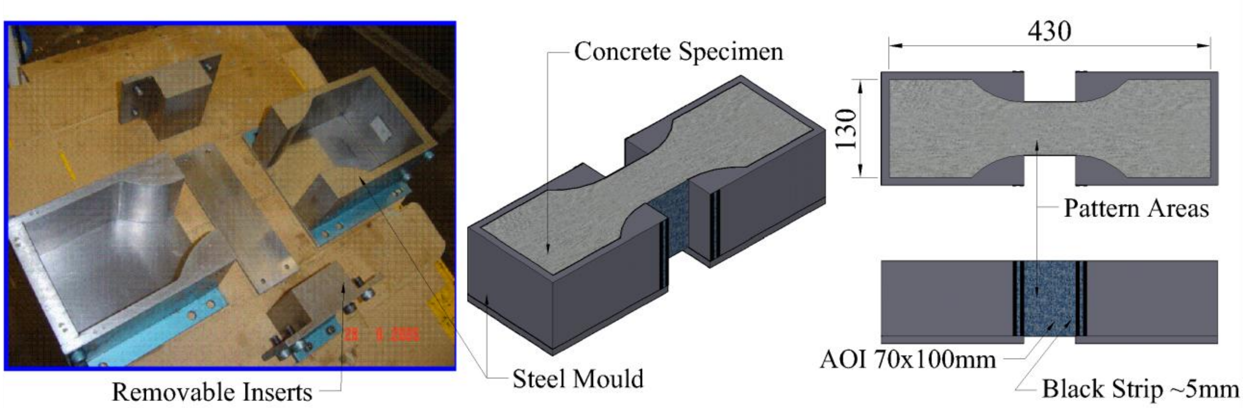


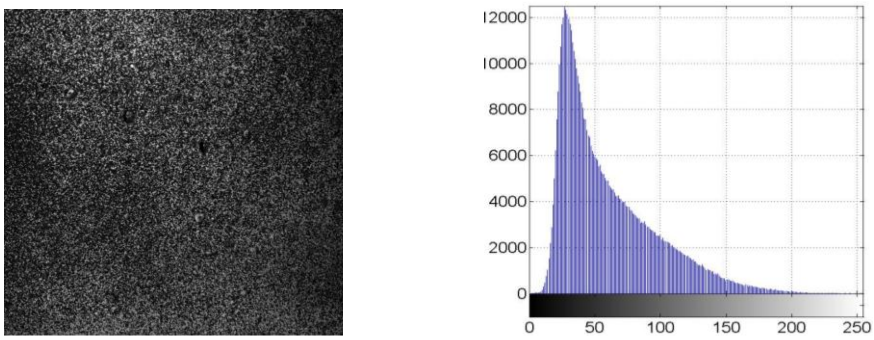
Figure 2. Testing Mould with Areas of Interest (AOIs)

Important Parameters

Speckle pattern

Appropriate contrast surface must be ensured during the test so that the camera can "recognize" and stay focus during the tracking of displacement. Contrast surface can be the natural pattern of the material itself, or can be artificially applied using mechanical or chemical methods. Popular pattern applications include surface degreasing, polishing, etching, or coating (Sutton, 2008). For concrete at early age, the material's natural dark grey colour requires artificial pattern application to supply sufficient contrast on the AOIs (Figure 2). A picture histogram is then used to assess its level of contrast, in which a bell-shaped distinguished intensity distribution is expected (Figure 3).

Average pattern size is decided in accordance with camera capacity and initial calibration. Pattern size (i.e. speckle size) is chosen in agreement with subset size (i.e. a small area of the image which is divided by a DIC software to track displacement) so that each subset achieves appropriate contrast. Too small speckle size can affect the accurate matching/correlation while too large speckle size reduces image spatial resolution. Once applying the surface pattern, further assessment is made to ensure pattern quality is adequate. The first aspect to consider is the smallest detectable pattern size, depending on equipment capacity and system setup. An average speckle size estimated ranges within 3-7 pixels is optimal for modest level of image sampling (Sutton, 2008).



(a) (b)

Figure 3. A typical speckle pattern and its histogram, applied on 5 hour age 40MPa concrete.

Subset size

Theoretically, image subset in digital camera discretization and segmentation can be at any shape depending on the pattern's grey/intensity value and its size (Jähne, 2005). In DIC, a continuous orthogonal subset system with rectangular-shaped subset is the most popular. Since the AOIs proposed in this test are square, a square-shaped subset system with approximately 10 pixel in size is adopted. Subset size is selected based on the speckle size, image contrast level and speckle pattern quality. Lower contrast image requires larger subset in order to ensure reliable results, while a higher contrast one allows smaller subset (Pan et al., 2009). Subsets need to be large enough to have sufficient intensity gradient to distinguish itself to neighbouring ones. On the other hand, large subsets often increase correlation errors due to the usage of shape functions. A novel parameter is used to determine the optimal value of subset size satisfying the conflicting criteria mentioned, which is call subset entropy (Yaofeng & Pang, 2007).

System calibration

System calibration takes an important part to obtain the extrinsic and intrinsic parameters for the camera's projection process. Intrinsic parameters refer to the internal characteristics of cameras, while extrinsic parameters are related to the cameras' position and rotation relative to the testing frame (Beaubier et al., 2013). There is currently no official specification for an optimum calibration, though researches on its improvement have been carried out continuously overtime (Beaubier et al., 2013; Sebastian & Patterson, 2012). System calibration can be based originally on a correlation target (i.e. a planar grid system or a 3D surface) or on the measured surface itself. It can also be conducted using a series of captured images or just one pair of them. In this research, due to the symmetry of AOIs which are two sides of the exposed concrete neck, two cameras are employed for two synchronized 2D DIC systems. The calibration process therefore is more special than other traditional 2D or 3D DIC systems. Each camera is used for each side yet they have to work simultaneously; the captured images are analysed separately for each side, the results however are to be averaged for further calculations. The whole process can be done using VIC-3D software and its accompanying equipment (CorrelatedSolutions, 2010).

TESTING PROCEDURE

Mixing is carried out using an available rotary drum mixer and the specimen is filled in two approximately equal layers. The surface is then levelled by a trowel, ensuring a flat plan for further testing. Temperature of concrete mix as well as laboratory temperature and humidity are regularly recorded during the curing and testing. The specimen is then placed into position. Connections to the load cell and lever arm are made. Next, the pin-connection is adjusted to create a small tensile force in the load cell in order to navigate the whole system. The two vertical inserts and central base plate are then gently removed.

Absorb tissues can be gently applied to remove any possible leaking water, after that black and white paint made of fast drying material is sprayed onto the AOIs to create sufficient contrast. The spray will dry out within 10-15 minutes. With the two inserts removed, DIC camera systems are installed to each side of the mould. Additional lights attached besides the cameras on the tripod frame are then turned on. Calibration is then made and the camera system is strictly required to maintain its position until the test is done. During testing, two sides of the specimen are moved apart at a constant rate of 0.05 mm/min. The test continues until crack forms and propagates throughout the cross section.

EXPERIMENTAL VALIDATION OF THE NOVEL TESTING METHOD

Data Verification

(a) Pattern quality can be assessed using the intensity histogram, subset entropy and mean intensity gradient. The intensity histogram is used to judge the uniformity of every speckle on the pattern, while the subset entropy determines the variation of intensity in each subset and from that verifies the uniformity of subset intensity gradient throughout the pattern. Lastly, as the name implies, the mean intensity gradient considers the mean intensity variation of the whole pattern, based on which comparisons between different patterns can be made. (b) Concrete quality can be assessed by inspecting the appearance of crack on the specimen. Under uniform loading rate, the smallest cross-section at the exposed neck is expected to have highest tensile stress, which is also the place cracking is expected to occur. (c) Measured values can be verified by comparing the applied displacement rate with that of the steel mould. Under constant displacement rate, two parts will obviously move apart with such rate, at least at the pre-cracked stage.

Data Analysis

From a full-field displacement data, a number of further investigation can be made, including: (a) Mechanical properties such as stress-strain curves, tensile strength, strain at maximum stress, Young's modulus; (b) Fracture characteristics such as fracture energy, characteristic length, crack tip opening; and (c) The initiation and propagation of cracks.

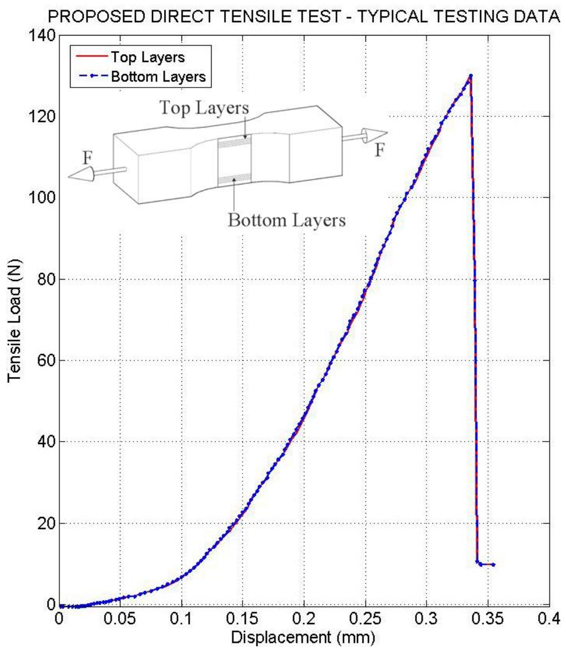


Figure 4. Load – Displacement of 40MPa concrete at 5-hour age.

Figure 4 illustrates typical data collected for a direct tensile test conducted on 40MPa concrete, 5 hour age. Full load-displacement curves (hence, stress-strain curves) were obtained with great agreement between different positions on AOIs. This proves the uniformity of applied loading as well as the reliability of DIC application.

CONCLUSIONS

A new system specifically designed for early-age tensile testing of concrete has been described. The novel use of digital image correlation in this system enables the desired deformation over the central region to be reliably captured in a non-contact way – a significant improvement compared to previous studies. The more reliable data to be collected would result in improved knowledge of concrete at early ages, including the tensile strength, Young's modulus, strain at peak stress, and fracture mechanics characteristics, as well as their interrelationships and development with time. This improved understanding would form a solid basis for more effective control of early-age cracking in concrete.

REFERENCES

Beaubier, B., Lavernhe-Taillard, K., Besnard, G., Lavernhe, S., Hild, F., & Roux, S. (2013) "CAD-Based Calibration of a 3D DIC System", *Imaging Methods for Novel Materials and Challenging Applications* Vol. 3, pp. 227-232, Springer New York.

Branch, J., Hannant, D. J., & Mulheron, M. (2002) "Factors affecting the plastic shrinkage cracking of high-strength concrete", *Magazine of Concrete Research*, Vol. 54, No. 5, pp. 347-354.

CorrelatedSolutions. (2010) "*Vic-3D 2010 Reference Manual*", pp. 0-108.

Dao, V. T. N., Dux, P. F., & Morris, P. H. (2009) "Tensile properties of early-age concrete", *ACI Materials Journal*, Vol. 106, No. 6, pp. 1-10.

Destrebecq, J. F., Toussaint, E., & Ferrier, E. (2011) "Analysis of Cracks and Deformations in a Full Scale Reinforced Concrete Beam Using a Digital Image Correlation Technique", *Experimental Mechanics*, Vol. 51, No. 6, pp. 879-890.

Gencturk, B., Hossain, K., Kapadia, A., Labib, E., & Mo, Y.-L. (2014) "Use of digital image correlation technique in full-scale testing of prestressed concrete structures", *Measurement*, Vol. 47, No. 0, pp. 505-515.

Hannant, D. J., Branch, J., & Mulheron, M. (1999) "Equipment for tensile testing of fresh concrete", *Magazine of Concrete Research*, Vol. 51, No. 4, pp. 263-267.

Helm, J. D. (2008) "Digital Image Correlation for Specimens with Multiple Growing Cracks", *Experimental Mechanics*, Vol. 48, No. 6, pp. 753-762.

Jähne, B. (2005) "*Digital Image Processing"*, Berlin Springer Berlin Heidelberg.

Küntz, M., Jolin, M., Bastien, J., Perez, F., & Hild, F. (2006) "Digital image correlation analysis of crack behavior in a reinforced concrete beam during a load test", *Canadian Journal of Civil Engineering*, Vol. 33, No. 11, pp. 1418-1425.

Pan, B., Qian, K., Xie, H., & Asundi, A. (2009) "Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review", *Measurement Science and Technology*, Vol. 20, No. 6.

Sebastian, C., & Patterson, E. A. (2012) "Calibration of a Digital Image Correlation System", *Experimental Techniques*.

Skarżyński, Ł., Kozicki, J., & Tejchman, J. (2013) "Application of DIC Technique to Concrete—Study on Objectivity of Measured Surface Displacements", *Experimental Mechanics*, Vol. 53, No. 9, pp. 1545-1559.

Sutton, M. (2008) "Digital Image Correlation for Shape and Deformation Measurements", *Springer Handbook of Experimental Solid Mechanics* pp. 565-600, Springer US.

Yaofeng, S., & Pang, J. H. L. (2007) "Study of optimal subset size in digital image correlation of speckle pattern images", *Optics and Lasers in Engineering*, Vol. 45, No. 9, pp. 967-974.