Construction and Building Materials 170 (2018) 392–401

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental analysis of cement-based materials under shear stress

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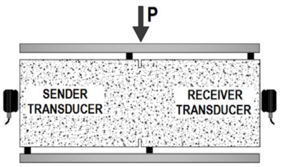
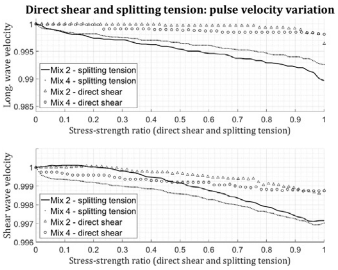
HIGHLIGHTS

- Ultrasonic pulse velocity is used to study cement-based materials under direct shear.
- Concrete shear strength has a strong correlation with ultrasonic shear pulse velocity.
- Applied shear in concrete do not induce strong ultrasonic pulse velocity variations.
- Fracture in shear and in splitting tests induce different pulse velocity variations.

GRAPHICAL ABSTRACT





ARTICLE INFO

Article history:
Received 20 October 2017
Received in revised form 2 March 2018
Accepted 5 March 2018

Keywords:
Concrete
Direct shear
Shear strength
Ultrasonic pulse velocity
Compressive strength
Iosipescu test

ABSTRACT

Mortar and plain concrete behavior under direct shear was investigated. Correlations between compressive and shear strength with ultrasonic pulse velocity were examined. Shear strength can be roughly estimated from longitudinal or transverse ultrasonic pulse velocity measured in the unloaded specimens, and both shear and elastic moduli calculated from ultrasonic pulse speeds can be correlated to shear and compressive strengths. Both longitudinal and transverse pulse speeds undergo little variation while applied shear stresses increase. Ultrasonic readings from specimens tested under splitting tension indicated that fracture mode in the Iosipescu test (mode II) differs from fracture in tension (mode I).

1. Introduction

For decades, a specter has been haunting concrete research: shear – and the questions about the assessment of shear stresses in concrete. Does shear fracture exist in concrete or is it [1] "sheer nonsense"? How can shear strength of concrete be evaluated? Is concrete shear strength simply a consequence of aggregate interlocking? Are the stress fields and fracture modes in four-point beam tests real mode II type – sliding mode – or are the stress fields and fracture mode the same tensile-type cracks obtained in splitting tension tests (mode I fracture, i.e., opening mode)? These questions have been preoccupying concrete researchers for decades [1,2] and can still considered open topics in experimental and numerical concrete research [3–5]. Some of these questions are associated with difficulties in measuring shear strains and with the way shear cracks propagate in concrete. Unlike experiments with concrete compressive stresses and strains, where stress measurements are straightforward and strains can be directly measured dividing axial deformation by specimen's initial length, measurement of shear stresses and strains are not easily obtained. Shear strains – defined as an angular measurement in radians – can be awkward and complicated to measure in concrete, and shear

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https://doi.org/10.1016/j.conbuildmat.2018.03.050

stresses are also difficult to apply experimentally in concrete specimens. Most difficulties are related to stress concentrations and localization of strains in the shear fracturing process of cement-based materials. While in compression concrete fracturing is diffuse and strains – as well as stresses – can be considered approximately uniformly distributed within the specimen's volume; in shear, at least in the experiments so far conceived, spurious stress concentrations and localized crack propagation make concrete stress-strain relations difficult to measure. Even in the most widely used test method to assess shear stress in concrete – Iosipescu test, conceived in 1967 for metals [6] – failure mechanisms of the beams used strongly depend on specimen's geometry, size, and boundary (supports) conditions [7,8].

In the development of shear strength test for metals, Iosipescu strongly relied on results from photoelasticity [6]. Almost 50 years after Iosipescu's procedure was published, digital image correlation, an approach that, mutatis mutandis, can be considered similar to photoelasticity, was used to analyze stresses and fracture propagation in a granular material [9]. Both techniques, though, have a strong limitation: they rely on surface strains and measurements alone, not being able to assess the interior of the specimens; and the crack front in the interior of the specimen is in plane strain, while in the surface the crack front is in plane stress [1]. Therefore, measurements taken with displacement transducers and strain gauges, since they are applied at the specimen's surfaces, do not provide information about the crack front propagation inside the specimens. Ultrasonic testing, on the other hand, since the pulses propagate through the volume of the specimens, crossing the materials under applied stress fields, where the fracture occurs, in the specimen's interior, is much more appropriate to assess damage and fracture due to shear stresses.

Ultrasonic testing has been used in concrete research for more than half century in applications such as crack detection in structural members [10], assessment of quality and uniformity [11,12], and distributed damage assessment [13–16]. More recent applications include estimates of grain-size distribution [17], and determination of concrete acoustoelastic properties [18,19]. Ultrasonic testing equipment and ultrasonic applications for concrete testing have greatly developed in recent decades. Nowadays, commercial pulse generators can be used in conjunction with longitudinal and shear wave transducers in order to determine elastic moduli of concrete. Ultrasonic signals can be digitalized, recorded and analyzed with great accuracy even with simple commercial digital oscilloscopes. One key aspect of ultrasonic testing of concrete is the fact that frequency ranges of transducers commercially available today can interact with the grain-size distribution of concrete mixtures as well as with the microcracking process of concrete due to specific damaging processes [13–15,17].

Ultrasonic testing of concrete can therefore be applied to assess damage due to cracking in strength tests of concrete specimens, such as compression tests [15] and tensile tests [19]. Ultrasonic pulse velocity variations have been frequently used in the assessment of continuous damaging processes in concrete and other cement-based materials [13–15]. The main idea is to try to measure damage through ultrasonic pulse velocity changes and to use damage parameters – frequently defined using elastic properties – to quantify damage. The approach has been applied to evaluate concrete damage due to compression loads [13–15], where diffuse damage associated with distributed microcracking occur. As shown in Nogueira and Willam (2001) [15], when concrete is loaded up to failure under uniaxial compression decay in ultrasonic longitudinal and shear pulse velocities are in the order of, approximately, 5%–25% of the initial velocities in the unloaded specimens, with a steep decay after around 75% of the maximum applied loads [15].

The research program investigates one of the most challenging aspects of concrete research: the existence and evaluation of shear. Understanding shear in concrete is extremely important not only to interpret shear tests' results correctly, but also to better evaluate structural members' strength and behavior.

2. Concrete behavior under shear stresses

Some concrete properties are related to the way it deforms under load and some are associated with its strength. The first group of properties are the elastic properties and include modulus of elasticity, shear modulus, Poisson's ratio, and third-order Murnaghan parameters [20,21]; the second group of properties measures the maximum capacity of concrete to withstand loadings and stresses. In concrete, not many difficulties exist in measuring modulus of elasticity or Poisson's ratio, but direct measurements of shear modulus can be quite complicated; likewise, measuring concrete strength under compression is relatively simple, while measuring shear strength is more difficult.

Since in the beginning of last century concerns about how to measure shear in concrete already existed. Almost one hundred years ago, in a publication about reinforced concrete, in the description of the physical properties of plain concrete, two of the main conclusions about shear in concrete were that (1) the methods adopted for the determination of shearing stress permitted the failure of the test specimens by tension before the ultimate resistance to shear had been reached, and (2) the term "shear" was wrongly used to denote complex action such as that taking place in the web of a beam, where diagonal tension is a governing factor [22]. The controversy about how to test concrete under shear in a way that the results obtained were not spuriously influenced by tensile stresses went on and on for decades and still persists today. Iosipescu, in 1967, emphasized that cutting tools acting in the same cross section do not create shearing stresses, instead, compression between the edges of the tool and tensile stresses, normal to the section, are created [6]. Experiments conducted by Bažant and Pfeiffer, in 1985, that aimed at assessing shear fracture of concrete in plain concrete beams with two notches concluded that [1] "shear fracture of concrete exists"; nonetheless, their experiments were studied and criticized by Ingraffea and Panthaki [23], who concluded that "tensile and not shear fracture occurred in the specimens." Commenting the analysis conducted by Ingraffea and Panthaki, Bažant and Pfeiffer stated that tensile fracture "can have no significant role in the failure" of the specimens used in the experiments and that the cracks observed during loading [24] "represent shear cracks". More recently, based on controlled experiments with beams under shear, Van Mier obtained the same crack patterns predicted by Ingraffea and Panthaki and concluded that the experiments by Bažant and Pfeiffer do not prove shear failure [25].

In 1997, Reinhardt et al. [26], introduced a new methodology based on the application of a compression load on a double-edge notched specimen; according to the reported experiments and numerical simulations with finite elements the procedure yielded a pure mode II (shear fracture) condition during the entire loading process. Contradicting the results from Reinhardt et al., Gálvez et al. [27] concluded that a mixed mode I/II fracture occurs in double-edge notched specimen tests; according to their results cracks initiate under mixed I/II but propagate under mode I. In 2016, a research program conducted by Helmick et al. [3] inferred from the roughness of the fracture surfaces of the specimens tested under splitting tension and under direct shear that "the Iosipescu test indirectly measures direct tension."

The above mentioned controversy about the very existence of concrete shear and about concrete shear strength tests and measurements also haunts numerical modelling of concrete under shear. Both works by Bažant and Pfeiffer [1] and by Ingraffea and