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Experimental and numerical analysis of strain gradient in tensile concrete prisms reinforced with multiple bars

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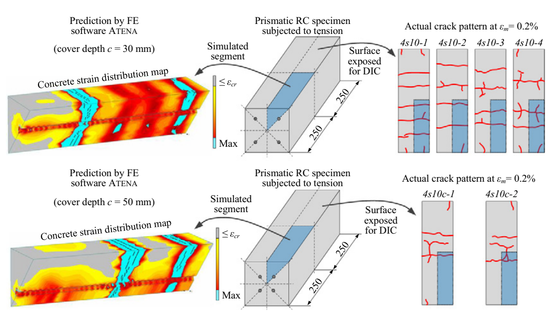
HIGHLIGHTS

- Deformation behavior of concrete is dependent on arrangement of the reinforcement.
- A new test methodology of concrete prisms with multiple bars is presented.
- The design concept and the components of the test setup are explained.
- Average deformations of concrete and reinforcement are different.
- Finite element technique as a versatile tool for analysis of the strain gradient.

GRAPHICAL ABSTRACT



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ABSTRACT

This work is a continuation of the ongoing research on deformation behavior of reinforced concrete elements under tension. The previous studies have revealed that deformation behaviors of elements reinforced with multiple bars and the traditional prismatic members reinforced with a center bar are essentially different. The latter layout, though typical of laboratory specimens, could not represent the norm of structures in real-life. Thus, a new test methodology to investigate the strain distribution in concrete prismatic members reinforced with multiple bars subjected to axial tension is devised. Prismatic concrete specimens with different reinforcement configurations were fabricated and tested using the proposed setup. Deformation behavior of the specimens is modeled with a tailor-designed bond modeling approach for rigorous finite element analysis. It is revealed that the average deformations of the concrete could be different from the prevailing approach of average deformations of the steel, and are dependent on the reinforcement configurations. Therefore, the efficiency of concrete in tension should be carefully taken into account for rational design of structural elements. The study endorses promising abilities of finite element technique as a versatile analysis tool whose full potential is to be revealed with the advent of computer hardware.

1. Introduction

Testing of composite elements under direct tension is of fundamental importance to reveal the tension load response and

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cracking behavior of reinforced concrete (RC). Although the direct tension test of a concrete prism embedded with a single reinforcing bar is the most widely adopted experimental arrangement for such purpose [1], the test configuration does not perfectly mimic the real structural behavior [2]; moreover, there is no standardized test setup established to-date. Notwithstanding the apparent simplicity of the setup, it might be difficult to interpret the test results: the experimental evidence often contradicts to the general assumption of similarity between average strains in the reinforcement and concrete. Moreover, the traditional tests typically provide measurements of average deformations along the embedded reinforcing bar and over the concrete surfaces, which is an over-simplification of the actual distribution of strains in the concrete. This limitation restricts the accurate assessment of the deformation and cracking behavior of concrete tension members [2].

Under the assumption that all tension at the cracked section is carried by the reinforcement, i.e. neglecting the softening behavior of the concrete after cracking and considering the idealized crack pattern (regularly distributed and fully formed transverse cracks), the predicted width of the cracks would be constant throughout the section depth. This is not in accordance with the reality, where the crack width and the tensile strain are not constant throughout the cracked section as confirmed by physical testing. Contradicting the experimental evidence (Fig. 1a and b), such over-simplified assumption does not enable the representation of actual distribution of the strains in the cover concrete over the cracked section, where the crack width would vary in the manner of a wedged shape [3,4]. To illustrate the variation of crack width over the concrete cover, the experimentally obtained crack widths reported by Borosnyói and Snóbli [4] are plotted in Fig. 1a. The measured crack widths at the upper and lower concrete surfaces are denoted as w_1 and w_2, respectively. From the experimental results, w_1 = 0.35 mm and w_2 = 0.45 mm. Through the concrete cover, the measured crack width varied almost linearly from the concrete surface towards the reinforcing bar, as shown in terms of ratios of w_1 and w_2 in Fig. 1a.

The current approaches in deformation analysis of RC members are commonly based on the assumption that only a part of concrete cross-section under tension can carry tensile loads [5]. This concrete part is referred to as "effective concrete area in tension". This area is schematically shown in Fig. 1c. In the cracked RC element, concrete undergoes complex stress-strain states, the cross-section becomes non-planar due to formation of primary and internal conical (Fig. 1b), also known as "Goto", cracks [6] and the corresponding bond stress transfer mechanism between concrete and reinforcement. In prevailing design approaches for the cracking analysis, the concrete is divided into two regions in resisting tension, namely the "effective" and "ineffective" regions [5]. The "effective" region is demarcated by the relative magnitude of tensile stress in the concrete. Typically, due to the transfer of stress between concrete and reinforcement through the bond action, the boundary of "effective" region manifests a parabolic shape, as illustrated in Fig. 1c. For the sake of simplification in structural design, an idealized stress-strain behavior may be assumed, such that the two regions are delineated with respect to their volume proportionately. However, a number of studies [4,7–9] have revealed noticeable limitations of the "effective area" concept related with its inability of representing the effects of concrete cover, loading conditions, stress-strain state, and configuration of the unreinforced area. The main uncertainty in connection with this concept is related to the complicacy of measurement of actual strain distributions in the volume of cracked concrete. Consequently, the real stress distribution in concrete is not perfectly understood and simplifications have to be applied in cracking and deformation analysis of RC structures. This introduces errors to the structural analysis and design processes. However, a scientific methodology to rectify the deficiency has been in lack.

A number of techniques have been developed for the strain monitoring of RC specimens [10,11]. The most straightforward and commonly used method is measuring the displacement between two points to obtain average strain in the gauge length. Such specimens are commonly instrumented with linear variable displacement transducers (LVDT), which are attached to the concrete surface. Such equipment enables assessing average surface strains of the concrete. However, as mentioned at the beginning of this section, the deformations of the concrete surface and internal bar reinforcement might be different. For realistic analysis of the experimental behavior, the deformations at both locations must be monitored during the tests. Instrumentation arrangement for such purpose as well as cross-verification by computational analysis are among the objectives of this study, through which the strain gradient variations for tensile concrete prisms with different reinforcing bar arrangements are realistically reflected.

The average strains of the reinforcement might be identified by various means. For exposed sections of the reinforcing bars, attaching LVDT devices to the surface of bar is viable. Furthermore, a specimen also can be equipped with advanced monitoring systems such as internal gauging system [12,13] or optical sensors [14,15], which are suitable for precise assessment of the bar strains. In addition, the digital image correlation (DIC) technique is becoming an increasingly useful tool for tracking deformations at the concrete surface [16]. Modern image back-scattering techniques, such as X-ray [17], acoustic emission tomography [18], and magnetic resonance imaging [19], are available as indirect means of deformation measurement. However, the interpretation of data obtained from these non-contact methods is often complicated and may require users' judgement, and they are limited to simple

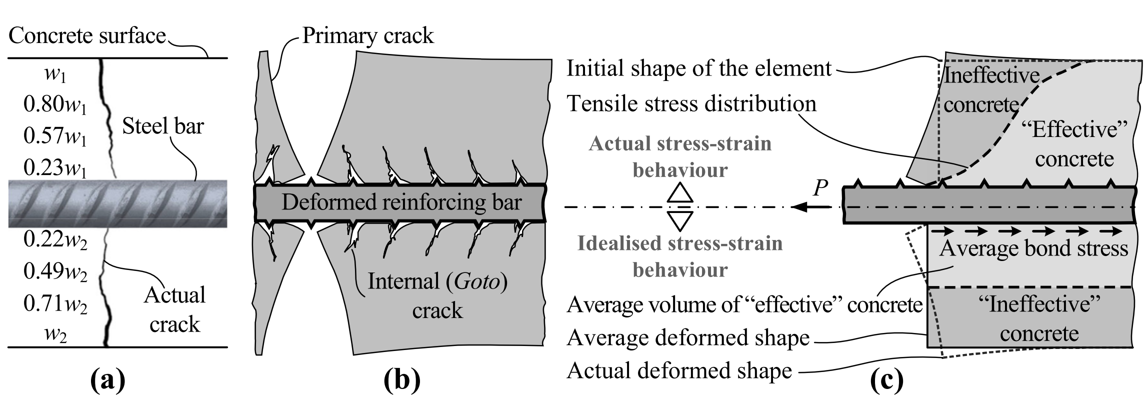

Fig. 1. The concept of effective concrete in tension: (a) experimentally attained variation of the crack width [4]; (b) development of the internal cracks [6]; (c) effective concrete model.