EVALUATION OF SHRINKAGE EFFECTS ON DIAGONAL CRACKING STRENGTH OF REINFORCED HSC BEAMS

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The use of high strength concrete is increasing, because it enables structural members to be designed with reduced cross-sectional area while enhancing durability. Nowadays, it is common for the target compressive strength of concrete to exceed 100N/mm^2. On the other hand, it is also well known that the autogenous shrinkage of high strength concrete is significant, resulting in a higher risk of early age cracking. For this reason, many studies have focused on the mechanical characteristics of plain, reinforced and prestressed high strength concrete as well as the control of autogenous shrinkage. However, few studies on the effect of early age concrete deformation on the structural response of reinforced and prestressed concretes have been carried out.

In this study, the effects of early age shrinkage as well as the distance from the compressive fiber to the centroid of the reinforcing bars (effective depth) on the diagonal cracking strength of reinforced high strength concrete beams without shear reinforcement are investigated. Fifty reinforced concrete beams made of conventional high-shrinkage and low-shrinkage high strength concretes (HAS and LAS) with a water-to-binder ratio of 0.23 are prepared for testing. The rectangular-section beams are 300mm in width, and have an effective depth of 250mm, 500mm and 1000mm. Tension reinforcement ratios are in the range 1.53-3.39%. In the case of the low-shrinkage concrete, shrinkage is reduced by the use of both an expansive additive and a shrinkage reducing agent. The shear span to effective depth ratio (a/d) of all of beams is fixed at 3.0.

The compressive strength (f_c’), splitting tensile strength (f_t), Young’s modulus (E_c), and fracture energy (G_f) of the concrete at the age of loading were 81-128N/mm^2, 4.8-8.3N/mm^2, 40-51kN/mm^2 , and 0.20-0.25N/mm, respectively. There were no noticeable differences in the mechanical properties of the HAS and LAS concretes. On the other hand, tension reinforcement strains just before loading were 190-360 x 10^{-6} in compression for HAS and 0-75 x 10^{-6} in compression for LAS, a difference of more than 200 x 10^{-6}.

The results of the loading tests showed that the diagonal cracking strength, defined as $\tau_c = V_c/bd$, was 2%, 12%, and 20% lower in high-shrinkage beams with effective depths of 250mm, 500mm, and 1000mm, respectively, compared with low-shrinkage beams. Here, V_c is the shear force at diagonal cracking and b is the beam width. The design equations of major codes like the ACI Building Code, the European Standard, and the JSCE Standard for diagonal cracking strength all include tension reinforcement ratio (p_s) as one of the major factors. The release at cracking of compression strain in tension reinforcement introduced by autogenous shrinkage increases the difference in tension reinforcement strain before and after loading. This larger strain change results in wider cracks and a thinner concrete compression zone, which probably decreases the transferability of shear along the cracks and the shear resistance of the concrete in compression. This hypothesis would mean that the higher tension reinforcement strain resulting from early age shrinkage is functionally equivalent to a decrease in the tension reinforcement ratio, because, according to the major design codes, a reduced tension reinforcement ratio results in lower shear strength at diagonal cracking. Based on this hypothesis, an "equivalent tension reinforcement ratio" is proposed", as given by the following equation and outlined in concept in Figure 1;

$$p_{s,e} = \left\{ \varepsilon_s / (\varepsilon_s - \varepsilon_{s0,def}) \right\} p_s$$

where, $p_{s,e}$: equivalent tension reinforcement ratio, p_s: nominal tension reinforcement ratio, ε_s : tension reinforcement strain at center of shear span at diagonal cracking, and $\varepsilon_{s0,def}$: tension reinforcement strain when concrete stress at the depth of the reinforcement is zero (and which is negative in compression).

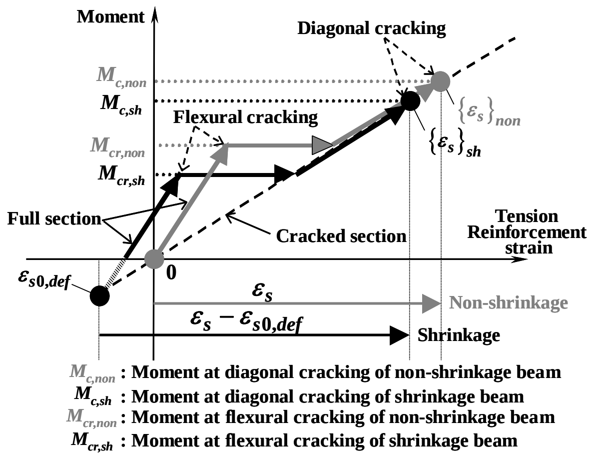


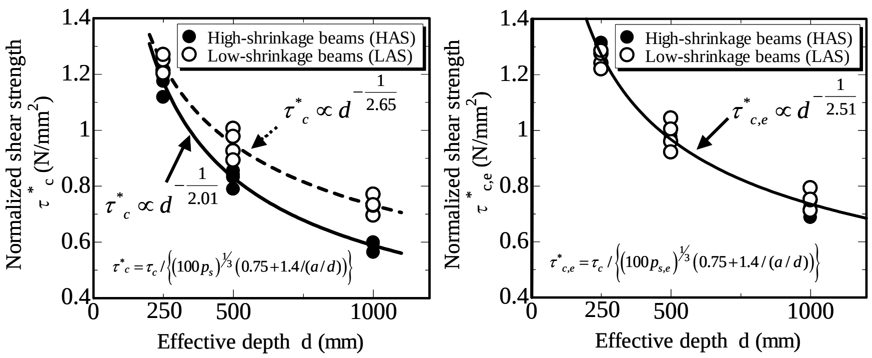
Figure 1 Concept of strain change in tension reinforcement due to early age shrinkage of concrete

Figure 2(a) shows the relationship between (τ^*_c), which is the shear strength (τ_c) normalized by the tension reinforcement ratio and shear span to effective depth ratio, and effective depth obtained from HAS and LAS beams with nominal tension reinforcement ratios. Regression curves obtained by the method of least squares are also shown for both types of beams. According to this figure, the size effect is apparently different depending on shrinkage, with effective depth for HAS and LAS beams raised to the power of -1/2.01 and -1/2.65, respectively. However, applying the concept of the equivalent tension reinforcement ratio, as is shown in Figure 2(b), the shear strength ($\tau^*_{c,e}$), which is (τ^*_c) normalized by the equivalent tension reinforcement ratio term, varies approximately with the effective depth to the power of -1/2.5 independent of shrinkage.

Gustafsson and Hillerborg (1988) presented results based on FEM analysis in which τ_c / f_t has an almost a linear relationship with d / l_{ch} on a logarithmic plot, where l_{ch} (=$E_c G_f$ / f_t^2) is the characteristic length. Assuming that this linear relationship is applicable to high strength concrete beams, the relationships between $\tau^*_{c,e}$ / f_t and $(d / l_{ch})^{-2/5}$ for all high strength concrete beams in the present experiment together with those from Fujita et al. (1988) are plotted in Figure 3. According to this figure, the relationship between $\tau^*_{c,e}$ / f_t and $(d / l_{ch})^{-2/5}$ applies well to high strength concrete beams. Using regression analysis, the following equation is proposed for predicting the diagonal cracking strength of reinforced high strength concrete beams;

$$\tau_c = V_c / (bd) = 0.206 \left(E_c G_f \right)^{2/5} f_t^{1/5} \left(100 p_{s,e} \right)^{1/3} d^{-2/5} \left(0.75 + 1.4 / (a/d) \right)$$

This proposed equation has been verified by comparing it with 57 experimental results. Satisfactory accuracy was obtained independent of the magnitude of shrinkage over the applicable concrete compressive strength range of 80-130N/mm^2.



(a) Shrinkage effect on shear strength and size effect law based on nominal tension reinforcement ratio

(b) Shrinkage effect on shear strength and size effect law based on equivalent tension reinforcement ratio

Figure 2. Relationships between normalized shear strength and effective depth

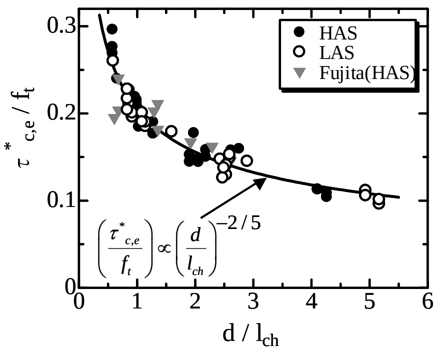


Figure 3 Unified evaluation of diagonal cracking strength based on concept of equivalent tension reinforcement ratio in the relationship ($\tau^*_{c,e}$/f_t) – $(d / l_{ch})^{-1/2.5}$

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