# TENSION STIFFENING OF REINFORCED HIGH-STRENGTH CONCRETE MEMBERS

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## 1. INTRODUCTION

The recent trend of employing reinforced high-strength concrete (RHSC) with a concrete strength of over 100 MPa has resulted in smaller member sizes which leads to higher tension stress in the reinforcement. In order to understand the deformation compatibility conditions when designing RHSC structures, the tension stiffness of concrete, which plays an important role in the deformation behavior of the reinforced concrete (RC) structures in the post-cracking region of concrete, needs to be considered. Although concrete is assumed to carry no tension at crack locations, it is still able to develop tensile stresses between the cracks through the transfer of bond forces from the reinforcement to the concrete. Tension stiffening arises from this ability of concrete to carry tension between cracks in an RC member, and helps control member stiffness, deformation, and crack widths related to satisfying serviceability requirements[1)]. Fig. 1 shows overall tension stiffening behavior as outlined by the CEB-FIP model code[2)]. According to past studies, the relationship between concrete strength and tension stiffness of concrete has not been clarified[1-4)]. A previous numerical study found that the tension stiffness of high-strength concrete (HSC) is lower than that of normal-strength concrete (NSC) [1)]. Fig. 2 shows the wide range of results predicted by various empirical models developed for tension stiffening in RC, all of which demonstrate a reduction in tensile capacity of cracked concrete with increasing strain. It seems tension stiffness of HSC cannot be accurately predicted by current models. Therefore, the objective of this paper is to experimentally evaluate the tension stiffness of axially loaded tension members of HSC and to propose a new more accurate model to predict tension stiffness of HSC members.

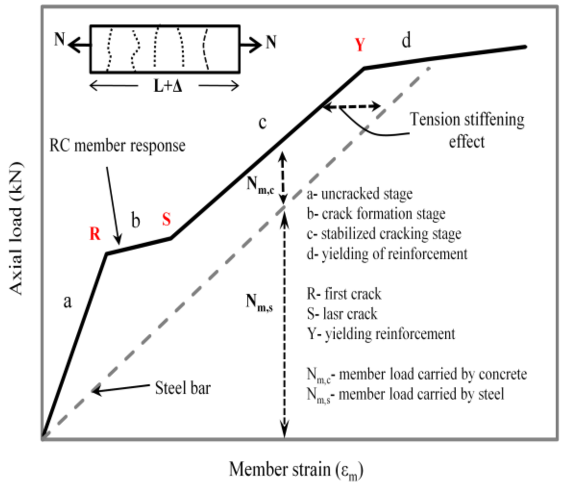


Fig. 1 Idealized behavior of RC ties.

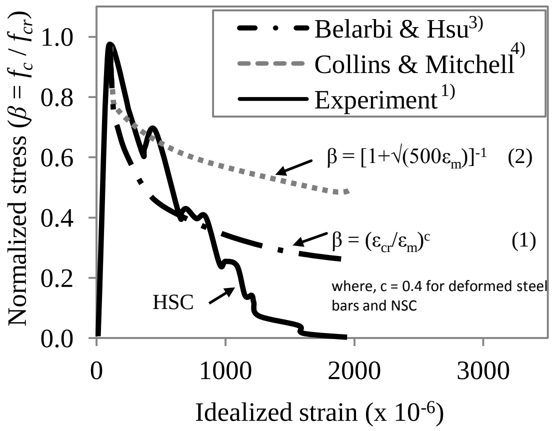


Fig. 2 Empirical models reported for tension stiffening factor $\beta$.
(Note: $f_c = N_{m,c}$/effective concrete area
$f_{cr}$: concrete cracking strength, $\varepsilon_{cr}$: cracking strain)

## 2. EXPERIMENTAL PROGRAM

Details of specimens are given in Table 1. Testing was carried out on six specimens that were axially loaded. Fig. 3 shows the geometry and instrumentation for a typical test specimen. All of the specimens had a length of 1200 mm. A single deformed steel bar, with a minimum concrete cover of 40 mm, was provided. Tension stiffening was evaluated for NSC (56 MPa) and HSC (102 to 145 MPa) using reinforcement ratios ($\rho$) of 1.99 and 2.252% respectively. The yield strength and Young’s modulus of steel were 722 MPa and 202.5 GPa respectively.

Specimens were loaded vertically through one-axial tension rods. Two linear variable displacement transducers (LVDT) were clamped to the steel reinforcing bar just outside of the concrete to measure the total elongation of the reinforced concrete specimen (Fig. 3). The complete response of each specimen was described by plotting the applied tension against the average member strain. Average early-age shrinkage was determined for all concretes from strain measurements on 100x100x400 mm shrinkage specimens that had the same moisture curing conditions as the tension specimen. Shrinkage was included in analysis of the member response by using the calculated shrinkage strain value from the early-age shrinkage specimens to determine the initial strain for each tension specimen (Table 1).

## 3. RESULTS AND DISCUSSION

Fig. 4 shows a comparison of the measured load-deformation response including shrinkage strains. The HSC specimens

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exhibited a larger cracking load than NSC specimens. Fig. 4 (a) compares the influence of concrete strength on the response of specimens reinforced with 16 and 25 mm bar sizes. This comparison clearly shows that the effect of tension stiffening at the stabilized cracking stage decreased with increasing concrete strength (Fig. 4 (a)).

Table 1 Specimen properties and test results

| Specimen | $d_b$ (mm), $c/d_b$ | Cross-section dimensions (mm) | $f'_c$ (MPa) | Strain | |
|---|---|---|---|---|---|
| | | | | $\varepsilon_{sh}$ (x10$^{-6}$) | $\varepsilon'$ (x10$^{-6}$) |
| NSC50-D16 | 16, 2.6 | 100x100, cover 40mm | 56 | -126 | -111 |
| HA80-D16 | | | 102 | -223 | -201 |
| HA160-D16 | | | 145 | -317 | -289 |
| NSC50-D25 | 25, 2.5 | 150x150, cover 40mm | 56 | -126 | -109 |
| HA80-D25 | | | 102 | -223 | -198 |
| HA160-D25 | | | 145 | -317 | -286 |

$d_b$: Steel bar diameter, $c$: Concrete cover
$f'_c$: Compressive strength of concrete, $\varepsilon_{sh}$: Early- age shrinkage
ε': Offset strain (initial strain) ($\mu\varepsilon = \varepsilon_{sh}/[1+n\rho]$)
n: Modular ratio ($E_s/E_c$), $\rho$: reinforcing steel ratio
$E_s$: Young's modulus of steel, $E_c$: elastic modulus of concrete
(Note: Shrinkage strains were assumed to be uniform over the cross section.)

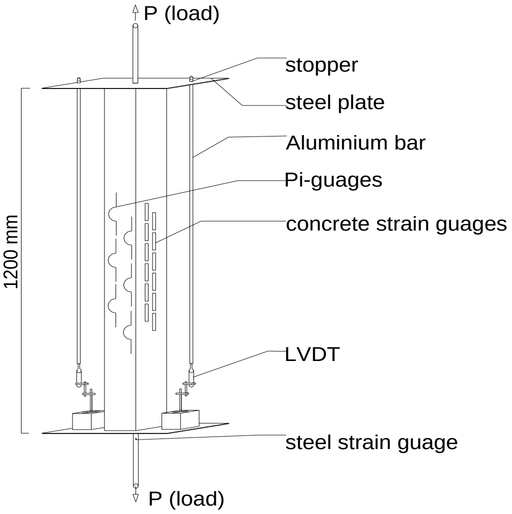


Fig. 3 Test setup

The tension stiffening reduction in HSC members can be explained using elastic theory. According to elastic theory, the bond behavior of HSC can be quantitatively drawn. Since the elastic modulus of concrete is a function of compressive strength, while that of steel remains constant, the composite structural system consisted of reinforcement and concrete is altered with concrete strength, which results in a different stress state in the interface. Furthermore, HSC is more brittle than NSC[1], and in turn, less stress redistribution can take place at the ultimate loading stage. These two material properties in HSC change the tensile stiffness of tension members.

As discussed previously, the present experimental results show that the tension stiffness of axially loaded members is highly dependent on concrete strength. According to Fig. 2, tension stiffness of HSC members after cracking cannot be sufficiently predicted by available models. Therefore, a new model is proposed to predict normalized stress, *β*, of HSC tension members. A best fit to the test results is obtained by using the following prediction equation [Fig. 4 (b)].

$$\beta = 2.5(1 - 0.135 ln\varepsilon_m) \quad (3)$$

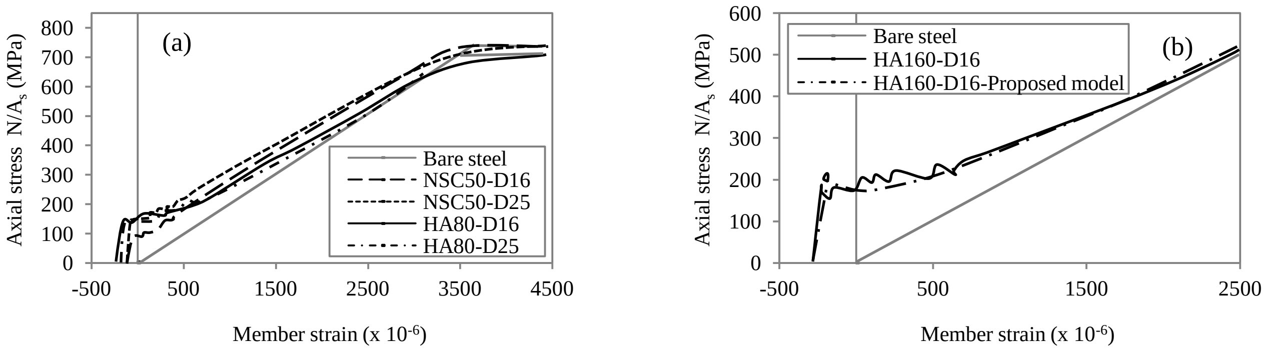


Fig. 4 Tension versus average strain response of normal-strength and high-strength concrete specimens

## 4. CONCLUSIONS

Tension stiffening behavior of both NSC and HSC was investigated. As the concrete strength increased from 56 MPa to 145 MPa, the tension stiffening effect became smaller for members with a $c/d_b$ ratio of 2.5. Based on the test results, a more accurate tension stiffening prediction equation is suggested for the design of RHSC members.

## REFERENCES

1) Perera, S.V.T.J.: Shear Behavior of RC Members Using High-Strength Concrete, PhD thesis, Department of Civil and Environmental Engineering, Saitama University, Japan, 2011.
2) CEB-FIP: CEB-FIP Model Code 1990, Comite Euro-International Du Beton, Paris, France, 1991.
3) Belarbi, A., and Hsu, T.T.C.: Constitutive Laws of Concrete in Tension and Reinforcing Bars Stiffened by Concrete, ACI Structural Journal, Vol. 91, No. 4, July-Aug. 1994, pp. 465-474.
4) Collins, M.P., and Mitchell, D.: Prestressed Concrete Structures, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1991, pp. 766.