J. Eng. Technol. Sci., Vol. 53, No. 2, 2021, 210209

Tension Stiffening Behavior of Polypropylene Fiber-Reinforced Concrete Tension Members

Aris Aryanto* **& Berto Juergen Winata**

Department of Civil Engineering, Institut Teknologi Bandung,
Jalan Ganesha No. 10 Bandung 40132, Indonesia
*E-mail: arisaryanto@ftsl.itb.ac.id

Highlights:

- The addition of polypropylene fiber into RC members can improve tension stiffening and the optimum fiber content can be known.
- The tension stiffening bond factor was identified for various fiber contents, which can be used for the prediction of tension stiffening and cracking behavior of such structures.
- The corrosion effect on tension stiffening and cracking behavior in PFRC members was investigated.

Abstract. This paper focuses on comparing the behavior of RC tension members with and without the addition of polypropylene fibers at various corrosion levels. Eight cylindrical tensile specimens were tested to evaluate their tension-stiffening and cracking behavior. The content of polypropylene fiber added into the concrete mix was the main variable (0.25%, 0.50%, 0.75%, and 1.0% of total volume). The corrosion level was varied from slight (5%), medium (10%) to severe (30%), and like the other variables, applied only to 1.0% polypropylene fiber-reinforced concrete (PFRC) specimens. The test results showed that the fiber addition significantly increased the tension-stiffening effect but was largely unable to reduce the effect of bond degradation caused by corrosion. Moreover, the addition of polypropylene fibers was able to improve the cracking behavior in terms of crack propagation, as shown by smaller crack spacing compared to the specimen without fiber addition at the same corrosion level.

Keywords: *corrosion; cracking; fiber-reinforced concrete; polypropylene fibers; tension stiffening.*

1 Introduction

For reinforced concrete (RC) structures that are exposed directly to the marine environment, such as jetties and bridges, corrosion of the reinforcements is one of the leading causes of structural degradation [1] induced by chloride penetration. Corrosion products will cause expansion around the steel bar perimeter, generate splitting stress in the concrete, and initiate cracking or even spalling of the concrete cover, resulting in the loss of reinforcing steel area and

Received 13 December 2019, Revised February 17th, 2021, Accepted for publication March 15th, 2021.
 ISSN: 2337-5779,
DOI: 10.5614/j.eng.technol.sci.2021.53.2.9

the loss of bonding strength between the concrete and the reinforcement [1,2]. Corrosion can also reduce the cross-sectional area of steel. Thus, corrosion can reduce the performance of RC structures and the ability of the structure to sustain loads and shorten the service life of the structure. Amleh, *et al.* in [1], Aryanto, *et al.* in [3], Dai, *et al.* in [4] and Shayanfar, *et al.* in [5] investigated the effect of corrosion on cracking and tension stiffening of tensile RC members without fiber addition.

Fiber addition to the concrete matrix is known to improve the mechanical properties of concrete, as discussed in [6] and [7]. It is well known that plain concrete is weak in tension. Cracks as a manifestation of tensile stress in concrete can be caused by loads or by environmental exposure. Water, oxygen, and chloride ions will penetrate through cracks and reach the steel reinforcement location. The wider the cracks in the concrete, the faster corrosion occurs in the reinforcement. Several researchers have attempted to mitigate crack damage and improve the properties of concrete by adding fibers. The most common fiber used in concrete is steel fiber, which has been investigated by many researchers [8-16], particularly focusing on tension stiffening and cracking behavior. Some provisions regarding the use of steel fibers in concrete are mentioned in design standards or codes, such as Model Code 2010 [17] and ACI 318-14 [18].

Another type of fiber is polypropylene fibers. Polypropylene fibers are a type of synthetic fibers shaped like strands, which may be in the form of micro- or macro-synthetic fibers. Like steel fibers, polypropylene fibers can have a crack-bridging effect, transferring load stress across cracks. Thus, a smaller crack width forms in concrete with fibers compared to plain concrete, which means better performance under corrosion. The addition of polypropylene fibers as reinforcement replacement is also expected to maintain the ability of the concrete to sustain loads when corrosion occurs. Based on the previous researches [16] and [19], polypropylene fiber-reinforced concrete (PFRC) has better performance than conventional reinforced concrete (RC). However, there is still limited research on the effect of polypropylene fibers on tension stiffening and cracking behavior, particularly in combination with corrosion. This study focused on evaluating the effect of polypropylene fiber content and corrosion on tension stiffening and cracking of PFRC tension members.

2 Experimental Program

2.1 Specimen Details

Eight specimens were prepared for tensile testing. For each specimen, a deformed bar with 19 mm was placed in the center of a concrete cylinder with a diameter of 127 mm. A machine-cut groove with a depth of 4 mm and a length of 680 mm was made in the reinforcing bar for placing the strain gauges (Figure 1(a)). These grooves were made to avoid damage to the strain gauges during the accelerated corrosion process. Before and after the grooving process, the bar's weight was measured to determine the reduction of the sectional area caused by the grooves. After attaching the strain gauges, the grooves were filled with waterproofing material. At the top and bottom parts of the concrete cylinder, 80 mm of bond insulation was installed around the steel bar to prevent cone damage.

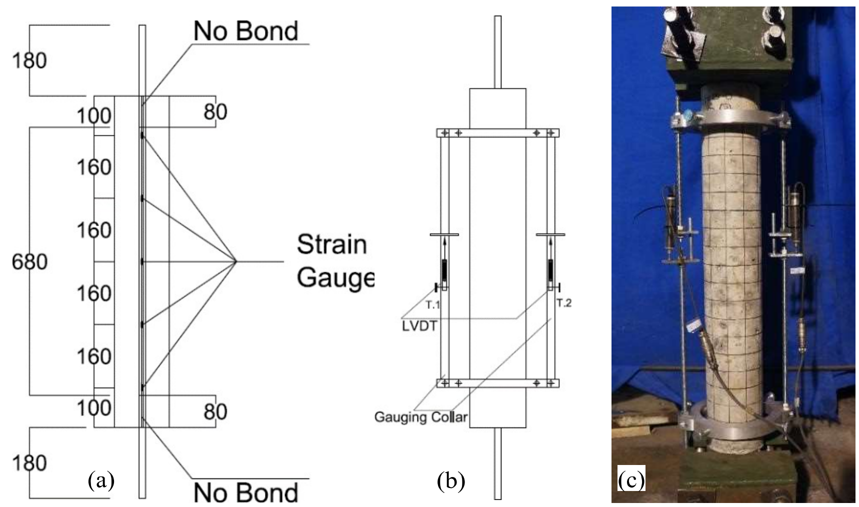


Figure 1 (a) Location of train gauges, (b) vertical jig, (c) test setup.

The specimens are divided into two main categories. The first category consists of uncorroded or healthy specimens, where the main variables are the content of macro-synthetic polypropylene fibers added into the concrete mix in terms of percentage of total volume. The properties of the fibers used in this study are shown in Table 1. The second category consists of corroded specimens, where the corrosion level of the steel bar is the main parameter. Corrosion of steel was varied from slight to severe and assumed as uniform corrosion; it was only introduced to the specimens containing 1.0% of polypropylene fibers.

Table 1 Properties of fibers.

Type of Fiber	Virgin Polypropylene	Units
Length	60	mm
Tensile strength	640	MPa
Young's modulus	12	GPa
Anchorage	Continuous embossing	

The specified compressive concrete strength of all specimens was 30 MPa, and the specified yield strength of the steel bars was 420 MPa. The details of the mixture proportions are given in Table 2. The details of the tensile test specimens are summarized in Table 3.

Table 2 Concrete mixture proportion in kg/m^3.

Cement	Sand	Coarse Aggregate	Water	HRWR
500	832	900	200	3

Table 3 Details of specimens and variables.

Specimen No.	Specimen Designation	Polypropylene Fiber Content [%]	Corrosion Level [%]
1	RC 000-C0	0	
2	PFRC 025-C0	0.25	
3	PFRC 050-C0	0.50	0
4	PFRC 075-C0	0.75	
5	PFRC 100-C0		
6	PFRC 100-C5	1.0	5
7	PFRC 100-C10		10
8	PFRC 100-C30		30

Note – Labeling definitions: RC = reinforced concrete; PFRC = polypropylene fiber-reinforced concrete; 000, 025, 075 & 100 = fiber content of 0%, 0,25%, 0,75%, and 1%, respectively; C0, C5, C10 & C30 = corrosion level of 0%, 5%, 10%, and 30%, respectively.

2.2 Accelerated Corrosion and Testing

An accelerated corrosion process was applied to the specimens after a minimum of four weeks of curing. The specimens were placed in a specific tank filled with a 3% NaCl solution during the process. The setup was arranged so that the reinforcing bar acted as an anode and the copper plate acted as a cathode, as shown in Figure 2. A constant current of 1.0 A, equivalent to 2.46 mA/cm^2, was applied to the steel bar. A monotonic tensile test was performed using a 1000-kN DARTEC Actuator.

A data logger continuously recorded the applied load and displacement. The displacement of the specimens was observed using two LVDTs installed on the specimens (Figure 1 (b)).

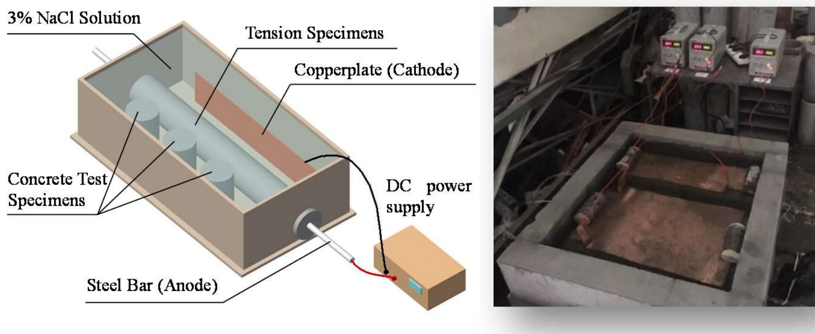


Figure 2 Accelerated corrosion process.

3 Experimental Results and Discussion

3.1 Corrosion Level Assessment

After the tensile test was completed, a corroded section with a length of 680 mm was taken out, soaked in 10% diammonium citrate to remove the rust, and then measured to determine the weight loss according to ASTM G1 [20]. The level of corrosion was defined as follows:

$$X_{corr} = \frac{W_0 - W_1}{W_0} \tag{1}$$

where W_0 and W_1 are the weight before corrosion and the residual weight, respectively. During the accelerated corrosion process, the corrosion level can be predicted from the applied current density using Faraday's law.

As shown in Table 4, the predicted corrosion level shows an underestimated result compared to the measured corrosion level, with the difference varying from 4% to 14%. The difference could be because the current was not measured in real-time but with an intermittent period, resulting in lower total current density.

Table 4 Corrosion level of the specimens.

Spec. No.	Specimen Designation	Weight Loss (g)		Corrosion level (%)		Difference (%)
		Predicted	Measured	Predicted	Measured	
6	PFRC100-C5	63.5	75	5.53	5.78	4.52
7	PFRC100-C10	129.54	140	10.26	10.81	5.36
8	PFRC100-C30	388.61	400	27.29	30.88	13.16

3.2 Crack Patterns

Crack patterns in the specimens are shown in Figure 3. In the uncorroded specimens, transverse cracks began to appear near the middle portion of the specimen. This first crack widened, or new cracks formed as the load was increased. The crack development was not uniformly distributed along the length of the specimens. The polypropylene fiber-reinforced concrete (PFRC) specimens exhibited more transverse cracks with a reduced crack width as the volume fraction of the fibers was increased. This cracking behavior may be attributed to the bridging action of the macro-synthetic polypropylene fibers at the cracks.

Meanwhile, in the corroded PFRC specimens, longitudinal cracks first appeared during the accelerated corrosion process due to splitting tension from the expansion of corrosion products. During the tensile test, the transverse cracks that appeared in the corroded PFRC specimens tended to have fewer cracks when the corrosion level of the steel bars increased. This can be attributed to the bond mechanism between the concrete matrix and the steel bar being reduced due to corrosion.

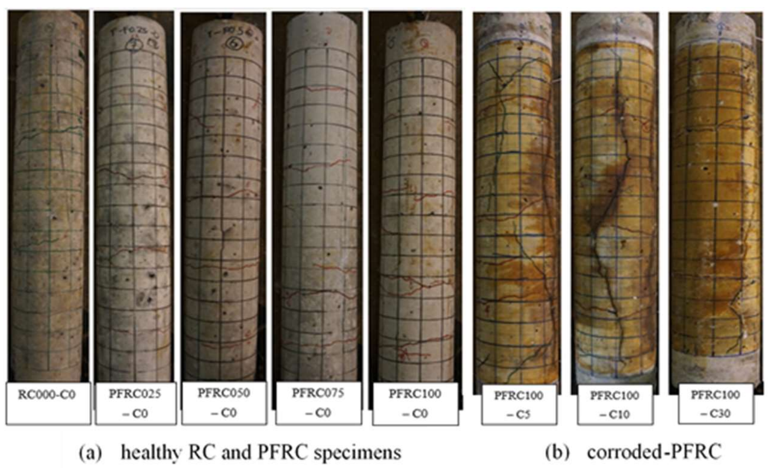


Figure 3 Crack patterns in the specimens.

Table 5 shows the result related to the axial tensile load response. All specimens with polypropylene addition produced a slightly higher first cracking load compared to the specimen without fiber (RC000-C0). A higher first cracking load indicates a better contribution from the concrete or tension stiffening at first cracking. Fiber addition in the concrete creates a better interlock mechanism between concrete, reinforcement, and fibers affected by increased bond strength. Stronger bonds cause better load transfer in specimens and a decrease in crack spacing. The corroded specimens, PFRC100-C5, C10, and C30, had lower first cracking loads than PFRC100-C0 or RC000-C0. This can be caused by corrosion cracking formed before the tensile test; once one crack is formed, it is easier to form a new crack. Corrosion also reduces the bond strength between the concrete and the bar, which contributes to the decrease of the bar's ability to transfer load from the steel bar to the concrete, hence increasing the crack spacing.

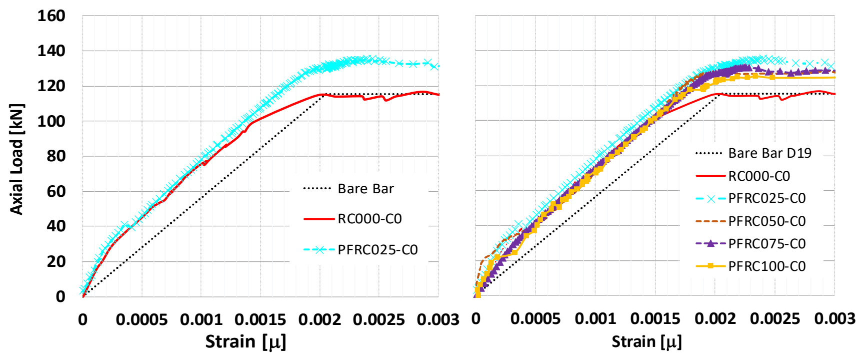
Table 5 Test results.

Specimen designation	First crack load (kN)	Maximum load (kN)	No. of transverse cracks	No. of longitudinal cracks	Average transverse crack spacing (mm)
RC 000-C0	20	114.58	3	-	190
PFRC 025-C0	23	131.44	4	-	160
PFRC 050-C0	24	127.02	4	-	147
PFRC 075-C0	23	127.03	6	-	100
PFRC 100-C0	24	122.94	6	-	84
PFRC 100-C5	19	110.53	4	1	113
PFRC 100-C10	17	92.79	5	1	120
PFRC 100-C30	12	49.66	3	1	300

3.3 Load-Deformation Behavior

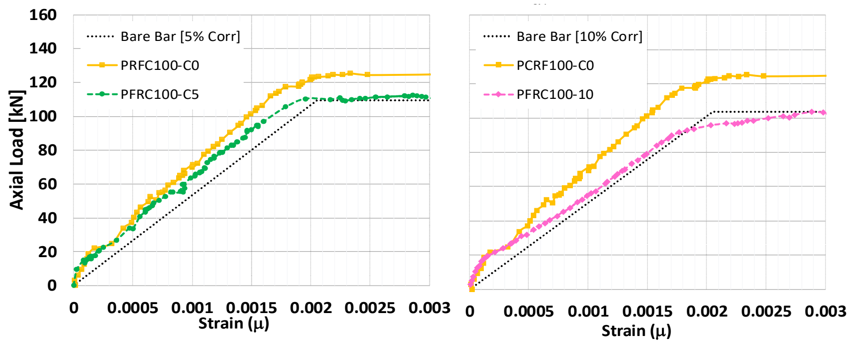
The load-deformation behavior of each specimen is described by plotting the axial load against the average member strain. The average strain is determined from the actual elongation of the specimen calculated over its whole length of 680 mm after considering the unbonded region of the bar at both ends of the specimen. Figure 4 shows the load-strain response of all specimens. For the corroded PFRC, the load-strain response of the bare bar is presented by using the equivalent bar area reduced by corrosion loss as mentioned in Subsection 3.1, and it was assumed to have uniform corrosion.

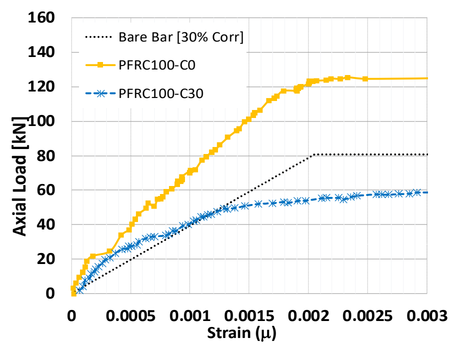
As shown in Figure 4, the presence of polypropylene fibers in the concrete matrix resulted in a slight increase in the pre-cracking stiffness and the cracking load. On the other hand, the pre-cracking stiffness and the cracking load reduced as the corrosion level increased. For the specimens without fibers, the tension stiffening at the yielding point of the steel bar was approximately the same as the bare bar or set to zero, whereas the specimens with fibers exhibited tension stiffening even beyond the yielding point of the steel bar, as shown in Figure 4(a). This is because the fibers are able to carry axial stress across the cracks, which is called crack bridging. As shown in Figure 4(b), the most substantial fiber contribution to tension stiffening was obtained for the specimen with 0.25% fiber content.



(a) RC and PFRC specimens with 0.25% polypropylene fibers

(b) PFRC specimens with 0.25, 0.5, 0.75, &1.0% polypropylene





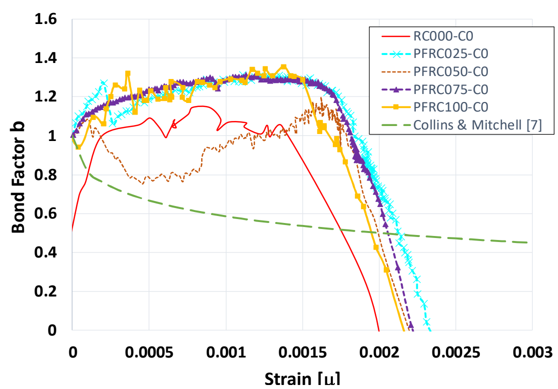
(c) PFRC specimens varying values of corrosion levels

Figure 4 Axial load-strain response of the tested specimens.

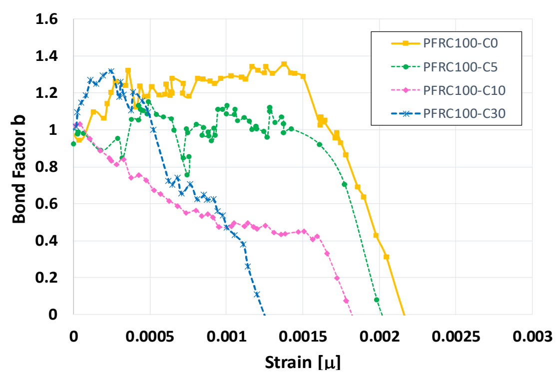
The tension stiffening significantly decreased as the corrosion level increased because the members have substantial bond loss between the steel and the surrounding concrete and contact loss at longitudinal splitting cracks due to corrosion. Polypropylene fiber addition offers little help to improve the tension stiffening effect in corroded specimens.

3.4 Tension Stiffening Bond Factor

The tension stiffening bond factor β represents the contribution of the concrete to tension stiffening, which is calculated by dividing the average load carried by the concrete, F_{cm}, with the load carried by the concrete at first cracking, F_{cr}. The value of F_{cm} is obtained by subtracting the total carrying load of the specimen with the bare bar response. An increase in the bond factor β indicates an increase in the stiffness of the members or tension stiffening. The bond factor β was calculated for all specimens in the present study.



(a) RC and PFRC specimens and varying value of fiber content



(b) PFRC specimens and varying value of corrosion level

Figure 5 Tension stiffening bond factor.

Figure 5(a) compares the bond factor of plain concrete and fiber concrete. It can be seen that the ratio F_{cm}/F_{cr} was more than unity for all PFRC specimens. This contradicts the previous findings in Collins and Mitchell [21], who proposed using β = 1/(1+$\sqrt{500\varepsilon_m}$) for plain concrete in which the bond factor is less than 1. This can be attributed to the bridging effect provided by the polypropylene fibers after cracking, which reduces the crack width and causes finer crack spacing. As can be seen in Figure 5(b), the bond factor tended to become smaller as corrosion increased. This reduction can be due to the loss of bond strength and contact area as a result of the effect of corrosion on the steel and the concrete.

3.5 Crack Spacing

Figure 6 shows the relationship between normalized crack spacing and corrosion level for the current study compared to the previous studies by Amleh *et al.* [1] and Shayanfar, *et al.* [5]. Normalization of crack spacing was also conducted so that the crack spacing increase caused by corrosion between the PFRC and the standard RC could be compared. Crack spacing normalization was done by dividing the average crack spacing of each corroded specimen by the average crack spacing of the healthy specimens. For the present work, specimen No. 1 was used as the control specimen to make a valid comparison with the other experiments. The PFRC specimen exhibited a smaller crack spacing compared to the standard RC specimen at the same corrosion level. The addition of fibers could reduce average crack spacing by 32.24% to 46.74%. This means that fiber addition can control the crack propagation in corroded RC structures.

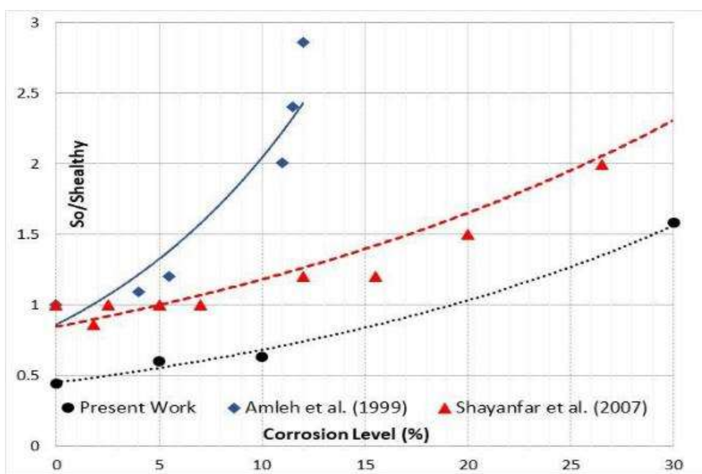


Figure 6 Normalized crack spacing-corrosion level relationship.

4 Conclusions

The addition of polypropylene fibers can improve the tension stiffening of polypropylene fiber-reinforced concrete (PFRC) even beyond the yielding point of the steel bar as long as the fibers have a crack bridging effect to transfer the stress load across the crack. However, the addition of polypropylene fiber content does not linearly increase the tension-stiffening effect. The fiber content of 0.25% exhibited the most significant effect on the tension stiffening in this study. Increased fiber content increases crack loading and reduce crack spacing. When subjected to corrosion, PFRC exhibits better crack spacing behavior in lower crack propagation than plain concrete, leading to better serviceability performance.

Acknowledgment

The authors acknowledge the financial support under the *Program Penelitian, Pengabdian pada Masyarakat dan Inovasi (P3MI)* from Institut Teknologi Bandung.

References

[1] Amleh, L. & Mirza, S., *Corrosion on Bond Between Steel and Concrete*, ACI Structural Journal, **96**(3), pp. 415-423, May-June. 1999.

[2] Al-Sulaimani, G.J., *Influence of Corrosion and Cracking on Bond Behavior and Strength of Reinforced Concrete Member*, ACI Structural Journal, **87**(2), pp. 220-230, Mar.-Apr. 1990.

[3] Aryanto, A. & Shinohara, Y., *Influence of Bond-slip Relationship and Tensile Strength on Bond Behavior Between Corroded Steel Bar and Concrete*, J. of Structural and Construction Engineering (Transaction of AIJ), **78**(685), pp. 559-567, 2013.

[4] Dai, J., Kato, E., Iwanami, M. & Yokota, H., *Cracking and Tension Stiffening Behavior of Corroded RC Members,* Report of the Port and Airport Research Institute, **46(**2), Nagase, Yokosuka, Japan, June 2007.

[5] Shayanfar, M.A. & Ghalehnovi, M., *Corrosion Effects on Tension-Stiffening Behavior of Reinforced Concrete*, Computers and Concrete, **4,** pp. 403-424, 2007

[6] Bentur, A. & Mindess, S., *Fiber Reinforced Cementitious Composites*, Elsevier Applied Science, London, UK, 1990.

[7] Shivakumar, A & Santhanam, M., *Mechanical Properties of High Strength Concrete Reinforced with Metallic and Non-metallic Fibers*, Cement and Concrete Composites, **29**(8), pp. 603-608, Sept. 2007.

[8] Bischoff, P.H., *Tension Stiffening and Cracking of Steel Fiber-reinforced Concrete*, Journal of Materials in Civil Engineering, ASCE, **15**(2), pp. 174-182, 2003.

[9] Fields, K. & Bischoff, P.H., *Tension Stiffening and Cracking of High-Strength Reinforced Concrete Tension Members,* ACI Structural Journal, **101**(4), pp. 447-456, July-Aug. 2004.

[10] Abrishami, H. & Mitchell, D., *Influence of Steel Fibers on Tension Stiffening*, ACI Structural Journal, **94**(6), pp. 769-776, Nov-Dec. 1997.

[11] Deluce, J.R., Lee, S.C. & Vecchio, F.J., *Crack Model for Steel Fiber-reinforced Concrete Members Containing Conventional Reinforcement*, ACI Structural Journal, **111**(1), pp. 93-102, Jan-Feb. 2014.

[12] Ganesa, N., Indira, P.V., & Sabeena, M.V., *Tension Stiffening and Cracking of Hybrid Fiber-reinforced Concrete*, ACI Materials Journal, **110**(6), pp. 715-721, Nov-Dec. 2013.

[13] Lee, S.C., Cho, J.Y., & Vecchio, F.J., *Tension Stiffening Model for Steel Fiber-reinforced Concrete Containing Conventional Reinforcement*, ACI Structural Journal, **110**(4), pp. 639648-721, July-Aug. 2013.

[14] Amin, A., Foster, S.J. & Watts, M., *Modelling the Tension Stiffening Effect in SFR-RC*, Magazine of Concrete Research, **68**(7), pp. 339-352, 2016.

[15] Moreno, D.M., Trono, W., Jen, G., Ostertag, C. & Billington, S.L., *Tension Stiffening in Reinforced High-performance Fiber-reinforced Cement-based Composites*, Cement and Concrete Composites, **50**, pp. 36-46, 2014.

[16] Thomas, L. & Jithin, J.S., *Effect of Steel and Polypropylene Fibre on the Tension Stiffening of Ultrahigh-performance Concrete*, International Journal of Engineering and Advanced Technology (IJEAT), **8**(4C), pp. 44-47, Dec. 2018.

[17] CEB-FIP, *Model Code 2010*: *Final Draft*, *fib* Bulletin 65, Federation Internationale du Beton, Lausanne, Switzerland, 2012.

[18] ACI 318 Committee, *ACI 318-14 Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, USA, 2014.

[19] Bernard, E.S., *Effect of Synthetic Fibers and Aggregate Size on Flexural Crack Widths*, ACI Structural Journal, **116**(3), pp. 19-26, May. 2019.

[20] ASTM International, *Standard Practice for Preparing, Cleaning, and Evaluation Corrosion Test Specimens (ASTM G1)*, ASTM International, 1999.

[21] Collins, M.P., & Mitchell, D., *Prestressed Concrete Structures*, Prentice-Hall, Englewood Cliffs, NI, 1991.