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BOND AND FLEXURAL BEHAVIOR OF SELF-CONSOLIDATING CONCRETE BEAMS REINFORCED WITH GFRP BARS

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Self-consolidating concrete (SCC) is widely used in the construction industry. SCC is a high-performance concrete with high workability and consistency allowing it to flow under its own weight without vibration. Despite the wide spread of SCC applications, bond behavior of FRP bars embedded in SCC beams has not been fully studied. This paper presents an experimental and analytical analysis of fifteen beams reinforced with glass fiber reinforced polymer (GFRP) bars. The test parameters were the concrete type, bar diameter, concrete cover thickness and embedment length. All beams were tested in four-point bending to failure. The average bond stresses of GFRP bars in SCC were found comparable to those in NVC. However, FRP bars embedded in SCC beams had higher bond stresses within uncracked region of the beams than those embedded in NVC beams. In contrast, GFRP bars in SCC had lower bond stresses than FRP bars in NVC within the cracked region. Results indicated that when cover concrete thickness dropped less than 2 d_b, the splitting bond failure is predominant.

Keywords: SCC, Glass fiber reinforced polymers, Bond stress, Development.

1 BACKGROUND

Self-consolidating concrete (SCC), with its excellent consolidation properties, can encapsulate reinforcing bars better than normal vibrated concrete (NVC). The interface between SCC and reinforcing bar more dense and consistent. Published literatures indicated that bond behavior of steel reinforcement in SCC is similar or better to that in NVC (Castel *et al.* 2006, Valcuende and Parra 2008). However, many researched works used pullout specimens or short embedment length steel bars, which may not accurately represent the bond behavior of flexural members.

Aly *et al.* (2006) found that critical splice lengths of GFRP reinforcing bars based on pullout failure using the ACI 440.1R-03 and CAN/CSA-S806-12 equations were conservative for small bar diameters and unconservative for larger bar diameters; however, predictions based on splitting failure using the ACI 440.1R-03 equation was more realistic. Mosley *et al.* (2008) indicated that at the same embedded length, the bond strength of the GFRP bars was approximately 50% that of steel bars. This ratio increased to about 65% when the bar spacing increased to 121mm. In fact, many researchers reported that as the embedment length of a bar increases, the bar force at bond failure increases but the average bond strength decreases (Rafi *et al.* 2007). The existence of concrete flexural cracks within the embedment length could decrease the bond stress.

Despite the wide spread of SCC applications, bond and flexural behavior of SCC beams reinforced or prestressed with FRP bars has not been fully studied. A comprehensive research study on these beams has been completed at University of Waterloo (Krem 2013). This paper presents flexural and bond stress of SCC beams reinforced with GFRP bars.

2 EXPERIMENTAL PROGRAM

Fifteen beams were fabricated: twelve beams were made from self-consolidating concrete (SCC) and three beams made from normal vibrated concrete (NVC). The beams were divided into five groups based on concrete type, bar diameter and cover thickness, Table 1. Where Groups (SG9.5, SG12.7, SG15.9, and SG12.7C) were made from SCC and Beams in Group (NG12.7) were made from NVC. Each group consisted of three beams. The cover thicknesses were maintained constant for all beams at 3 d_b, except beams of Group SG12.7-C, in which each beam had a different cover thickness: 2.0 d_b, 1.5 d_b and 1.0 d_b. Beam specimens were selected because beam flexural testing provides the actual bond behavior of flexural members. The beams configuration and reinforcement design were selected to maintain a tension mode of failure. Tension mode of failure provides the opportunity to explore the bond behavior under a wide range of tensile stresses in the tension reinforcement. The shear reinforcement was designated to prevent shear mode failure. All beams were subjected to a four-point static bending test up to failure. Measurements of load, midspan deflection, bar slip at beam ends and strain in GFRP bar at various locations were collected using a National Instrumentation Data Acquisition System.

Table 1. Test matrix details.

Group(1)	**Beam size, (b×h×l) mm**	**Cover thickness, mm**	**Concrete mix**	**Reinforcement**	
				Tensile	**Shear**
SG9.5	150×200×2200	28.5	SCC-1	G9.5	8M-75
SG12.7	150×200×2200	38.1	SCC-2	G12.7	8M-75
SG15.9	150×300×2200	47.7	SCC-1	G15.9	8M-100
NG12.7	150×200×2200	38.1	NVC-1	G12.7	8M-75
SG12.7C	150×200×2200	25.4, 19.1, 12.7	SCC-2	G12.7	8M-75

3 MATERIAL PROPERTIES

The GFRP bars were made of continuous longitudinal fibers impregnated in a thermosetting vinyl ester resin, with a typical fiber content of 77.8% by weight for GFRP bars. The bars had their surfaces sand-coated to improve their bond ability with the surrounded concrete. The mechanical properties are given in Table 2.

Table 2. Geometric and Mechanical properties of GFRP bars (Pultrall Inc. 2007).

Diameter, mm	**Cross sectional area, mm^2**	**Guaranteed tensile strength, MPa**	**Tensile modulus, GPa**	**Tensile strain, %**
9.5	71.30	765.0	45.4	1.89
12.7	126.7	708.0	46.3	1.70
15.9	197.9	683.0	48.2	1.56

Three concrete batches were used to fabricate all the specimens of this study. Two mixes were SCC and one mix was NVC. The slump flow and confined flow for the SCC mixes were between 680 mm and 720 mm. The confined flow J-ring test results for the SCC mix were between 625 mm and 690 mm. SCC mix-1 and SCC mix-2 had a Visual Stability Index (VSI) of 1.0 and 0, respectively. These results are within the definition of the SCC fresh properties as prescribed by ACI 237 (2007). However, SCC mix-1 was susceptible to segregation risk since it was on the border of the acceptance limit.

The concrete compressive strengths of SCC-1, SCC-2 and NVC were 49.6 MPa, 70.9 MPa and 64.5 MPa, respectively. The average measured modulus of elasticity of SCC-1 was 22.7 GPa, SCC mix-2 was 30.6 GPA, and NVC was 37.5 GPa. The experimental values of the modulus of elasticity of SCC ranged from 0.67 to 0.82 of that predicted by the ACI 318 design code. NVC modulus of elasticity exceeded the prediction values by 4%. The possible explanation of this trend in the modulus of elasticity of the SCC mixes is related to less coarse aggregate content and smaller maximum aggregate size than that typically used in NVC mixes. Full details of the concrete mixes and test results are available in Krem (2013).

4 FLEXURAL TEST RESULTS

All beams showed a bilinear moment-deflection behavior. The initial linear segment of the curve had a very steep slope, which corresponds to the uncracked stiffness. After the first crack, the beam's stiffness was significantly reduced, and flexural cracks continued to form. The slope of the second segment was less than the slope of the first part. The deflection rate was higher after the beam cracked, which is an indication of the stiffness reduction. As the load increased, more cracks formed, but the load deflection behavior remained linear up to failure. Two failure modes were observed: bond failure and rupture of the tension FRP reinforcing bar. Bar rupture was a clear mode of failure where the tension reinforcing FRP bar suddenly ruptured and the load dropped to zero instantly. Bond failure, however, was relatively gradual. Two types of bond failures were observed: bond pullout and bond splitting.

A typical applied moment versus midspan deflection of groups SG12.7 and NG12.7 are shown in Figure 1 and Figure 2 respectively. Results of flexural testing of all beams is shown in Table 3. Beams in Group SG12.7 were tested at shear spans of 350, 450 and 600 mm. A bond pullout failure was recorded for the shortest shear span of 350mm while the other two beams failed due to bar rupture. The longitudinal strains in the GFRP bars of Beams SG12.7-3.0-350, SG12.7-3.0-450, and SG12.7-3.0-600 were 1.1%, 1.29% and 1.37%, with tensile stress of 518, 570, and 614 MPa, respectively. The guaranteed tensile stress of the 12.7 GFRP bar was reported as 708 MPa.

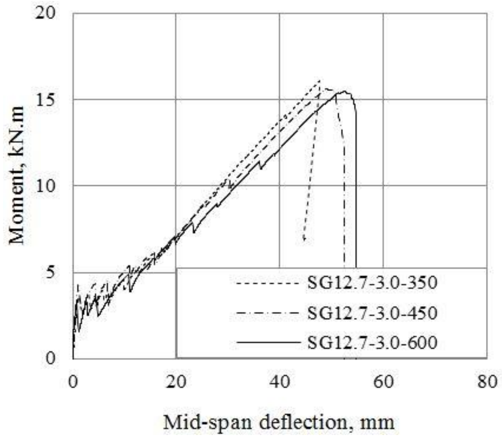

Figure 1. Flexural test responses of SCC beams Group SG12.7.

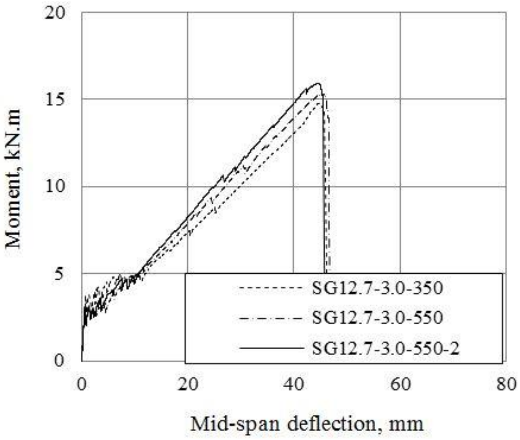

Figure 2. Flexural test responses of NVC beams Group NG12.7.

The moment versus midspan deflection of beams in Group NG12.7 (Figure 2) which were made from NVC. As the shear span increased, the midspan deflection was decreased for a given moment. Beam NG12.7-3.0-350 failed by bond pullout failure. An end slip of 3.0mm was recorded for this beam. The peak moment of this beam was 14.4 kN-m, which was slightly greater than that of a similar beam made from SCC, SG12.7-3.0-450, that had a peak moment of 12.9 kN-m. This result indicates that the reinforcing GFRP bar in the NVC beam achieved a higher tensile stress than that in the SCC beam. Beam NG12.7-3.0-550 failed due to bar rupture; however, an end slip of 0.05 mm was recorded. For this reason, the third beam was tested with the same shear span of 550 mm to confirm this result. No end slip was recorded during testing of the third beam. The peak moments of these two beams NG12.7-3.0-550 and NG12.7-3.0-550-2 were 15.3 kN-m and 15.9 kN-m, respectively. The companion beams made from SCC, SG12.7-3.0-450 and SG12.7-3.0-600 failed by bar rupture at applied moments of 14.4 kN-m and 16.9 kN-m, respectively.

Table 3. Flexural test results of all beams.

Group	**Beam label***	**Cracking**		**Ultimate**		**Mode of failure**
		Moment kN-m	**Deflection mm**	**Moment kN-m**	**Deflection mm**	
SG9.5	SG9.5-3.0-300	2.9	0.91	6.7	45.5	pullout
	SG9.5-3.0-450	2.7	0.85	7.5	43.0	rupture
	SG9.5-3.0-600	3.1	0.94	8.7	40.8	rupture
SG12.7	SG12.7-3.0-350	3.5	1.06	14.1	41.1	pullout
	SG12.7-3.0-450	4.3	1.07	15.6	49.2	pullout/rupture
	SG12.7-3.0-600	3.2	0.91	15.5	52.6	rupture
SG15.9	SG15.9-3.0-450	8.2	0.85	33.2	27.7	pullout
	SG15.9-3.0-600	7.9	1.60	45.5	33.5	rupture
	SG15.9-3.0-750	8.6	0.75	37.7	30.9	rupture
SG12.7C	SG12.7-2.0-450	3.4	0.83	22.1	51.0	rupture
	SG12.7-1.5-450	3.2	0.89	21.1	49.9	pullout/splitting
	SG12.7-1.0-450	3.6	1.10	22.9	47.1	splitting
NG12.7	NG12.7-3.0-350	3.7	0.73	14.4	43.9	pullout
	NG12.7-3.0-550	2.9	0.59	15.3	44.7	pullout/rupture
	NG12.7-3.0-550-2	3.1	0.62	15.9	44.1	rupture

Despite the higher compressive strength of SCC mix-2, the average cracking moment of beams made from SCC-mix2, Group SG12.7, and beams made from NVC, Group NG12.7, was similar. This is attributed to similar tensile strength of the two mixes. However, the average midspan deflection of beams made of SCC was about 1.5 times the midspan deflection of beams made from NVC. The increased midspan deflection of the SCC beams can be attributed to the lower modulus of elasticity of SCC than NVC.

5 BOND ANALYSIS

5.1 Effect of Concrete Type

The normalized bond stress versus normalized embedment length for beams that failed by bond pullout were calculated and presented graphically in Figure 3. Beams that failed by bar rupture were not included in this analysis because the GFRP bars in these beams reached the rupture tensile stress before the bond strength was reached. Figure 3 shows that for both types of concrete, the normalized bond stress and normalized embedment length have a nonlinear relationship. The normalized bond stress of the GFRP bars in SCC beams was about 20% larger than that in NVC beams at an embedment length to bar diameter ratio of 10. The difference in normalized bond stress between the SCC and NVC decreased as the normalized embedment length increased, and vanished at an embedment length to bar diameter ratio of about 37.5. This result explains why SCC had a higher bond stress than NVC based on pullout specimens as reported in literature. The possible explanation of SCC having higher bond stresses within the uncracked region is because the concrete around the bar is more homogeneous in SCC and able to perfectly encapsulate the FRP reinforcing bar.

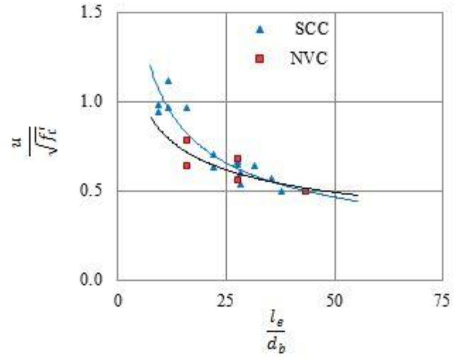

Figure 3. Normalized average bond stress versus normalized embedment length.

5.2 Effect of Bar Diameter

The normalized average bond stress of beams that failed by bond pullout versus the embedment length to bar diameter ratio is presented in Figure 4. A clear trend of the effect of bar diameter was evident when the normalized bond stress was plotted against the normalized embedment length. The figure shows that when the bar diameter was increased from 9.5 mm to 12.7 mm, the decrease in the normalized bond stress was insignificant, and there was a slight decrease in normalized average bond stress when the bar diameter was increased from 12.7 mm to 15.9 mm. Although only two points are available for a bar diameter 9.5 mm, the nonlinear relationship plotted was similar to that for the other two bar diameters.

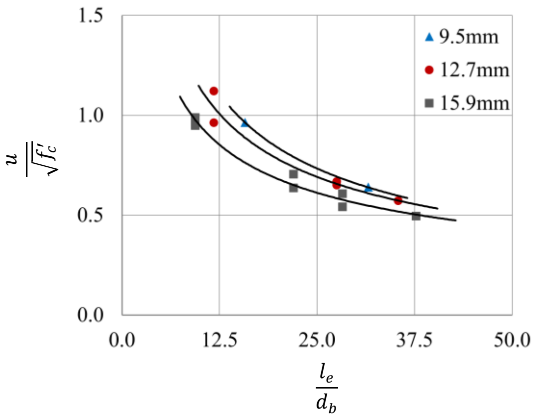

Figure 4. Effect of bar diameter on normalized average bond stress of SCC beams.

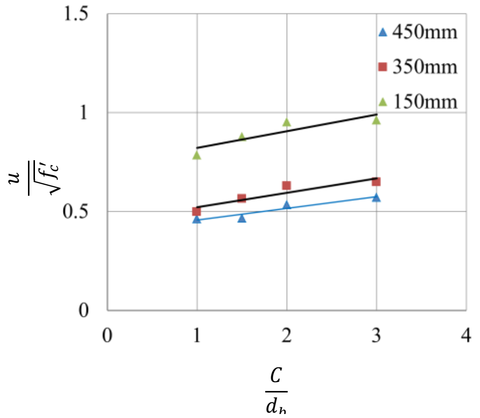

Figure 5. Average normalized bond stress versus normalized cover thickness.

5.3 Effect of Concrete Cover Thickness

The results for beams in Group SG12.7C are presented graphically in Figure 5. The figure shows the effect of cover thickness on the normalized average bond stress at embedment lengths of 150 mm, 350 mm and 450 mm. The line representing the normalized bond stress at an embedment of 150 mm had larger values than the other two lines. At an embedment length of 450mm, the data indicated that the normalized bond stresses dropped from 0.571 when the cover thickness was 3.0 d_b to 0.534 when the cover thickness decreased to 2.0 d_b (a 6.5% drop in normalized bond stress). The most significant drop was recorded when the cover thickness dropped from 2.0 d_b to 1.5 d_b. A similar relationship was found at embedment lengths of 150 mm and 350 mm. This result is consistent with the observed mode of failure, which changed from bond pullout failure to bond splitting failure when the cover thickness dropped from $2.0\ d_b$ to $1.5\ d_b$.

6 CONCLUSIONS

The conclusions can be drawn as follows:

(a) Flexural responses of beams made from SCC exhibited slightly increased deflection than NVC beams.

(b) The average bond stress of GFRP bars in SCC beams was slightly less than that in beams made from NVC. However, bond stresses in uncracked region were higher than those in similar beams made from NVC. The normalized average bond stress profile of GFRP bars in SCC decreased as the embedment length to bar diameter ratio increased. This is because the local bond stress in cracked region is less than that in the uncracked region and for long embedment length, the cracked portion contribution is increased.

(c) The mode of bond failure in SCC beams reinforced with GFRP bars changed from a pullout to splitting failure when the cover thickness was reduced below twice the bar diameter.

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