TEST OF PRESTRESSED CONCRETE BEAMS WITH BFRP TENDONS

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Abstract

Concrete structures are normally reinforced with steel tendons. In marine or chemical environment steel has its limitations. Replacing steel with FRP reinforcement has been practiced for many years but using basalt fiber reinforcement polymer tendons (BFRP) as a structural material is rather new. Tension strength of BFRP tendon is about twice the tension strength of steel reinforcement, but the elastic modulus is only 40-50 GPa while steel has 200 GPa. Therefore, elastic lengthening of BFRP tendons is much more than of steel and strain in the tension zone of concrete structures will be over acceptable limits. To utilise the high-tension strength of BFRP and prevent cracking of concrete, the tendons could be prestressed. In this research, four beams were concreted. Three of them were prestressed. The main findings were that the stiffness and bearing capacity of the beam increase relative to un-prestressed beam. Long-term relaxation of prestressed BFRP tendons is estimated close to 20%. New formula for shear resistance is derived from EC2.

Keywords: Basalt fiber, BFRP, concrete beam, experimental work, prestress, shear strength

1. Introduction

Prestressed concrete is one form of reinforced concrete. The compressive force is applied to members through a tensioned steel tendon or Fiber Reinforced Polymer (FRP) tendons, which is anchored at the ends or have a good bond to the concrete. This compression due to prestress causes stresses that reduces or nullifies the tensile stress in concrete, which is caused by bending due to applied load. If there is no tensile stress in the concrete, the cross section will not crack, and bearing capacity will increase.

Several research studies on fibre reinforcement polymer (FRP) have been conducted at The Reykjavik University in collaboration with The Innovation Center Iceland for the last years. The main findings are that FRP tendons are promising for reinforcing concrete members. Basalt fiber tendons (BFRP) have a tensile strength about 1000 MPa. In comparison regular steel reinforcement has tensile strength around 500 MPa. This experimental study is in a sequel of these former studies where usages of basalt fibers as a reinforcing material for concrete structures are giving promising results and is a very interesting option [1].

The main topic of this experimental research is to investigate prestressed BFRP tendons as an internal reinforcement and to find out the shear capacity of the prestressed beams.

The Shear strength of concrete members reinforced with FRP longitudinal reinforcement and without shear reinforcement (stirrups) cannot be calculated using the same equations as for steel reinforced members. There is a need to take into account the effects of material properties of the dowel. In an experimental research by Zou [2], where ten prestressed beams were investigated, some were reinforced with steel tendons and some with CFRP tendons. The beams that were reinforced with steel tendons failed in bending as supposed but the beams reinforced with CFRP tendons failed unexpectedly due to shear. The conclusion that the Zou drew from this is that the dowel action of CFRP is less than for steel due to lower transverse shear strength of CFRP. Few research had been done with BFRP prestressed beams, and no standard or guidelines cover this subject with BFRP.

2. Experimental procedure

BFRP tendons that were used in this experiment were imported from Magmatech in the UK.

Figure 1. 10 mm BFRP bars with sanded surface from Magmatech - Rockbar

The length of each beam was decided to be 2.0 m, width 200 mm and height 200mm. The a/d proportion is then 795/150=5.3. See figure 2.

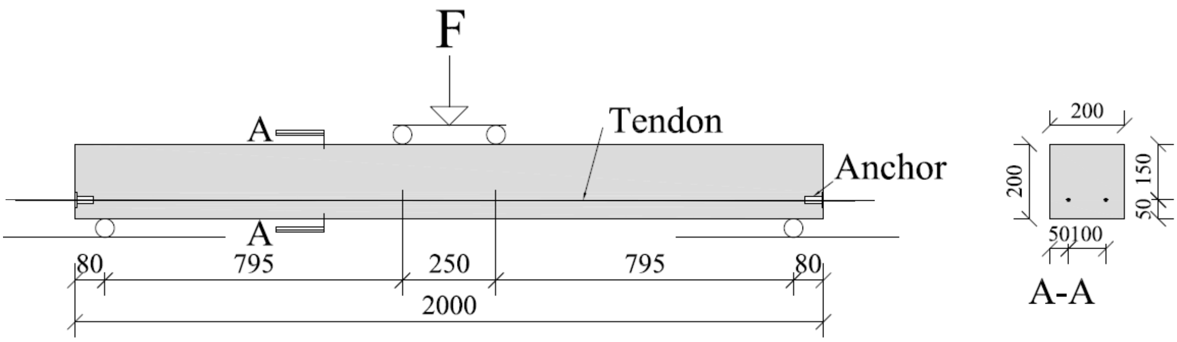

Figure 2. Schematic drawings of bending test setup and beam cross section

Four beams were tested. Three beams prestressed with mean concrete cylindrical strength 60 MPa (beam 1-3) and one beam un-prestressed of mean cylindrical strength 23 MPa (beam 4).

The anchor for the BFRP tendons was made of rolled circular pipe and tendons glued with HIT-RE-500 (manufacturer Hilti) after the prestressing has taken place. Similar technique was used in previous experiments, [3]. To check the tension capability of this combination, a small test was performed. BFRP tendon was glued inside two 15 cm long steel pipes and then pulled until the tendon failed, and that was at approximately 87 KN or almost twice as much as the intended prestressed force.

Prestress force was decided about 47 KN, which gave around 600 Mpa stress in the BFRP tendons. That is approximately 50% of the ultimate tensile strength of the tendons. This is in the recommended zone for prestressing FRP according to American concrete Institute, *ACI 440.4R-04*, 2004. There it is recommended to prestress FRP tendons 40%-65% of ultimate tensile strength. Steel tendons are normally tensioned up to 85% of their yield strength.

The strain in tendons was measured by strain gauges that were placed on the middle of the tendons, at the constant moment zone. The strain gauges were glued on small aluminium plate and the plate subsequently glued to the tendon with steel repair filler. The wires that are connected to the gauges were protected from the concrete with tiny tubes, and afterwards this was all carefully wrapped with insulating tape.

3. Test results

All the prestressed beams failed in shear, and the un-prestressed beam failed in bending and shear. Shear strength in beam nr. 1 was 29.5 KN, shear strength in beam nr. 2 was 33.5 KN and shear strength in beam nr. 3 was 27 KN. The angle of the shear cracks was measured. In beam 1 the angle was approximately 21°, for beam 2 the angle was 20° and for beam 3 the angle was 20°.

Figure 3. Beam 1, shear failure.

In table 1, the test results are compared with calculated values. In the first rows are jacking force F for service limit state (SLS), rupture point on figure 4. In the second rows are ultimate limit state (ULS) according to figure 4. The tests are compared with calculated values for SLS and ULS. In ULS first is calculated jacking force F due to bending strength the due to shear strength.

It is assumed that maximum service load is when the concrete cracks. These calculations give 30.2 KN force for the prestressed beams and 8.2 KN for beam 4, which was not prestressed. Calculating SLS for prestressed beam with concrete C23, max force is 25.7 KN. That is close to three time's higher SLS resistance of the prestressed beam than of the un-prestressed beam.

According to the Jónsson report [4] the ultimate force for bending 71, 1 KN and 11.4 KN prestressed and un-prestressed.

Table 1. Test result, force and displacement

	Test, F		Theory, F			Test, displacement		L/400 limit
	SLS, KN	ULS, KN	SLS, KN	ULS, KN	ULS, KN	SLS, mm	ULS, mm	mm
Beam 1	33	59*	30.2	71.1	84.6***	2.1	22	4.6
Beam 2	35	67*				1.8	24	
Beam 3	33	54*				1.7	15	
Beam 4	8 - 12	58**	8.2	11.4		0.2-0.8	36	

Note: * shear failure

** beam was pushed to the foundation, both shear and flexural failure

*** F due to expected shear strength of concrete

Figure 4 shows force F vs. displacement in the middle for all the beams on one graph. See setup of the experiment in figure 2.

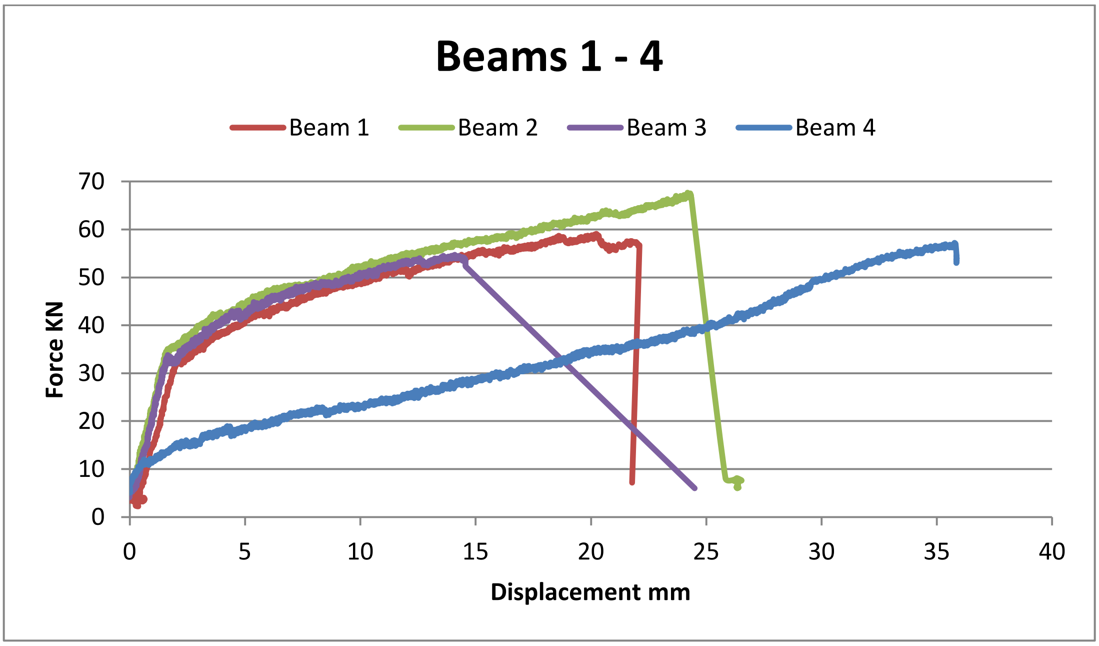

Figure 4. Force-displacement relationship, beams 1-4

For theory value of F for shear failure, many formulas were compared (table 3). The last equation is modified by authors based on EC2:2004 and fib 40 is giving promising results of shear strength of FRP concrete beams without shear reinforcement.

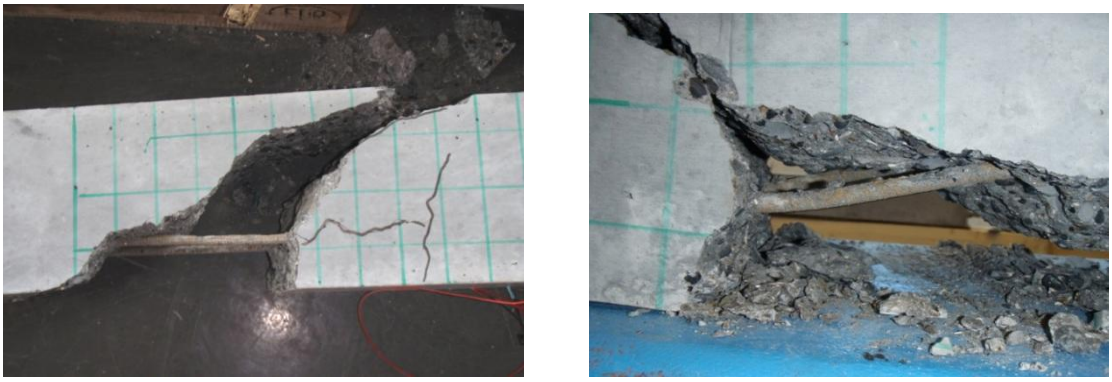

Figure 5. Shear failure. BFRP tendons are ductile.

In figure 5 is shown ductile shear failure. The dowel action for FRP is less than for steel tendons because the elastic module is approximately four times lower than for steel. The shear failure will then not be brittle as can be seen in figure 5. As mention before the authors had taken this advantages into account in the shear formula and rewritten Eurocode 2 shear formula. After this modification, the calculated values compare with test results, see table 2.

Table 2. Calculated shear strength of concrete, modified formula - Vcf

V_{cf}	Prestress loss		Untensioned	
Concrete	0%	20%		
C23	24.0	21.9	13.4	KN
C60	29.0	26.9	18.4	KN

Table 3. Comparing shear strength of concrete beams without shear reinforcement

Shear strength		Steel/FRP	Code	Formula
	KN			
V_c	38,7	Steel	ACI 318-08	$V_c = \left(\frac{\lambda \cdot \sqrt{f'_c}}{6}\right) \cdot b_w \cdot d$
V_c	33,3	Steel	EC2:2004	$V_{Rd,c} = (C_{Rd,c} \cdot k(100 \cdot \rho_I \cdot f_{ck})^{1/3} + k_1 \cdot \sigma_{cp})b_w \cdot d$
$V_{c,min}$	33,6	Steel	EC2:2004	$V_{Rd,c} = (v_{\min} + k_1 \cdot \sigma_{cp})b_w \cdot d$
V_c	22,7	Steel	EC2:2004	$V_{Rd,c} = (C_{Rd,c} \cdot k(100 \cdot \rho_I \cdot f_{ck})^{1/3})b_w \cdot d$
$V_{c,min}$	23,0	Steel	EC2:2004	$V_{Rd,c} = v_{\min} b_w \cdot d$
V_{cf}	2,9	FRP	ACI 440.1R-03	$V_{c,f} = \frac{\rho_f \cdot E_f}{90 \cdot \beta_1 \cdot f'_c} \cdot V_c$
V_{cf}	10,9	FRP	ACI 440.1R-06	$V_c = 5 \cdot \sqrt{f'_c} \cdot b_w \cdot c$
V_{cf}	13,7	FRP	CNR-DT 203	$V_{Rd,ct} = 1{,}3 \cdot \left(\frac{E_f}{E_s}\right)^{1/2} \cdot V_{Rd,c}$
V_{cf}	18,5	FRP	fib40(EC2)	$V_{cf} = 0{,}12 \cdot (1 + \sqrt{\frac{200}{d}}) \cdot (100 \cdot \frac{A_f}{b_w \cdot d} \cdot \frac{E_f}{E_s} \cdot \phi_\varepsilon \cdot f_{ck})^{1/3} \cdot b_w \cdot d$
V_{cf}	31,4	FRP	fib40(ACI)	$V_{cf} = V_c \cdot (\frac{E_f}{E_s} \cdot \phi_\varepsilon)^{1/3}$
V_{cf}	**29**	**FRP**	**EC2(fib 40)**	$V_{Rd,c} = (C_{Rd,c} \cdot k\left(100 \cdot \rho_I \cdot \frac{E_f}{E_s} \cdot \phi_\varepsilon \cdot f_{ck}\right)^{1/3} + k_1 \cdot \sigma_{cp})b_w \cdot d$

The strain loss over the curing period is approximately 15% according to strain gauge measurements. Calculating shear strength for prestressed C60 beams with that loss gives V_{cf} =27.5 KN. Comparing to test results 27-33.5 KN.

In table 3, various formulas are used to calculate shear strength, as can been seen shear strengths with steel tendons are higher than with FRP. Furthermore, it may notice that advantage of prestress force is not included in ACI and fib formulas. However, in EC2 shear strength formula, special part takes into account the influence from prestress. As mention before when prestress force are applied the shear crack angle is less than without prestress, in this study 20 degrees.

4. Conclusions

Failure mode of the beams prestressed by BFRP tendons was due to shear failure, angle of the shear cracks that caused the collapse was in all cases close to 20°. The first cracks were due to bending in the constant maximum moment zone. The beam 4, which was not prestressed failed due to the combination of bending and shear. First cracks occurred at the constant moment zone and finally with shear cracks, 40°-48°. The un-prestressed beam deflected a lot, the cross section cracked and was totally ruined. The tendon has so many elastic lengthening capacities that when the load was released the beam got up in the middle almost at the horizontal level again.

The Gan Yil et al., [5] presented that SLS for prestressed beam is higher than for un-prestressed beam, but ULS is equal. That is alike to the results from this experimental work.

The ultimate force applied was similar in both cases. It is not easy to say when the un-prestressed beam reached its ultimate load. It did not collapse, but it was ruined. So it can be argued when the beam has reached its ultimate force. The load that caused the first crack is the primary limit state when designing prestressed beam. It is desirable to have the cross section without cracks. The first crack load was three times higher for the prestressed beam than for the un-prestressed one. For prestressed beams like the one that was investigated here the service load should be limited a little under the first crack load. The ultimate load was around twice as high as the first crack load. So the global safety factor is close to two.

The conclusions that can be drawn from this study:

Ultimate bearing resistance of a beam with prestressed BFRP tendons is not much higher than of un-prestressed beams but the SLS bearing resistance is much higher and the deflection is smaller.

Special care should be taken when designing members without shear reinforcement.

The SLS bearing capacity of the prestressed beams was triple compared to un-prestressed beam.

It is suggested to use Eurocode 2/fib 40 modified equation to calculate shear resistance of concrete $V_{Rd,c}$ in members who are prestressed with FRP.

$$V_{Rd,c} = (C_{Rd,c} \cdot k\left(100 \cdot \rho_I \cdot \frac{E_f}{E_s} \cdot \phi_\varepsilon \cdot f_{ck}\right)^{1/3} + k_1 \cdot \sigma_{cp})b_w \cdot d \qquad (1)$$

In fib 40 the ratio between both Elastic modulus and strain of FRP and steel is considered. This equation is a modification, using the prestressing portion according to EC2.

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