Shear-Tendon Rupture Failure of Concrete Beams Prestressed with FRP Tendons

FRP를 사용한 프리스트레스트 콘크리트 보의 전단 텐던 파괴

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요 약

FRP는 비부식성 및 고강도의 뛰어난 성질에도 불구하고 콘크리트 구조에 사용하는데 있어서 소성의 결핍 및 낮은 전단강도와 같은 몇가지의 기술적인 단점을 가지고 있다. 특히 이 두가지 성질은 프리스트레스트 콘크리트 보에 있어서 다우월 작용이 일어나는 전단균열 단면에서와 같이 인장과 전단의 복합효과가 일어날 때 텐던의 조기 파괴를 일으키기 쉽다. 본 논문에서는 탄소 FRP 연선을 사용한 프리스트레스트 콘크리트 보에서의 텐던파열에 의한 전단파괴를 연구하였다. 전단시험 결과에 의하면 전단 텐던 파괴는 FRP 를 사용한 프리스트레스트 보에서만 일어나는 유일한 파괴형식으로 보의 전단강도를 저감시키는 것으로 확인되었다. 이러한 전단 텐던 파괴 과정을 규명하기 위하여 다우월 시험을 실시하고 최초로 실용적인 시험장치 및 과정을 소개하였다. 다우월 시험 결과에 의하면 FRP 연선은 인장과 전단의 상호작용에 의해 Tsai-Hill파괴 기준에 따라 파괴되었다.

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1. Introduction

In recent years, Fiber Reinforced Plastic (FRP) reinforcement for use in concrete structures have aroused considerable worldwide interest in the construction industry and among researchers. This is primarily because FRP reinforcement, in comparison to conventional steel reinforcement, offer some excellent advantages, such as non-corrosive, non-magnetic, high strength, and light weight properties. In particular, non-corrosion is the most important property for civil engineering infrastructures because the deterioration due to corrosion causes the most serious economic and technical problems in repairing existing structures in many countries.

However, FRP reinforcement also have some disadvantages such as non-plastic behavior, very low shear or transverse strength, susceptibility to stress-rupture, and high cost. From a structural engineering viewpoint, the most serious of these are the lack of plastic behavior and the very low shear strength in the transverse direction. Such characteristics may lead to premature tendon rupture in a diagonally cracked prestressed concrete beam where dowel action is activated. Thus, it is expected that shear-tendon rupture failure initiated by dowel action results in less shear resistance and shear ductility in concrete members prestressed with FRP tendons.

This paper presents the results of an experimental investigation of the shear-tendon rupture failure of concrete beams prestressed with carbon FRP tendons. It also presents the results of dowel tests for tensioned FRP tendons subjected to dowel shear to explain the failure mechanism of shear-tendon rupture.

2. Statement of The Problem

As illustrated in Fig. 1, the shear resistance of concrete beams is provided by both concrete (Vc) and shear reinforcement (Vs). The contribution of concrete (Vc) to the shear transfer mechanism in reinforced or prestressed concrete beams consists of three components: the shear forces carried by the compression zone (Vcz), aggregate interlock (Va), and dowel action (Vd).

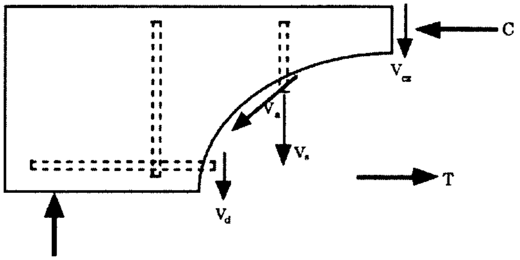

Fig. 1 Internal shear forces carried by concrete and shear reinforcement

The longitudinal reinforcement, which is designed primarily to resist flexural tension, is often required to carry a shear force by dowel action across a diagonal tension crack. If the crack opens (rotates) slightly, a shear displacement will result from the rotation of a beam about the crack tip and the shear slip due to the shear force along the crack face. During this displacement, the bars or tendons develop dowel shear forces to resist

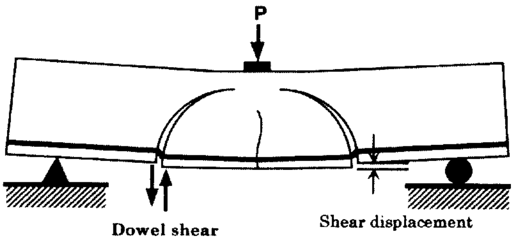

Fig. 2 Dowel action in a concrete beam

differential shear displacement between the crack faces. This counteraction of the bars or tendons to displacement is called "dowel action" (Fig. 2).

In a diagonally cracked prestressed concrete beam, dowel action leads to a bending moment and a shear force in the tendon itself, in addition to the tensile force due to the effective prestressing force and the applied load. As the bending moment due to dowel action increases with loading, a bending stress initiates in the wires of the FRP tendon. On the other hand, as the shear force due to dowel action increases, a shear stress initiates in each wire of the tendon. Under these tensile and shear stresses, the wire may fail by the interaction of both stresses at a critical value of dowel force.

Fig. 3 shows schematically the shear-tendon rupture failure mode in concrete beams prestressed with FRP tendons and other shear failure modes in beams with FRP and steel tendons.

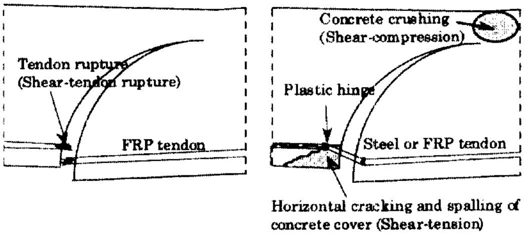

Fig. 3 Shear-failure modes in PC beams with FRP and steel tendons [4]

3. Experimental Program For Shear Test

To investigate the shear-tendon rupture failure of concrete beams prestressed with FRP tendons, an experimental program for shear test was carried out and the test results were analyzed, compared, and discussed. The failure was related to the differential shear displacement and crack width at the shear-cracking plane.

3.1 Test Beams and Data Acquisition

The loading arrangement and cross sectional dimensions are shown in Fig. 4. All beams were 130 mm wide, 270 mm deep, and 1650 mm long. They were fabricated without stirrups. For testing, the beams were simply supported and subjected to one concentrated load at midspan. The selected shear span-to-depth ratio was 2.5 for all beams. Experimental variables for the test beams are summarized in Table 1.

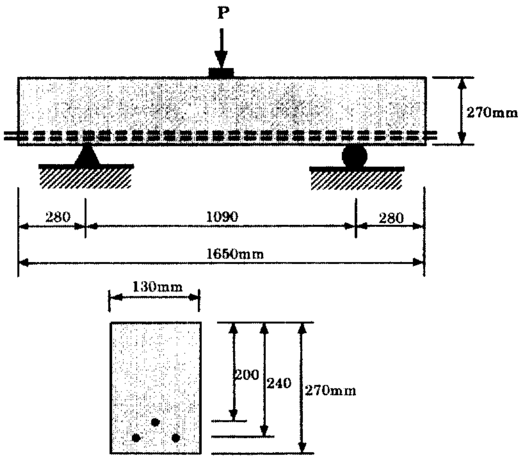

Fig. 4 Loading arrangement and typical cross section for shear test

Table 1 Details of test beams

Beam ID	Longitudinal reinforcement	Effective depth (mm)	Effective prestressing force(ton)	Reinforcing index(ω)*	Concrete strength (kg/cm²)	Remarks
C1	CFRP 3ϕ7.5	218	10.1(51.5%)	0.22	450	
C2	CFRP 3ϕ7.5	218	10.1(51.5%)	0.21	470	
S1	Steel 3ϕ9.5	229	8.8(28.3%)	0.23	432	
S2	Steel 3ϕ9.5	229	8.8(28.3%)	0.23	424	

*$\omega = \frac{A_{fs}}{bd_f}\frac{f_{fu}}{f_c'}$ for FRP tendons, $\omega = \frac{A_{ps}}{bd_p}\frac{f_{ps}}{f_c'}$ for steel tendons

The CFRP strands used had a diameter of 7.5 mm, and an effective section area of 30.45 mm² with a specified strength (fpu) of 21.63

ton/cm^2. According to the manufacturer [6], the stress-strain relationship of the strand is linear elastic up to failure with a tensile modulus of 1400 ton/cm^2 and an elongation of 1.6% at break. The results of tension tests carried out in this study, showed that the average breaking strength of the CFRP strands was about 22.96 ton/cm^2, slightly higher than the specified strength, and their average tensile modulus was about 1370 ton/cm^2, almost the same as the specified elastic modulus. The steel strands used had a diameter of 9.5 mm and were of Grade 19 ton/cm^2 with a tensile modulus of 2040 ton/cm^2.

A non-contacting motion measuring instrument (Optotrak) was used to measure crack displacements and crack widths. The Optotrak is a three dimensional digitizing and motion analysis system. It operates by tracking the 3-D coordinates (x, y, z) of active infrared emitting diodes attached to the test specimen. For each beam, about thirty-two markers were glued on the surface of the beam. At the level of the longitudinal reinforcement, markers were placed at 50 mm intervals.

The test beam was loaded using displacement control at a loading rate of 0.025 mm per second. Continuous readings of applied load and coordinates of infrared markers were recorded every second. The following data were obtained by the Optotrak System: (1) load from the load cell of the Instron loading machine, (2) deflection at midspan, and (3) crack width and differential shear (transverse) displacement at the cracked plane from the markers at the level of the longitudinal tendons.

3.2 Analysis and Discussion of Shear Test Results

Relevant test results are summarized in Table 2.

Table 2 Summary of shear test results

Beam ID	Failure mode*	Ultimate load (ton)	Max. deflection (mm)	Max. shear displacement (mm)	Max. crack width (mm)	Shear cracking load(ton)	Exp. shear load** (ton)
C1	STR	18.9	6.1	0.76	0.43	14.8	11.6
C2	STR	19.8	7.4	0.69	0.61	13.0	11.7
S1	SC	22.3	8.9	2.34	0.81	12.4	11.2
S2	SC	21.5	9.7	2.44	1.17	12.6	11.1

* STR : Shear tendor rupture failure, SC : Shear compression failure

** Expected ultimate shear load by the ACI code

To evaluate the effect of FRP versus steel tendons, the test results of Beams C1 and C2 are compared with those of Beams S1 and S2. A marked difference between the test beams was in their mode of failure. Beams C1 and C2 failed by shear-tendon rupture, while Beams S1 and S2 failed by shear-compression. As shown in Figs. 5 and 6, Beam C1 was split into two segments by the tendon rupture at the critical shear-cracking plane, while beam S1 remained together. Also Beam C1 had smooth failure faces, while beam S1 had the concrete crushed in the compression zone.

Another notable difference between the

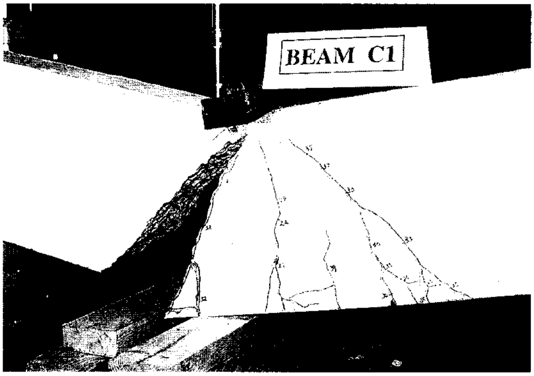

Fig. 5 Shear-tendon rupture failure and crack pattern of Beam C1

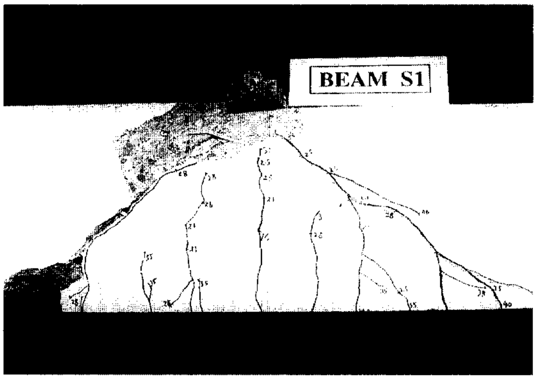

Fig. 6 Shear-compression failure and crack pattern of Beam S1

two types of reinforcement, is in the differential shear displacement at the critical shear-cracking plane. As can be seen in Table 2, the average differential shear displacement, 0.72 mm, of Beams C1 and C2 at the ultimate load was about 30% of that of Beams S1 and S2. Also, the average crack width, 0.51 mm, of Beams C1 and C2 at the failure load was about 50% of that of Beams S1 and S2.

In terms of crack pattern, secondary shear cracks in the lower part of the primary shear-cracking plane were observed in Beams C1 and C2 while well developed flexural-shear cracks in the midspan area were noted in Beams S1 and S2. The angle of the critical shear cracking was about 50 to 55 in Beams C1 and C2, and about 45 in Beams S1 and S2.

Different types of failure led to different shear capacities. On average, Beams C1 and C2, which failed by shear-tendon rupture, had about 12% less shear carrying capacity, 19.3 ton, than Beams S1 and S2 which failed by shear-compression in the concrete (Table 2). Also, the average ultimate deflection, 6.8 mm, of Beams C1 and C2 at midspan was about 30% less than that of Beams S1 and S2. For the beams failed by shear, the measured ultimate loads were considerably higher than the expected shear strength computed using the ACI code. Beams C1 and C2 had about 65% higher ultimate shear strengths, while Beams S1 and S2 had about 95% higher

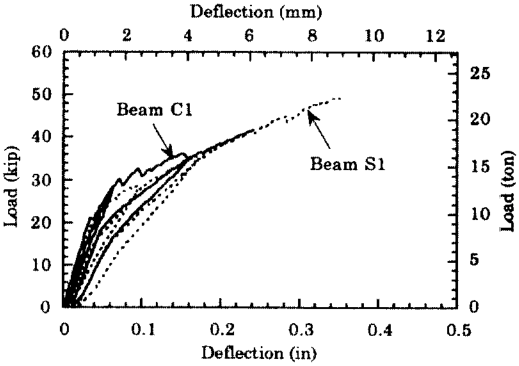

Fig. 7 Load-deflection curves for Beams C1 and S1

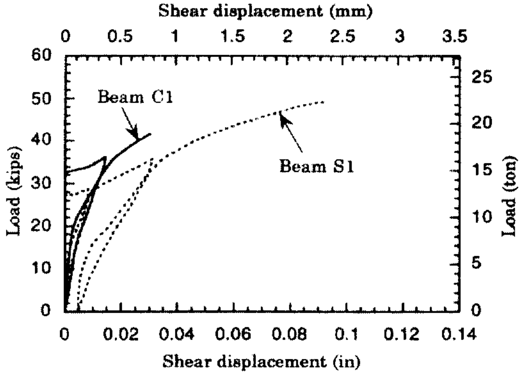

Fig. 8 Load-shear displacement curves for Beams C1 and S1

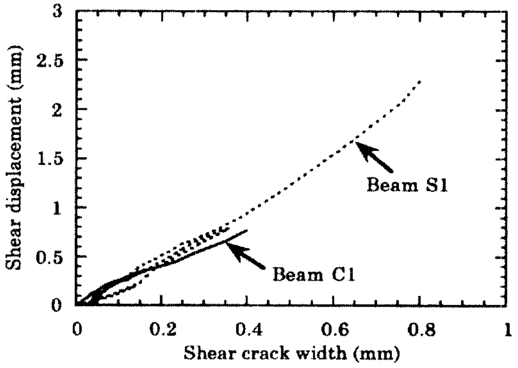

Fig. 9 Shear displacement-crack width curves for Beams C1 and S1

ultimate shear strengths (Table 2).

It is seen from Figs. 7 and 8 that the load-deflection response of Beams C1 and S1, and the general shape of their load versus shear displacement, are very similar. Fig. 9 illustrates the relationship between the differential shear displacement and crack width, which is almost linear.

4. Experimental Program for Dowel Test

Previous experimental shear test results showed that shear-tendon rupture failure is a unique mode of failure characteristic of concrete beams prestressed with FRP tendons. It is due to tendon rupture by dowel shear at the critical shear-cracking plane. Longitudinal FRP reinforcement in prestressed concrete members is subjected to not only tensile force but also dowel shear force at the shear crack. Therefore, the behavior of FRP tendons under a combination of tensile and shear forces should be known in order to explain shear-tendon rupture. Within this framework an experimental study of dowel action was carried out to investigate dowel behavior and failure of FRP tendons subjected to combined tensile and shear forces.

4.1 Test Specimens and Data Acquisition

The experimental program for the investigation of dowel action comprises eight specimens with different tension ratio. All specimens were 200 mm deep and 850 mm long in which the central concrete block was 150 mm long. The loading arrangement and typical cross section is shown in Fig. 10.

Each dowel specimen was cast in a wood form with a Plexiglas box inserted in the center. The Plexiglas box had the same dimensions as the center block in each dowel specimen; the concrete block was cast after removing the Plexiglas box from the hardened specimen. Two layers of polyethylene having a thickness of 0.15 mm were placed at the shear planes to induce an artificial crack before concrete pouring. FRP and steel tendons were pretensioned to the desired jacking forces by means of a hydraulic jack. The prestress losses were calculated by the time-step method [2].

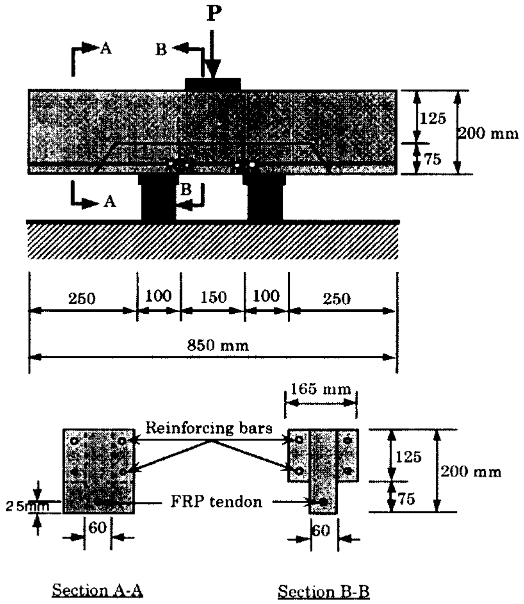

Fig. 10 Loading arrangement and typical cross section for dowel test

At the level of longitudinal reinforcement, four markers were attached to the specimen between the intentionally induced cracks (shear planes). The test specimen was loaded using displacement control at a loading rate of 0.5 mm per minute by the Instron loading machine. The load from the Instron was applied to the steel loading plate placed on the center block of the specimen. Therefore, the central concrete block was pushed down, so that the FRP tendon was subjected to a shear force at the induced artificial shear plane. The readings of the applied load and coordinates of infrared markers were recorded every second. Therefore, the shear displacements (shear slips) between the induced cracks and corresponding loads were measured.

4.2 Analysis and Discussion of Dowel Test Results

Dowel test results are summarized in Table 3.

Table 3 Tension ratios and results of dowel test

Specimen ID	Test parameter	Effective prestressing force (ton)	Concrete strength (kg/cm²)	Ultimate dowel shear force (ton)	Ultimate displacement (mm)
1	F_j=0%	0	400	0.449	0.68
2	F_j=0%	0	400	1.220	2.41
3	F_j=40%	1.87(26.7%)	400	1.137	1.85
4	F_j=40%	1.87(26.7%)	400	1.184	1.65
5	F_j=60%	3.01(43.1%)	390	1.110	1.33
6	F_j=60%	3.01(43.1%)	390	1.100	1.20
7	F_j=80%	4.10(58.7%)	370	0.957	1.02
8	F_j=80%	4.10(58.7%)	370	1.020	1.07

where F_j=jacking force ratio

All FRP dowel tendons except for the tendon in Specimen 1 were ruptured at the level of the dowel shear force, between 0.9 to 1.2 ton, with a soft snapping sound. The seven wires of the tendons were broken one by one. The overall dowel response curves of the tendons are given for various pretensioning ratios in Fig. 11.

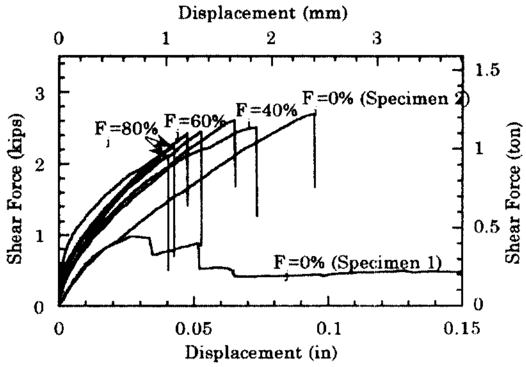

Fig. 11 Dowel shear force-displacement curves for various tensile forces

All response curves were curvilinear with slightly decreasing stiffness. Considering the elastic property of the FRP tendons, the slightly decreasing stiffness up to the failure can be attributed to the localized concrete micro-cracking and crushing under the tendons close to the shear planes. At the failure of the tendons, horizontal cracks occurred along the tendons due to the impact of the rupture; this did not happen for the tendons having no pretensioning force.

In Specimen 1, which was pushed against a concrete cover with the support at a distance of 100 mm from the shear plane, horizontal cracking occurred at the level of dowel shear force, about 0.5 ton. Before horizontal cracking, the shear force versus displacement curve of Specimen 1 followed the same path as Specimen 2, which had no free concrete cover. Specimen 1 sustained the ultimate dowel shear force even after horizontal cracking until the shear displacement reached about two times the displacement. The concrete cover was spalled off at a large shear displacement of 3.8 mm.

As shown in Fig. 11, the ultimate dowel shear force and shear displacement decrease as the tension ratio increases. This decrease in dowel strength is attributed to the effect of the tensile force in the tendon, that is, there is an interaction between shear and tensile forces. On the other hand, the stiffness of the dowel shear force versus shear displacement curve increases as the tensile force increases. This increase is mainly attributed to the cable effect, which leads to an upward resisting force caused by the change in curvature in the tensioned cable.

As shown in Fig. 12, it can be stated that generally, the relationship between tensile and shear forces at failure of the FRP tendons is almost elliptical, even though there is no sufficient data at higher tensile forces. Theoretically this failure criterion falls under the maximum work theory, commonly referred to as the Tsai-Hill criterion, not under the maximum stress criterion [1,7,8]. Another interesting finding is that the ultimate shear displacement of the test results decreased linearly with the applied tensile force, as shown in Fig. 13. This fact implies that the FRP dowel tendons and surrounding concrete remain within a elastic range up to failure.

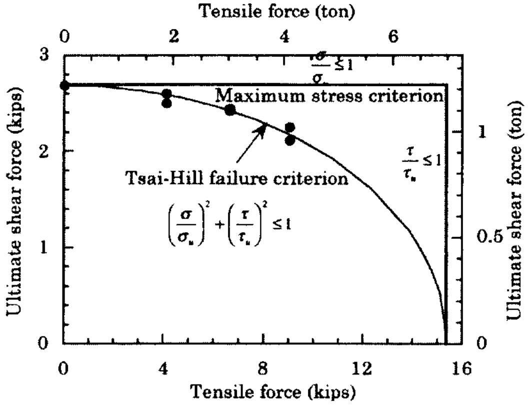

Fig. 12 Relationship between tensile and shear forces at failure

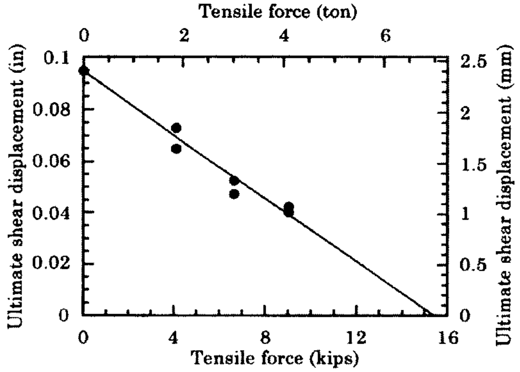

Fig. 13 Relationship between tensile force and shear displacement at failure

6. Conclusions

On the basis of this experimental investigation of shear and dowel tests the following conclusions can be drawn.

1) The shear-tendon rupture failure is a unique mode of failure characteristic of concrete beams prestressed with FRP tendons. It is due to tendon rupture by dowel shear at the shear-cracking plane. This premature failure is attributed to the poor resistance of FRP tendons in the transverse direction and their brittle behavior.

2) The ultimate shear resisting capacity and deflection of concrete beams prestressed with FRP tendons was about 15% and 30% less than that of beams prestressed with steel tendons, respectively. For about the same prestressing force and reinforcing index, the beams with FRP tendons failed by shear-tendon rupture and the beams with steel tendons failed by shear-compression.

3) The ultimate shear displacement of beams prestressed with FRP tendons that failed by shear-tendon rupture was about one third that of similar beams prestressed with steel tendons. For all beams tested, an almost linear relationship was observed between the shear crack width and the differential shear displacement at the critical shear-cracking plane.

4) The ultimate dowel shear force of the FRP dowel tendons subjected to tensile and dowel shear forces decreased elliptically as the tensile force increased. Theoretically, this failure criterion satisfies the maximum work theory, commonly referred to as the Tsai-Hill criterion.

5) The ultimate shear displacement of the

FRP dowel tendons under combined tensile and dowel shear forces decreased linearly with the increase of the tension ratio.

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ABSTRACT

Despite their excellent properties, such as high corrosion resistance and high strength, FRP reinforcements have several technical drawbacks for use in concrete structures, particularly their lack of ductility and low transverse strength. These properties are likely to lead to premature tendon rupture, particularly when combined effects are present, such as at shear-cracking planes where dowel action exists in prestressed concrete beams. This study deals with the shear-tendon rupture failure of concrete beams prestressed with CFRP tendons. The shear test results confirmed that premature shear-tendon rupture failure is characteristic of concrete beams prestressed with FRP tendons, resulting in reduced shear resisting capacity. To explain the shear-tendon rupture failure, a dowel study of FRP tendons was carried out and included first the development of a realistic test set up and procedure. The test results showed that FRP tendons fail due to interaction of tensile and shear forces following the Tsai-Hill failure criterion.

Keywords : FRP reinforcements, dowel action, prestressed concrete beam, shear- tendon rupture failure, shear strength

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