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REPAIR AND STRENGTHENING OF REINFORCED CONCRETE BEAMS USING CFRP LAMINATES

Volume 4: Behavior of Beams Strengthened For Shear

by

Antoine Naaman
Sang Yeol Park
Maria del Mar Lopez

Project Coordinator: Roger D. Till, MDOT
Project Advisor: Thomas D. Gillespie, GLCTTR

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16. Abstract

Repair and strengthening techniques using glued-on carbon fiber reinforced plastic (CFRP) plates (also called sheets, tow-sheets, and thin laminates) form the basis of a new technology being increasingly used for bridges and highway superstructures.

The study described in this report (Volumes 1 to 7) focused on the use of carbon fiber reinforced plastic (CFRP) laminates for repair and strengthening of reinforced concrete beams. Its primary objectives are: 1) to ascertain the applicability of CFRP adhesive bonded laminates for repair and strengthening of reinforced concrete beams; 2) to synthesize existing knowledge and develop procedures for implementation in the field; 3) to identify key parameters for successful design and implementation; and 4) to adapt this technique to the specific conditions encountered in the state of Michigan.

This report consists of 7 volumes:
Volume 1 – Summary Report
Volume 2 – Literature Review
Volume 3 – Behavior of Beams Strengthened for Bending
Volume 4 – Behavior of Beams Strengthened for Shear
Volume 5 – Behavior of Beams Under Cyclic Loading at Low Temperature
Volume 6 – Behavior of Beams Subjected to Freeze-Thaw Cycles
Volume 7 – Technical Specifications

The part of the investigation dealing with reinforced concrete beams strengthened in shear is described in this volume (volume 4), where the results are also analyzed, compared, and discussed. The experimental program comprised three rectangular concrete beams and three T-beams. The test parameters included two different shear-span ratios. Two commercially available strengthening systems were tested, the Sika CFRP plate system (CarboDur), and the Tonen CFRP sheet system. Both systems were used for shear strengthening and for two specimens they were also used for shear and bending strengthening. Other selective parameters investigated included two levels of longitudinal steel reinforcement ratio before strengthening and two steel shear reinforcement levels. Conclusions are drawn and some recommendations for design are suggested.

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Michigan Department of Transportation - Technical Advisory Group

Roger D. Till, *Project Coordinator*
Materials and Technology Laboratories

David Juntunen
Materials and Technology Laboratories

Jon Reincke
Materials and Technology Laboratories

Glenn Bukoski
Construction

Steve Beck
Design

Raja Jildeh
Design

Michel Tarazi
Design

Steve O'Connor
Engineering Services

Sonny Jadun
Maintenance

John Nekritz
Federal Highway Administration

Great Lakes Center for Trucks and Transit Research

Thomas D. Gillespie, *Project Advisor*
University of Michigan Transportation Research Institute

University of Michigan - CEE Research Team

Antoine Naaman, *Project Director*

Sang Yeol Park, *Research Fellow*

Maria del Mar Lopez, *Graduate Research Assistant*

Luke R. Pinkerton, *Graduate Research Assistant*

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Project Director: Antoine E. Naaman, UM
Project Coordinator: Roger D. Till, MDOT
Project Advisor: Thomas D. Gillespie, GLCTTR

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Department of Civil and Environmental Engineering
University of Michigan, 2340 G.G. Brown building
Ann Arbor, MI 48109-2125
Tel: 1-734-764-8495; Fax: 1-734-764 4292

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The opinions expressed in this report are those of the authors and do not necessarily reflect the views of the sponsors.

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PREFACE

This project titled: *"Repair and Strengthening of Reinforced Concrete Beams using CFRP Laminates"* is aimed at providing experimental verification and recommendations for implementation of a new technology, in which thin fiber reinforced plastic laminates are glued-on the surface of concrete beams in order to strengthen them.

The primary objectives of the project were:

- To ascertain the applicability of Carbon Fiber Reinforced Plastic (CFRP) glued-on plates for repair and strengthening of concrete beams;
- To synthesize existing knowledge and develop procedures for implementation in the field;
- To adapt this technique to the specific conditions encountered in the state of Michigan.

The project consisted of 8 tasks as follows:

- A report containing a literature review and a comprehensive synthesis of the latest state of knowledge on the glued -on FRP technique (Task 1);
- Laboratory testing and verification of the selected CFRP glued-on technique according to the proposed experimental program: bending (Task 2), shear (Task 3), freeze-thaw (Task 4), temperature and high cyclic amplitude load (Task 5);
- An interim and final report summarizing the experimental results (Task 6). The interim report will cover the bending and freeze-thaw tests;
- A summary of field specifications and "how to" details for implementation in field applications;
- Guidelines for design based on the experience developed from the experimental work (Task 7);
- Field monitoring of application of the technique to one bridge selected by MDOT (Task 8a);
- Bridge testing before and after application of the glued-on plate (Task 8b to be conducted by professor A. Nowak, U of M)

This report summarizes the experimental program of beams strengthened for shear as per Task 3.

ABSTRACT

Repair and strengthening techniques using glued-on carbon fiber reinforced plastic (CFRP) plates (also called sheets, tow-sheets, and thin laminates) form the basis of a new technology being increasingly used for bridges and highway superstructures.

The study described in this report is part of a larger investigation on the use of carbon fiber reinforced plastic (CFRP) sheets for repair and strengthening of reinforced and prestressed concrete beams. Its primary objectives are: 1) to ascertain the applicability of CFRP glued-on plates for repair and strengthening of concrete beams, 2) to synthesize existing knowledge, 3) to identify optimum parameters for successful implementation, 4) to develop procedures for implementation in the field, and 5) to adapt the technique to the specific conditions encountered in the state of Michigan.

The experimental program includes four main parts: 1) tests of RC beams strengthened in bending; 2) tests of RC beams strengthened in shear; 3) freeze-thaw tests of strengthened beams followed by their test in bending; and 4) tests in bending and shear of strengthened beams under low temperature (-29° C) and high amplitude cyclic loading.

The part of the investigation dealing with reinforced concrete beams strengthened in shear is described in this report, where the results are also analyzed, compared, and discussed. The experimental program comprised three rectangular concrete beams and three T-beams. The test parameters included two different shear-span ratios. Two commercially available strengthening systems were tested, the Sika CFRP plate system (CarboDur), and the Tonen CFRP sheet system. Both systems were used for shear strengthening and for two specimens they were also used for shear and bending strengthening. Other selective parameters investigated included two levels of longitudinal steel reinforcement ratio before strengthening and two steel shear reinforcement levels. Conclusions are drawn and some recommendations for design are suggested.

1. GENERAL

The study described in this report is part of a larger investigation on the use of carbon fiber reinforced plastic (CFRP) sheets for repair and strengthening of reinforced concrete beams. Its primary objectives are: 1) to ascertain the applicability of CFRP glued-on plates for repair and strengthening of concrete beams, 2) to synthesize existing knowledge and develop procedures for implementation in the field, and 3) to adapt the technique to the specific conditions encountered in the state of Michigan.

The experimental program includes: 1) tests of RC beam strengthened in bending; 2) tests of RC beams strengthened in shear; 3) freeze-thaw tests of strengthened beams followed by their test in bending; and 4) tests in bending and shear of strengthened beams under low temperature, -29 C and high amplitude cyclic loading. The part of the investigation dealing with reinforced concrete beams strengthened in shear is described in this report, where the results are also analyzed, compared, and discussed.

2. EXPERIMENTAL PROGRAM

The experimental shear program comprised three rectangular and three T section concrete beams. The loading arrangement and cross sectional dimensions are shown in Figures 1 and 2 for rectangular and T beams, respectively. The rectangular beams were 100 mm wide, 250 mm deep, and 1.32 m long. The T beams with 100 mm webs were 300 mm deep and 1.93 m long. Their flanges were 300 mm wide and 50 mm thick. In most cases, the clear concrete cover for the reinforcing steel was kept at 50 mm.

To investigate the shear behavior, a three point shear test set-up was used (Figure 1). The selected shear span-to-depth ratio was 2.5 for the rectangular beams and 3.5 for the T beams. The rectangular beams were made without steel stirrups and strengthened for shear using CFRP sheets or plates. The T beams were provided with a flexural and shear reinforcement ratio of $0.89\rho_{max}$

and 0.91 $A_{v\ (max)}$ respectively and strengthened for bending and shear using CFRP sheets or plates. $A_{v\ (max)}$ is the shear reinforcement required for a reinforced concrete beam to resist a load at midspan that is allowed with the maximum longitudinal reinforcement ratio, ρ_{max}. Throughout the experimental study, the types of failures were closely observed. Also, the applied load, corresponding deflection and strains of longitudinal reinforcing bar, stirrup, and CFRP sheet (or plate) for flexural and shear strengthening were measured.

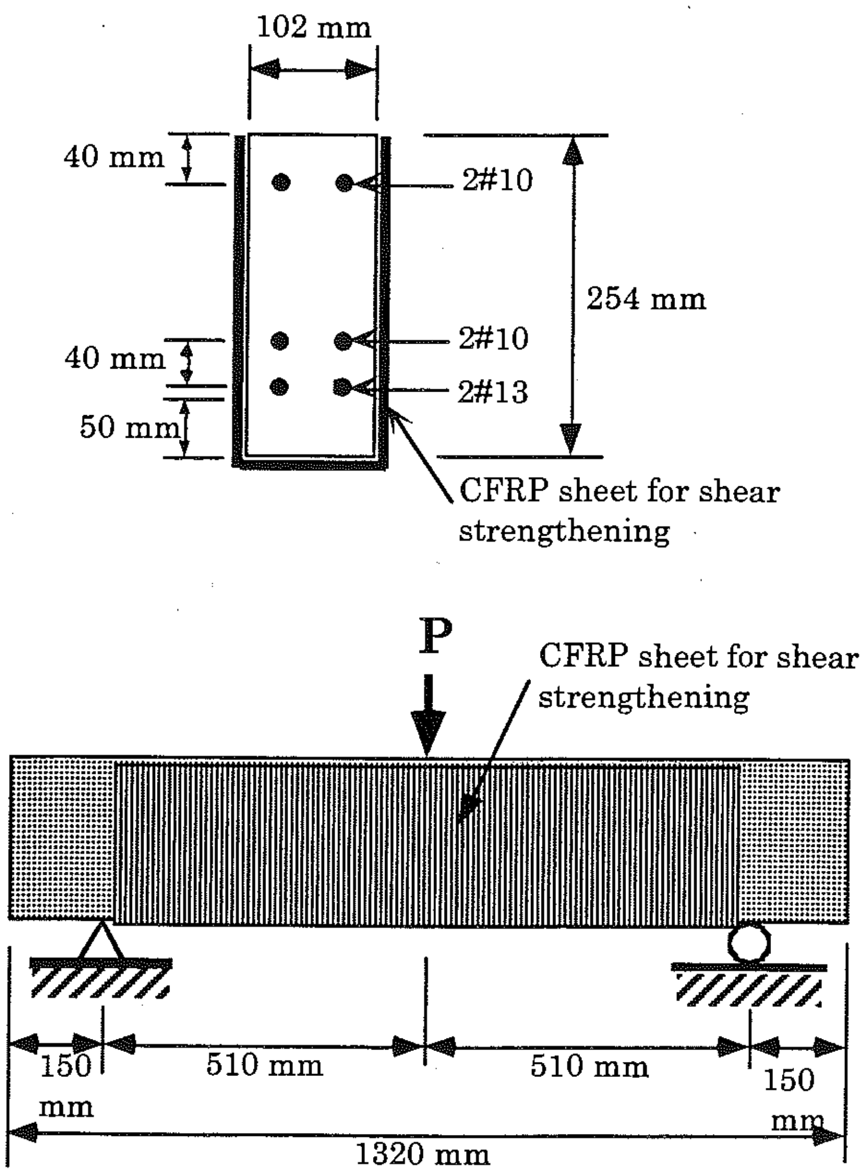


Figure 1 Typical cross section and loading arrangement for rectangular beams.

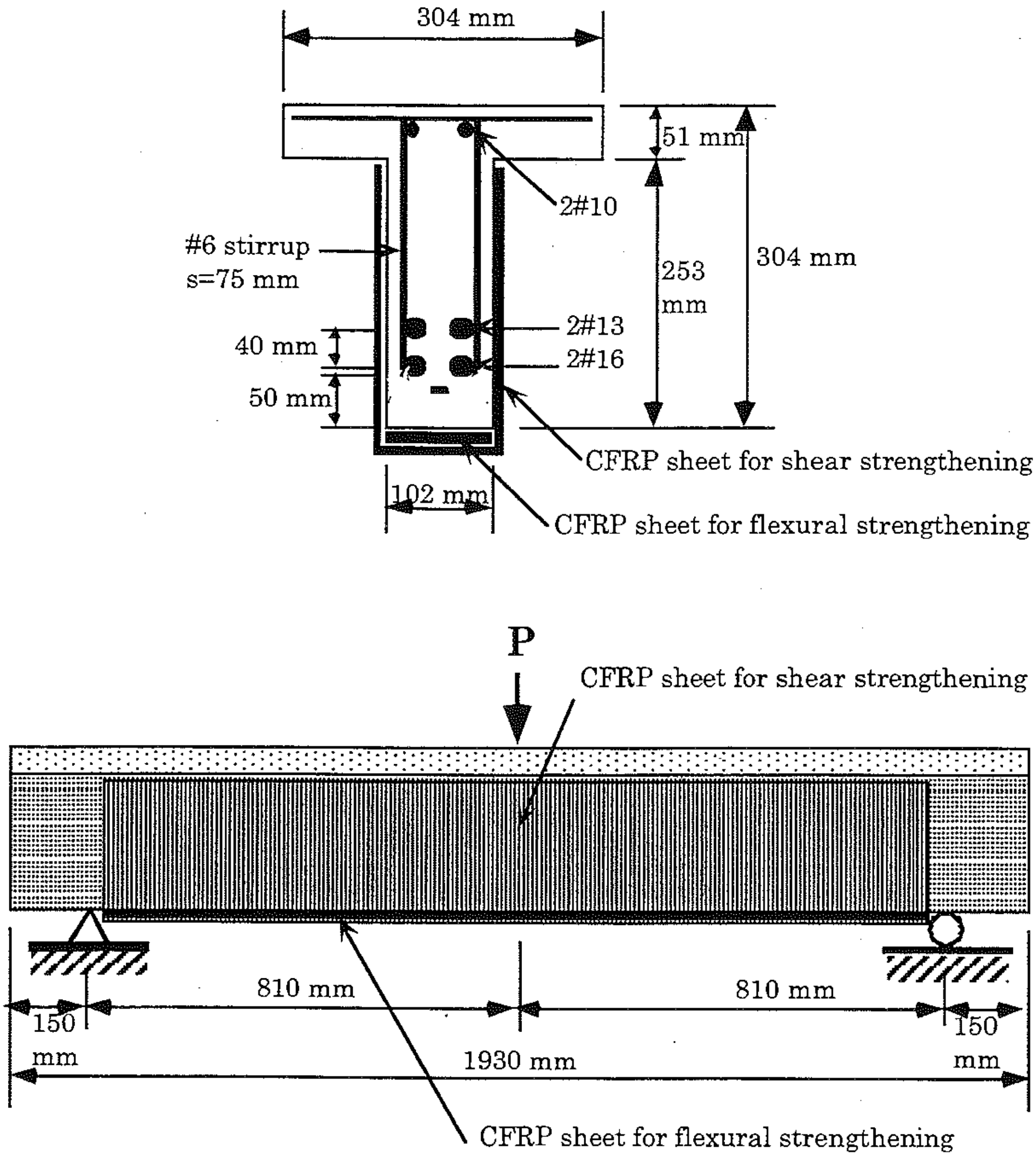


Figure 2 Typical cross-section and loading arrangement for T beams

2.1 Test Parameter

Several possible parameters for shear testing were proposed by the research team and evaluated by the Technical Advisory Group. Test parameters and experimental variables for the shear test are summarized in Table 1 and shown in Figures 3 & 4.

Initially, it was decided to use a high longitudinal reinforcement ratio in order to increase the ultimate bending resistance, be shear critical and observe shear strengthening effect. Accordingly, the longitudinal reinforcement ratio was designed to be approximately ρ_{max} for the rectangular beams and 0.5 ρ_{max} for the T-beams. These values were based on a target design compressive strength f'_c = 34.5 Mpa. However, the actual compressive strength of concrete (from the ready mix concrete company) was on the average 25.4 MPa. As a result the target values of reinforcement ratios were not achieved; actual values (summarized in Table 1) were significantly higher. It can be observed from Table 1 that the longitudinal reinforcement ratio of the rectangular beams was 1.41 ρ_{max} exceeding the balanced ratio, while for the T beams it was 0.89 ρ_{max} quite close to the maximum ratio, ρ_{max}, recommended by the AASHTO Code, as shown in appendix A. The rectangular beams did not have any steel stirrups. They were strengthened for shear using the CFRP sheets or plates. The T beams had steel stirrups reinforcement corresponding to 91% of the required area of stirrups for a reinforced concrete beam to resist a load at midspan that is allowed with a longitudinal reinforcement corresponding to ρ_{max} (maximum reinforcement ratio as recommended by the AASHTO Code). They were strengthened for shear to accommodate both the lack in shear resistance and the increase in bending resistance provided by the CFRP plate.

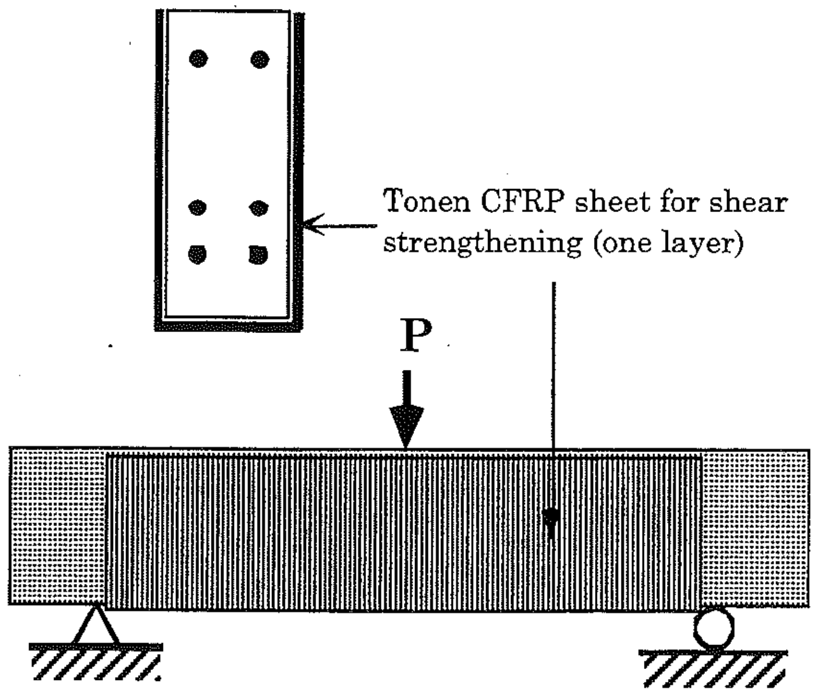
To investigate and evaluate the different strengthening systems, Tonen CFRP sheet (Forca Tow sheet) and Sika CFRP plate (CarboDur plate) were used for shear strengthening. For rectangular beams, one layer of Tonen CFRP sheet was glued on the web of Beam No. 2, and 25 mm wide Sika CFRP strips were glued on the web of Beam No. 3 at a spacing of 75 mm. The width and spacing of Sika CFRP strips were determined to be equivalent to the one continuous layer of Tonen CFRP sheet, based on equal tensile strength. The fiber direction of CFRP sheet or plate for shear strengthening was normal to the longitudinal direction of the beams.

Table 1 Test parameters and variables for shear test

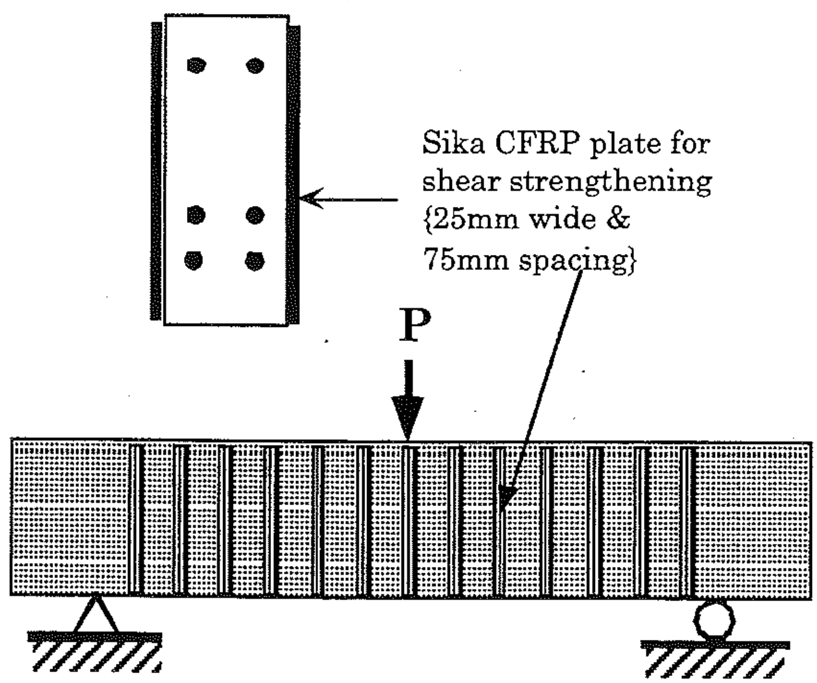
Beam No.	Section type	Shear reinforcement (A_v) Stirrup	CFRP sheet	Shear span-to-depth ratio (a/d)	Long. Steel reinforcement ratio (ρ)	Strength-ening
1	102x254 Rect.-section	None	None	2.5	1.41 ρ_{max}	Control
2		None	$A_{v(FRP)}$ Tonen sheet	2.5	1.41 ρ_{max}	Shear
3		None	$A_{v(FRP)}$ Sika plate	2.5	1.41 ρ_{max}	Shear
4	304x304 T-section	0.91 $A_{v\,(max)}$	None	3.5	0.89 ρ_{max}	Control
5		0.91 $A_{v\,(max)}$	$A_{v(FRP)}$ Tonen sheet	3.5	0.89 ρ_{max}	Shear & Bending
6		0.91 $A_{v\,(max)}$	$A_{v(FRP)}$ Sika plate	3.5	0.89 ρ_{max}	Shear & Bending

Note: 1. Actual concrete compressive stress, f'c=25.4 MPa. Actual steel yield stress, fy=496 MPa and 483 MPa for rectangular and T sections

2. Maximum shear reinforcement ratio, $A_{v\,(max)}$, is for maximum longitudinal reinforcement ratio, ρ_{max}.

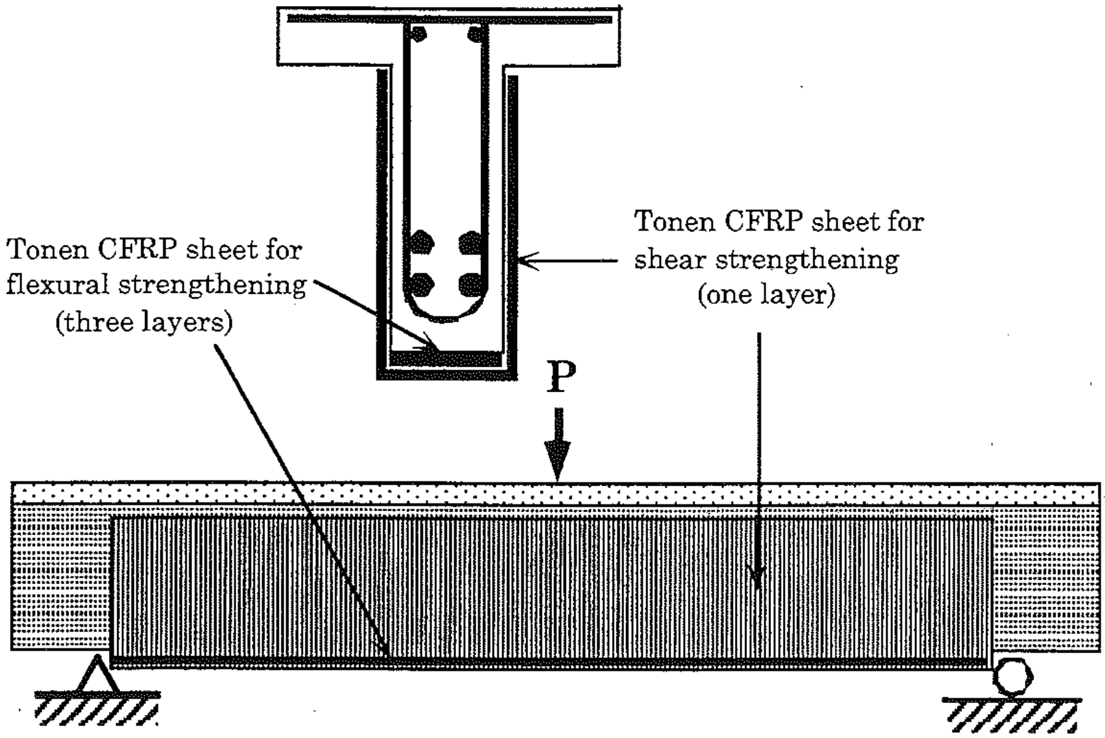


Beam No. 2

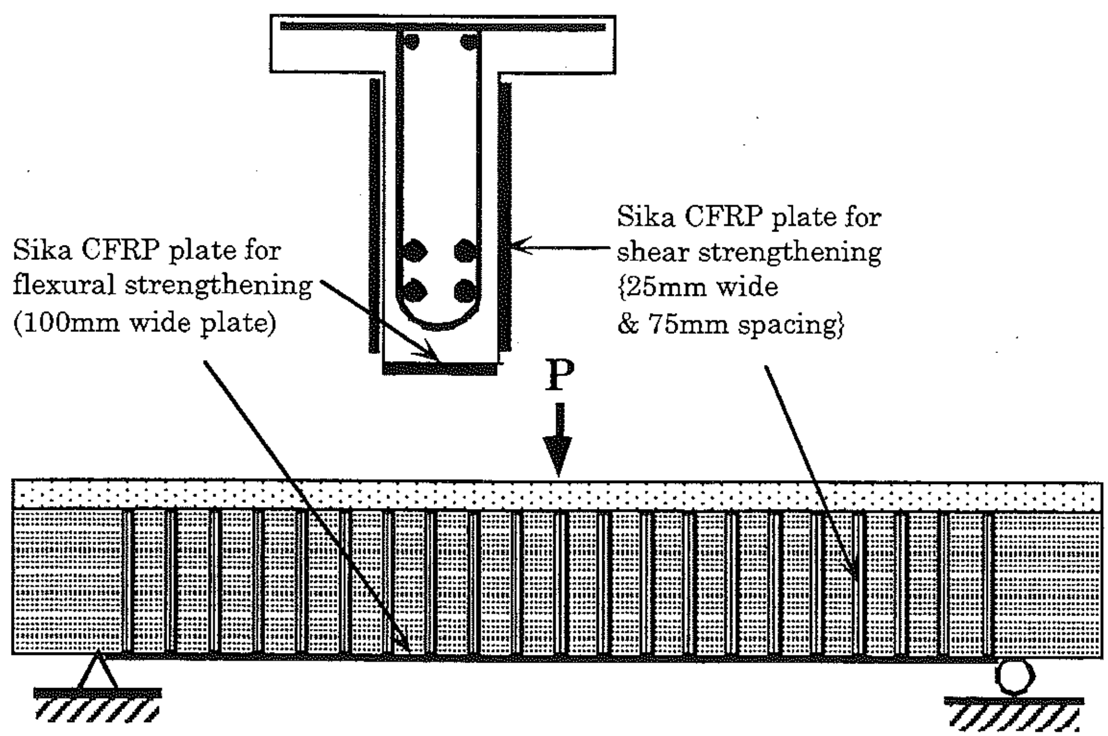


Beam No. 3

Figure 3 Test parameters for rectangular beams



Beam No. 5



Beam No. 6

Figure 4 Test parameters for T beams

For the T beams, Tonen CFRP sheet and Sika CFRP plates were used for flexural and shear strengthening. Three layers of Tonen CFRP sheet were glued on the bottom of Beam No. 5 for flexural strengthening, and one layer of CFRP sheet was glued on the web of the beam for shear strengthening. A 100 mm wide Sika CFRP plate was glued on the soffit of Beam No. 6 for flexural strengthening, and 25 mm wide Sika CFRP stripes were glued on the web of Beam No. 6 at a spacing of 75 mm. The fiber direction of all of CFRP sheets or plates was parallel to the beams for flexural strengthening and normal to the beams for shear strengthening.

For one selected set of parameters, two different shear span-to-depth ratios were used to study the influence of shear span-to-depth ratio. A shear span-to-depth ratio, 2.5, was used for rectangular beams, and 3.5 for T beams. T beams were strengthened for both flexure and shear to simulate a beam to be generally upgraded in capacity.

For all beams, the concrete surface to be glued on was ground with disk grinder for better bonding according to the recommendation of the strengthening system supplier.

2.2 Preparation of Test Beams

2.2.1 Materials

Test beams were made in the structural laboratory by the research team. Ready-mixed concrete with a target compressive strength of 34.5 MPa was requested for the test beams. However, the average compressive strength of the concrete matrix obtained from cylinder tests was about 25.4 MPa, which was less than the target strength. Table 2 summarizes the compressive strength of the concrete cylinders and the age of the beams on the test date.

Table 2 Compressive strength of concrete cylinders and time of beam test

Cylinder No.	Age, day	Compressive strength, MPa	Test beam No.	Age, day
1	26	25.3	1	24
2	26	24.7	2	24
3	26	25.0	3	24
4	26	23.8	4	25
5	26	27.0	5	25
6	26	26.4	6	25
Average	26	25.4	Average	24.5

For strengthening of the test beams, Forca Tow Sheet FTS-C1-30 (Tonen CFRP sheet) and CarboDur plate (Sika CFRP plate) with appropriate epoxy adhesives were used. The properties of the CFRP sheet or plate and adhesives are summarized in Table 3. According to the manufacturer, CFRP material is linear elastic up to failure.

Deformed steel reinforcing bars used for longitudinal reinforcement had a diameter of 10 mm (No. 10), 13 mm (No. 13), and 16 mm (No. 16) and a specific yield strength of 410 MPa with a tensile modulus of 200 GPa. No. 6 (6 mm diameter) steel reinforcing bar was used for stirrups for T beams. No. 2 reinforcing bar had a diameter of 6 mm and a specific yield strength of 280 MPa. Table 4 presents the actual yield strength and maximum tensile strength.

Table 3 Properties of CFRP sheets (plates) and adhesives.

Supplier		Tonen			Sika
System		Forca Tow Sheet			CarboDur
CFRP Sheet	Type	FTS-C1-20	FTS-C1-30	FTS-C5-30	CarboDur Strip
	Tensile Strength, N/mm	383	574	487	2868
	GPa	3.48	3.48	2.94	2.40
	Tensile Modulus, kN/mm	25.4	38.5	61.3	178.6
	GPa	228	228	372	150
	Thickness[1], mm	0.11	0.17	0.17	1.19
	Elongation, %	1.5	1.5	0.8	1.4
	Width, mm	500			50, 80, 100
	Length, m	Unlimited			Up to 250
Epoxy	Type	FR-E3P	FR-E3PS	FR-E3PW	Sikadur 30
	Application temperature, °C	Standard	Summer	Winter	≥4
	Tensile strength, MPa				24.8
	Elastic Modulus, GPa				4.48
	Elongation, %				1
	Shear strength, MPa				24.8
	Shrinkage				0.0004
	Pot-Life, min.	40	110	20	70
	Viscosity, cps	20,000	20,000	10,000	
Primer	Type	Standard, Summer, Winter, Penetrative, Summer damp surface, Winter damp surface			No Primer

1: Total cross sectional area of fibers per mm.

Table 4 Yield and maximum tensile strength of reinforcing bars.

Reinforcing bar		Yield stress, f_y MPa	Maximum stress, f_u MPa
No. 6	#6-1	315	319
	#6-2	327	330
	#6-3	335	338
	Average	325	329
No. 10	#10-1	458	652
	#10-2	454	644
	#10-3	452	656
	Average	454	650
No. 13	#13-1	513	711
	#13-2	519	721
	#13-3	530	733
	Average	521	722
No. 16	#16-1	458	741
	#16-2	455	729
	#16-3	454	733
	Average	456	734

2.2.2 Fabrication of Test Beam

Test beams were fabricated in the structural laboratory with ready-mixed concrete. All test beams had four longitudinal reinforcing bars, placed in two rows; two in the lower row at a clear distance of about 51 mm from the bottom fiber and two in the upper row with a clear distance of 40 mm from the lower row. Two strain gages were attached on the lower two reinforcing bars at the midspan location of each beam before assembling the reinforcement cage. For T beams, two-leg closed stirrups made of No. 6 reinforcing bar were placed at a spacing of 75 mm throughout the beams. Figure 5 shows steel cages and wood molds.

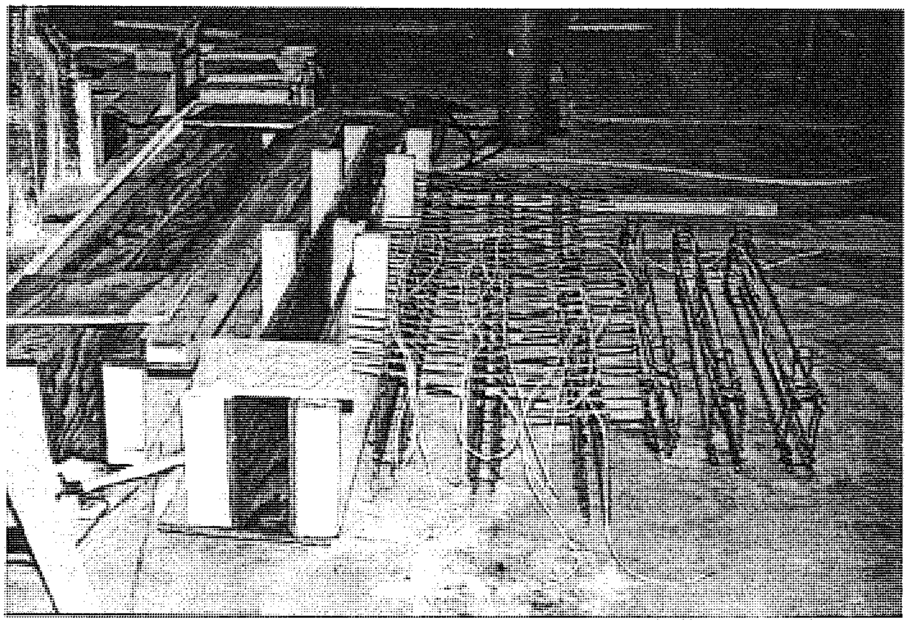


Figure 5 Steel reinforcement cages and wood molds for test beams

One batch of ready-mixed concrete was used for all test beams. After casting of concrete, the beams were covered with plastic sheet to keep moisture inside the beams. The test beams were removed from the molds 3 days after casting of concrete and stored in the laboratory.

The concrete surface to be bonded to was ground enough to remove laitance and provide open texture of aggregates by disk grinding. After grinding, dust and cement particles were removed by brushing and vacuum cleaning. Tonen CFRP sheet and Sika CFRP plate was cut to proper length by sharp knife and disk cutter, respectively. The CFRP sheet and plate was cleaned with a white cloth before gluing to remove soiling as well as carbon dust.

Adhesives were mixed according to the technical data sheets provided by the strengthening system supplier. For Tonen strengthening system, primer and epoxy adhesive were applied using a roller according to the commercial specifications. A hard roller was used to press the CFRP sheet into the epoxy adhesive. For the Sika strengthening system, a trowel was used to apply the epoxy adhesive to the surface of beam soffit or web and CFRP plate. Also, a hard roller was used to press the CFRP plate into the adhesive and to force any air pockets out from the interface. Note that the beams were not precracked before applying the CFRP plates or sheets. Figure 6 shows the test beams after gluing CFRP sheet or plate.

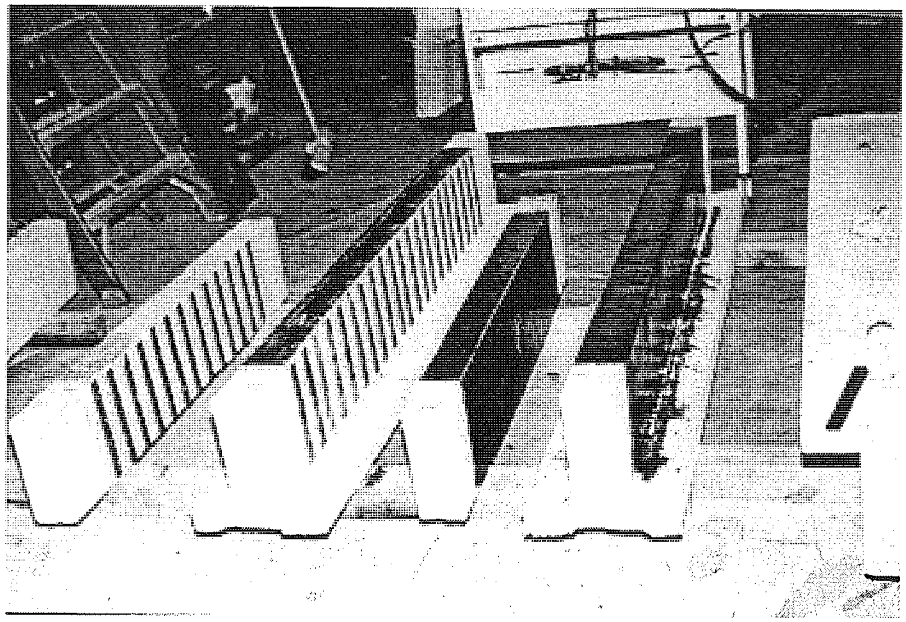


Figure 6 Test beams after gluing CFRP sheet or plate

2.3 Data Acquisition and Test Procedure

Figure 7 shows instrumentation layout for shear test. A computer data acquisition system (Megadack System) was used to measure the load and corresponding deflection as well as strains of longitudinal reinforcing bar, stirrup, and CFRP sheet or plate for flexural and shear strengthening.

Each test beam was loaded monotonically up to failure using displacement control at a loading rate of 0.025 mm per second by the Instron loading machine having a capacity of 450 kN. Each beam was pre-loaded to about 8.9 kN before testing to remove any residual stress and deformation in the test beam and stabilize the instrumentation. At every 8.9 kN interval, loading was temporarily stopped to observe the development of cracks and to mark them. All test beams were loaded monotonically up to their failure.

The following data was obtained every second by the data acquisition system:

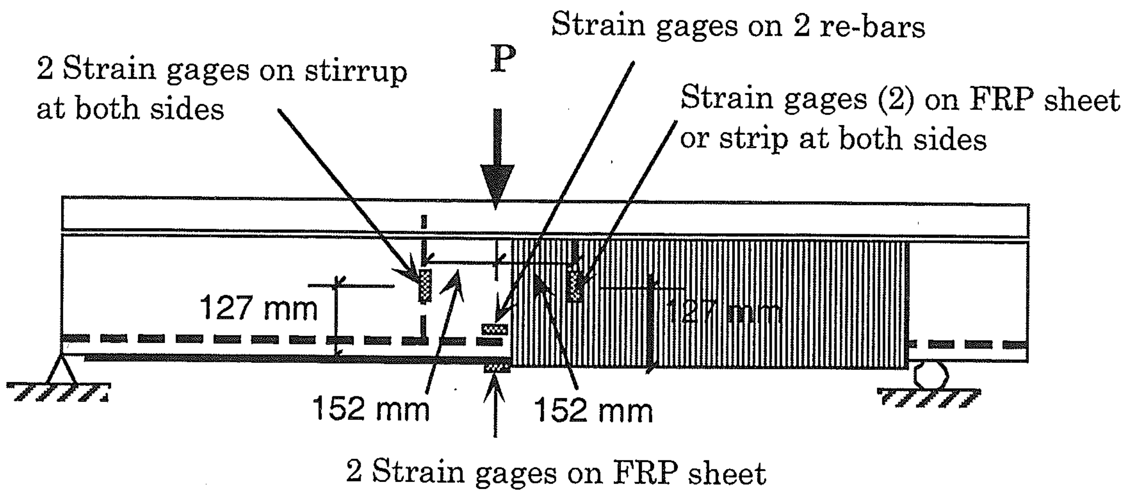
(1) load and deflection from the Instron loading machine

(2) strains of longitudinal reinforcing bars at midspan

(3) strains of both legs of single stirrups

(4) strains of CFRP sheet or strip on the web of beams (2 strains)

(5) strains of CFRP sheet or plate on the bottom of beams at the middle of span



Note: Location of strain gages for rectagular beams is the same as T beams

Figure 7 Instrumentation layout for shear test

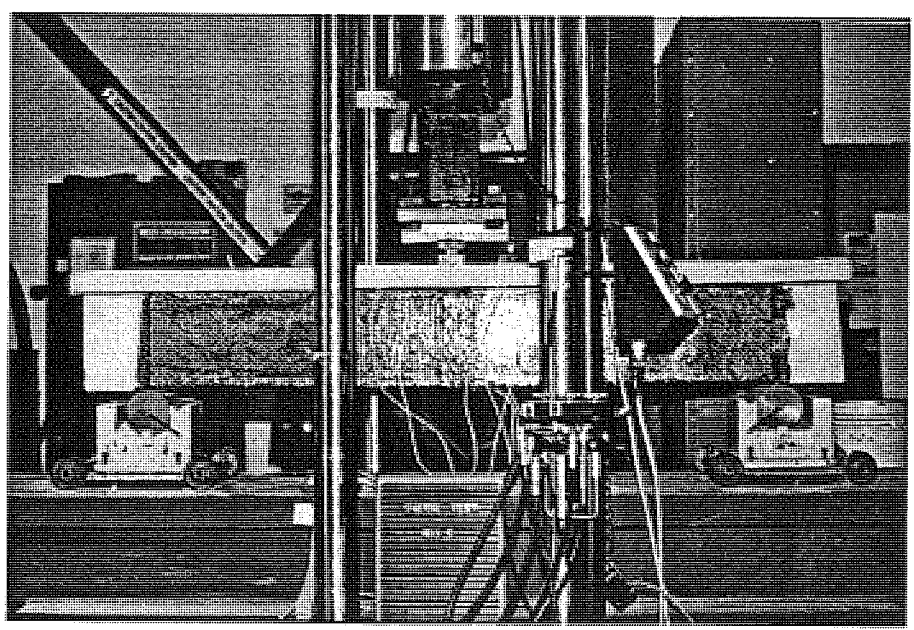


Figure. 8 Shear test set-up for T beam strengthened with CFRP sheet

3 ANALYSIS AND DISCUSSION OF TEST RESULTS

Relevant parameters and test results are summarized in Tables 5a and 5b.

3.1 Rectangular Beams

To evaluate the effect of shear strengthening using CFRP sheet or strips in rectangular beams, the test results of Beams No. 2 and No. 3 are compared with those of the control beam, Beam No. 1. Beams No. 2 and No. 3 were made without shear reinforcement (no steel stirrups) and were strengthened using one layer of Tonen CFRP sheet and or 25 mm wide Sika CFRP plate at a spacing of 75 mm, respectively. To ensure shear failure and avoid flexural failure prior to shear failure, three rectangular beams were initially reinforced with the maximum flexural reinforcement ratio according to the AASHTO code, assuming a target compressive strength of 35 MPa. After recalculations using the actual concrete and steel strength, the beam had a 141% reinforcement ratio (ρ_{max}) compared with the maximum value given by AASHTO. All beams were subjected to a concentrated load at midspan with a shear span-to-depth ratio of 2.5.

Control beam, Beam No. 1 failed by shear (diagonal tension failure) long before yielding of the longitudinal reinforcing bars. A critical diagonal tension crack occurred at a load of about 52 kN; which suddenly developed from the loading point at midspan to the support, resulting in diagonal tension failure (Figure 9).

Table 5a Summary of test results of shear test

Beam No.	Section type	Shear reinforcement (A_v)		a/d	Longitudinal Reinforce-ment	Failure Mode	Ultimate load, kN	Ultimate deflection, mm	Predicted failure load (bending failure)[1] kN	Predicted failure load (shear failure)[2] kN
		Stirrup	CFRP							
1	Rectangular	None	None	2.5	$1.41\rho_{max}$	Shear failure	51.8	3.0	106.75	31.14
2	Rectangular	None	CFRP sheet (Tonen)	2.5	$1.41\rho_{max}$	Steel yielding & Delamination	130.5	7.4	106.75	615.16
3	Rectangular	None	CFRP strip (Sika)	2.5	$1.41\rho_{max}$	Delamination shear failure	88.1	4.3	106.75	1001
4	T-section	$0.91A_v$ max (64.5 mm^2)	None	3.5	$0.89\rho_{max}$	Steel yielding & shear failure	164.2	15.5	161.75	166.71
5	T-section	$0.91A_v$ max (64.5 mm^2)	CFRP sheet (Tonen)	3.5	$0.89\rho_{max}$	Steel yielding & Delamination	240.2	12.2	257.15	745.75
6	T-section	$0.91A_v$ max (64.5 mm^2)	CFRP strip (Sika)	3.5	$0.89\rho_{max}$	Delamination shear failure	214.5	9.9	301.35	1131.75

Note: 1. See Appendix for detail calculations

2. See Appendix for detail calculations

Table 5b. comparison actual to controlling predicting failure loads

Beam #	1	2	3	4	5	6
Predicted Failure load (kN)	31.14	106.75	106.75	161.75	257.15	301.35
Actual Failure load (kN)	51.8	130.5	88.1	164.2	240.2	214.5
Ratio actual/predicted	1.66	1.22	0.83	1.02	0.93	0.71

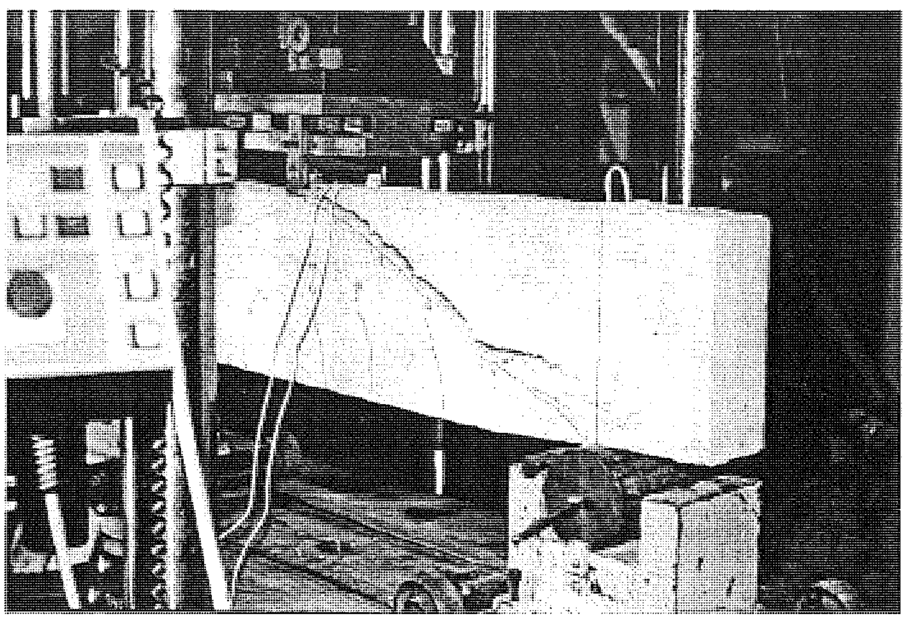


Figure 9 Diagonal tension failure of Beam No. 1

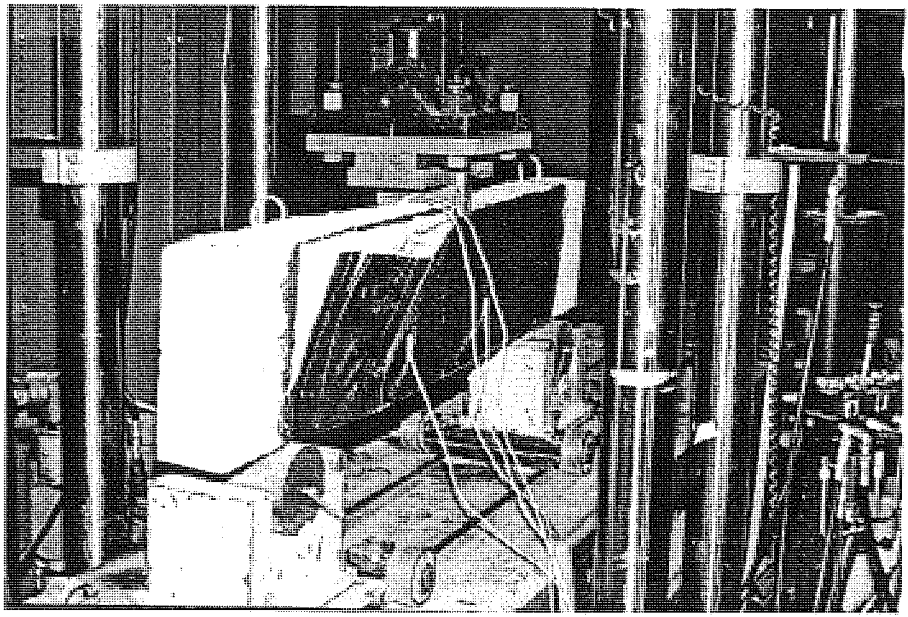


Figure 10 Shear-failure after delamination of CFRP sheet in Beam No. 2

Beam No. 2 with Tonen CFRP sheet, failed by shear-compression failure after delamination of the CFRP sheet used for shear strengthening. Shear-compression failure is characterized by crushing of the concrete in the compression zone at the end of the shear crack. Delamination occurred from the top of the web at maximum load, about 130 kN, after yielding of the longitudinal reinforcing bars. One side of the CFRP sheet was completely separated from the web due to the spalled concrete at the compression failure. Beam No. 2 attained its nominal flexural load carrying capacity, because reinforcement yielding occurred before the delamination of CFRP sheet. Thus, strengthening for shear with CFRP sheet significantly increased the ultimate load and deflection in beams with no existing shear reinforcement as shown in table 5b. Figure 10 shows the shear-compression failure of Beam No. 2 after delamination of the CFRP sheet.

Beam No. 3 with the Sika CFRP strips bonded to the web failed by diagonal tension failure just after delamination of some of the CFRP strips. Delamination suddenly occurred at a load of about 88 kN, before yielding of the longitudinal reinforcement. The shorter length side (with respect to the diagonal crack) of the CFRP strip at the critical diagonal crack was delaminated. The critical diagonal crack had a angle of about 40 degrees. Figure 11 shows the diagonal tension failure due to delamination of CFRP strip.

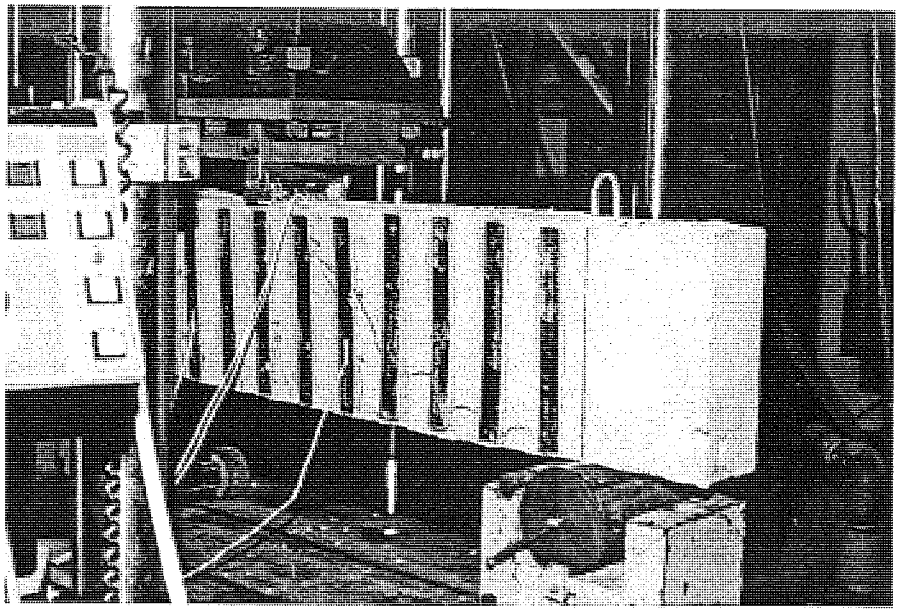


Figure 11 Shear failure due to delamination of CFRP strip in Beam No. 3

Figure 12 gives the load-deflection curves of the control beam and two shear strengthened beams using the two different strengthening systems. Beam No. 1 shows linear elastic behavior up to diagonal tension failure. Due to this premature failure by shear, Beam No. 1 had the lowest load carrying capacity of the three beams.

Beam No. 2 strengthened for shear with the Tonen CFRP sheet had the highest load carrying capacity and ductility of the three beams. The CFRP sheet used for shear strengthening significantly increased the maximum ultimate load and helps to maintain this maximum load up to relatively high deflection values before failure. The ultimate load of Beam No. 2 was about 250% that of the control beam and its deflection at ultimate was about 240% that of the control beam (Table 5a and Figure 12). The reason for the high load carrying capacity and ductility is that the CFRP sheet, by providing shear strengthening, prevented the beam from failing by shear prior to yielding of the longitudinal reinforcement. The yielding of reinforcing bars before shear failure is confirmed for beam No. 2 (2 gages) in Figures 13 and 14 that show the load-strain and deflection-strain curves of the reinforcing bars (strains at failure were larger than 0.2%, yielding strain for steel).

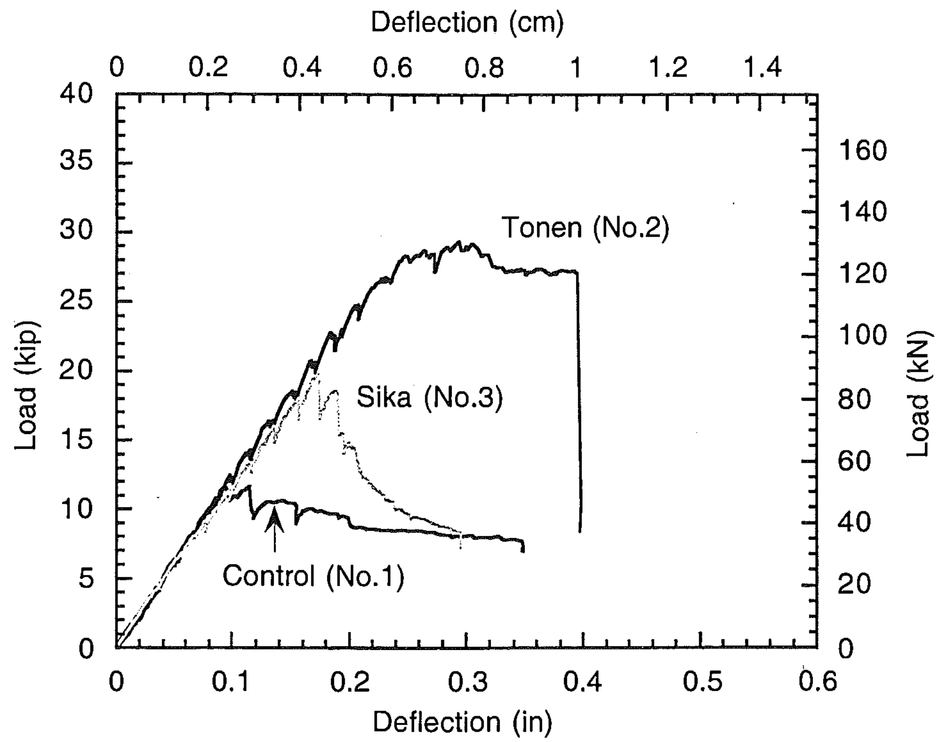


Figure 12 Load-deflection curves of rectangular beams

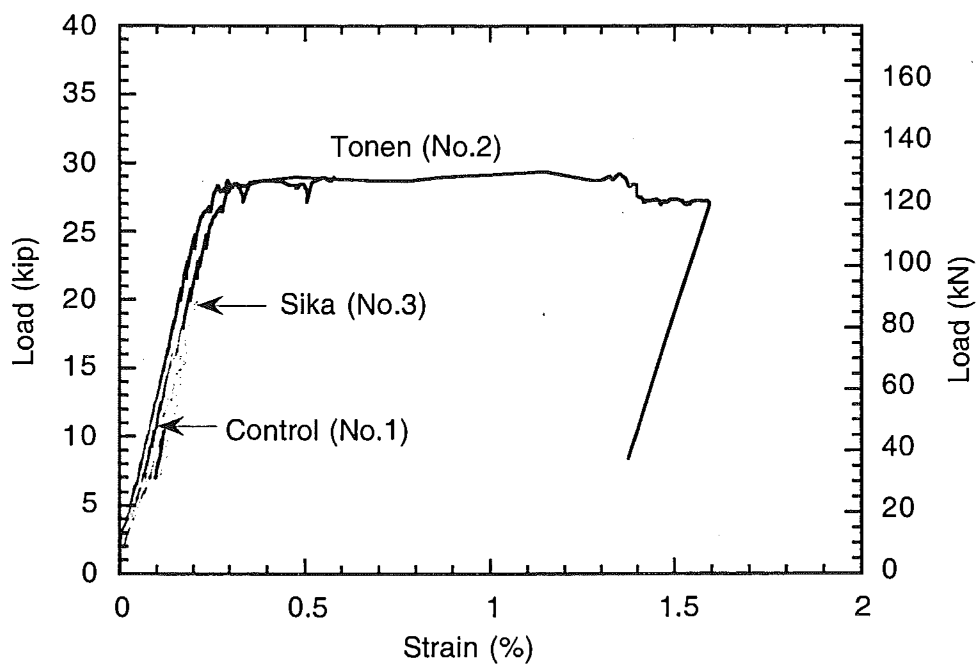


Figure 13 Load-strain curves of reinforcing bar in rectangular beams

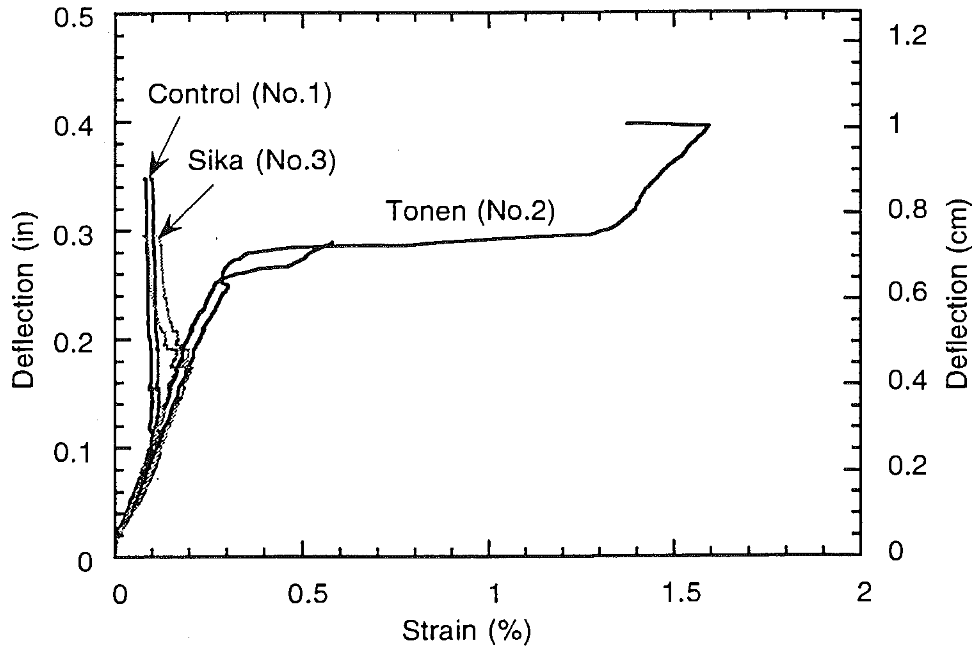


Figure 14 Deflection-strain curves of reinforcing bar in rectangular beams

Beam No. 3 with the Sika CFRP strip had higher load carrying capacity than the control beam, Beam No. 1, but had a lower load capacity than Beam No. 2. The beam had about 70% higher ultimate load and 40% higher ultimate deflection than the control beam (Table 5a and Figure 12). This is because shear failure was delayed by the CFRP strip used for shear strengthening, but it occurred before yielding of the flexural reinforcement.

Delamination of the Sika CFRP strip at a lower load than for Beam No. 2 is attributed to the fact that the strips were not anchored by wrapping around the web as with the Tonen sheets, and their bonded area was smaller in spite of equivalent shear strengthening. It is likely that L shaped strips will improve their anchorage and lead to a more effective strengthening. Figure 13 also shows that the longitudinal reinforcing bars in Beam No. 3 were within the elastic range at failure (strain less than yield) .

Figures 15 and 16 show the load-strain and deflection-strain curves of CFRP sheet or plate (strip) for shear strengthening. It can be observed that the CFRP sheet or strip contributed to shear resistance after shear cracking. The steep initial portion of the curves likely represent the load prior to cracking while the second portion corresponds to loads where microcracks have occur. Tonen CFRP sheet and Sika CFRP strip had an average strain of about 0.22 % and 0.08 % at the maximum ultimate load, respectively. These strains are much smaller than the tensile strain capacity at failure, 1.5% and 1.4 % respectively, of the Tonen CFRP sheet and Sika CFRP plate.

The strain of 0.22% in the Tonen CFRP sheet corresponds to 500 MPa tensile stress, while the strain of 0.08% in the Sika CFRP plate corresponds to 120 MPa tensile stress. Considering the area of CFRP sheet and strip, tensile forces in the Tonen CFRP sheet and Sika CFRP strip are 82.3 N/mm and 143.6 N/mm, respectively. It is believed that a 25 mm Sika CFRP strip involves a higher resisting width of concrete and thus seems more efficient. This could be confirmed from observing the Sika strip that separated from the web, after testing. Indeed a 25 mm Sika CFRP strip tore out a strip of concrete cover wider than 25 mm.

Dividing the tensile force per unit width by the bonded length of CFRP sheet or strip gives the shear resisting stress of concrete, based on the assumption of uniform shear stress distribution. Therefore, shear stresses of concrete at delamination were 0.32 MPa and 0.27 MPa for Tonen CFRP sheet and Sika CFRP strip, respectively. These values are of the order of $0.063\sqrt{f_c'}$ and $0.054\sqrt{f_c'}$, respectively, assuming $f_c' = 25.40 MPa$. Given the limited number of tests with the Sika system, this procedure seems reasonable at this time.

Figures 15 and 16 show that, in beams without existing steel stirrups, the strains in the CFRP sheet and strip vary roughly linearly with the load and deflection prior to the onset of delamination.

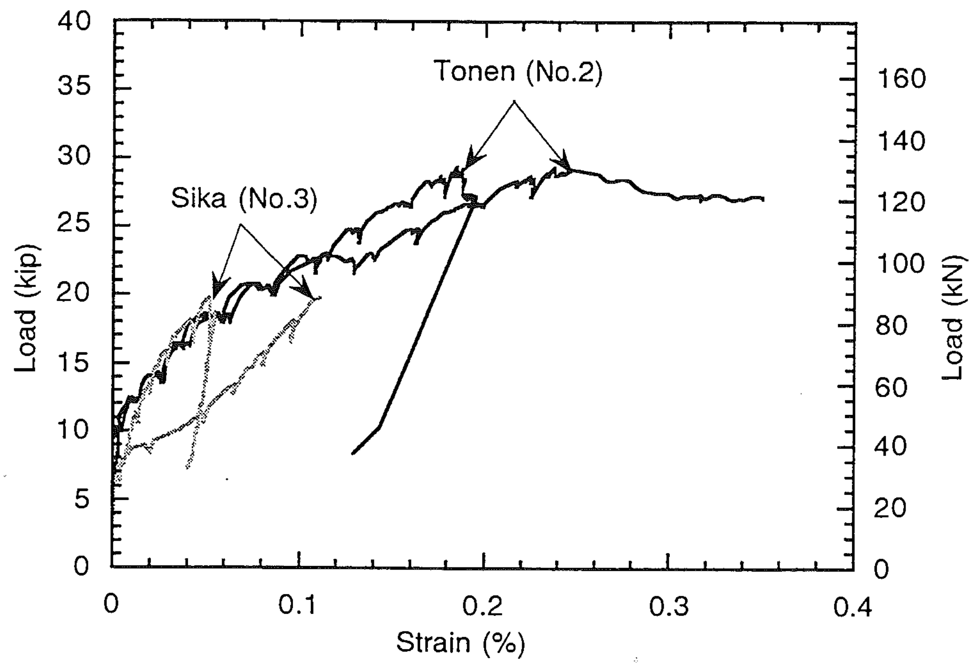


Figure 15 Load-strain curves of CFRP sheet (strip) for shear in rectangular beams

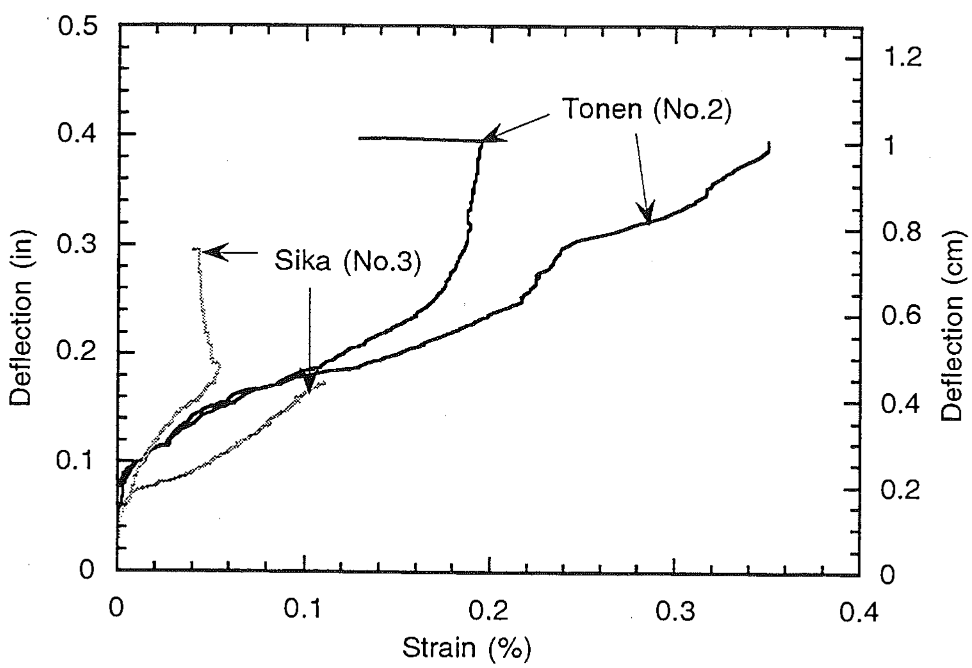


Figure 16 Deflection-strain curves of CFRP sheet (strip) for shear in rectangular beams

3.2 T-section Beams

To evaluate the effect of combined flexural and shear strengthening using CFRP sheet or plate, the test results of Beams No. 5 and No. 6 are compared with those of the control beam, Beam No. 4. Steel stirrups were provided for all three T beams in amounts corresponding to 91% of the required shear reinforcement for a reinforced concrete beam to resist a load at midspan that is allowed with longitudinal reinforcement equal to the maximum allowable by the AASHTO code (ρ_{max}). Beams No. 5 and No. 6 were strengthened using one layer of CFRP sheet (Tonen CFRP sheet) and 25 mm wide CFRP strip (Sika CFRP Plate) at a spacing of 75 mm, respectively. Also, all three T beams were intended to be provided with about one half of maximum flexural reinforcement according to the AASHTO code. Recalculations using the actual concrete and steel strength led to a new value of 89% the maximum flexural reinforcement. All beams were subjected to a concentrated load at midspan with a shear span-to-depth ratio of 3.5. In their failure modes, the control beam, Beam No. 4 failed by compression strut failure after yielding of the longitudinal reinforcing bars. At a load of about 133 kN to 156 kN, several diagonal cracks developed from one of the supports resulting in crushing failure of compression strut near the support. The compression strut had an angle of about 40 degrees. Figure 17 shows the compression strut failure of Beam No. 4.

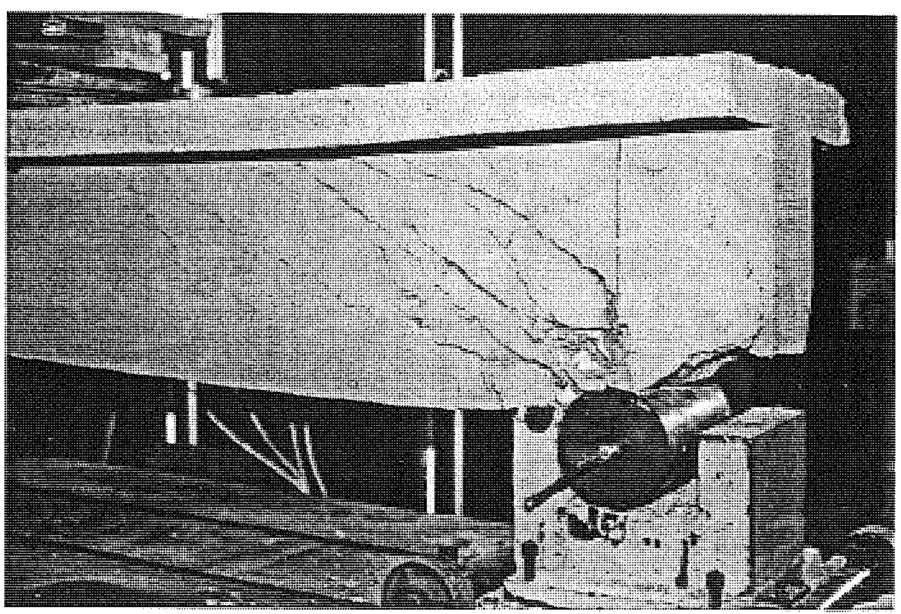


Figure 17 Compression strut failure of Beam No. 4

Beam No. 5, reinforced with Tonen CFRP sheet, failed by shear-compression failure after delamination of the CFRP sheet (that was bonded to the web for shear strengthening) and subsequent tensile failure of CFRP sheet that was bonded to the bottom for flexural strengthening. Delamination of the CFRP sheet bonded to the web started at a load of about 240 kN, just after yielding of longitudinal reinforcing bars. One side of the CFRP sheet was completely separated from the web due to the compression failure of concrete. Beam No. 5 exhibited the highest ultimate load of the three T beams.

Note that the CFRP sheet for flexural strengthening ruptured after delamination of the CFRP sheet for shear strengthening. This tensile rupture is attributed to stress concentration due to dowel action at a critical inclined crack plane. Indeed the measured strain at tensile failure of the CFRP sheet was about 0.9 % at midspan, which was smaller than the 1.5 % tensile failure strain. The critical inclined crack developed with an angle of about 50 degrees from the loading point at midspan. The beam finally failed by shear-compression after tensile failure of the CFRP sheet used as flexural reinforcement. Figure 18 shows the shear-compression failure of the beam.

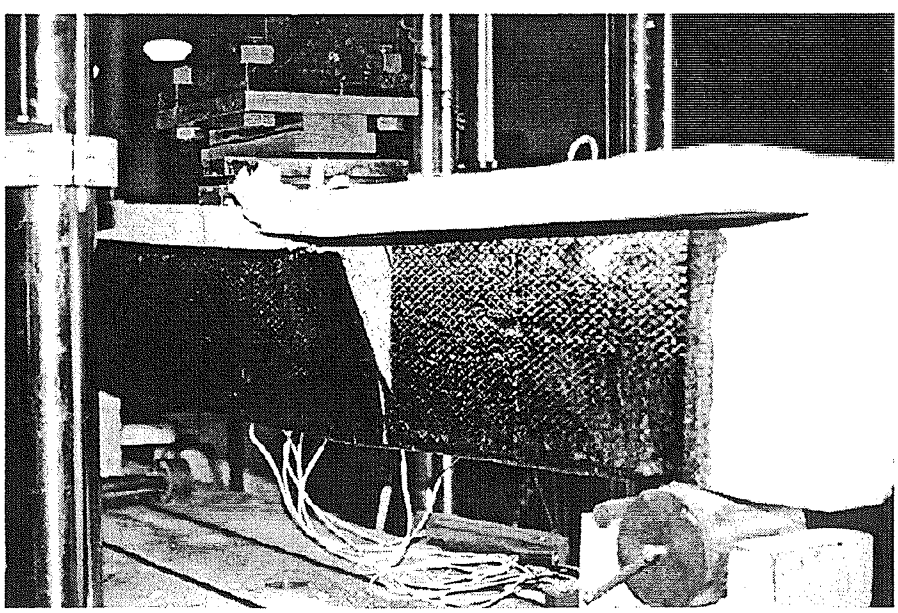


Figure 18 Shear-failure after delamination of CFRP sheet in Beam No. 5

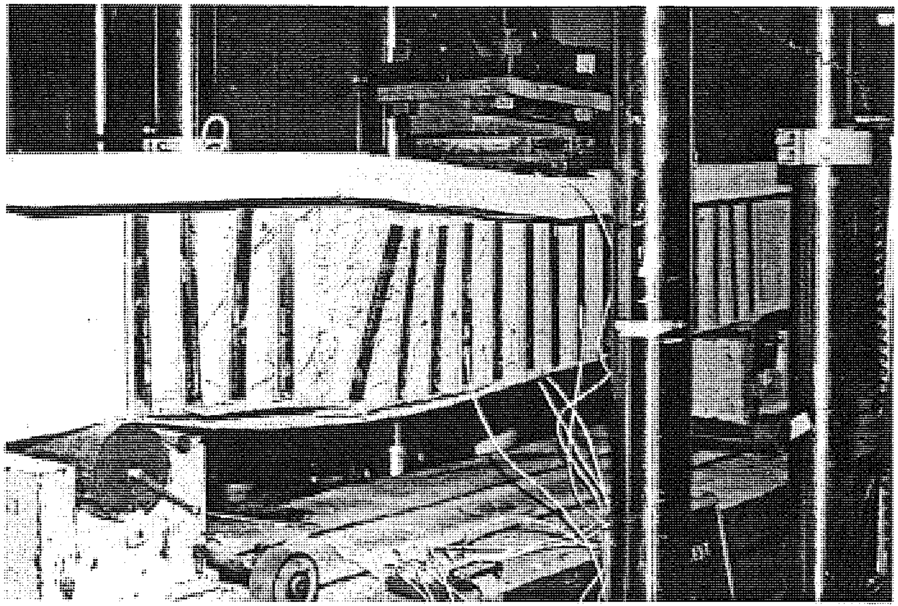


Figure 19 Shear failure due to delamination of CFRP strip in Beam No. 6

Beam No. 6 with Sika the CFRP plate failed by compression strut failure after delamination of the CFRP plate bonded to the web and the CFRP plate bonded to the bottom of the beam. Delamination occurred progressively starting at loads about 133 kN up to the ultimate load, about 214 kN, and before yielding of longitudinal reinforcement. At a load of 214 kN, the CFRP plate for flexural reinforcement suddenly delaminated. Beam No. 6 had higher ultimate load than Beam No. 4 (control beam), but a lower ultimate load than Beam No. 5. The delamination of CFRP strips for shear strengthening resulted in large shear deformation in the delaminated area of the web and led to the delamination of the CFRP plate for flexural strengthening. Figure 19 shows the compression strut failure in Beam No. 6.

Figure 20 shows the load deflection curves of the control beam and the two flexure and shear strengthened beams with the Tonen and Sika system. Beam No. 5 which was strengthened for both flexure and shear with Tonen CFRP sheet had the highest load carrying capacity of the three beams. It had an ultimate load about 45% higher than that of the control beam. The reason for the high load carrying capacity is that the CFRP sheet for flexural strengthening increased flexural resistance and the CFRP sheet for shear strengthening delayed shear failure resulting in a higher ultimate load. Yielding of the longitudinal reinforcing bar occurred before shear failure as shown in Figure 21.

Beam No. 6 with Sika CFRP plate had a higher load carrying capacity than the control beam, Beam No. 4, but had a lower load carrying capacity than Beam No. 5. Its ultimate load was about 30% higher than that of the control beam but 10% less load than that of Beam No. 5. For the same reason explained earlier for Beam No. 3, delamination of CFRP shear strip at a lower load than Beam No. 5 is attributed to lack of anchorage and smaller bonded area. As shown in Figure 20, Beam No. 6 abruptly lost its load carrying capacity due to delamination of the CFRP plate for flexural strengthening. At the time of failure or sudden drop in load, the longitudinal reinforcing bars were within their elastic range as shown in Figure 21.

Figures 23 and 24 show that the strain in the stirrups were in the linear elastic range from the onset of shear cracking to just before the onset of delamination of the CFRP sheet or strip used for shear strengthening. Indeed the maximum strain was in all cases less than 0.15% that is less than ε_y=0.2% (yielding strain).

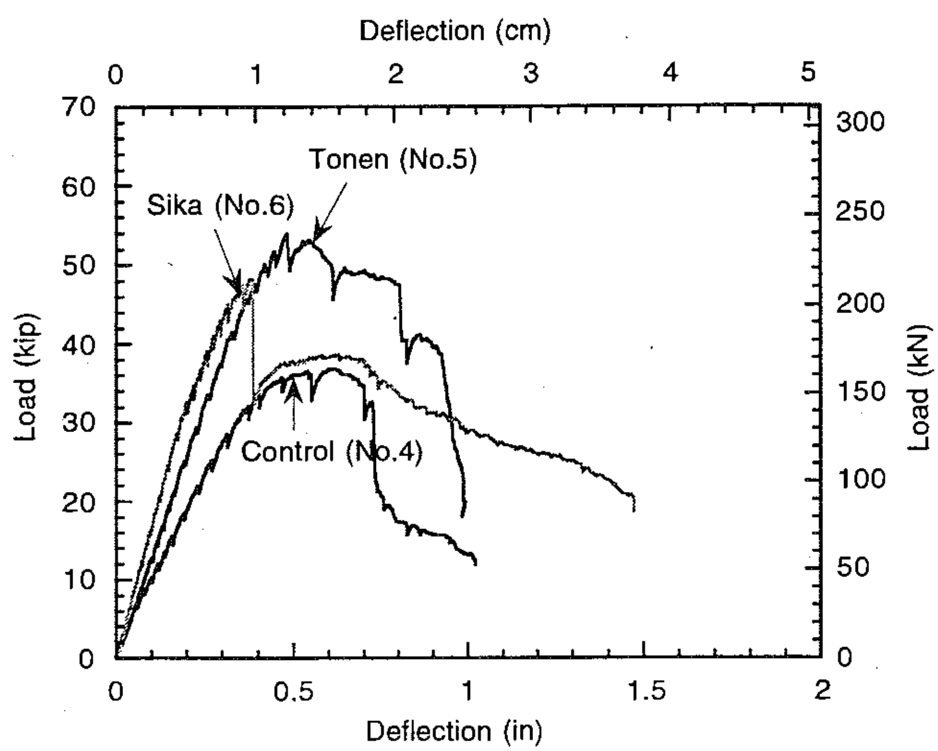


Figure 20 Load-deflection curves of T beams

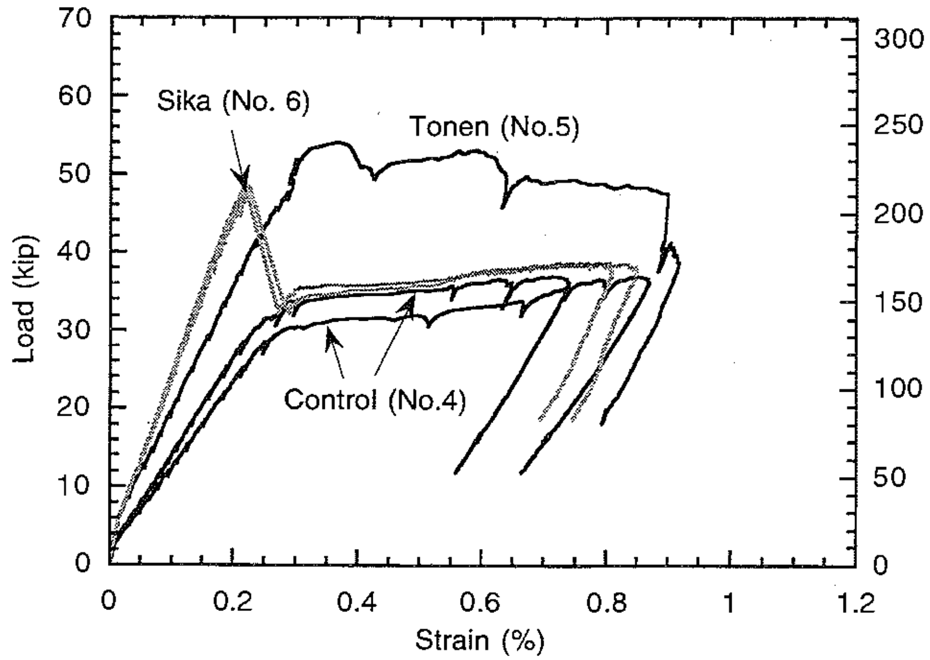


Figure 21 Load-strain curves of reinforcing bar in T beams

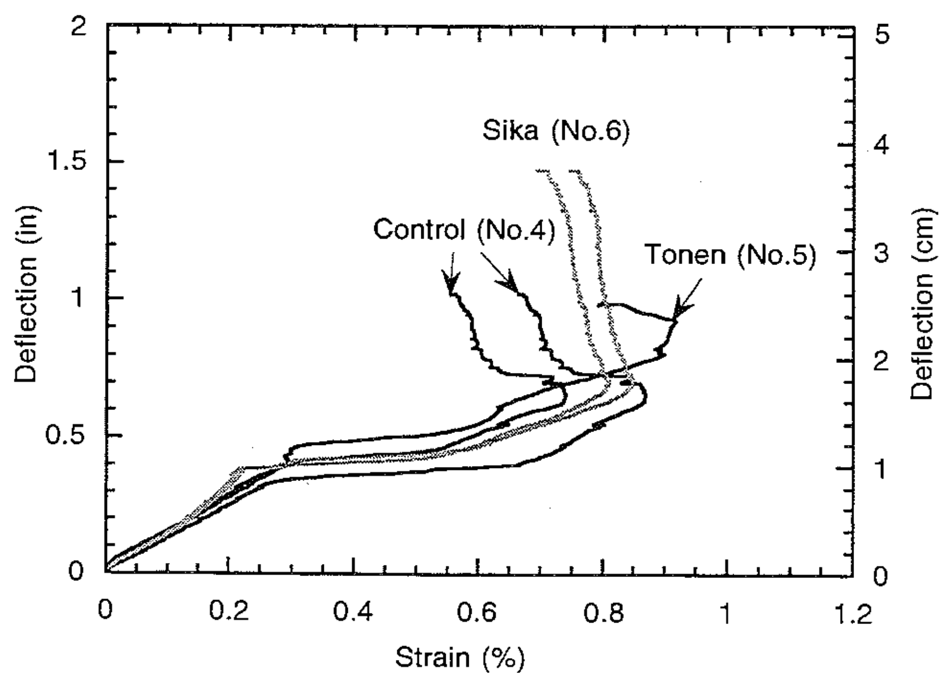


Figure 22 Deflection-strain curves of reinforcing bar in T beams

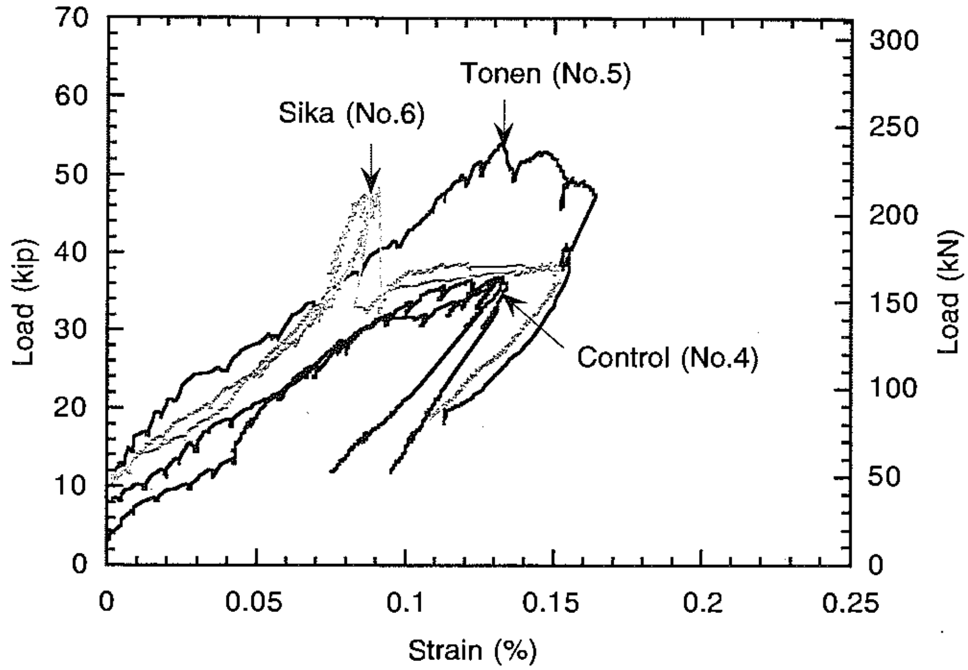


Figure 23 Load-strain curves of stirrups in T beams

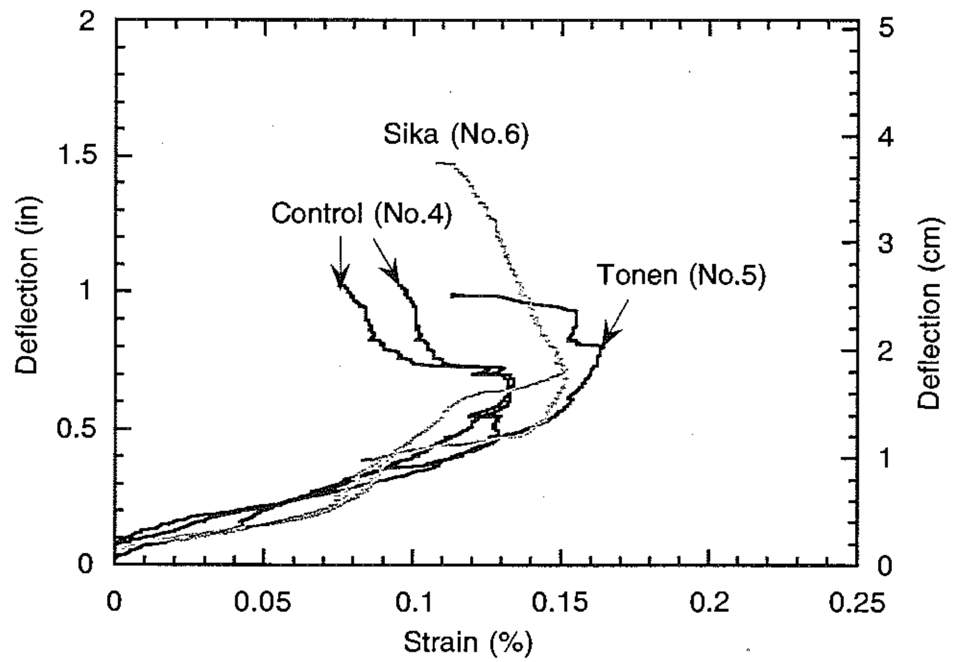


Figure 24 Deflection-strain curves of stirrups in T beams

Figures 25 and 26 show the load-strain and deflection-strain curves in CFRP sheet or plate used for shear. It can be observed that the CFRP sheet or strip contributed to shear resistance immediately after shear cracking and the contribution (strain) was almost proportional to the load up to the onset delamination. Tonen CFRP sheet and Sika CFRP strip had an average strain at the maximum load of about 0.21% and 0.07 %, respectively.

The strain of 0.21% in Tonen CFRP sheet corresponds to 478 MPa tensile stress, while the strain of 0.07% in Sika CFRP plate corresponds to 105 MPa tensile stress. Considering the area of CFRP sheet and strip, tensile forces in Tonen CFRP sheet and Sika CFRP strip are 78.8 N/mm and 126.1N/mm, respectively. Dividing the tensile force per unit width by the length of CFRP sheet or strip gives the average shear resisting stress of the concrete based on the assumption of uniform shear stress distribution. Average shear stresses of concrete observed at onset of delamination are 0.31 MPa and 0.50 MPa for Tonen CFRP sheet and Sika CFRP strip, respectively. These values are of the order of $0.062\sqrt{f_c^{'}}$ and $0.10\sqrt{f_c^{'}}$, respectively ($f_c^{'} = 25.4MPa$).

As shown in Figures. 27 and 28, the tensile strains of CFRP sheet and plate used for flexure were also proportional to the load and deflection before the onset of delamination of the CFRP sheet and strip used for shear strengthening.

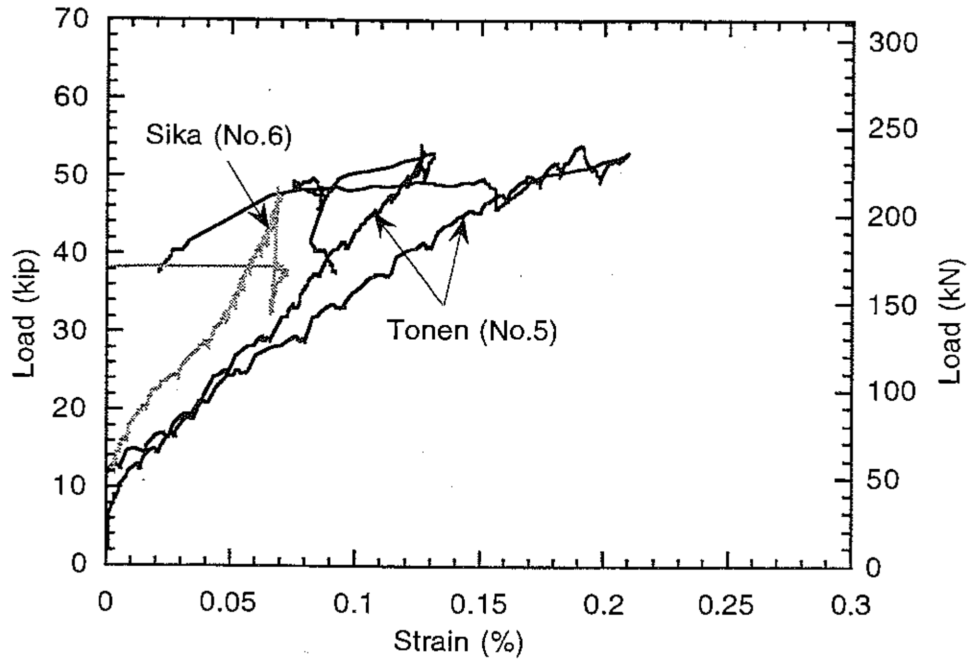


Figure 25 Load-strain curves of CFRP sheet or strip for shear in T beams

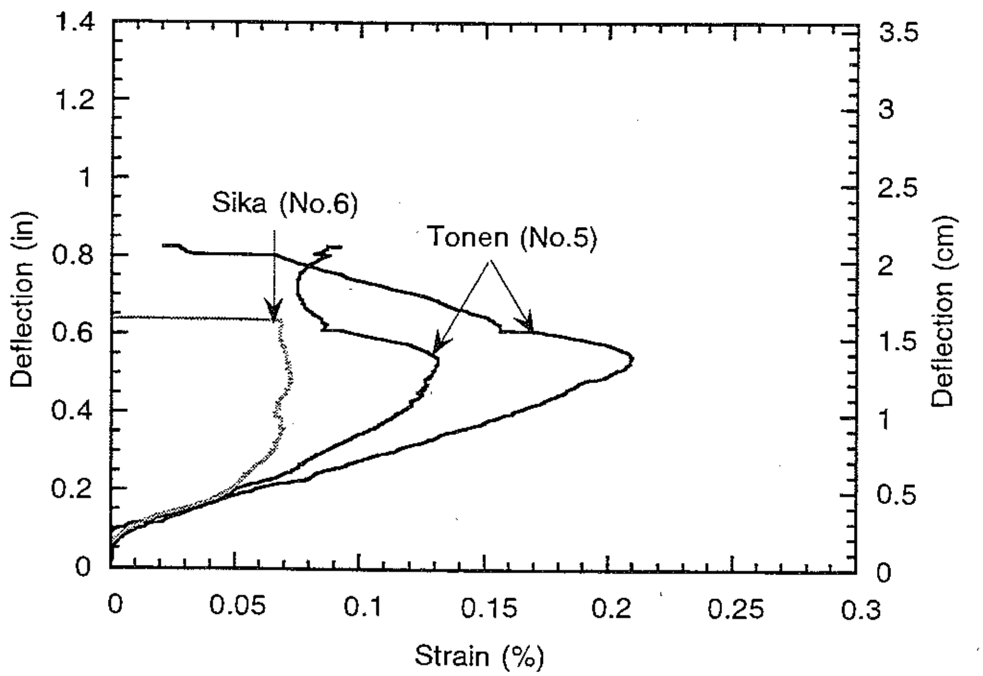


Figure 26 Deflection-strain curves of CFRP sheet or strip for shear in T beams

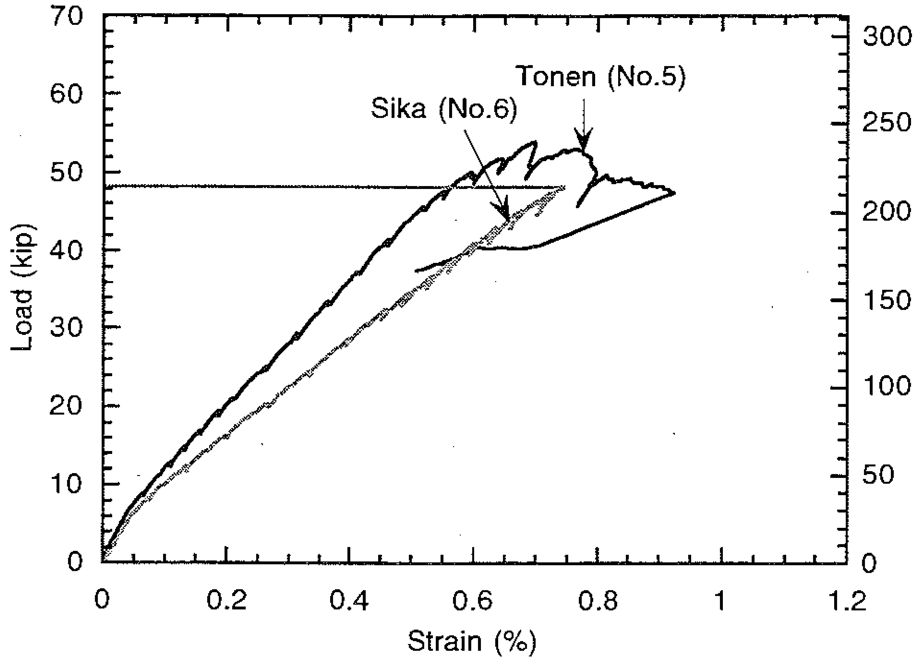


Figure 27 Load-strain curves of CFRP sheet or plate for flexure in T beams

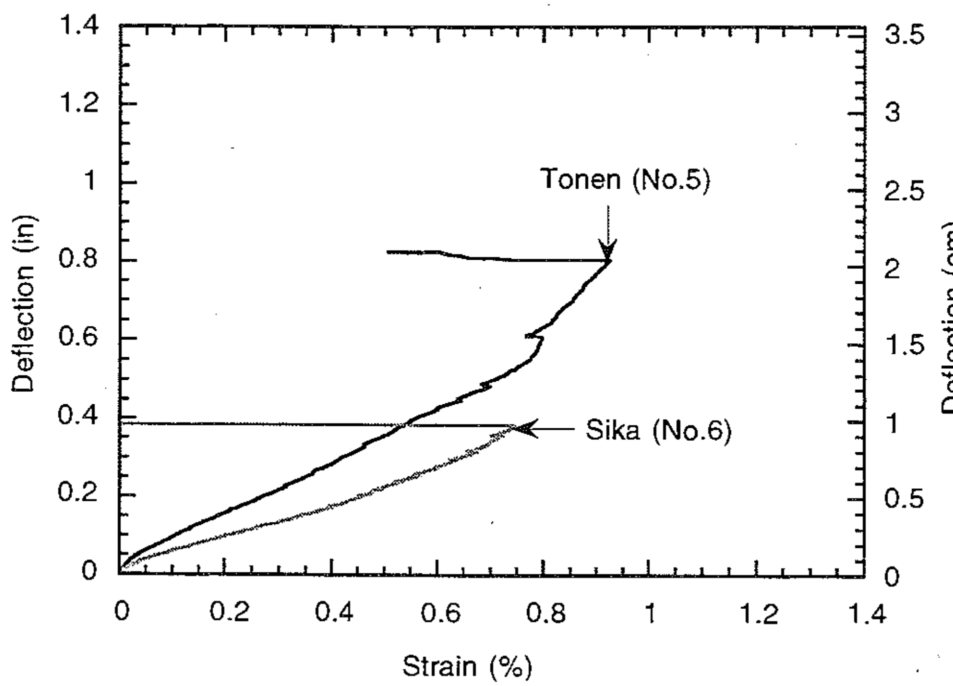


Figure 28 Deflection-strain curves of CFRP sheet or plate for flexure in T beams

4. CONCLUSIONS

This investigation dealt with the shear behavior of reinforced concrete beams strengthened using bonded carbon fiber reinforced plastic (CFRP) sheets or plates. Based on the observation and analysis of the experimental test results the following conclusions are drawn.

1) The strengthening for shear using externally bonded CFRP sheets or plates can significantly improve the ultimate loading capacity of reinforced concrete beams having deficiency in shear. Because shear failure is delayed, their ultimate deflection is also significantly increased. In beams insufficiently reinforced for shear, the use of CFRP shear strengthening led to an increase in load capacity of at least 30%.
2) The Tonen CFRP sheet led to a higher shear strengthening effect than the Sika CFRP because of its larger bond area and because it was better anchored by wrapping around the web. The development of L or Z shaped Sika CFRP plates should improve the strip anchorage and contribute to its increased efficiency.
3) It was generally observed that shear strengthened beams fail by delamination of the CFRP sheet or plate used for shear strengthening, resulting in shear failure of concrete.
4) The tensile stresses generated in the bonded CFRP sheet or plate used for shear are very low compared to their tensile strengths. In this study they were about one twentieth and one seventh the tensile strength of CFRP Tonen sheet and Sika plate, respectively.
5) In this study, shear stresses of concrete at onset of delamination of CFRP sheet and plate used for shear were of the order of about $0.06\sqrt{f_c'}$ and $0.10\sqrt{f_c'}$ for Tonen CFRP sheet and Sika CFRP plate, respectively.

6) The strains in the steel stirrups and the CFRP sheets or plates used for shear varied linearly with the applied load in the range following shear cracking and before onset of delamination.
7) The stresses in the CFRP sheet or plate used for flexure increased linearly with the load and deflection in the range prior to delamination of CFRP sheet and plates used for shear.

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6. APPENDIX A

Moment Capacity Calculations

- **Input Information**

- Distance from centroid of steel to top layer of concrete

For beam No.1-3:

d_1=(10-2-4/8*1/2)*25.4 = 197 mm, d_2=(10-2-4/8*1/2-1.5)*25.4 = 159 mm

d_e = (7.75*0.4+6.25*.22)/0.62*25.4 = 183 mm

For beam No.4-6:

d_1=(12-2-5/8*1/2)*25.4 = 246 mm, d_2=(9.6875-1.5)*25.4 = 208 mm

d_e = (9.6875*.62+8.1875*0.4)/1.02*25.4 = 231 mm

- Concrete compressive strength = 25.4 MPa , β_1 = 0.85
- Steel yield strength:

For beams 1-3, f_y = (65.9*0.22+75.5*0.4)/0.62*6.895 = 496 MPa

For beams 4-6, f_y = (75.5*0.4+66.1*0.62)/1.02*6.895 = 482 MPa

- **Computation of As Balanced**

Rectangular beams $\rho_b = 0.85*\beta_1*f'_c/f_y*(e_{cu}/e_{cu}+e_y)$ = 0.02021

$\rho_{max} = 0.75\rho_b$ = 0.01515, A_{smax} = 283 mm^2

A_s (used) = 400 mm^2

T-section behavior:

A_s balanced = Concrete force due to equilibrium(C_c) /f_y

For d_e = 231 mm, c_b **(neutral axis)** for balanced condition = 137 mm> flange height (hf = 51 mm). Find C_c for T-section:

$C_c = (b-bw)*hf*0.85*f'c + 0.85*f'c*bw*\beta_1*c_b$

C_c = 477 kN

A_s balanced = 477,000/482 = 987 mm^2 , A_{smax} = 0.75 A_s balanced = 742 mm^2

A_s (used) = 658 mm^2

- **Computation of M_{max}**

$M_{max} = A_{smax}*f_y*(d_e-a/2)$, where $a=A_{smax}*f_y/(0.85*f_y*bf)$

if a>hf T-section behavior, therefore this equation can not be applied.

-<u>T-section beams</u>:

For A_{smax} = 742 mm^2, d_e = 231 mm, a = 61 mm > 51 mm, T-section,

M_{max} = 72.88 kN-m

For A_s = 658 mm^2, d_e = 231 mm, a=48.26mm<51 mm, rectangular section behavior

M_{As} = 65.73 kN-m, P(expected) = 4*M/L(length) = 4*657300/1620 = 161.75 kN

-<u>Rectangular beams</u>:

For A_s = 400 mm^2, d_e = 183 mm, a=91mm

M_{As} = 27.41 kN-m, P(expected) = 4*M/L(length) = 4*27408/1020 = 106.75 kN

Computation of M_u

-<u>For the T-section beams</u>

$M_u = C_{cf}*(h-h_f/2) + C_{cw}*(h-a/2) - A_s*f_y*(h-d_e)$, where $a=C_{cw}/(0.85*f'_c*b_w)$

For 3 layers of Tonen sheet:

$C_{cf} = 0.85*f'_c*(b_f-b_w)*h_f$ = 222.62 kN

$T_{CFRP} = A_{CFRP}*Ft_{CFRP}$ = 52.02*3480 = 181.03 kN

$C_{cw} = (A_s*f_y+T_{FRP})- C_{cf}$ = 270 kN

a = 123 mm

M_u = 104.5 kN-m, P(expected) = 4*M/L(length) = 4*104500/1620 = 257.15 kN

For 1 sika plate (w = 100 mm):

$C_{cf} = 0.85*f'_c*(b_f-b_w)*h_f$ = 222.62 kN

$T_{CFRP} = A_{CFRP}*Ft_{CFRP}$ = 119*2400 = 285.6 kN

$C_{cw} = (A_s*f_y+T_{FRP}) - C_{cf}$ = 386 kN

a = 176 mm

M_u = 122.47 kN-m, P(expected) = 4*M/L(length) = 4*122470/1620 = 301.35 kN

-For the Rectangular beams: Since no CFRP was use for flexural strengthening, M_u=M_{As} calculated above.

- **Computation of Shear Reinforcement (T-section beams)**

M_u=P*L/4, for M_u=M_{max} = 72.88 kN-m, P_u= 179 kN

V_u=P_u/2 = 89.7 kN

$V_c = 0.17\sqrt{f'_c}*b*d$ = 19.66 kN, V_s= V_u-V_c = 70 kN

#6 rebar actual f_y = 325 MPa

$A_{v(max)} = V_s*s/(f_y*d)$ = 71 mm^2

$A_{v(used)}$ = 64.5 mm^2

- **Computation of Shear Capacity**

  - For the rectangular section

For control beam:

$V_c = 0.17\sqrt{f'_c}*b*d$ = 15.56 kN, P(expected) = V_c*2 = 15.56*2 = 31.14 kN

For beam with CFRP shear reinforcement:

V_{As} = 0

$V_{ACFRP} = A_{CFRP}*f_{CFRP}*h/s$, assuming development of full capacity of the CFRP strip in tension

V_{ACFRP} (Tonen) = 2*0.17*3480*254 = 292 kN,

P(expected) = (V_{ACFRP}+V_c)*2 = 615.16 kN

V_{ACFRP} (Sika) = 2*29.75*2400*254/75 = 485 kN,

P(expected) = (V_{ACFRP}+V_c)*2 = 1001 kN

  - For the T section beams

For control beam:

$V_c = 0.17\sqrt{f'_c}*b*d$ = 15.56 kN

$V_{control} = V_{As} + V_c$ = 83.36 kN,

P(expected) = $V_{control}$*2 = 166.71 kN

For beam with CFRP shear reinforcement:

$V_c = 0.17\sqrt{f'_c}*b*d$ = 15.56 kN

$V_{control} = V_{As} + V_c$ = 83.36 kN

$V_{ACFRP} = A_{CFRP}*f_{CFRP}*(h - h_f)/s$, assuming development of full capacity of the CFRP strip in tension.

V_{ACFRP} (Tonen) = 2*0.17*3480*254 = 292 kN,

P(expected) = $(V_{control}+V_{CFRP})$*2 = 745.75 kN

V_{ACFRP} (Sika) = 2*29.75*2400*254/75 = 485 kN,

P(expected) = $(V_{control}+V_{CFRP})$*2 = 1131.75 kN