

## Experimental Investigation of Reinforced Concrete Beams Strengthened by Skeleton Steel and Ferrocement Cover

Pragasit Jantanakit<sup>1</sup>, Panuwat Joyklad<sup>2</sup> and Amorn Pimanmas<sup>3</sup>

Sirindhorn International Institute of Technology, Thammasat University

PO Box 22, Thammasat-Rangsit Post Office Pathumthani 12121, Thailand

Tel: 0-2986-9009 Ext. 2403, Fax: 0-2986-9009 Ext. 1900

E-mail: <sup>1</sup>pj\_bank2@hotmail.com, <sup>2</sup>joy.civil@gmail.com, <sup>3</sup>amorn@siit.tu.ac.th

### Abstract

The method of strengthening reinforced concrete beams using ferrocement and skeleton steel attached on the side faces of the beam is presented in this paper. The study is based on an experimental program carried out on five beams designed to fail in shear. One of the specimens is control specimen and the others are strengthened specimens with various skeleton web steel arrangements and ferrocement covers. The ferrocement is 20 mm thick, thus adding little extra dead weight to the beam.

The difference among strengthened specimens is the shape of ferrocement cover (side cover or U-cover), spacing of additional external web reinforcements and surface roughness between original beam and ferrocement cover. Results from tests, such as ultimate strength, ductility and cracking pattern of strengthened specimens are compared with control specimen. Load-deflection responses are obtained up to the failure or the capacity limit of measuring devices. The performance of the various proposed methods are analyzed using conventional ACI procedures. The effect of various parameters, such as shapes of ferrocement cover (side or U), spacing and configuration of external web reinforcements and surface roughness are discussed. Results show that the proposed strengthening techniques improve ductility, ultimate strength and produce desirable flexural failure mode.

### 1. Introduction

The need for upgrading existing structures has been enormous in the past years, due to the deterioration and/or the requirements on the existing structures to carry more loads.

There are a number of methods to strengthen existing structures depending on the types of construction and conditions. The selection of strengthening materials and methods is generally aimed at maximizing future performance and durability. Therefore, the selection must be based on the knowledge of the physical and chemical properties and the environments in which the structures will be placed.

The strengthening solution with skeleton steel combined with ferrocement cover is one of several suitable choices for use in developing country. Ferrocement is a type of thin composite material made of cement mortar reinforced with uniformly distributed layers of continuous, relatively small diameter, wire meshes and skeleton steels. Originally, ferrocement materials were used only in housing applications. However, during the last two decades, the applications of ferrocement in the field of repair and strengthening have been developed rapidly. Ferrocement construction requires conventional technology and offers better performance even when handled by less experienced workers.

Ferrocement involves materials that are readily available in local areas, thus offering economical solution. The advantages of ferrocement in increasing the flexural

capacity of reinforced concrete beams have been widely studied [1-5]. However, the research on using ferrocement to increase shear capacity has been limited. In this paper, the authors apply the combined use of external skeleton steel and ferrocement cover for shear strengthening of reinforced concrete beam.

The proposed method focused on strength and ductility. The simple calculations recommended by ACI code are also compared with tested results in order to guide the designers.

## 2. Past study

Paramasivam et al. [6] reported the test of six simply-supported inverted T-beams under static and cyclic loads applied at mid-span. Except for the control beam, all beams were strengthened with ferrocement attached on the faces of the beams' web. Prefabricated ferrocement reinforcement with two methods of attachment was examined: with bar shear connectors installed through the web or through the flange of the beams. This method was compared with conventional strengthening methods where additional "U-shaped" stirrups were inserted through predrilled holes in the flange before bending at the ends to form closed links. The beams were subjected to cyclic loading. The results show that the beams were substantially strengthened and stiffened with the provision of additional stirrups and wire meshes in the thickened sections encasing the beams' web and the tension face. Beam strengthened using prefabricated stirrup cages attached with mild steel dowel bars anchored either through the web or through the flange performed better than the conventional method.

Rafeeqi [8] et al. tested five reinforced concrete beams designed to fail in brittle shear-compression. The flexural reinforcement was kept at the minimum amount that is normally provided in non-engineered construction. Except for the control beam, all beams were strengthened by a complete ferrocement wrap and equally spaced strips, with one and two layers of woven square mesh. The beams were loaded to

service load level, unloaded and strengthened prior to test up to failure. The strengthened beams showed a marked improvement in performances at service load, greatly improved ductility at ultimate load with either a ductile shear failure or seemingly a transition from shear to the flexural mode of failure.

## 3. Experimental Program

In the present study, simply supported reinforced concrete beams failing in shear are strengthened by external skeleton bars and ferrocement cover. The study parameters are different strengthening techniques. The beams are tested statically in four point bending until failure. Five identical reinforced concrete beams were cast and tested. The cross section was 200 mm wide and 300 mm high. The effective depth was 257.5 mm. The total length of all beams was 2400 mm, whereas the simply supported span was 2200 mm. The control beam was designed to fail in shear mode. The nominal moment capacity to nominal shear capacity ratio,  $M_n/(aV_n)$ , and shear span-to-effective depth ratio,  $a/d$ , were kept greater than 1.2 and less than 3.0, respectively. The details of material properties and test set up are described in the next section.

### 3.1 Material Properties

All beams were cast at the same time using the same batch of ready mix concrete. The beams were reinforced with 4DB20 as main flexural reinforcements and 2DB12 as hanger bars. The transverse reinforcements consisted of RB6 bars spaced at 125 mm center to center. The tested yield and tensile strength of reinforcements are reported in Table 1.

**Table 1** Mechanical property of reinforcing bars

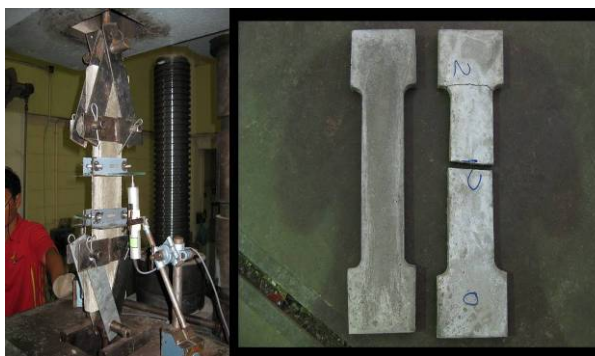
Diameter (mm)	Grade	Yield strength (MPa)	Tensile strength (MPa)
20	SD30	347.13	512.73
12	SD40	479.19	605.90
9	SR24	341.20	471.24
6	SR24	406.61	511.85

Hexagonal wire mesh was used for ferrocement. The mortar mix is made of 1:1.8 cement per fine sand by weight. The water-cement ratio was 0.40 by weight. The average cylindrical compressive strength of concrete is reported in Table 2.

**Table 2** Mechanical property of concrete

Specimens	$f'_c$ (MPa)	$f'_m$ (MPa)
CON	20.40	-
S200	23.05	48.74
S200SR	23.64	48.75
S200CL	23.54	48.75
U200	23.54	48.35

The average 50 mm x 50 mm x 50 mm cube strength of mortar was 49 MPa. The tensile force of mortar was evaluated through direct tensile test, using 20 mm x 100 mm specimen as shown in Fig.1. The average tensile force of mortar was found to be 3.48 kN. In addition, the ferrocement panel, without skeleton steels, with the identical section of mortar specimens was also tested. The specimens had the same section as mortar panels except that two layers of hexagonal wire meshes were reinforced. Based on the test results, the average tensile force of ferrocement panel was found to be 4.71 kN.



**Fig.1** Direct Tensile Test of pure mortar and ferrocement specimen

### 3.2 Details of Test Specimens

The experimental program consisted of one control (unstrengthened specimen) and four strengthened specimens as shown in Table 3.

The CON specimen was a control specimen without strengthening. It is provided for comparison with other strengthened specimens.

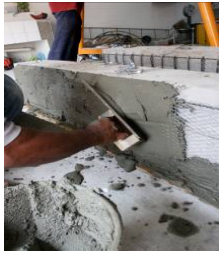
The S200 specimen was strengthened by ferrocement attached on the side faces of the beam. Before the 20 mm thick ferrocement panels were plastered on the beam, the beam was predrilled by an augur on both sides. The spacing of the holes was 200 mm which was the spacing of additional external web reinforcements (Table 3). Next, the prefabricated skeleton steel, made of RB6 with 2 layers of wire meshes, was attached on the beam faces. Then, RB9 reinforcing bars that had been bent in C-shape were inserted into holes and fixed with beam via chemical epoxy as shown in Fig. 2.

**Table 3** Description of specimens

Specimens	Spacing of Main additional rebars (mm.)	Special Detail
CON	-	-
S200	200	-
S200SR	200	Surface roughness
S200CL	200	extra clip reinforcements
U200	200	-



(a) C-shaped reinforcement (external web reinforcement)



(b) Plastering



(c) Finishing the surface

**Fig. 2** Construction procedure for specimen S200.

Specimens S200SR and S200CL had the same properties as S200 with some modifications. For S200SR, the surface of the original beam was roughened by chisel to increase the bonding between concrete substrate and ferrocement covers (Fig. 3 (a)).

To reduce the cost of drilling hole and epoxy and save the construction time and labor, specimen S200CL, with 200 mm c/c spacing of C-shaped reinforcements, was also provided with additional C-clip steels spaced at 200 mm. It should be noted that the C-clip steels were not inserted into the drilled hole. In effect, the spacing of external reinforcements in S200CL was 100 mm c/c (Fig. 3 (b)). For specimen U200, the beam was covered with ferrocement panel on the side face as well as the bottom face (U-shape). The RB9 external web reinforcements were bent in U-shape as shown in Fig. 4(a). The spacing of these reinforcements was 200 mm.



(a) Increasing the surface roughness for S200SR



(b) Extra C-clip steel for S200CL

**Fig. 3** Specific details for specimens S200SR and S200CL



(a) U-shape external web reinforcements



(b) Installing U-shape bars and skeleton steel



(c) Plastering mortar at the bottom face

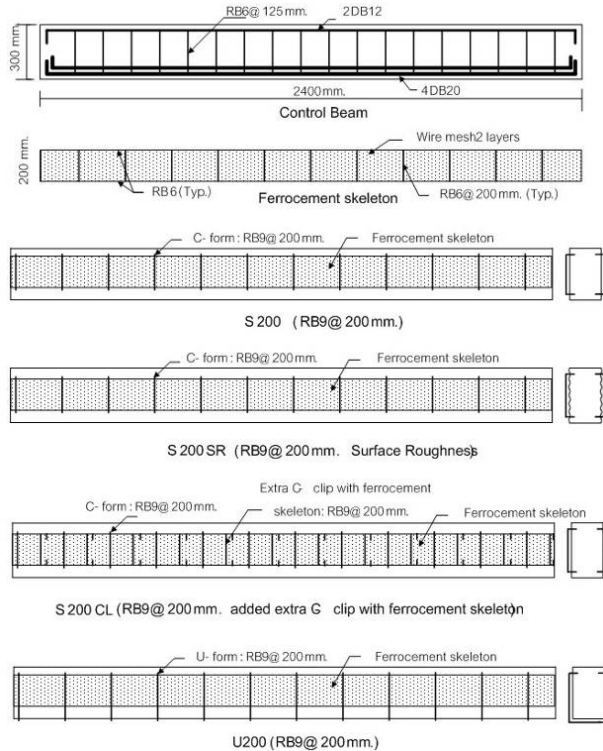


(d) Finishing the surface

**Fig. 4** Specific details for specimen U200

Figure 5 shows details of the five beams together with specimen designation. It shall be noted that ferrocement

cover was not patched the full depth of the beam, but the clear distance of 10 mm offset from the loading face of beam was provided to prevent any non-uniform contact between load and the ferrocement cover.



**Fig.5** Details of specimens

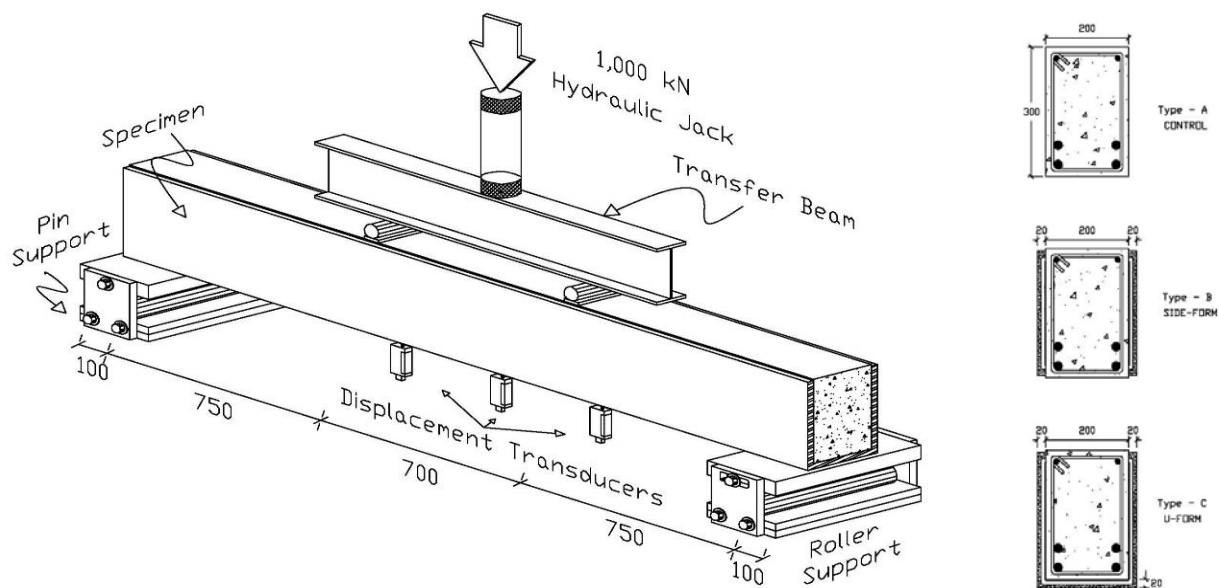
### 3.3 Test Setup

Figure 6 shows the test setup. The specimens were tested in a strong steel frame. The load was applied with a hydraulic jack mounted vertically over the test beams. The load set-up adopts four-point bending. The specimens were supported by roller allowing horizontal movement on one end and by pin support on the other end. In the first stage, before reinforcements reached the yield strength, specimens were tested under load control with monotonically incremental load of 10 kN for each load step.

After reinforcements reached the yield strength, specimens were tested under displacement control with monotonically incremental displacement of 1.0 mm in each step.

### 3.4 Instrumentation

Applied load, vertical displacements, strain and crack patterns were monitored throughout the tests. Displacements were measured at mid span and at the location of distributed loads. The displacement transducers with maximum capacity of 100 mm were used.



**Fig. 6** Test Setup and Reinforcement Details



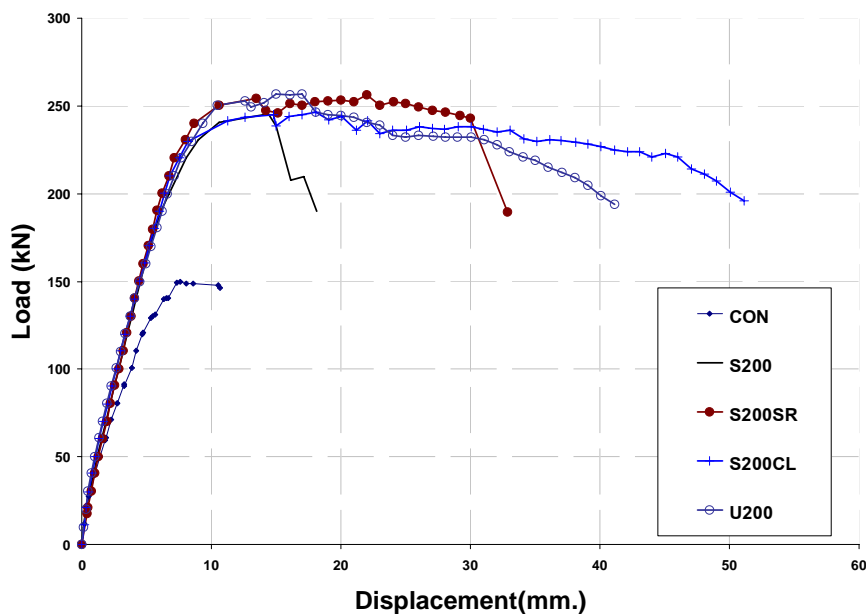
**Table 3** Experimental Results

Code	$M_n$ (kN-m)	$V_n$ (kN)	$M_n/(aV_n)$	$P_n$ prediction (kN)	Failure Type (Prediction)	$P_t$ test (kN)	$P_p/P_t$	Ductility ratio	Failure (Test)
CON	89.28	86.73	1.37	167.28	Shear	147.40	1.13	1.39	Shear
S200	94.93	147.34	0.85	253.14	Flexure	239.20	1.05	1.71	Shear
S200SR	94.93	147.83	0.85	253.14	Flexure	249.40	1.01	3.00	Flexure/ shear
S200CL	94.93	182.95	0.69	253.14	Flexure	241.95	1.04	5.00	Flexure
U200	95.54	149.60	0.85	254.77	Flexure	254.75	1.00	4.00	Flexure

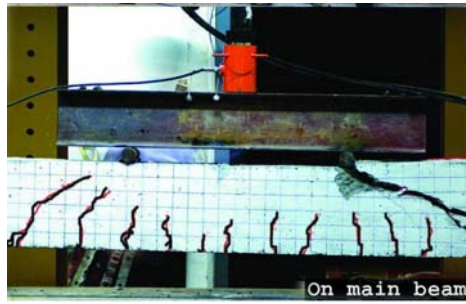
#### 4. Results and Discussions

Figure 7 shows the load versus displacement curves for all specimens. The plotted displacement was the vertical deflection at mid-span where the load was applied. The experimental results are summarized in Table 3. The failure patterns are shown in Figure 8. The control specimen was designed to fail in shear. The maximum load is reached when a large single shear crack developed. The failure was sudden and was shear failure. All other specimens demonstrated dramatic improvement in shear capacity up to flexural yielding of the beams.

The mode of failure in most specimens changed from shear to flexure. Only one specimen S200 failed in combined shear and flexure. Nevertheless, all specimens show significant increase in load capacity. U200 shows the same level of strength enhancement as S200, but the failure of U200 is flexural failure with higher ductility. As shown in Table 3, the ductility ratio of U200 is 4.00, which is higher than specimen S200. Consequently, the U-shaped ferrocement has certain benefits compared with side ferrocement.



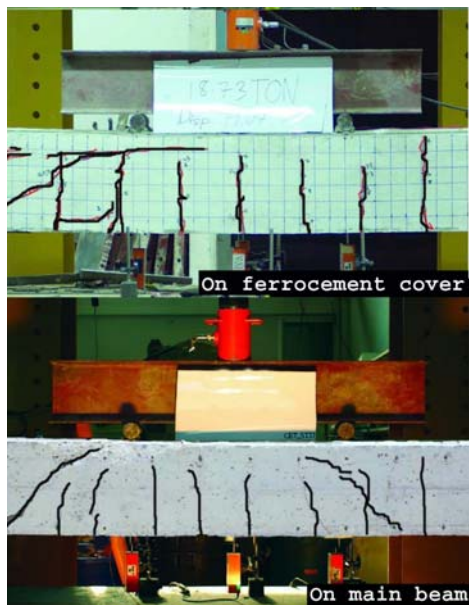
**Fig. 7** Load-displacement curves for all test specimens



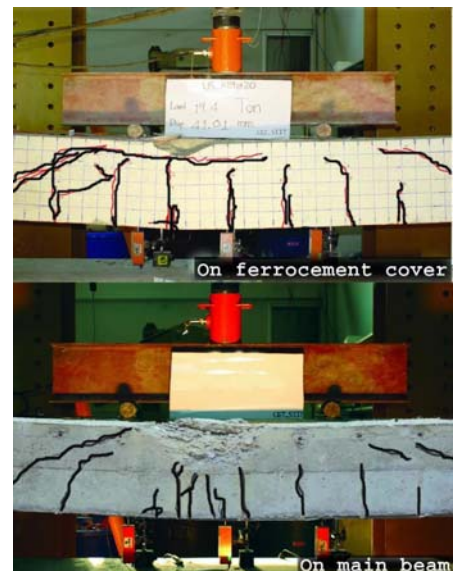
(a) CON



(a) S200CL



(b) S200



(b) U200



(c) S200SR

**Fig. 8** Crack pattern at failure of specimen

In order to increase bonding between surfaces of two materials, the roughness between original beam and ferrocement cover was added by roughening the surface of the original beam. The effect of surface roughness can be evaluated by comparing the result of S200 and S200SR. The maximum load capacity is almost the same in both specimens but the ductility of S200SR is larger.

To prevent shear failure in S200, specimen S200CL was provided with extra clip reinforcements attached on the surface of the beam. It is noted that the extra clip reinforcements are not fixed into the holes. As a result, there is no extra cost of drilling hole and adhesive. As shown, the specimen shows better performance as compared with S200 and S200SR. The failure mode is flexural failure with large ductility.

## 5. Prediction of Capacity using ACI Code [9]

In order to predict the capacity of strengthened beams, the general procedures of ACI318 had been adopted and modified to analyze beam with ferrocement cover.

### 5.1 Ultimate Moment Capacity

The theoretical ultimate moment capacity of the composite beam sections were calculated by means of the conventional reinforced concrete theory. The compressive force contributed by concrete was calculated based on simplified stress block proposed in ACI318. The influence of ferrocement in the compression zone was omitted. The tensile forces of the section were contributed by tension steels and ferrocement tensile force. In this case, ferrocement tensile force was previously obtained via tensile test of ferrocement panels. The compression forces acting on the section can be expressed as,

$$C = 0.85 f'_c ab + \sum A_{sc} f_y \quad (1)$$

The total tensile forces in the tension zone can be expressed as,

$$T = \sum A_{st} f_y + T_f \quad (2)$$

where

$f'_c$  = compressive strength of concrete, (MPa)

$f_y$  = tensile strength of steels, (MPa)

$T_f$  = tensile force of ferrocement, (N)

$A_{st}$  = tension steel area, (mm.<sup>2</sup>)

$A_{sc}$  = compression steel area, (mm.<sup>2</sup>)

$a$  = depth of compressive stress block, (mm.)

$b$  = section breadth, (mm.)

Based on equilibrium of forces on the section, the depth of compressive zone can be determined. The moment capacity can then be computed as the product between either tension or compression force and moment arm. Figure 9 shows the equilibrium of forces on the composite beam section.

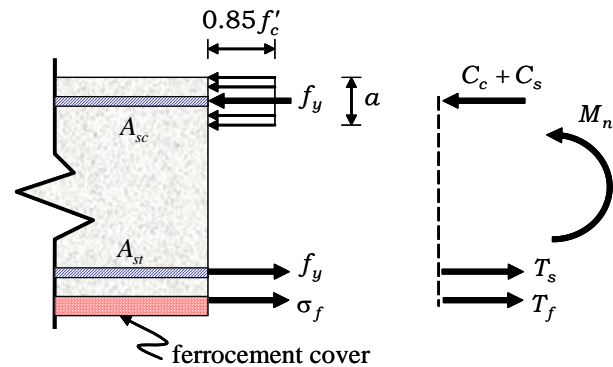


Figure.9 Stresses and forces on the section

### 5.2 Shear Strength

The shear strength of concrete section was evaluated using ACI318 simplified equation.

$$V_c = (1/6) \sqrt{f'_c} bd \quad (3)$$

The shear strength contributed from mortar was ignored. Additional shear strength contributed by internal and external web reinforcements were computed by conventional formula.



$$V_s = \frac{A_v f_y d}{s} \quad (4)$$

where

$d$  = effective depth, (mm.)

$s$  = spacing of web reinforcements, (mm.)

## 6. Practical Application of the Method

The construction cost (material and labor) of ferrocement cover strengthening method proposed in this paper is moderate. Based on the results of the testing program, the proposed method has been applied in real building. The 20 year old three-story residential house was strengthened in shear by ferrocement cover with additional web reinforcements. The side cover method was applied to the edge beam while the U-cover method was applied to the intermediate beams. The contractor's opinion was that this strengthening method offered lots of advantages in terms of fast time construction, low budget, low labor demand and easy constructability. Figure 10 shows the real application in the field.

## 7. Conclusions

An experiment was carried out to study the strengthening methods of beam using ferrocement cover. Five reinforced concrete beams were tested under monotonic loading. The main parameters are the shape of ferrocement cover, surface roughness and extra clip reinforcement. From these experiments, the following conclusions can be drawn.

- The proposed method can change the mode of failure from shear to flexure.
- The capacity of strengthened specimens increased approximately 70% compared to the control specimen.
- The ductility of strengthened beams can be greatly enhanced by this strengthening method.
- Using special C-clip bars can save the construction times, prevent shear failure and gain more ductility.
- The surface roughness can increase ductility.

- The specimen with U ferrocement cover has higher load carrying capacity, preventing shear failure, and larger ductility compared with specimens strengthened by side cover ferrocement.
- The conventional ACI method can be adopted for strengthening design purposes.



(a) Side-cover for edge beams



(b) Finishing the surface



(c) U-cover for intermediate beams



(d) Finishing the surface

**Fig. 10** Real application in the field

## 10. Acknowledgements

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