Experimental Responses of Jacketed RC Beams

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***Abstract*—Repair and strengthening of reinforced concrete (RC) beams is commonly carried out by "jacketing". Jacketing is the addition of concrete or cement mortar and steel reinforcement to an existing beam. This paper describes an experimental investigation into the behavior of reinforced concrete beams strengthened by jacketing. Static load tests to failure were carried out on five reinforced concrete shallow beams. The mortar used in the jacket was non-shrink cement grout. The steel bars were fixed to the beams by using two inexpensive and simple anchorage systems i.e., epoxy anchorage system and mechanical expansion anchors with steel plate anchorage system. Based on experimental results, it was noted that jacketing using mortar and steel bars is very effective method to enhance ultimate load carrying capacity of RC beams compared with control beams. Proposed anchorage systems were pr oved effective to securely attach the steel bars to the beam. The anchorage system with mechanical anchors is resulted into higher load carrying capacity of RC beams compared with epoxy anchorage system. The control beam failed at the peak ultimate load of 23.70 kN. The RC beams jacketed using epoxy anchorage were failed at 13% to 27% higher peak load compared with control beam, whereas RC beams jacketed using mechanical anchors were failed at 84% to 105% increased load compared with control beam.**

***Index Terms*—flexural strengthening, anchorage system, jacketing, epoxy, mechanical anchors**

I. Introduction

Strengthening reinforced concrete (RC) beams can be done by different methods such as steel plate jacketing [1], [2], jacketing by fiber reinforced concrete [3] jacketing by RC [4], [5] and recently jacketing by wrapping fiber reinforced polymer (FRP) composites [6], [7]. The technique of gluing mild steel plates to the soffits of reinforced concrete beams can be used to improve the flexural performance of RC beams as it increases the strength and rigidity and also reduces the flexural cracks widths in the concrete [8]. This plating technique has further advantages as it has been found in practice to be simple to apply. It does not reduce the height of the structure and can be applied while the structure in use. This procedure has been used to repair buildings [9] and to strengthen bridges [10], especially in many European countries. Steel jacketing is proved very effective and has been widely used all over the world, however, experimental tests show that shear and flexural forces can cause these externally bonded plates to peel away before the design load is reached [8]. Other issues such as corrosion, heavy weight and installation difficulties (in case of high rise buildings) are also reported. In recent years, fiber-reinforced polymer (FRP) composites are introduced and demonstrated to be successful for strengthening concrete structures. Common types of FRPs that have been successfully used for strengthening reinforced concrete beams are carbon (CFRP), glass (GFRP), and aramid (AFRP) [11]. A large number of studies have been carried out in the last decade on the behavior of FRP-strengthened beams. These FRPs are found very effective to enhance ultimate load carrying capacity and ductility of strengthened members. Many of these studies reported premature failures by de-bonding of the FRP with or without the concrete cover attached. The most commonly reported de-bonding failure occurs at or near the plate end, by either separation of the concrete cover or interfacial de-bonding of the FRP plate from the RC beam [12]. Tom Norris et al. (1997) performed an experimental study to investigate the behavior of damaged or understrength concrete beams retrofitted with thin carbon fiber reinforced plastic (CFRP) sheets. In their study, the CFRP sheets were epoxy bonded to the tension face and web of concrete beams to enhance their flexural strength. The effect of CFRP sheets on strength and stiffness of the beams was considered for various orientations of the fibers with respect to the axis of the beam. The authors concluded that CFRP sheets can provide the increase in strength and stiffness to existing concrete beams when bonded to the web and tension face. The failure mode of CFRP strengthened beams were reported as peeling of the CFRP [13]. Wu et al. (2011) has enlisted different methods which were successfully applied to prevent the FRP de-bonding such as mechanical anchors, near-surface mounted (NSM) installation, wrapping of FRP strips in different shapes, use of protruding fiber and anchor bolts, using comb-shaped anchors and mechanical-interlocking anchorage systems [14]. Although these FRPs are proved very successful for the strengthening propose due to their light weight, superior strength-to-weight ratios, corrosion

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resistance, and easy installation, cost of FRPs, however is very high compared with local traditional materials such as concrete and steel. Further, in developing countries, the use of FRP is still very limited due to high price and availability issue. In contrast to the steel plate and FRP jacketing, relatively less number of studies have been conducted in the past to investigate the strengthening of reinforced concrete beams using concrete or mortar jacketing and there is still need to develop inexpensive and easy anchorage systems to securely attach the steel bars to the beam soffit. Therefore the primary objective of this study was to study the experimental responses of jacketed RC beams. Different anchorage systems were proposed to attach steel bars to beam soffit. The proposed anchorage systems were evaluated for steel bars of varying diameter.

II. Experimental Program

A. Specimen Details

A detailed description of the test beams is shown in Fig. 1. All test beams had a constant cross section with the width of 120 mm and total depth of 150 mm. The total length of the beam was 1460 mm and span length was 1260 mm. Each beam contained two DB10 (deformed bars with a yield strength of 414 MPa) at the tension face, and top two RB9 bars (round bars with a yield strength of 350 MPa) at the top face. The shear reinforcement consisted of RB6 (round bars with a yield strength of 240 MPa) placed at different spacing as shown in Fig.1. A clear 15 mm thick concrete cover was provided on all sides of beams, and the beams were cast using molds made of plywood sheets as shown in Fig. 2.

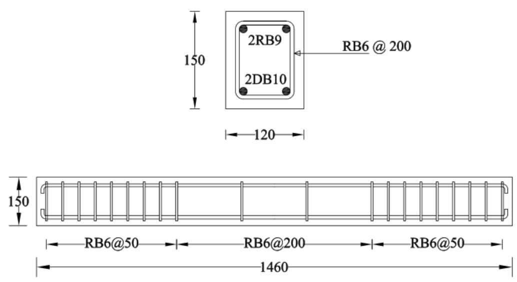

Figure 1. Beam specimen details (mm)

Figure 2. Concreting process

B. Test Matrix

In this experimental program a total of five reinforced concrete (RC) beams were constructed and tested. The details of test matrix are shown in the Table I. One beam specimen (i.e., CONT) was tested without jacketing to serve as control beams. Two beams (beams in group A) were jacketed using non-shrink cement grout and steel bars. In these beams, steel bars were fixed to the beam soffit using epoxy anchorage system. Remaining two beams in group B were also jacketed using non-shrink cement mortar and steel bars; however the steel bars were fixed to the beam soffit using mechanical expansion anchors with steel plates. Each beam was jacketed with two external steel bars. The beam name are given to identify anchorage system and diameter of external steel bars. For example in beam name EAS-6; first letter EAS stands for epoxy anchorage system and last digit is representing diameter of steel bar i.e., 6 mm. The details of anchorage systems are discussed in the following section.

TABLE I. Test Matrix

Group	Beam designation	Anchorage system	External steel bars
A	CONT	-	-
B	EAS-6	EAS	2-RB6
	EAS-10	EAS	2-DB10
C	MEAS-6	MEAS	2-RB6
	MEAS-10	MEAS	2-DB10

C. Anchorage Systems

In this study, steel bars were externally attached to the beam soffit using simple and inexpansive anchorage systems i.e., epoxy anchorage system and mechanical expansion anchors with steel plate anchorage system.

D. Epoxy Anchorage System

In the epoxy anchorage system (EAS), steel bars of U shape were fixed to the beam soffit using Sikadur Cement based Epoxy Mortar (manufactured by Sika Thailand Co., Ltd.). Before the installation of steel bars, holes were drilled at the desired location and cleaned with high water pressure to remove dust. The installation process and other details are shown in Fig. 3 and 4.

E. Mechanical Expansion Anchors with Steel Plate’S Anchorage System (MEAS).

This anchorage system is comprised of mechanical expansion anchors, threaded bolt, washers, nuts and steel plates as shown in the Fig. 5-7. Anchorage system was installed in the following steps; 1) holes of 8 mm diameter were drilled at the desired locations, 2) holes were cleaned with high water pressure to remove dust particles, 3) mechanical expansion anchors were installed along with steel plates, 4) straight steel bars were welded to the steel plates as shown in the Fig. 6 and 5) Steel bars and plates were covered with non-shrink cement grout as shown in Fig. 7.

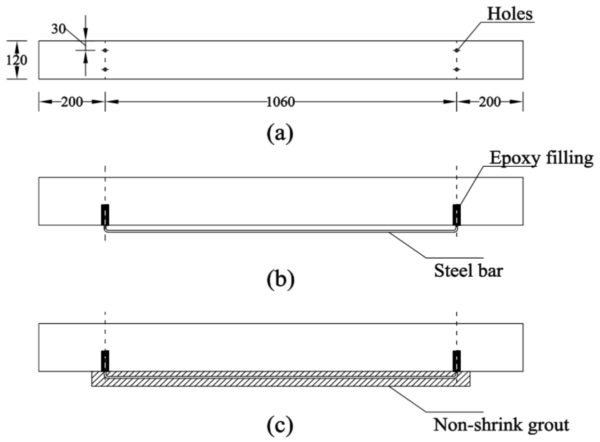

Figure 3. Epoxy anchorage system (mm)

Figure 4. Installation of epoxy anchorage system

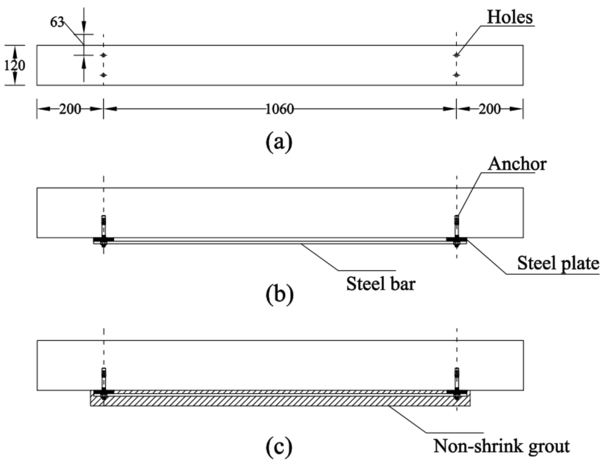

Figure 5. Mechanical expansion anchors with steel plate's anchorage system (mm)

Figure 6. Welding of steel bars with steel plate

Figure 7. Grouting process (Non-shrink cement grout)

F. *Material Properties*

A single concrete mix (28 day's target strength of 25 MPa) was used to construct concrete beams. The concrete mix proportions are given in Table II. The concrete was made of ordinary Portland cement and coarse aggregate with the maximum size of 19 mm. The actual concrete strength at the testing days (around 40-45 days) was slightly higher than the target design strength. In this experimental program commercially available high performance non-shrink cement grout manufactured by Sika (Thailand) Limited was used for jacketing purpose.

TABLE II. CONCRETE MIX PROPORTIONS

Mix Components	(kg/m3)
Water	180
Cement	360
Fine aggregates	760
Coarse aggregates	1015

G. *Loading Setup*

Reinforced concrete beams were tested under three point bending as shown in the Fig. 8 and 9. The specimens were tested under a concentrated load applied at the mid-span in a simply supported arrangement. A load is applied monotonically through a hydraulic jack of 300 kN capacity at a constant rate of 70 N per second until failure occurred. The applied load was recorded by a calibrated load cell placed under the loading piston of the hydraulic jack. Linear variable differential transducers (LVDTs) were placed under the beam at the mid span to measure vertical deflection. During the test, the initiation and propagation of cracks were visually inspected and recorded by photographs.

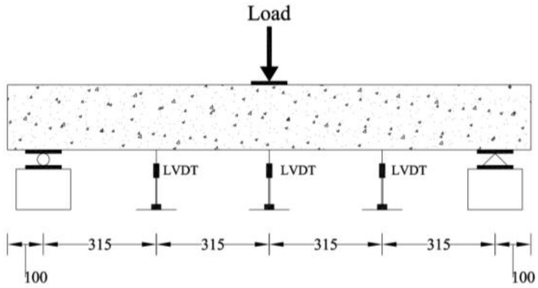

Figure 8. Schematic of loading setup (mm)

Figure 9. Loading setup

III. Test Results and Discussions

The experimental results in terms of cracking load, ultimate load, mid span deflection at the peak load and failure modes are summarized in Tables III and IV. The load-deflection curves of jacketed RC beams along with control beam are shown in Fig. 10. The experimental results are further discussed in detail in the following sections;

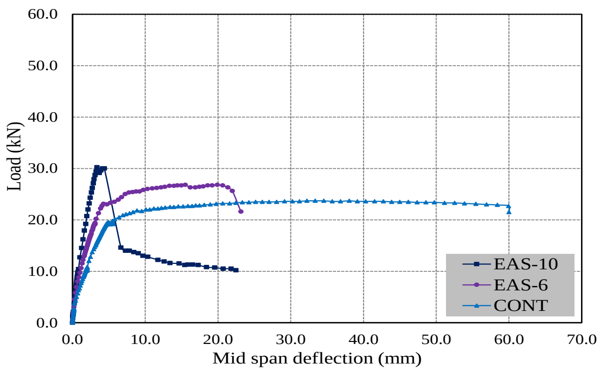

Figure 10. Load versus deflection curves of beams (Group A and B)

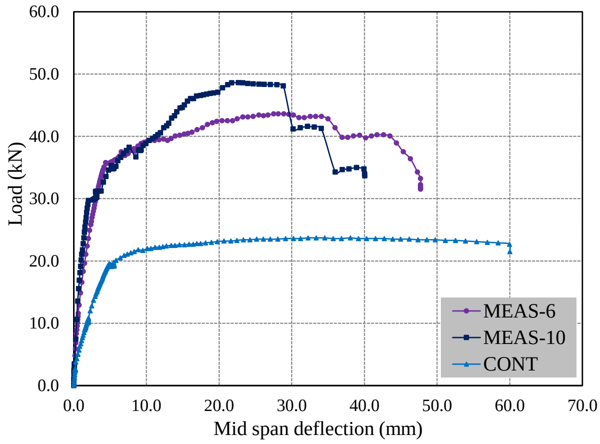

Figure 11. Load versus deflection curves of beams (Group A and C)

TABLE III. Experimental Results

Group	Beam designation	Ultimate load (kN)	% Increase in ultimate load	Mid span deflection (mm)
A	CONT	23.70	-	38.06
B	EAS-6	26.80	13	19.91
	EAS-10	30.20	27	3.37
C	MEAS-6	43.63	84	22.65
	MEAS-10	48.63	105	28.91

A. Cracking Load

In the control beam, small cracks were observed at the mid-span prior to the appearance of large inclined cracks. The cracking load of the control beam was 8.70 kN. With the further increase in load, new inclined flexural cracks were also appeared at the mid span and near the support region. In the jacketed RC beams the cracking load was observed higher than the control beam. This is due to the presence of the additional external steel bars at the soffit of the beam. The increase in cracking load is proving the effectiveness of the proposed anchorage systems. The cracking loads are summarized in the Table IV. Similar to the control beam, small cracks were observed at the mid-span prior to the appearance of large inclined cracks in the jacketed RC beams. A further load increase resulted in the widening of flexural cracks as well as the initiation of new flexural and diagonal cracks.

TABLE IV. Cracking Load

Group	Beam designation	Cracking load (kN)	% Increase in cracking load
A	CONT	8.70	-
B	EAS-6	12.00	38
	EAS-10	20.50	136
C	MEAS-6	16.00	84
	MEAS-10	19.00	118

B. Load Carrying Capacity and Mid Span Deflection

The load deflection curves of jacketed RC beams along with control beam are shown in the Figs. 10 and 11. This data can be used to evaluate the impact of the jacketing on the load carrying capacity of the beams. The load and deflection curves of beams in group B along with control beam are shown in Fig. 10. The control beam failed at the peak ultimate load of 23.70 kN. As shown in Fig. 10, the 13% and 27% increases in peak load were recorded for the beams jacketed using epoxy anchorage system i.e., EAS-6 and EAS-10. Similar to the beams in group B, the jacketed beams in group C also failed at higher load compared with control beam. In this group, 84% and 105% increased load were observed for beams MEAS-6 and MEAS-10, respectively.

1) Effect of Anchorage Systems

In this experimental study, two different types of anchorage systems namely EAS and MEAS were proposed and investigated. Based on experimental results it can be concluded that both systems are effective to securely attach the external reinforcement to the beam soffit. However the efficiency of MEAS system was found higher than the EAS system. This is supposedly due to the stress transfer over a large area in MEAS (due to the presence of steel plate) compared with stress transfer in EAS. The comparison of both anchorage systems is shown in Fig. 12.

2) Effect of Reinforcement Ratio

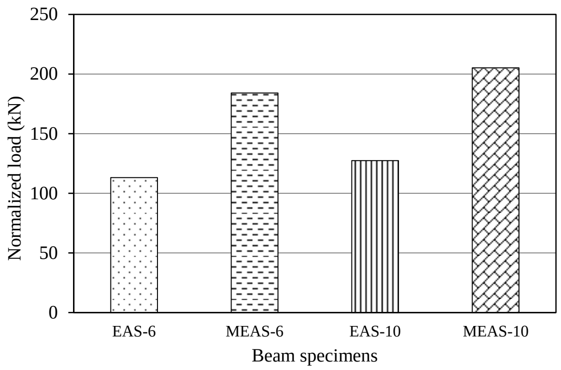

Figure 12. Comparison of normalized load (effect of anchorage system)

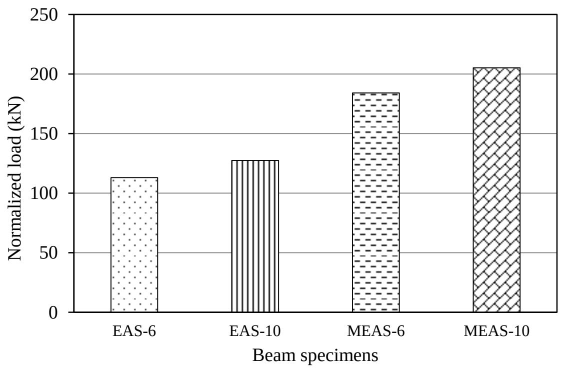

Figure 13. Comparison of normalized load (effect of reinforcement ratio)

In the experimental program external reinforcement was provided using different diameters of steel bars (i.e., 2RB6 and 2DB10). A comparison of normalized load is shown in Fig. 13. It can been seen that reinforcement ratio had a significant impact on ultimate load carrying capacity of RC beams. There is found an increase in the load carrying capacity with an increase in reinforcement ratio. As shown in Fig. 13, the increase in ultimate load carrying capacity of 13% and 11% were recorded for beams EAS-10 and MEAS-10 compared with beams EAS-6 and MEAS-6, respectively.

C. Failure Modes

A summary of failure modes of all specimens is provided in Table V. In the experimental test, a typical pattern of crack formation was observed. The first flexural crack occurred in the mid-span of the beam, and was followed by the formation and propagation of many smaller cracks which were symmetrically distributed about the mid-span of the beam. The un-strengthened (control) beam failed in a conventional flexural manner with the concrete crushing in compression in the mid span of the beam as shown Fig. 14. In all concrete jacketed RC beams with anchorage systems, no pullout of re-bars and anchors were observed prior to the final failure of the beams except beam MEAS-10. These beams (i.e., EAS-6, EAS-10 and MEAS-6) were failed due to the inclined cracks that were formed along the loading and anchoring points as shown in Figs 15-17. The beam MEAS-10 was failed suddenly due to the separation of anchorage system from beam soffit as shown in Figs 18 and 19. This separation was occurred due to the failure of threaded bolt in mechanical expansion anchored with steel plate anchorage system.

TABLE V. FAILURE MODES

Group	Beam designation	Failure Modes
A	CONT	Flexural Crack
B	EAS-6	Flexural and diagonal cracks
	EAS-10	Flexural and diagonal cracks
C	MEAS-6	Flexural and diagonal cracks
	MEAS-10	Separation of anchorage system

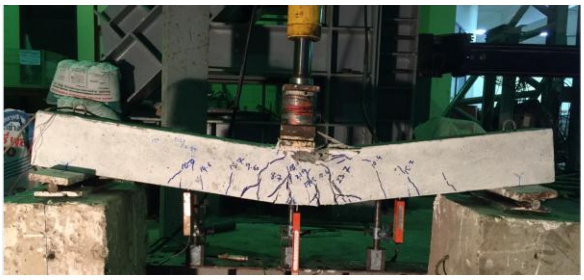

Figure 14. Failure mode of control beam

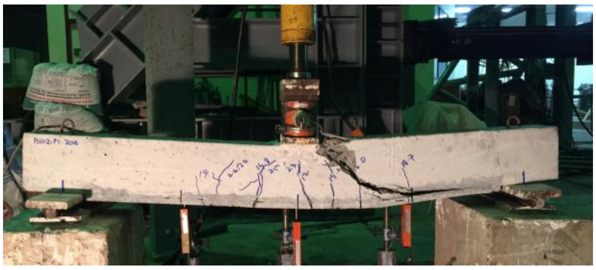

Figure 15. Failure mode of beam EAS-6

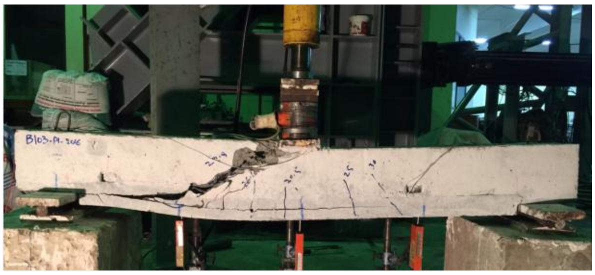

Figure 16. Failure mode of beam MEAS-6

Figure 17. Failure mode of beam MEAS-6

Figure 18.Failure mode of beam MEAS-10

Figure 19. Jacketing separation in beam MEAS-10

IV. Conclusions

This paper has provided the experimental investigation on responses of jacketed reinforced concrete beams. The investigation included use of different anchorage systems to fix external steel bars and percentage of external reinforcement. Based on the experimental results, the following conclusions can be drawn:

1. Jacketing using non-shrink cement grout is very effective method to enhance ultimate load carrying capacity of RC beams.
2. Both proposed anchorage systems are found capable to securely attach the external reinforcement to the beam soffit.
3. Overall, the increase in ultimate load carrying capacity is found increasing with steel reinforcement ratio for both types of anchorage systems.
4. Future studies should examine a wider range of beam geometry such as beam size and externally fixed rebar materials such as carbon and glass.

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