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Strengthening of Reinforced Concrete Beams Using Externally Bonded Aluminium Alloy Plates

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ABSTRACT
Many RC structures around the world are deteriorated over the years due to various environmental factors. As a result, these structures either need to be replaced or strengthened. Recently developed high strength Aluminum alloys have desirable characteristics that make them attractive as externally bonded strengthening materials. The critical gap in this research area is to carry out further experimental studies to confirm the effectiveness of using bonded AA plates and to investigate the effect of their different orientations. This project investigates the potential of using Aluminum alloy plates for shear strengthening of reinforced concrete (RC) beams. A shear deficient control beam and three shear deficient RC beams externally strengthened using Aluminium alloy plates in 30, 45 and 60 degree orientations were casted and tested. It is observed that the ultimate load capacity of strengthened beams increased in the range of 4.83% - 66.42% over the control beam. The ultimate load capacity is obtained maximum for the beam strengthened with plates at 60 degree orientation.

Keywords :- Aluminium alloy, External strengthening, Shear deficient RC beams, Ultimate load capacity.

I. INTRODUCTION

There are number of RC structures around the world that can no longer be considered safe, as they deteriorated over the years due to various environmental factors, including carbonation, chloride attack, corrosion, etc. As a result, these structures either need to be replaced, which is costly, or strengthened using new and innovative materials. The existing methods for strengthening concrete structures nowadays are either by using steel plates or fiber reinforced polymer (FRP) plates or sheets. But there are some disadvantages of using FRP and steel as the strengthening materials of choice, so that many researchers are trying to overcome by using other materials.

Recently developed high strength aluminum alloys (AA) are some of the most promising metals that can be bonded externally to structural elements and contribute significantly in increasing their load carrying capacity and has the desirable mechanical properties that can overcome some of the deficiencies in steel and FRP. Aluminum as a metal has many effective structural properties such as being isotropic, highly ductile, a good thermal and corrosion resistance, and high strength to weight ratio. As a result, this study is mainly focused on experimentally investigating the potential of using aluminum alloys as externally bonded strengthening material.

II. STRENGTHENING OF BEAMS

The existing methods for strengthening concrete structures nowadays are either by using steel plates or fiber reinforced polymer (FRP) plates or sheets. A brief background of effectiveness of steel plates or FRP plates or sheets as external strengthening materials is given below along with an introduction of AA plates.

A. Using FRP

There are many researches going on shear strengthening of RC beams using FRP materials. Although FRP materials are effective in shear strengthening, they have unavoidable shortcomings include low thermal resistance, brittle behaviour with no well-defined yield point and unidirectional properties.

B. Using steel plates

Although steel has proven to be very effective in shear strengthening of RC beams, they have some disadvantages include, low corrosion resistance, heavy weight and high maintenance cost due to need for painting and coating.

C. Aluminium alloys

Aluminium alloys are alloys in which aluminium (Al) is the predominant metal. There are different types of aluminium alloys that belong to eight different series (1000–8000 series).

1) ***Applications of aluminium alloys:*** Aluminium alloys are economical in many applications. They are used in the automotive industry, ship buildings, aerospace industry, in construction of machines, appliances etc. The recent development of high strength aluminium alloys and the reduction in cost have encouraged structural engineers to consider aluminium alloy in several other applications.

2) ***Aluminium alloys as external reinforcement***: Although FRP and steel materials have proven to be very effective in shear strengthening of RC beams; however, they have their unavoidable shortcomings. Recently developed high strength aluminum alloys are some of the most promising metals that can be bonded externally to structural elements and contribute

significantly in increasing their load carrying capacity while overcoming some of the drawbacks of using FRP and steel. Some of the desirable characteristics for using aluminum alloys in particular as externally bonded strengthening material are their high strength to weight ratio, high ductility, high corrosion resistance, high thermal resistance and their reasonable cost. Aluminum is an isotropic material that is easy to form and easy to bond to RC surface using epoxy with or without mechanical anchorages.

The material used in this investigation is annealed wrought AA5083-0, available in sheets and plates, and has been selected for its exceptional performance in extreme environments, such as seawater and industrial chemicals. Furthermore, it has the highest strength among the non-heat treatable alloys. AA5083-0 ultimate tensile strength ranges between 290– 294 MPa, its tensile yield strength ranges between 145–147 MPa, its modulus of elasticity is 72 GPa and its elongation at break is around 22%.

TABLE I
CHEMICAL COMPOSITION, PHYSICAL AND MECHANICAL PROPERTIES OF 5083-0 AA PLATE

Chemical composition		**Physical and mechanical propertirs**	
Chemical element	**% present**	**Property**	**Value**
Aluminium, Al	92.4 – 95.6 %	Density	2.65 g/cc
Chromium, Cr	.05 - .25	Melting point	570^0C
Copper, Cu	$\leq 0.1\%$	Thermal expansion	$25\text{x}10^{-6}$/K
Iron, Fe	$\leq 0.5\%$	Modulus of Elasticity	72 GPa
Magnesium, Mg	4 – 4.9%	Thermal conductivity	121W/m.K
Manganese, Mn	0.4-1%	Electrical resistivity	$0.056\text{x}10^{-6}\Omega$m
Others, each	$\leq 0.05\%$	Proof stress	145 MPa
Others, total	$\leq 0.15\%$	Tensile strength	300 MPa
Silicon, Si	$\leq 0.4\%$	Elongation A50 mm	23%
Titanium, Ti	$\leq 0.15\%$	Shear strength	175 MPa
Zinc, Zn	$\leq 0.25\%$	Hardness Vickers	75 HV

III. EXPERIMENTAL PROGRAM

A. *Test beams*

Four shear-deficient reinforced concrete beams were designed, casted and tested. Three of these beams were strengthened by externally bonding AA plates of 5mm width, 199mm length and 1.6 mm-thick to the web sides with different orientations include 30 degree (AA30 beam), 45 degree (AA45 beam) and 60 degree (AA60 beam). Each beam specimen has a total depth of 230 mm, width of 150 mm, total length of 2000 mm and a clear span length of 1700 mm. The shear span region was extended for 566 mm from each support. The beams were cast with no stirrups in the shear span to ensure shear failure of the tested specimens. Four 8mm diameter stirrups were provided only in the constant moment region to easily manufacture the steel cage and also to avoid any stress concentration in the concrete under the loading points. All beams were reinforced in flexure with 2 numbers of 12mm diameter bars with a concrete cover of 25mm. In the compression zone the beams were reinforced with 2 numbers of 10mm diameter bars. The dimensions and reinforcement details of all the beams are shown in Fig.1

B. *Materials*

During the casting process, cube specimens were prepared to determine the compressive strength of concrete mix. Three cubes of dimensions 150mm x 150mm x 150mm were tested at 7^{th} day and 28^{th} day yielding average compressive strength of 15.96 MPa and 24.76 MPa at 7^{th} day and 28^{th} day respectively. The nominal yield strength of the primary steel reinforcement was reported by the manufacturer to be 550MPa. The 5083-0 AA plates have the mechanical properties as listed in Table I.

Sikadur-31epoxy was used as the bonding material between the Aluminium Alloy plates and the beams. This epoxy was preferred because of its high strength and abrasion resistance and ease of application owing to its thixotropic property, meaning that it is fluid when agitated and solid when allowed to stand. It is Suitable for dry and damp concrete surfaces and having high initial and ultimate strengths. The elastic modulus, compressive strength, and tensile strength of the adhesive were given by the manufacturer as 4300MPa, 60MPa, and 15MPa, respectively. Density is 1.85kg/l at +27°C. The two-part epoxy was mixed in the ratio of 2:1 using a drill with a speed not exceeding 600 rpm.i A uniform glue line thickness along the plate was achieved.

C. *Testing of beams*

The control beam and three strengthened beams with externally bonded AA plates were tested under two point loading using loading frame. Loading frame is the equipment used to test the various structural elements like beams, columns, slabs and portal frames. The control beam was used as a benchmark for comparison with the strengthened beams. Load is applied at each step and continued until failure. Compression type load cells are used to measure the load applied on the test specimen, in which it is fixed to the ram of the hydraulic jack, which will be pressing the specimen under the given load.

The beams were tested under two point loading using loading frame. The vertical displacement of each beam at its mid span was measured at each load step by a Linear Variable Displacement Transducer (LVDT). A strain gauge was attached to the middle of one of its shear span on the underside of the beams to get the strain variation. Load cell of

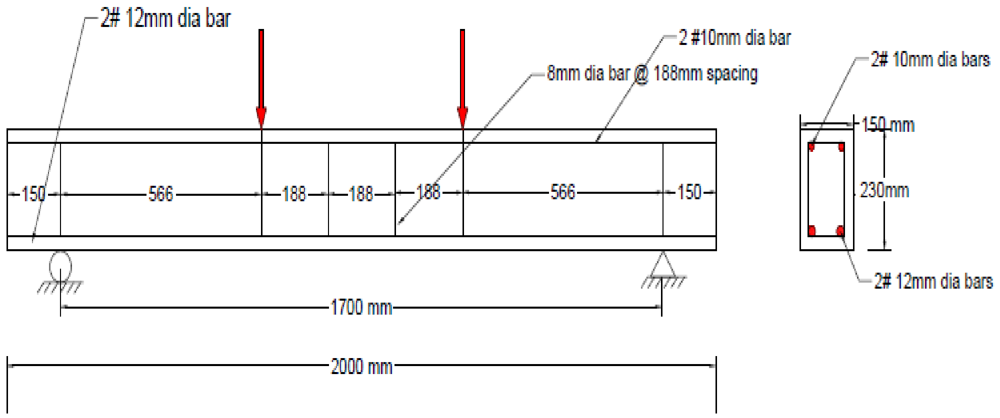


Fig. 1 Reinforcement profile and cross section

Fig. 2 Reinforcement cage for all beams

200 kN capacity was used for testing. The DAQ software, used to take the reading should be set to zero in order to find out the maximum load, strain, and the deflection of the beam. Details of the strengthened beams are shown in Fig.3.

IV. RESULTS AND DISCUSSIONS

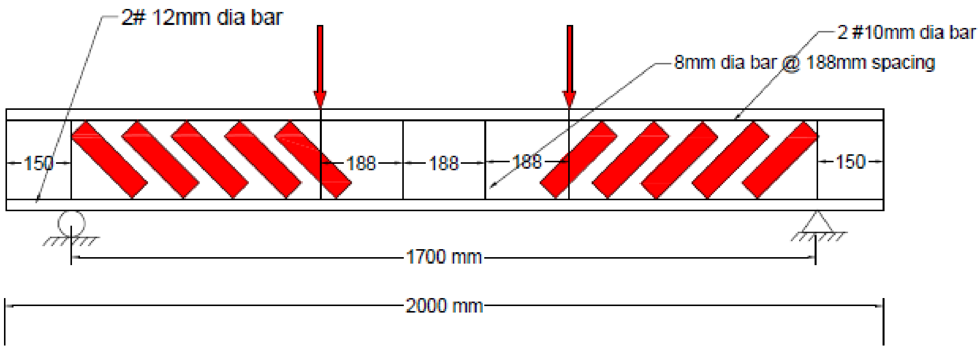
The control beam and strengthened beams were casted. The ultimate load (P_u) and the corresponding ultimate deflection (δ_u) at the mid span for all the tested beams have been determined. The experimental test results of all specimens will be discussed in this section with respect to their strength, load-deflection response curves, failure modes and crack patterns. The obtained test results of all the specimens are summarized in Table II.

A. *Control Beam (CB)*

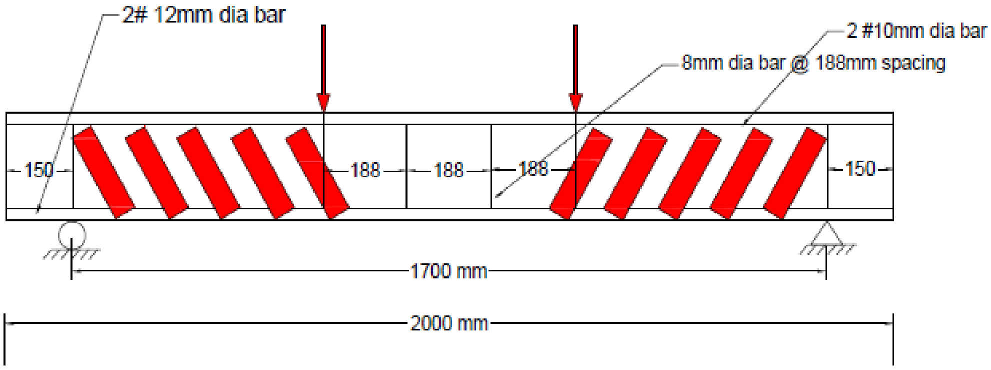
1) ***Strength and Load- deflection response***: The ultimate load capacity for the CB was obtained as 41.4kN and the corresponding ultimate deflection was 5.52mm.
2) ***Failure mechanism discussion***: The CB after testing is shown in Fig.5 It was observed that the specimen failed at a load of 41.4kN by a major shear crack. The crack initiated from the support and then propagated to the loading point.
3) ***Crack propagation:*** The first crack was formed at a load of 28.5kN in the tension region nearer to the loading point in the shear span. It is observed that the specimen failed at a load of 41.4kN by a major shear crack.

B. *AA30 beam*

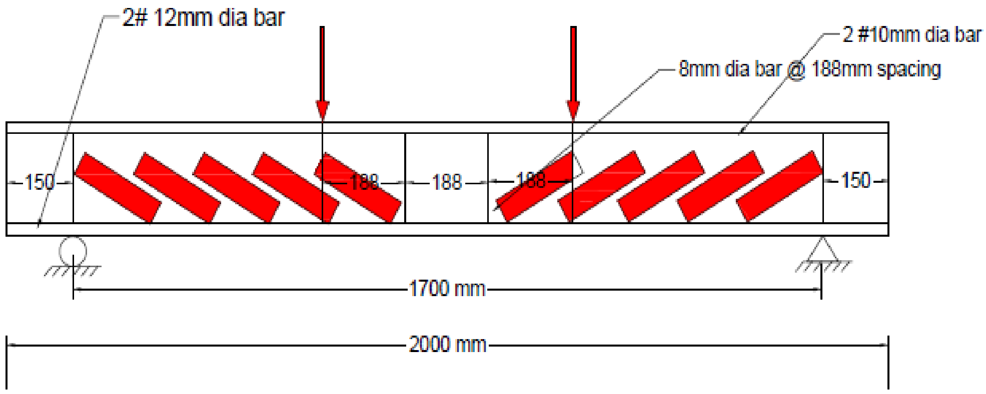
1) ***Strength and Load- deflection response***: The ultimate load capacity of AA30 is obtained as 43.4kN which is 4.83% more than that of CB and the corresponding mid span deflection is 8.01mm which is 45.11% more than that of CB.
2) ***Failure mechanism discussion:*** The AA30 beam failed at 43.4kN by a major shear crack started at the support and propagated approximately at 45 degree inclination towards the load point as shown in Fig .6. The AA plates near the loading point were less effective in capturing the shear crack. Whereas the plates near the support captured the major shear



(a)



(b)



(c)

Fig.3 Details of strengthened specimens (AA30, AA45 and AA60)

crack and resulted in de-bonding. The AA plates captured the shear crack and increased the load carrying capacity by a small amount than that of CB.

3) ***Crack propagation:*** The first crack was formed at a load of 24.1kN in the tension region nearer to the loading point in the shear span. It is observed that the specimen failed at a load of 43.4kN by a major shear crack. The two AA plates near the support were de-bonded at a load of 41.3kN.

TABLE II

SUMMARY OF TEST RESULTS AND PERFORMANCE COMPARISON

Specimen	Strength parameters						
	Ultimate load, Pu (kN)	**Ultimate deflection, δu (mm)**	**Load at first crack (kN)**	**Load at de-bonding(kN)**	**Failure mode**	**$P_u/P_{u\,CB}$**	**% increase in P_u**
CB	41.4	5.52	28.5	-	Shear	1	-
AA30	43.4	8.01	24.1	41.3	Shear	1.05	4.83
AA45	60.3	7.12	43.0	57.7	Shear	1.46	45.65
AA60	68.9	6.89	35.0	58.9	Shear	1.67	66.42

C. ***AA45 beam***

1) ***Strength and load- deflection response***: In the case of AA45, the ultimate load capacity is 60.3kN and the corresponding mid span deflection is 7.12mm. i.e. the ultimate load capacity and the mid span deflection are increased over the CB by 45.65% and 28.98% respectively.

1) ***Strength and load- deflection response***: The ultimate load capacity is 68.9kN and the ultimate6.89mm which is 66.42% and 24.82% more than CB respectively.

2) **Failure mechanism discussion***:* AA45 failure mechanism started with a minor shear crack and then got blocked by the adjacent AA plates as shown in Fig.7 and resulted in crushing of concrete at the compression zone near the loading point. This resulted in higher load carrying capacity than CB.

3) **Crack propagation**: The first crack was formed at a load of 43kN. The two AA plates near the loading point were de-bonded at 57.7kN.

*D.**AA60beam***

2) ***Failure mechanism discussion***: The beam failed by a major shear crack. The plates near the loading point captured the shear crack.

3) ***Crack propagation***: The first crack was formed at 35kN. The two AA plates near the loading point were de-bonded at 58.9kN.

The load-deflection curves for all tested beams is shown in Fig.4

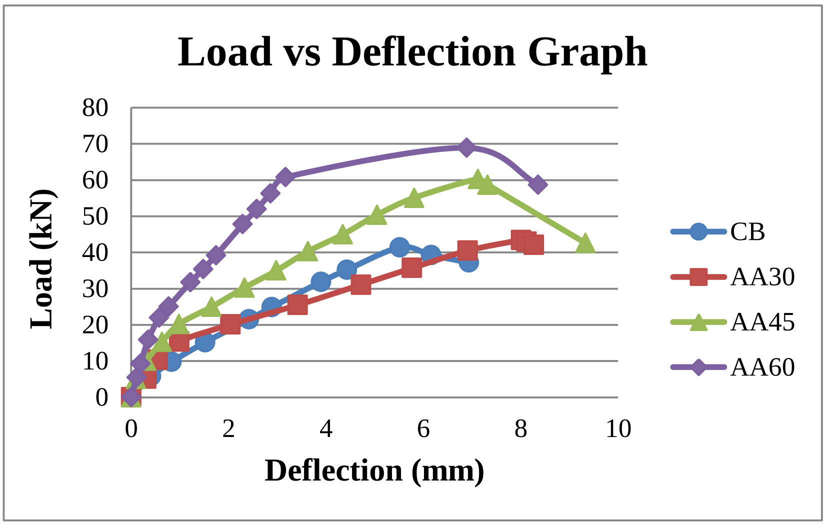


Fig.4 Load- deflection curves for all tested beams

Fig.5 Failure mode of Control beam

Fig.6 Failure mode of AA30 beam

Fig.7 Failure mode of AA45 beam

Fig.8 Failure mode of AA60 beam

E.Summary of results

The load – deflection response curves for all specimens are plotted in Fig.4 As presented earlier, there is an increase in the load carrying capacity of strengthened beams ranging between 4.83% and 66.42%. The highest increase was reached by the AA60 specimen. This verifies that the use of AA plates as an external reinforcement for concrete beams is highly effective technique in increasing the load carrying capacity of beams. It is also observed that there is a decrease in shear cracks during the loading process of strengthened beams. The strength of the strengthened specimens depends mainly on the bond strength of the epoxy adhesive used for bonding AA plates on the beams.

V. CONCLUSIONS

The flexural behavior of RC beams strengthened with externally bonded AA plates with different orientations was investigated. The load-deflection response, failure modes, crack propagation and load-strain response of the tested beams were analyzed, and the following observations and conclusions were drawn.

- It is observed that the loading capacity, mid span deflection and failure modes vary with AA plates orientation. Thus, it can be concluded that the orientation of AA plates has a great influence on external strengthening.
- AA plates can be effectively used to externally strengthen reinforced concrete beams. Based on the result of this investigation, the load carrying capacity of AA30, AA45 and AA60 beams increased by 4.83%, 45.65% and 66.42% respectively. Therefore, use of AA plates is a highly effective technique in increasing load carrying capacity of RC beams.
- The deformational characteristics were generally enhanced for strengthened beams compared to those of CB. The mid span deflection of AA30, AA45 and AA60 increased by 45.11%, 28.98% and 24.82% respectively over CB.
- The failure mode and crack patterns of all the strengthened beams were primarily governed by the AA plate de-bonding and this was also reflected in the load carrying capacity of beams.
- The load at first crack formation is improved for AA45 and AA60 over CB by 50.88% and 22.81% respectively. Whereas, that of AA30 is decreased by15.44%. In each case, the beam was failed by a major shear crack. The crack initiated under the loading point and propagated to the edge of the beam near the support.
- The maximum strain value of strengthened beams is less than that of CB.
- The result of this investigation validates the viability of using AA plates as alternative to the prevailing external strengthening techniques.

FUTURE STUDY

Further experimental studies are required to confirm the effectiveness of using bonded AA plates in strengthening and also to investigate the effect of different other orientations, grades and thicknesses of AA plates in strengthening of RC beams.

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