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The flexural behavior of bolting and bonding Aluminum Alloy plates to RC beams

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Abstract

The aim of this experimental investigation is to study the effect of using externally bonded and bolted Aluminum Alloy (AA) plates on the strength, stiffness, ductility and failure modes of Reinforced Concrete (RC) beams. The test matrix of this study consisted of three RC beams including one unstrengthened control beam and the other two beams were externally strengthened with AA plates using two types of strengthening techniques – bonding only and bolting as anchorage in addition to bonding. The specimens were tested under monotonic loading until failure. The results indicated that the beam with bonded AA plates showed a 32% increase in load capacity and 45% increase in deflection compared to the control beam, whereas the beam with bolted and bonded AA plates showed a 24% increase in load capacity and 84% increase in deflection compared to the control beam. It was concluded that the combination of bolting and bonding, as an alternative anchorage technique, greatly enhanced the ductility in the strengthened specimen and reduced the debonded length of the AA plate while scarified a relatively small reduction in the beam's capacity as a trading off.

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Keywords: Bolting; Aluminum Alloy plates; Flexure; Ductility; Stiffness.

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1. Introduction

The deterioration and aging of reinforced concrete (RC) structural members has led several engineers and researcher to develop methods and techniques to strengthen and rehabilitate them (Abdalla et al. 2018, Hawileh et al. 2018, Colotti et al. 2001). These strengthening applications were studied by several researchers that conducted different experiments to monitor the flexural and shear behavior of strengthened specimens by varying the types of composites used and anchorage technique applied, e.g., Hawileh et al. 2014, Hawileh et al. 2011, Al-Tamimi et al. 2011 and Gao et al. 2011. Mainly, the first material used for strengthening was externally bonding steel plates on the substrates of the structural member (Oh et al. 2003, Aykac et al. 2013). However, its high-corrosive properties and its increased density made steel plates a poor externally bonded retrofit (EBR) material. Therefore, on-going investigations were directed towards implementing fiber-reinforced polymers (FRP) as EBR materials for strengthening structural members, e.g., Hawileh et al. 2015 and Panigrahi 2014, where researchers conducted studies on increasing the flexural capacity of RC beams by bonding FRP sheets to their soffits, e.g., Esfahani et al. 2007, Hawileh et al. 2011, Hawileh et al. 2011 and Attari et al. 2012.

As a result, the stiffness was greatly increased, whereas the failure modes were sudden and involved the detachment of the FRP sheet from the concrete substrate (also commonly known as a debonding failure). This encouraged researchers to explore different anchorage techniques such as: forming U-wraps and implementing FRP mechanical fasteners and bolts, e.g., Ali et al. 2014, Khan et al. 2011 and Zhang et al. 2018; whereby debonding was delayed or, in very few cases, shifted to FRP rupture. Meaning, the FRP strengthened specimens, whether anchored or not, still exhibited premature sudden failures. Therefore, recent studies were conducted by the co-authors of this paper in implementing Aluminum Alloy (AA) plates as an alternative for shifting the failure mode causing the section to be ductile (Rasheed et al. 2017, Abdalla et al. 2016, Abu-Obeidah et al. 2012).

In this study, three RC beam specimens were casted and prepared; one of the RC beams was left unstrengthened and the other two beams were strengthened using AA plates with two types of anchorage techniques: bonding only and bolting plus bonding. The aim of this study is to investigate the effect of anchorage techniques on RC beams strengthened with AA plates and also on their stiffness, ductility, and failure modes.

2. Literature Review

Externally bonding (EB) plates and sheets on the surfaces of structural member is a common practice for the strengthening of RC structures. Several researchers have investigated the effects of anchoring different composites such as: Glass FRP (GFRP), Carbon FRP (CFRP), and AA plates; by means of U-wraps and mechanical bolts. Gao et al. (2017) have investigated the utilization of different plating material, loading cases, and end anchorage techniques. Nineteen beams were prepared, where 17 of them were externally strengthened by means of plating and two of them left unplated, as control specimens. Five out of 17 specimens were plated with CFRP, without anchorage, six were plated with CFRP plates using U-wrap sheets as an end anchorage, and six were plated with steel bolt anchorage. As a result, the CFRP plated specimens exhibited two failure modes; failure due to debonding of CFRP plates at ends and shear failure of concrete. Interestingly, the CFRP plated specimens, with U-wraps, all failed in flexure due to rupture in both the plate and a thin layer of concrete. Finally, the bolted steel plate specimens failed due to either shear failure in bolts or shear failure in the supports. Other researchers promoted the incorporation of U-wrap anchorage as an alternative to bonding sheets or plates during retrofit, e.g., Ali et al. 2014, Khan et al. 2011 and Zhang et al. 2018.

Furthermore, Rasheed et al. (2017) conducted an experimental study on strengthening RC beams using AA plates as an EBR retrofit with and without single-layer and double-layer U-wrapped CFRP sheets. The results indicated that the strengthened beams, without U-wraps, had demonstrated a 40% increase in strength and similar ductility to that of the reference specimen. However, these strengthened specimens failed immediately by end-debonding due to the accumulation of interfacial shear stresses in between the concrete surface and epoxy resin at the ends of the AA plates, whereas the control specimen typically failed by crushing of concrete coupled with yielding of steel. Furthermore, the strengthened beams anchored with U-wrap CFRP sheets exhibited similar load capacities as those without U-wrap CFRP sheets but shifted the failure mode from end-debonding to intermediate debonding; causing the specimens to achieve a higher ductility than the specimens without U-wraps. Other applications regarding the utilization of AA plates in shear strengthening schemes and Finite Element Modeling were conducted by the co-authors of this paper (Abdalla et al. 2016, Abu-Obeidah et al. 2012).

3. Experimental Program

3.1. Test beams

In this study, three RC beams were designed, constructed, and tested. One of the RC beams was left unstrengthened (CB) and used as the reference specimen, the other two beams were strengthened with AA plates whereby the first specimen was plated by means of externally bonding an AA plate to the soffit of the beam (CBE), whereas the other beam was strengthened by bolting and bonding an AA plate to the soffit of the beam (BEM12E). The aforementioned anchorage techniques were applied based on the following materials: an adhesive epoxy called Adesilex PG2 and HST3 M12 bolts. Prior to strengthening, the RC beams' and AA plates' surfaces were grinded and cleaned to achieve a rough surface for uniform bonding of epoxy between the concrete and AA plate. Moreover, to ensure composite action between the bolts and epoxy in BEM12E, the bolts were hammered to the soffit beams, followed by applying epoxy on concrete's grinded, and finally the plate was pressed against the epoxy where the bolts were tightened with a torque value of 60 N-m, in accordance with Hilti (2018).

All the beams were designed using identical dimensions; 125 mm × 240 mm × 1840 mm with a clear span of 1690 mm between the supports. Normal strength steel was used as the reinforcement in which the tension and compression zones consisted of 10 mm and 8 mm bars, respectively, and the shear zone was reinforced with 8 mm bars spaced at 100 mm to increase the shear capacity and ensure a flexural failure before shear. The dimensions of the AA plates were 3 mm × 50 mm × 1350 mm, the layers of epoxy were approximately 2 mm thick, and the HST3 M12 bolts used to anchor the AA plates had a diameter of 12 mm and a height of 115 mm. In order to utilize the full strength of the AA plates, the bolts were spaced at 100 mm until the cracking moment region was reached such that the effective area in the maximum moment region remained homogeneous. Fig. 1 shows the geometry of specimens.

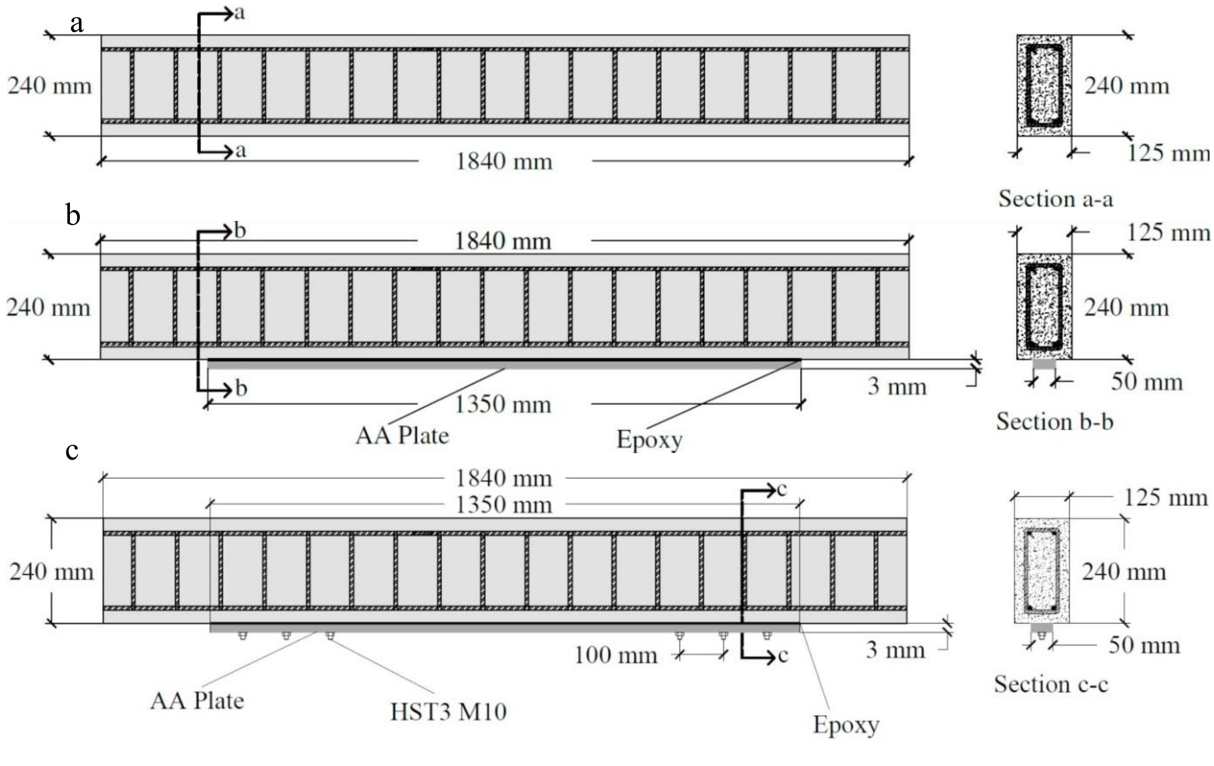

Fig. 1. (a) CB; (b) CBE; (c) BEM12E.

3.2. Mechanical properties

Coupon tests were conducted to measure the mechanical properties of concrete, steel reinforcement, and AA plates by means of compressive and tensile tests, respectively. The compressive strength of concrete was measured during the testing phase, where three concrete cubes were crushed using the compression-testing machine. As a result, the average compressive strength and crushing strain of concrete was measured as 46 MPa and 0.00298, respectively. In addition, tensile tests were conducted for both steel reinforcement and AA plates, as shown in Table 1, where E, f_y, f_u, and ε_{yield} is the Young's modulus of elasticity, ultimate tensile strength, yielding tensile strength, and yield strain, respectively. The mechanical properties of Adesilex PG2 and HST3 M12 were obtained from the manufacturers' technical datasheets (MAPEI 2016, Hilti 2018) where Adesilex PG2 consisted of a shear strength and compressive modulus of elasticity of 12 MPa and 2000 MPa, respectively, and the ultimate tensile stress of HST3 M12 was 800 MPa.

Table 1: Mechanical properties of steel bars and AA plates.

Material	E (MPa)	f_y (MPa)	f_u (MPa)	ε_{yield}
Steel Bar	201.3	548.9	645.1	0.00272
AA Plate	44020.8	151.6	316.6	0.00344

3.3. Test setup

The beams were loaded, monotonically, under four-point bending in which a displacement control protocol was followed throughout the testing process with a loading rate of 2 mm/min. The shear span was limited to 600 mm while the distance in the maximum moment region was 540 mm, as shown in Fig. 2. In addition, strain measurements were taken via strain gages that were bonded to the bottom steel reinforcement, concrete top surface, and AA plate at mid-span of each beam specimen, as shown in Fig. 2.

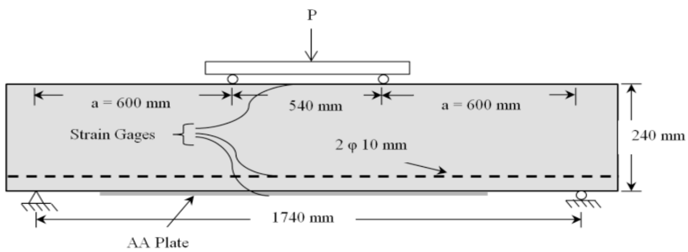

Fig. 2. Load configuration of tested specimens.

4. Results and Discussion

As a result, the effects of bolting epoxy-bonded AA plates were capable of shifting the debonding failure to intermediate debonding whereby BEM12E maintained ductility at a higher loading capacity than CBE, which failed immediately by debonding. The strain measurements for all samples were measured to quantify the failure modes of each beam; concrete crushing (CC), steel yielding (SY), end-debonding (ED), and intermediate debonding (ID).

4.1. Load and deflection curves

The incorporation of AA plate in strengthening applications was to ensure ductility and stiffness throughout the loading life of the strengthened RC beam. Fig. 3 shows the load versus deflection curve of all the beams that were monotonically tested and strengthened during this study. It can be observed that there is an increase in the loading capacity between CB, and both CBE and BEM12E, whereby CB attained a peak load capacity of 64.2 kN whereas CBE and BEM12E reached peak load capacities of 84.3 kN and 80 kN, respectively. The increase in load capacity between the strengthened specimens, CBE and BEM12E, and the reference specimen, CB, was due to the addition of an AA plate to the cross-section of the specimen in which it contributed to the specimen's flexural capacity by having an additional lever arm. However, the difference in peak load capacities between the strengthened specimens could be due to the presence of bolts, in BEM12E, which simulated a fixed support condition at the ends of the AA plate thereby reducing the plate's effective length of the linearly distributed axial force, imposed by the bending moment, and delaying the AA plate's ability to reach its full axial force capacity. This delay allowed the large accumulation of interfacial shear stresses between the AA plate and concrete surface to occur prior to AA plate rupture. As a result, BEM12E reached a peak load value of 80 kN followed by a slight drop in load caused by shear stress concentration in the anchorage system, however, since BEM12E's AA plate was bolted on its ends, the shear stress concentration occurred at mid-span and weakened the section's composite action until the plate latched off from the middle and debonded. This tradeoff in load capacity caused BEM12E to exhibit the ability to be ductile and achieved a maximum deflection of 25.3 mm; approximately 81.6% of the maximum deflection demonstrated by CB, 31 mm, whereas CBE exhibited 14 mm deflection; approximately 45.2% of the maximum deflection of CB, as shown in Fig. 3. This large difference in ductility between the strengthened specimens was the product of the shear stress concentration, in CBE, occurring throughout the entire length of the AA plate, which resulted in the immediate end-debonding. Therefore, the incorporation of bolting epoxy-bonded AA plates to strengthened specimens increased the ductility of the RC beam.

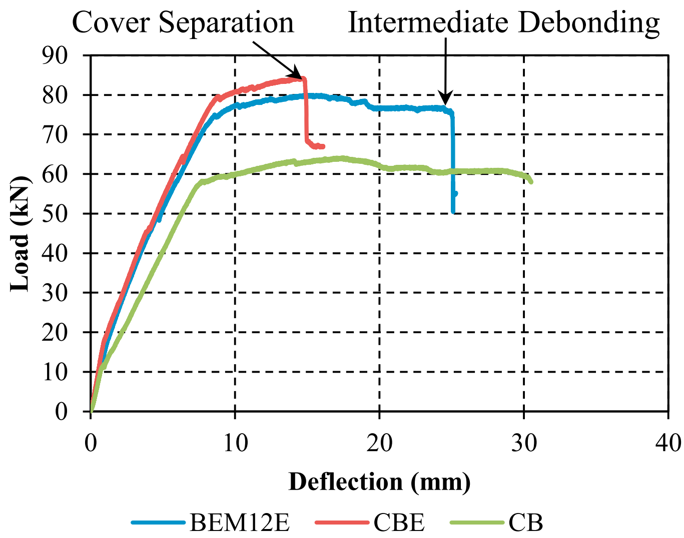

Fig. 3. Load versus deflection curves for the tested specimens.

4.2. Failure modes

The failure modes exhibited in this study were visually inspected after testing and are depicted in Fig. 4. It can be observed that CB experienced both crushing and cracking in both top and bottom fibers of concrete as shown in Fig. 4a), CBE demonstrated concrete crushing followed by immediate debonding, by cover separation, which precluded the beam's ability to resist further loading, and BEM12E experienced both concrete crushing and cracking in both top and bottom fibers of concrete followed by intermediate debonding that was not accompanied by cover separation, as shown in Fig. 4c). Furthermore, the strain measurements corresponding to the ultimate loading capacity of each tested specimen was obtained and tabulated in Table 2 to inspect the mechanical performance of each material individually. CB performed similar to a typical RC beam where its section utilized the mechanical properties of both concrete and steel since their corresponding strain gages measured values of 0.00304 and 0.00283, respectively. Therefore, both materials exceeded their strain capacities during loading; indicating that CB's section utilized their full strength. Although CBE attained a greater peak load capacity than that of CB, its section was not efficiently utilizing the steel's capacity since its strain gage measured a value of 0.000852; hence, hindering the ability for the steel rebar to contribute to the section's capacity during loading. However, the addition of an AA plate allowed for the presence of another lever arm; thereby increasing the section's flexural capacity. Generally, this increase in flexural capacity is a function of three parameters; the lever arm distance, the tensile stress, cross-sectional area of the AA plate. As a result, the strain gages attached to the AA plate measured a strain value of 0.0126 indicating that the AA plate was contributing to the section's flexural capacity; thereby increasing its maximum load capacity. This contribution allowed the loading process to continue until the interfacial shear stresses accumulated at the ends of the plate causing end-debonding to occur coupled with cover separation. The best performance from the test matrix was BEM12E, since the strain gage measurements for both concrete, steel, and the AA plate reached values of 0.00332, 0.0162, and 0.0165, respectively. Therefore, the section fully utilized the mechanical properties of all the materials during loading; hence, maintaining ductility at a higher load capacity as shown in the load versus deflection curve in Fig. 3. In addition, the presence of HST3 M12 bolts shifted the accumulation of interfacial shear stresses from the ends of the AA plate to the middle of the AA plate; hence, reaching a maximum load capacity of 80 kN at a deflection (Δdef) of 25.3 mm.

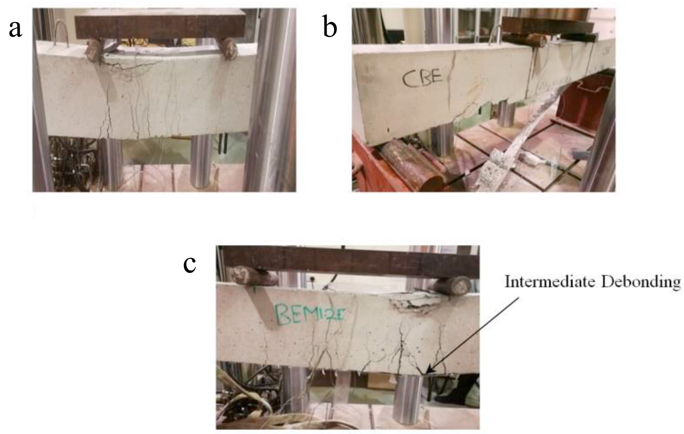

Fig. 4. (a) CB flexural failure mode; (b) CBE end-debonding failure mode; (c) BEM12E intermediate debonding failure mode.

Table 2: Strains and failure modes of specimens at ultimate loads and deflections.

Specimen ID	$\varepsilon_{concrete}$	ε_{steel}	ε_{AA}	P_u (kN)	Δ_{def} (mm)	Failure Mode
CB	0.00304	0.00283	-	64.2	31	CC+SY
CBE	0.00301	0.000852	0.0126	84.3	14	CC+ED
BEM12E	0.00332	0.0162	0.0165	80	25.3	CC+SY+ID

5. Conclusion

This study explored the utilization of AA plates as a strengthening material. It showed promising results owing to its relatively high strength and ductility as opposed to typical retrofit applications; FRP and steel. Moreover, the employment of bolting and bonding as opposed to bonding only indicated that this application provided sufficient anchorage to resist more interfacial shear stresses than typical bonding – mainly postponing the failure mode such that the strengthened specimen exhibits a higher stiffness and similar ductility to that of an ordinary beam. Moreover, this study concluded that:

- Both strengthened specimens, whether by bonding alone or bolting and bonding, presented higher stiffness than that of an ordinary beam coupled with reasonable ductility.
- The specimen consisting of a bolted and bonded AA plate demonstrated lower load capacity than the specimen with bonded AA plate only. This is due to the occurrence of drilled holes that reduced the cross-sectional area of the AA plate; hence, reduced the contribution of the AA plate during loading.
- The specimen with bonded AA plate alone showed 45% increase in deflection whereas the specimen with bolted and bonded AA plate showed an increase of 84% in deflection compared to the control beam. This demonstrated that bolting increases the ductility drastically.

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