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Use of Aluminum Alloy Plates as Externally Bonded Shear Reinforcement for R/C Beams

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Abstract

Fiber Reinforced Polymers (FRP) and steel had proven to be very effective as externally bonded shear strengthening materials. However, they both have their shortcomings. Recently developed high strength Aluminum Alloy (AA) plates possess desirable characteristics that may overcome some of the shortcomings of FRP and steel. The aim of this paper is to study the behavior of Reinforced Concrete (RC) beams strengthened with externally bonded AA plates as shear reinforcement. Three RC beams were designed to fail in shear and two of them were strengthened with externally bonded AA plates that were oriented at 90° and at 45°. The beams were tested under four-point bending until failure while magnitudes of loads and mid-span deflections were recorded. The results of the tested beams showed an increase in the load carrying capacity of up to 38% compared to the capacity of un-strengthened control beam. All beams failed in shear with diagonal shear cracks followed by de-lamination/de-bonding of AA plates near the support and near the applied load. This study demonstrated that AA plates can be used as externally bonded material to enhance the shear capacity of RC beams, however, further investigation is needed to further validate these results.

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Keywords: Aluminum Alloy; externally-bonded material; shear strengthening; shear-deficient beams; Fiber Reinforced Polymers.

1. Introduction

Reinforced concrete structures tend to deteriorate and lose some of their strength over time. This could be due to many reasons including corrosion of steel reinforcement, chloride attack of concrete, carbonation of concrete,

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damage due to earthquakes or under design. Also, increase in the load specification in the design codes, and increase in the general live loads may be additional reasons for strengthening RC members. Therefore, the need for strengthening reinforced concrete members becomes necessary. The most widely used method for strengthening reinforced concrete structures nowadays is bonding steel plates or fiber reinforced polymer (FRP) sheets/plates to external faces of RC members as has been investigated by many researchers for flexural reinforcement, e.g., Esfahani et al. (2007), Al-Tamimi et al. (2011), Attari et al. (2012), Hawileh et al. (2014), Ali et al., (2015) and Hawileh et al. (2018). Shear reinforcement using externally bonded FRP was investigated by several researchers, e.g., Al-Sulaimani et al. (1994), Chajes et al. (1995), Khalifa et al. (2000), Belarbi et al. (2012) and Mofidi et al. (2014) while the use of bonded steel plates as shear reinforcement was studied by Adhikary et al. (2000) and Barnes et al. (2006). Effects of bonded flexural FRP sheets and plates on shear capacity of RC beams were studied by Hawileh et al. (2015) and Nawaz et al. (2016). In spite of that, there are some shortcomings in using steel and FRP as externally strengthening materials that need to be overcome. For instance, the disadvantages of using steel plates as externally bonded strengthening material are: (1) low corrosion resistance; (2) heavy weight; (3) protective coating; (4), and high maintenance cost [Kissell et al. (1995)]. The disadvantages of using FRP sheets/plates as externally strengthening materials are: (1) low thermal resistance; (2) low ductility; (3) unidirectional properties that limit its use.

Newly developed Aluminum Alloys (AA) has the potential of overcoming the shortcomings of steel and FRP as externally bonded strengthening materials. Some of the desirable characteristics of AA is that it has high strength to weight ratio, high ductility, high corrosion resistance, high thermal resistance and reasonable cost. They are also isotropic material that is easy to form and bond to concrete surfaces using epoxy adhesive with or without mechanical anchorages. Therefore, AA may have the desirable mechanical properties that make it contribute significantly in increasing the load carrying capacity of different structural elements and overcome some of the disadvantages of using FRP and steel. The use of AA as externally strengthening material did not receive wide attention yet, however, there are some attempts by the authors and others to investigate the viability of using AA as a new strengthening material besides steel and FRP, e.g., Abdalla et al. (2011) and Abu-Obeidah et al. (2012). Bond behavior of AA-concrete interface was studied by Abdalla et al. (2017), the use of AA as externally bonded flexural strengthening materials was investigated by Rasheed et al. (2017) and AA as shear strengthening material was studied by Abdalla et al. (2016) and Abu-Obeidah et al. (2015).

This study aims to investigate the performance and effectiveness of using AA plates as externally bonded material in strengthening shear deficient reinforced concrete beams. It also studies the behavior of the shear deficient beams with externally bonded AA plates and their mode of failure.

2. Experimental Program

2.1. Material

All specimens were cast using design mix targeting normal concrete strength of 30 MPa. Standard concrete cubes were also cast and tested after 28 days. The average compressive cube strength of the concrete cubes was found to be equal to 37.2 and therefore the concrete compressive strength (f'_c) was taken as 30 MPa. Steel bars were tested to get the mechanical properties of the steel used in this study. The average yield strength and modulus of elasticity of the tested steel bars was found to be 590.4 MPa and 199.9 GPa, respectively.

Aluminum Alloy AA5083-H111 is used as externally bonded strengthening material. AA5083-H111 is an alloy with work hardening imparted by shaping processes [Alcao (2009)]. It is commonly used in highly stressed welded assemblies, dump truck boxes, vehicle bodies, rail cars, shipbuilding, storage tanks, pressure and cryogenic vessels. Table 1 shows the mechanical properties of AA5083-H111.

Table 1. Mechanical properties of AA5083-111 [18]

Property	Value
Tensile strength	288.6 MPa
Yield strength	148.8 MPa
Shear strength	175 MPa
Modulus of elasticity	70 GPa
Elongation	20.9%
Thickness	3 mm
Density	2650 kg/m ³

The epoxy used in this study to bond AA plates to concrete is a two-component adhesive, Part A and Part B [Sika 2009]. It has many advantages such as easy to mix and apply, no primer is needed to install the plates, high strength, and suitable for dry and damp concrete surfaces. The compressive strength, flexure strength and shear strength of the epoxy, according to the manufacturer specifications, are 85 MPa, 25 MPa and around 17 MPa, respectively. To ensure the maximum bond strength, concrete surface and aluminum plates were all grinded to achieve high friction rate.

2.2. Specimens preparation

Figure 1 shows a typical sample of the test beam specimen. The beam is 1840 mm long, 250 mm deep and 150 mm wide. The beam span is 1550 mm. The shear span zones, which are 650.0 mm, begins from the loading point and ends at the supporting point as shown in Fig. 1. The beams were cast without stirrups on one side and with No.8 @ 50 mm center-to-center stirrups on the other side. This is to ensure shear failure of the tested specimens on the side without stirrups. The beams were reinforced in flexure with 3#19 mm bars in the tension zone located at 209 mm from the beam top. In the compression zone, the beams were reinforced with 2#10 mm bars. The Aluminum plates were bonded on the sides of the shear span zone only which is one side of the beam. Two beams were strengthened in shear using 3 mm thick Aluminum Alloy plates (AA5083-111) that were installed on both vertical sides. The AA plates were bonded on the sides of both shear span zones with different orientations (90° and 45°) as the only shear reinforcement. The strengthening procedure of the tested beams included surface preparation by grinding the shear face of the concrete beam and the aluminum plates to create a rough surface in order to ensure sufficient bond between them. Once the surfaces were prepared, the epoxy resins were applied on both surfaces and the AA plates were bonded.

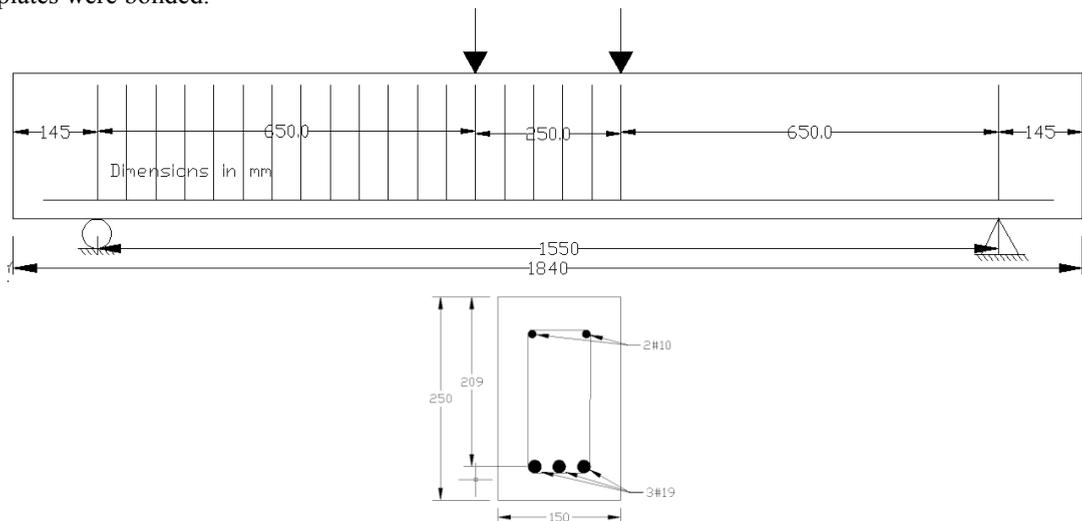


Fig.1. Control beam specimen details (all dimensions are in mm).

Figure 2 shows a beam strengthened with 50 mm x 200 mm x 3 mm vertical (90°) AA plates spaced at 110 mm center-to-center. This beam is designated as AA90. Figure 3 shows a beam strengthened with 50 mm x 200 mm x 3 mm AA plates bonded at an orientation of 45° and spaced at 150 mm center-to-center. This beam is designated as AA45.

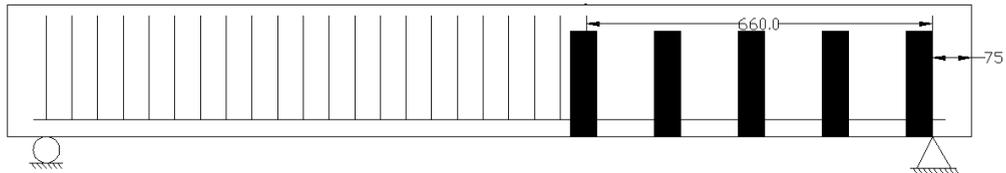


Fig. 2. AA90 specimen details (all dimensions are in mm).

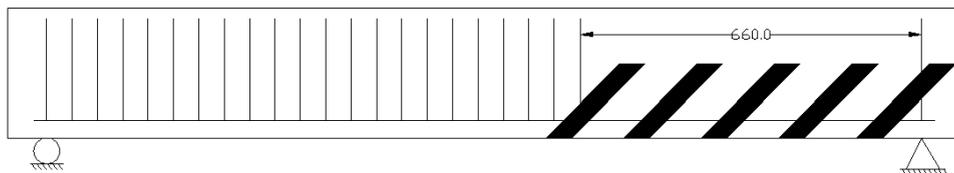


Fig. 3. AA45 specimen details (all dimensions are in mm).

2.3. Test setup

All the beams were tested under four point bending. The control beam (CB) with no shear reinforcement on one side and the two strengthened beams (AA90 and AA45) with externally bonded AA plates were all tested under four-point bending to failure. The beams were loaded monotonically using a Universal Testing Machine (UTM) at a rate of 10 kN/min. The test results of the control beam are used as a bench mark for comparison with the test results of the strengthened beams. Strain gauges on some of the AA plates were installed to capture the strain response values during loading. From the strain readings, the AA plates did not yield, however, they worked efficiently to increase the shear capacity of the tested beams.

3. Results and Discussion

The control beams were tested under four-point loading and failed in shear with a capacity of approximately 119 kN. This measured failure load is very close to the value predicted by ACI318-08 shear equation. The calculated strength of the control beam according to ACI 318-08 code is 109.8 kN. Fig. 4 shows the load versus deflection for the control specimen. As observed in Fig. 4, the beam shear capacity reached almost 117.41 kN with 6.51 mm deflection. The failure load, which is the drop of the ultimate load to 80% of its ultimate value, was 95.5 kN with a deflection of 6.94 mm. Figure 5 shows the mode of failure of the control beam. It is observed that the shear crack formed from the point of application of the load to the edge of the beam near the support.

Specimen AA90 was tested under four-point loading and failed in shear with a capacity of approximately 139 kN. There is an increase in AA90 capacity of 19% over the control beam. Figure 6 shows the load-deflection response of AA90 specimen. The shear capacity of the beam reached almost 139.53 kN with 5.74 mm deflection. As shown in Fig. 7 the shear crack formed from the point of load application to the edge of the beam near the support.

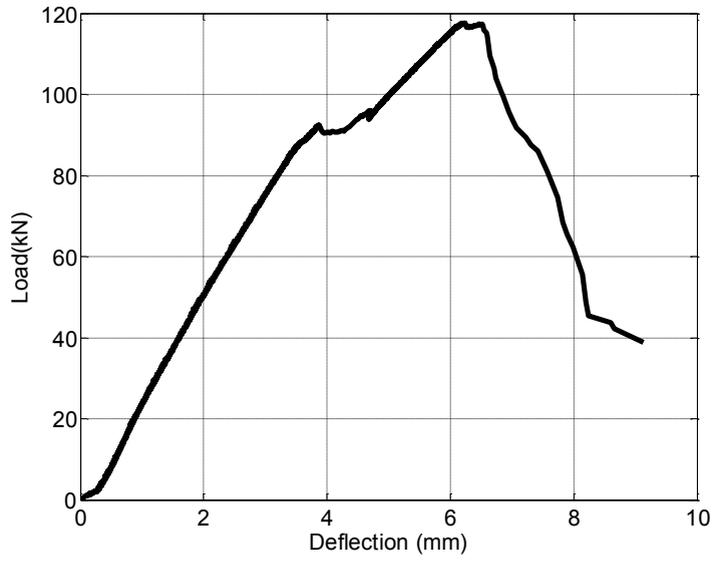


Fig. 4. Load-deflection response of the control beam



Fig. 5. Failure mode of the control beam.

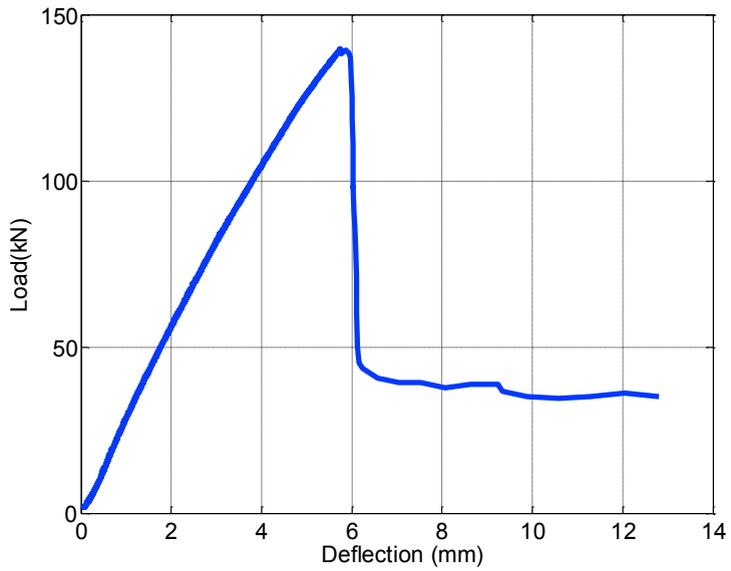


Fig. 6. Load-deflection response of AA90 specimen



Fig. 7. Failure mode of the AA90.

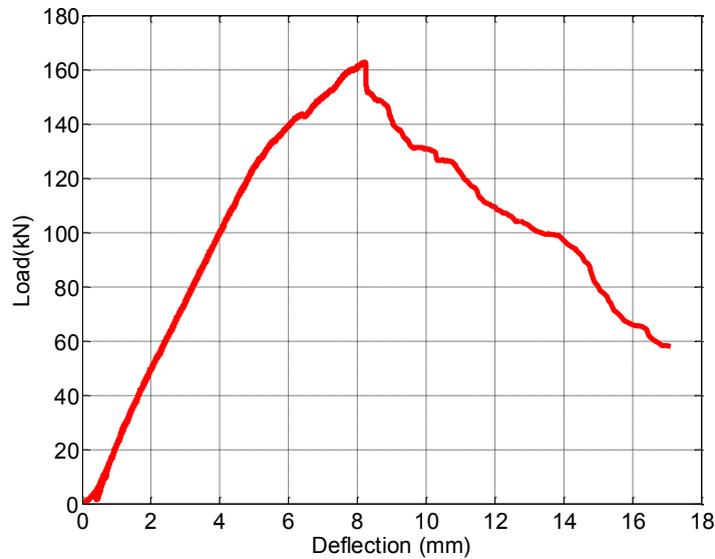


Fig. 8. Load-deflection response of AA45 specimen



Fig. 9. Failure mode of the AA45.

Specimen AA45 was tested under four-point loading and failed in shear with a capacity of approximately 162.79 kN. There is an increase in AA45 capacity of around 39% over the control beam. Fig. 8 shows the load versus deflection for AA45 specimen. The shear capacity of the beam reached almost 162.79 kN with 8.23 mm deflection. As shown in Fig. 9 the shear crack formed from the point of load application to the edge of the beam near the support.

Table 2 shows a summary of ultimate loads, ductility index of the test specimens and their failure modes. Ultimate and yield ductility indexes for the tested beams were measured. Table 2 also shows the measured ductility values for all the beams. The ultimate ductility index is defined as the ratio of the deflection at failure (δ_f) over deflection at ultimate (δ_u) and the yield ductility index is defined as the ratio of the deflection at failure over deflection at yield (δ_y). The failure load is defined as 80% of the ultimate load and the corresponding deflection considered the deflection at failure. As observed, the ductility index decrease with the increase in the capacity from the control beam. Figure 10 shows the load deflection of all specimens.

Table 2. Capacity increase and Ductility index

	P_u	P_u/P_{uCB}	δ_y	δ_u	δ_f	Ductility Index		Failure Mode
						δ_f/δ_u	δ_f/δ_y	
CB	117.41	-	3.83	6.51	7.01	1.08	1.83	Shear
AA90	139.53	1.19	5.74	5.74	5.75	1.00	1.00	Shear
AA45	162.79	1.39	6.29	8.23	9.57	1.16	1.52	Shear

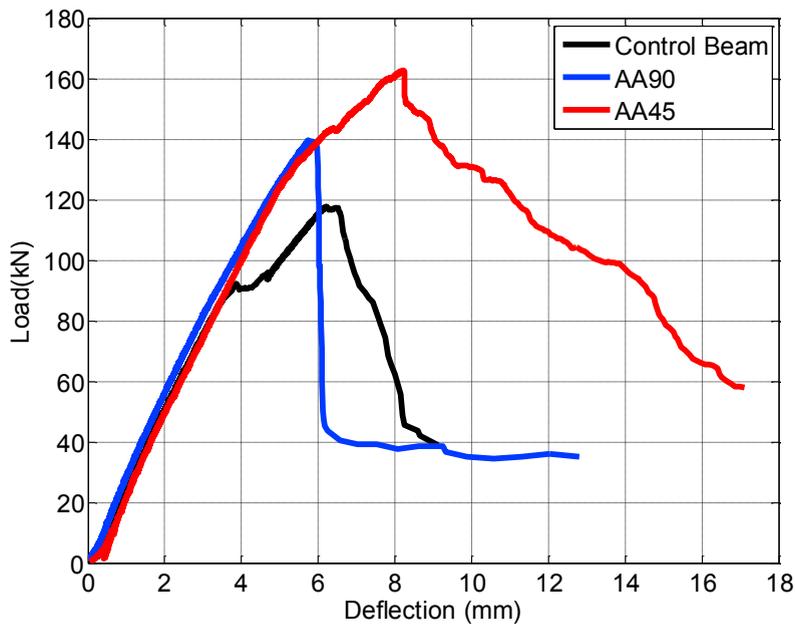


Fig. 10. Load-deflection response of all specimens.

4. Conclusion

This paper presents the results of testing of three shear deficient reinforced concrete beams and investigated the potential of using AA plates as externally bonded strengthening material. Two of the beams were strengthened with externally bonded AA plates oriented at 90° and 45°, respectively. Based on this investigation the following observations and conclusions can be made:

- Aluminum alloy plates can be used to externally strengthen reinforced concrete beams in shear. Based on the result of this investigation, the increase in shear capacity was between 19% and 39% for the two strengthened beams as compared to the control beam. Therefore, using Aluminum plates is a highly effective technique in increasing the beam shear capacity.
- Orientation of aluminum alloy plates, as external strengthening material, has a major effect on the ductility and on the load carrying capacity of the strengthened reinforced concrete beams.

- More elaborated experimental studies is warranted to investigate the effect of plate orientation, surface roughness, AA plate thicknesses in strengthening RC beams deficient in shear.

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