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Flexural behavior of reinforced concrete beams strengthened with externally bonded Aluminum Alloy plates

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ABSTRACT

The objective of this experimental investigation is to study the viability and effectiveness of using Aluminum Alloy (AA) plates as externally bonded flexural reinforcement for reinforced concrete (RC) beams. Ten RC beams were prepared and nine of them were strengthened with externally bonded 2 mm and 3 mm thick AA plates with different mechanical properties. Four strengthened beams had no end wraps or anchorages. Single-layer and double-layer U-wrap CFRP sheets were used in the transverse direction as end anchorages for four strengthened beams and one beam had three double anchorages (two at the ends and one at mid-span). The beams were tested under monotonic load until failure. The goal is to study the effect of using AA plates as externally bonded flexural strengthening material and to explore the effect of end anchorages on the flexural strength and ductility of these beams. The increase in strength over the control unstrengthened specimen ranged from 13% to 40% while the ductility significantly surpassed that of beams strengthened with CFRP sheets. It is observed that the use of end anchorages enhanced the ductility but not the strength of the tested beams. It is also observed that beams without end anchorage failed predominantly in flexure with full de-bonding while beams with end anchorage failed by localized de-bonding and flexure. Furthermore, the performance of the tested beams was compared with numerical predictions by a computer program developed in this study. The results of the numerical models were in close agreement with the measured experimental data. It was concluded that AA plates could be used as an external strengthening material to enhance both the strength and ductility of RC beams in flexure.

1. Introduction

Strengthening and retrofitting of deteriorated and aging building and bridge members is a common practice due to its cost effectiveness nowadays. As a result, various techniques and strengthening materials emerged in the last four decades. Steel and fiber reinforced polymers (FRP) have been used extensively for this purpose as externally bonded reinforcement (EBR). As flexural reinforcement, steel plates and FRP sheets and plates are usually bonded and may be anchored to the soffit of beams to increase the flexural capacity [1–7]. Steel was used as externally bonded/anchored reinforcement material due to its high tensile strength and ductility. However, the susceptibility of steel itself to corrosion and the deterioration of bond strength between steel and concrete due to corrosion made steel plates less attractive to use as EBR. Consequently, FRP emerged and became the dominant EBR material for the last three decades. FRP has superior tensile strength to weight ratio and high resistance to corrosion. However, its brittle rupture and fast degradation under high temperature lead researchers to search for new materials that overcome the shortcomings of steel and FRP. Newly developed Aluminum Alloys (AA) with high tensile strength and ductility comparable to that of steel, light weight comparable to that of FRP as well as high resistance to corrosion and to high temperature degradation made them viable candidates for externally bonded reinforcement materials [8–11].

The use of steel plates as externally bonded flexural reinforcement material has been investigated by many researchers in the 1980's [1,12–14]. Motivated by its light weight and corrosion resistance, FRP replaced steel as EBR material for flexural strengthening of concrete members [3,15–22]. Other developments in terms of using hybrid CFRP and GFRP strengthening materials to accomplish pseudo ductility have been contributed [23,24]. Guidelines for the design and construction of reinforced concrete members strengthened with externally bonded FRP systems were developed by ACI

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committee 440 [25]. Specialized textbooks for the design of strengthened reinforced concrete members with FRP started to appear in the literature [26].

In this study, an experimental program is conducted to qualify the viability and potential of using AA plates as EBR strengthening material to reinforced concrete beams. The behavior of AA strengthened beams is tested with and without CFRP sheets acting as end anchorage U-wrap devices. The tensile stress-strain curve of the AA plates is also tested and modeled using analytical formula similar to that of PCI prestressing strand equation [27]. This formula is then incorporated into an interactive nonlinear analysis program to predict the response of RC beams strengthened with AA plates. Comparisons between the experimental and numerical results are also made.

2. Experimental program

2.1. Test beams

A series of ten RC beams were designed, constructed and tested. The first beam was tested as a control specimen (named CB), see Fig. 1. The remaining nine RC beams were strengthened in flexure with AA plates with and without transverse CFRP sheet anchorage systems. Four beams were strengthened without anchorage, two of them using 2 mm thick 5083-0 AA plates (named B1NW and B2NW) and two of them using 3 mm thick 5083-H111 AA plates (named B5NW and B6NW), see Fig. 2a. Four other beams, two using 5083-0 plates (named B3SW and B4DW) and two using 5083-H111 plates (named B7SW and B8DW), were anchored with a single and double end U-wraps respectively, see Fig. 2b. The last beam specimen was strengthened with 5083-H111 plate and it was anchored with double U-wraps applied at the two ends and at mid-span (named B9TDW), see Fig. 2c.

The authors made two identical specimens of each of the beams with no U-Wraps for the sake of repeatability or capturing different failure modes, if any, since this is the first time the behavior of AA strengthened flexural beams is studied. The designation and detail of each beam specimen are also summarized in Table 1.

Each identical beam was 125 mm × 240 mm × 1840 mm in dimensions. The clear span between simple supports was 1690 mm. The beams were reinforced with 2 No. 10 mm bars at the bottom, 2 No. 8 mm bars on top and No. 8 mm stirrups at 80 mm c/c, Fig. 1. The AA plates were 1352 mm long by 50 mm wide and 2 mm or 3 mm thick based on the plate type. The width of the CFRP U-wrap sheet was 200 mm, which was applied in the transverse direction in case of the single wrap and in case of the double wrap (90° with the beam axis). The U-wraps anchored the AA plate and were wrapped up to the full height of the beam sides, Fig. 2b–c.

2.2. Materials

During the casting process, three cylinders were prepared to determine the compressive strength of the concrete mix. The three cylinders were tested at 28 days as shown in Table 2 yielding an average compressive strength of 38.78 MPa. The nominal yield strength of the primary steel reinforcement was reported by the manufacturer to be 550 MPa. Nevertheless, three rebar specimens were tested in the laboratory yielding the results presented in Table 3. The average yield strength was found to be 540.14 MPa, while the average tensile strength was determined to be 640.17 MPa. The average modulus of elasticity came out to be 199.97 GPa. Three specimens of each type of the AA plates used in flexural strengthening were tested in tension in the laboratory. The 5083-0 AA plates with 2 mm thickness have the mechanical properties listed in Table 4. The 5083-H111 AA plates with 3 mm thickness have the mechanical properties listed in Table 5. The experimental stress-strain curves of the two types of plates are shown in Fig. 3. The modulus of elasticity of the 5083-0 AA plates was 50,000 MPa. On the other hand, the modulus of elasticity of the 5083-H111 AA plates was 20,425 MPa. The CFRP U-wrap sheets used were SikaWrap-300C with the following manufacturer properties: thickness of 0.17 mm, tensile strength of 3900 MPa, ultimate strain of 1.5%, and modulus of elasticity of 230 GPa [28].

Sikadur-30LP [29] is the epoxy adhesive used in this study. It is an adhesive used for bonding structural strengthening reinforcements. It has compressive strength, flexural strength and shear strength of 85 MPa, 25 MPa and 17 MPa, respectively. The epoxy used with SikaWrap-300C CFRP sheet is Sikadur-330 [30]. It has a tensile strength of 30 MPa and tensile modulus of elasticity of

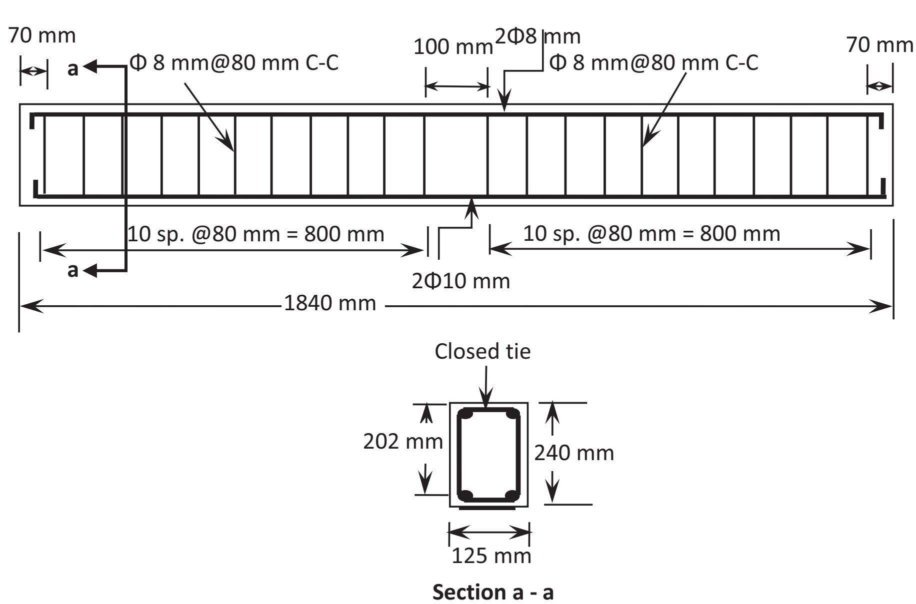

Fig. 1. Dimensions and reinforcement details of tested beam.