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Shear strengthening of reinforced concrete beams using externally-bonded aluminum alloy plates: An experimental study

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HIGHLIGHTS

- Use of AA plates as externally-bonded shear strengthening of R/C beams is studied.
- The capacity of the strengthened beams has increased in the range of 24%–89%.
- Major code equations were used to predict shear capacity of the strengthened beams.
- The SMCFT prediction is the most accurate compared to the experimental values.
- This study demonstrated the potential of using AA plates as strengthening material.

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ABSTRACT

Recently developed high strength aluminum alloys (AA) have desirable characteristics that make them attractive as externally bonded strengthening materials. This paper investigates the potential of using AA plates for shear strengthening of reinforced concrete (RC) beams. Five shear deficient RC beams were externally strengthened using AA plates with different orientations. It is observed that the shear capacity of the strengthened beams has increased in the range of 24%–89% compared to the un-strengthened beam. Shear capacity of the strengthened beams was also predicted using the ACI440, FIB14, TR55 and SMCFT design guidelines with the later one giving the most accurate predictions.

1. Introduction

There is a considerable number of RC structures around the world, that can no longer be considered safe [1], 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. Also, the increase in live loads due to change in building functionality and traffic load demand on bridges, made it necessary to consider strengthening and retrofitting of such structures. The strengthening methods implemented should be simple, effective and economical to be considered as viable option. Strengthening of shear deficient reinforced concrete beams today are mainly accomplished by externally bonding steel plates or transverse fiber reinforced polymer (FRP) sheets or plates to the web faces of these beams. The choice of FRP sheets and plates in shear strengthening of structural concrete members were investigated by many researchers and proved to be effective [2–20]. Also, the use of steel plates as externally bonded material has proven to be effective as investigated by other researchers [1,21–25].

Alternatively, aluminum alloy (AA) has the desirable mechanical properties that can overcome some deficiencies in steel and FRP and qualifies it as a superior external strengthening material. As a result, this study is mainly focused on experimentally investigating the potential of using aluminum alloys as externally bonded strengthening material. The recently developed aluminum alloys possess desirable characteristics that can overcome the deficiencies in steel and FRP. These alloys are economical, effective and easy to install as demonstrated by a preliminary study conducted by the authors [26–28] to proof the concept. To the best of the authors' knowledge, the use of AA plates as externally bonded strengthening material has not been investigated, yet. Therefore,

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the significance of this research is to investigate the feasibility and the effectiveness of using AA plates in external shear strengthening of deficient reinforced concrete beams

2. Background

A brief background of the experimental investigations in shear strengthening of RC beams using FRP and steel is given below, along with an introduction of the superior advantages of using AA plates.

2.1. Shear strengthening using FRP

In the last two decades, extensive research on shear strengthening of RC beams using externally bonded CFRP and GFRP composite materials have been conducted by many researchers [2,6,11–13, 15,29–31]. The shear strengthening methods employed, involve side bonding of sheets or plates and U-wrapping of sheets at different orientations and configurations. The results showed that there is a considerable increase in the shear capacity of deficient beams exceeding 90% [29]. Hawileh et al. [32,33] and Nawaz et al. [34] investigated the effect of longitudinal flexural reinforcement of CFRP sheets and plates on shear capacity of RC beams. They concluded that the increase in the capacity of the specimens strengthened with longitudinal CFRP sheets was in the range of 10% to 70% [32] and for those strengthened with longitudinal CFRP plates was in the range of 13% to 138% [34] compared to the control specimens. The effect of U-jacketing or U-wrapping using CFRP and GFRP sheets on shear strengthening of RC beams was also studied by several investigators [2,6,11,12,16,35–37]. They concluded that FRP sheet U-Wrapping significantly increases the shear capacity of deficient beams. The U-wrap with end anchorage was shown to be the most effective configuration in increasing shear capacity [6]. Shear strengthening of RC beams subjected to cyclic loading was conducted by Calalillo and Sheikh [14] who concluded that using CFRP sheets was effective in increasing the capacity of the under designed beams in the range of 25% to 114%.

2.2. Shear strengthening using steel plates

Other researchers have also studied the use of steel plates in shear strengthening of RC beams [1,22–25,38]. Adhikary et al. [1] and Adhikary and Mutsuyoshi [23] studied the effect of epoxy-bonded continuous horizontal steel plates with different thickness and width on the shear capacity of beams under-reinforced in shear. They observed that continuous steel plates bonded externally to beam webs showed shear strength levels 84% higher than the respective values of the control beam. In another study, Adhikary and Mutsuyoshi [24] examined the effect of different strengthening schemes and techniques including steel strips, externally anchored steel stirrups, small plates of steel and steel brackets on the under-reinforced shear capacity improvements. They observed that epoxy bonded steel plates provided around 72% increase in shear capacity, while beams with externally anchored stirrups yielded 117% increase in shear capacity compared to the control beam. Barnes et al. [22] tested several beams to investigate the effect of externally bonded and anchored steel plates in the shear capacity improvement of RC beams. They investigated different (a) plate thicknesses, (b) shear span-to-depth ratios and (c) connections to the beam's side surfaces. The ultimate capacity of the beams with bonded plate was increased up to 90% compared to the control beam. Altin et al. [38] investigated the effect of side bonded steel plates on the shear capacity of RC T-beams. All the plates were bonded using epoxy adhesive along the shear span of the beam web. The results showed that the externally bonded steel plates improved beams strength, stiffness and ductility. The increase in the shear capacity of the RC beams ranged between 88% and 98% of the control beam. Barnes and Mays [25] tested several R/C rectangular beams and T- beams strengthened with steel plates and steel links bonded with epoxy adhesive. The increase in the shear capacity of the rectangular beams ranged between 30% and 194% and for the T-beams from 5% up to 88%.

2.3. Aluminum alloys

Although FRP and steel materials have proven to be very effective in shear strengthening of RC beams, however, they have their unavoidable shortcomings. For instance, the disadvantages of using steel plates as externally bonded material are their low corrosion resistance, heavy weight and the need for coating and painting that result in high maintenance cost [39]. Also, the weaknesses of FRP materials are their low thermal resistance, brittle behavior with no well-defined yield point and the unidirectional properties that limit their use. 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 and compelling reasons 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.

Until recently, aluminum alloys are used predominantly in the aerospace industry and in ship-buildings. In recent years, aluminum alloys found applications in pedestrian bridges and in some light structures. The recent development of high strength aluminum alloys [40,45] and the reduction in cost have encouraged structural engineers to consider aluminum alloy in several other applications.

There are different types of aluminum alloy materials that belong to eight different series (1000–8000 series). The 5000 series (e.g., 5083 and 5086) are called marine grade aluminum alloy. These are mainly used in ship-buildings and pressure vessels and they are available in sheet forms. Their ultimate tensile strength ranges between 275–350 MPa. The 6000 series, e.g., 6061, 6063 and 6082 are called structural aluminum alloy and are used for structural components. Their ultimate strength reaches 300 MPa. The 7000 series, e.g., 7068, 7075 are of high strength and are used in aircraft and aerospace industries. Their ultimate tensile strength reaches 570 MPa. In addition, the newly developed 2000 series (e.g., 2524, 2224), 7000 series (e.g., 7475, 7055) and new generation aluminum–lithium (Al–Li) alloys (e.g., 2050, 2099) [40–45] with high tensile strength, among other desirable characteristics, are very promising as externally bonded strengthening materials [46].

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 [45], such as seawater and industrial chemicals. Furthermore, it has the highest strength among the non-heat treatable alloys. The chemical composition, physical and mechanical properties of AA5083-0 are shown in Table 1. This type of aluminum alloy is typically used in shipbuilding, rail cars, vehicle and truck bodies, dump truck boxes, storage tanks and pressure vessels [45]. AA5083-0 ultimate tensile strength ranges between 290–294 MPa, its tensile yield strength ranges between 145–147 MPa, its modulus of elasticity is 70 GPa and its elongation at break is around 22%.