Engineering Structures 126 (2016) 53–65

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Flexural performance of concrete beams reinforced with aluminum alloy bars

Guohua Xing [a], Osman E. Ozbulut [b],*

[a] School of Civil Engineering, Chang'an University, Xi'an, China
[b] Department of Civil and Environmental Engineering, University of Virginia, Charlottesville, VA, USA

ARTICLE INFO

Article history:
Received 18 December 2015
Revised 17 June 2016
Accepted 20 July 2016

Keywords:
Aluminum alloys
Concrete structures
Reinforcement
Flexural response
Beams

ABSTRACT

One of the main factors that lead to the deterioration of reinforced concrete structures is the corrosion of reinforcing steel. The aluminum alloy (AA) bars, which have favorable characteristics such as good ductility, low specific weight, good corrosion resistance, and recyclability, can be used as an alternative to steel reinforcement to increase service life of concrete structures. This study investigates the feasibility and performance of AA reinforced concrete beams. A total of nine specimens reinforced with AA bars and two specimens reinforced with plain steel bars, which serve as benchmark, were fabricated and tested under four-point bending up to failure. The longitudinal reinforcement ratio and the concrete strength were the main test variables for the specimens. The load-deflection curves, failure modes, crack patterns, crack width, and reinforcement strains were evaluated and discussed for each specimen. A modified section analysis and a strut-and-tie model were used to predict the load carrying capacities of AA reinforced beams for flexural and shear failure modes. The results indicate that the AA bars, if properly treated, can be utilized as reinforcement in concrete beam with satisfactory performance.

1. Introduction

The corrosion of steel reinforcement has been considered as the main cause for the deterioration of reinforced concrete structures [1–3]. To increase the service life of concrete structures by preventing the corrosion of steel reinforcement, several protection measures such as increasing the concrete cover over the steel reinforcing bars, using low-permeability concrete, coating the steel bars with an epoxy polymer, and applying cathodic protection systems have been developed and implemented in real structures over the past decades [4,5]. Although the adoption of these methods can reduce the corrosion problem in some cases, the corrosion of steel reinforcement is still a major problem for the concrete structures exposed to moist and aggressive environments. The use of non-corrosive reinforcement can be an effective strategy to overcome this problem.

Both nonmetallic and steel-alloy corrosion resistant reinforcements have been studied to prevent corrosion and increase durability in concrete structures. A promising class of non-corrosive materials is fiber reinforced polymers (FRPs), which consists of fibers in a polymer-based matrix [6]. In addition to its good corrosion resistance, FRP bars possess high tensile strength, lightweight, and non-magnetization properties. However, FRP bars are not free from drawbacks that need to be resolved before they can be implemented as reinforcement for concrete structures. FRPs have nearly linear elastic stress-strain behavior up to rupture and fail in a brittle manner. As a result, FRP reinforced concrete members exhibit little ductility. Furthermore, due to low modulus of elasticity of FRPs, concrete members reinforced with FRP bars may experience large deflections. The other obstacles include variation of bond strength according to FRP product type, weakness in shear and high initial cost [3,7,8].

Stainless steel reinforcing bars have also been considered as an alternative to carbon steel rebars for use in concrete structures [9–11]. Stainless steel contains a minimum of 10.5% chromium, which provides excellent resistance to corrosion by forming a very thin self-regenerating oxide layer [12]. A wide variety of stainless steel is available for different applications. The cost of stainless steel bars is about 4–9 times higher than that of carbon steel bars [9,10]. Stainless steel rebars generally offer acceptable mechanical properties. In particular, hot-rolled stainless steel rebars are found to exhibit higher ductility compared to carbon steel, while cold-rolled stainless steel rebars demonstrates lower ductility [12]. The use of stainless steel rebars in concrete structure is still rare due to the limited knowledge about the behavior of structural members reinforced with stainless steel bars.

---

* Corresponding author.
E-mail address: ozbulut@virginia.edu (O.E. Ozbulut).

http://dx.doi.org/10.1016/j.engstruct.2016.07.032
0141-0296/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

A_a	cross-sectional area of the aluminum alloy bar at the bottom
A'_a	cross-sectional area of the aluminum alloy bar at the top
A_{cs}	cross-sectional area at one end of a strut
A_{nz}	area of a section through a nodal zone
A_s	total cross-sectional area of longitudinal reinforcement
b	width of the beam section
C	compressive stress resultant in concrete acting on node 2
c	distance to neutral axis measured from top concrete fiber
d	effective depth of the beam section
d_c	depth of compression reinforcement
E_a	modulus of elasticity of aluminum alloy bar
E_s	modulus of elasticity of steel bar
F_{nn}	nominal compressive resistance of a nodal zone
F_{nnv}	compressive resistance in vertical direction of a nodal zone
$F_{nn(1)}$	compressive resistance in horizontal direction at the support
$F_{nn(2)}$	compressive resistance in horizontal direction at the loading point
F_{ns}	nominal compressive resistance of a strut
F_{strut}	statically determinate load shown in Fig. 16
F_{tie}	force acting on node 1 at the support
f_{cu}	cube compressive strength of concrete
f'_c	cylinder compressive strength of concrete
f_t	tensile strength of concrete
f_u	ultimate strength of steel bar
f_{ua}	ultimate strength of aluminum alloy bar
f_y	yield strength of steel bar
$f_{0.2}$	nominal yield strength of aluminum alloy bar
h	depth of the beam section
h_n	depth of the horizontal strut
h_{tie}	height of Node 1 on the vertical face
I_g	second moment of area of the uncracked section
k_m	empirical coefficient
k_1, k_2	correction factors used in Eq. (3)
M_c	total bending moment given by the concrete with respect to the neutral axis
M_{cr}	cracking moment of concrete beam
$M_{cr,p}$	predicted value of cracking moment of concrete beam
$M_{cr,t}$	test value of cracking moment of concrete beam
M_u	ultimate moment of concrete beam
$M_{u,p}$	predicted value of ultimate moment of concrete beam
$M_{u,t}$	test value of ultimate moment of concrete beam
M_y	yielding moment of concrete beam
P	concentrated force applied on the distribution beam
P_{cr}	cracking load
P_u	ultimate load
P_y	yielding load
w_s	width of the inclined strut
α	strut angle
β_n	reduction factor for a nodal zone
β_s	reduction factor for a strut
Δ_{max}	midspan deflection at failure
Δ_u	midspan deflection at P_u
Δ_y	midspan deflection at P_y
ε'_a	strain in compression aluminum alloy bar
ε_c	concrete strain at the extreme compression fiber
ε_{cu}	ultimate strain of concrete
ε_{ua}	strain corresponding to f_{ua}
ε_0	concrete strain at peak stress
$\varepsilon_{0.2}$	strain corresponding to $f_{0.2}$
μ	ductility ratio
ρ	longitudinal reinforcement ratio of concrete beam

Due to their favorable properties such as low specific weight, good corrosion resistance, easy shaping of profiles by extrusion, recyclability, and aesthetics, the aluminum alloys (AAs) have been used in many engineering applications. Besides their non-corrosive characteristics, they exhibit a plastic behavior with a nominal yield plateau. The AAs have also been explored for use in structural engineering applications [13,14]. They have been considered as a viable option for long-span roof systems due to their lightness and for structures situated in aggressive environments such as swimming pool roof systems and offshore structures due to their corrosion resistance [14]. Several studies have been conducted on the concrete-aluminum composite systems. In particular, the use of aluminum alloys beams in bridge superstructures together with concrete deck has been explored [15]. The use of aluminum alloy bars as reinforcement in concrete structures has yet to be investigated.

In this paper, the material properties of AA bars and potential problems that may arise when they are embedded in concrete are discussed first. Then, an extensive experimental program, which includes testing of eleven 1/3-scale concrete beams reinforced with AA bars or steel bars, is described. The test results are evaluated in the terms of load-deflection curves, failure modes, crack patterns, crack width, and reinforcement strains. The load carrying capacities of AA reinforced beams for flexural failure and shear failure are predicted and evaluated using section analysis and the strut-and-tie model, respectively. To the authors' knowledge, the research presented in this study is the first to address the response of concrete beams reinforced with aluminum alloy bars.

2. Aluminum alloys

Aluminum is the second most commonly used metal after steel. Pure aluminum has low strength, which limits its application and popularity in construction industry. To increase the strength of aluminum, it is usually alloyed with other elements such as copper, manganese, silicon, magnesium and zinc. Among various aluminum alloy groups, alloy of series 5xxx and 6xxx are most applicable for civil infrastructure applications.

Aluminum and its alloys form a thin invisible oxide film on their surfaces as soon as they are exposed to atmosphere. This film provides high corrosion resistance to the metal by preventing further oxidation. Fig. 1 illustrates both steel and AA bars, in the form of longitudinal reinforcement and stirrup, after being exposed to atmospheric environment for about ten days. It can be seen that AA bars remained fully protected against corrosion as a result of its natural corrosion protection from its oxide layer, whereas steel bars severely corroded.

Aggressive environments may affect the stability of the aluminum oxide layer. The protective oxide coating is not stable at acid (pH < 4) or alkaline (pH > 9) environments. When embedded into concrete, AA bars are susceptible to corrosion in such an alkaline environment. Direct contact with concrete that is internally wet might promote serious corrosion of AA bars especially if the concrete contains calcium chloride and steel that is electrically connected to aluminum. Without the presence of chloride and coupling to steel, corrosion of aluminum in the high pH environment of the concrete is not expected to be severe. Also, little or no