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Experimental and analytical study of carbon fiber-reinforced polymer (FRP)/autoclaved aerated concrete (AAC) sandwich panels

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The structural behavior of hybrid fiber-reinforced polymer (FRP)–autoclaved aerated concrete (AAC) panels has been investigated. FRP laminates can be used to reinforce externally the plain AAC producing a very high stiff panel. The resulting hybrid FRP/AAC panel can be used as structural or non-structural member for the housing construction. In order to accomplish this, FRP/AAC panels have been fabricated and prepared for testing. The specimens have been processed using the advanced semi-mechanical processing technique VARTM (Vacuum Assisted Resin Transfer Molding). The concept of the FRP/AAC panel is based on the theory of sandwich construction with strong and stiff skins, like FRP composites, bonded to a core material, like AAC panel. The FRP composite material was made of carbon reinforcing fabrics embedded in an epoxy resin matrix. The panels were tested under four-point bending test to investigate their strength and ductility responses using a Tinius–Olsen Universal Testing Machine. Experimental results showed a significant influence of FRP laminates on both strength and ductility of the FRP/AAC panels. A theoretical analysis was conducted to predict the strength of the FRP/AAC member and results found were in good accordance with the experimental ones.

1. Introduction

The structural design and materials used in housing construction can be improved through the development and application of composite materials that capitalize on multifunctional components. This can be achieved by using panelized construction. Panelized systems developed and analyzed in this paper are based on the theory of sandwich structures. Panelized construction has many advantages such as low cost, high strength to weight ratio, and lower skill required for field construction, etc. Autoclaved aerated concrete (AAC) is an ultra-lightweight concrete with a distinct cellular structure. It has approximately 1/5 the weight of ordinary concrete with a dry bulk density ranging from 0.4–0.8 g/cm^3 and a compressive strength ranging from 2–7 MPa [1]. Entrained air bubbles are the main reason for its enhanced physical properties. The low density and porous structure give AAC excellent thermal and sound insulation properties. Currently this material is reinforced with a special kind of reinforcing steel. Reinforced AAC elements are in the form of panels for roof and floor decks, panels for exterior walls and for lintels. Some studies have been conducted at the University of Alabama at Birmingham to understand the structural behavior of plain and reinforced AAC. Dembowski [2] has conducted a research program on plain and reinforced AAC. The main goal of his research was to develop a database of the material properties and structural behavior of the American-made AAC. The tested panels represent floors, walls, and lintels. In this study, the failure in floor panels occurred suddenly due to the sudden pull-out of steel bars. This failure mode contributes to the fact that the bond between steel and concrete depends mainly on the strength of the concrete. Since AAC has low strength compared to normal concrete, pull-out failure was common in floor panels. Wall panels were tested under both concentric and eccentric loads. The common mode of failure was cracking of the concrete cover at the top and/or the bottom of the panels. Further, no signs of steel buckling were observed. In addition, Snow [3] conducted an investigation on the material properties and structural behavior of AAC products. In this research, some floor and wall panels produced with reinforced AAC were tested. For floor panels, at the ultimate load, Snow observed that the steel did not begin to yield; for wall panels, a brittle and sudden failure at the top of the panels was observed.

Fiber-reinforced polymers (FRPs), because of their high specific stiffness and high specific strength, have been used in the aircraft and automotive industries. In recent years, FRP composites have been increasingly used in highway bridge decks [4]. Fiber-reinforced composites are also being used to repair or strengthen reinforced concrete bridges and other structures. It is therefore, proposed here that since AAC is ultra-lightweight in nature and FRP is very stiff and has high specific strength, the two could be used together to form hybrid structural panels.

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Notation

T_{FRP}	Tensile force carried by FRP skin in the tension side
C_{FRP}	Compressive force carried by FRP skin in the compression side
C_{AAC}	Compressive force carried by AAC in the compression zone
b	Width of FRP/AAC panel
t_{FRP}	Thickness of FRP skin
ε_{uFRP}	Ultimate strain of FRP
$E_{FRP}^{Comp.}$	Modulus of elasticity of FRP in compression
$E_{FRP}^{Tens.}$	Modulus of elasticity of FRP in tension
d	Distance between the two skins
M_n	Nominal flexural strength
$M_{\exp.}$	Experimental flexural strength
V_{AAC}	Shear strength of AAC
V_f	Shear strength carried by FRP
V_u	Maximum shear at support
V_n	Total shear strength of the FRP/AAC panel

To determine the axial compressive strength of plain AAC wrapped by FRP, a set of tests were done by UAB investigators. Khotpal [5] tested plain AAC and FRP/AAC sandwich panels. The objectives were to evaluate the load-carrying capacity of the confined AAC cube and to observe the mode of failure of FRP/AAC panels. The compressive strength is the maximum load the material can support divided by the area over which the load is applied. The compressive strength is determined from the average strength of three concentrically loaded 100 mm cubes. For plain AAC, the compressive strength was about 3.2 MPa while, for wrapped AAC, it was 5.66 MPa; i.e., there is an increase in the compressive strength of about 77% of the original strength. Table 1 lists the mechanical properties of AAC being used in the current research. Cost-effective semi-automatic VARTM processing has been used in this study to reduce the processing time due to construction and surface preparation efforts. In addition to improving strength and ductility, the reinforcement of the AAC panels with FRP composite skins is also expected to enhance durability performance leading to reduced maintenance costs of structures. In the present research, SIKA WRAP HEX 103C unidirectional carbon fibers, SIKAWRAP HEX 113C bidirectional carbon fibers, and SIKADUR HEX 300 resin were used. The mechanical properties of resin as well as laminates, as provided by the company [6], are listed in Table 2.

2. Research significance

AAC is currently used in the form of steel-reinforced panels using rebars as internal reinforcement. These rebars would be subjected to corrosion on the long run and are expensive compared with those used for the normal concrete. Moreover, they do not play any role in the shear strength of the panels. Therefore, the panels need to be thicker to overcome the shear and lower flexural strength problems. Thus, the need to increase both shear and flexural strengths with lesser cost becomes an urgent goal. The concept is to replace these rebars by FRP laminates (Glass or Carbon). Carbon FRP was used in this research while the low cost Glass FRP could also be used. These hybrid panels can be manufactured by wrapping the plain AAC with FRP laminates (Glass or Carbon). Based on the detailed analyses reported elsewhere [7], a cost analysis for reinforced AAC and FRP/AAC panels is summarized in Appendix A, a thinner FRP/AAC structural panel (about 1/2 the size) can be as cost-effective as the original reinforced thicker AAC panel. Although, both AAC and FRP are brittle materials, they have showed good results in combination with each other in terms of strength and ductility as demonstrated in this paper. In addition, as this combination is lightweight in nature, it has the potential to be used for speedy panelized construction purposes, for disaster mitigation and to prevent labor intensive construction. Despite the high strength resulting from this combination, the strength is not the only criterion governing the design of the panel [8]; the deflection is another aspect that controls the design of the hybrid panels.

Table 1
Mechanical properties of plain Autoclaved aerated concrete (AAC).

Property	Value
Density	640 kg/m^3
Compressive strength	3.2 MPa
Modulus of elasticity	1800 MPa
Shear strength	0.12 MPa
Poisson's ratio	0.25

In traditional construction, different layers of materials and structural components are brought individually to the jobsite and assembled, with each typically satisfying a single primary function. For example, a stud wall consists of studs to provide structural resistance to gravity loads combined with exterior sheathing to provide resistance to lateral loads. Insulation is placed in the wall to provide energy efficiency. Gypsum wallboard is then placed on the inside surface of the wall to provide a finished surface or, in some cases, a layer of fire protection. Four separate components are required to provide four separate functions. These four separate components can be replaced by one sandwich panel, referred as FRP/AAC panel, which is durable and can perform all of these functions and provide much higher strength. Although FRPs are expensive, there are some types available at low prices in comparison to the others. For example, E-glass reinforced FRP are much cheaper than CFRPs used in this research. FRPs are also characterized by high corrosion resistance as well as high durability, which reduce future maintenance and overall life cycle costs. In addition, the quantity of FRPs used for manufacturing the panels is very low in which one lamina of thickness 1.016 mm with AAC core thickness ranging from 76.2 to 304.8 mm can carry much higher loads than traditional construction. Moreover, the processing method of the panels proposed here saves manufacturing time and does not require any skilled labors, thus reducing the cost. As a result of savings in time, materials, and labor, potential exists for significant cost reduction compared to the traditional construction.

3. Objectives

The main objectives for this investigation were (1) to assess a half-scale FRP/AAC member performance under a four-point bending test and discuss results in terms of load, deflection, ultimate strength, and failure mode; (2) to compare two systems for wrapping AAC, the first one by using unidirectional FRP lamina and the second by using bidirectional FRP lamina; (3) to propose and validate the theoretical formulas developed for analyzing FRP/AAC section. The paper published on the FRP/AAC panels in ACI by the authors [9] primarily involves the manufacturing process optimization of low cost VARTM versus traditional hand lay-up method as well as structural characterization of mainly small scale FRP/AAC panels with unidirectional FRP laminates, whereas the primary focus for this paper is to investigate the structural behavior of larger scale AAC panels wrapped by both bidirectional FRP laminates and those wrapped by unidirectional laminates in detail, and to develop an understanding of the basis of the proposed theoretical formulas for predicting shear and flexural strengths for practical size FRP/AAC member. It is anticipated that