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Structural behavior of hybrid fiber – reinforced polymer-Autoclave Aerated concrete panels

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ABSTRACT

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 TiniusOlsen 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.
Keywords: Fiber-reinforced polymer , Flexural strength, Shear strength, Autoclaved aerated concrete

INTRODUCTION

Chlorides and other corrosive factors. This has cost a huge amount of expense on the part of repairing, renovating and replacement of the damaged structures across the world. This issue and its aftermath are not only considered as an engineering subject but of a serious social one. Repair and replacement of the damaged concrete structures have caused millions of dollars loss. Over 40% of bridges over highways in the U.S.A. need replacement or reconstruction. Reconstruction or repair expense of parking structures in Canada has estimated $ 4-6 million Canada dollar. The expense of repairing highway bridges in America has estimated to be about $ 50m whereas it has been predicted that the reconstruction of all America's damaged concrete structures – due to rebar corrosion- need astronomical budget $ 1-3 trillion! There are also destructive effects of aggressive chlorides and sulfates within marine and coastal environments on concrete piers of the bridges, pools, dams and canals causing the corrosion of concrete steel across Iran, which have cost heavy renovation expenses.

If we tend to construct all these structures over, we would have to incur high expenses. Thus, we can lower these expenses taking measures to renovate these structures.

There are several techniques developed and employed to prevent the corrosion of attached steelwork to the structure and steel corrosion in the reinforced concrete among which we can refer to:

Epoxy coating on steelworks and rebars, polymer injection to concrete and cathodic protection of rebars. However, the efficiency of each technique has not been absolute.

Recent researchers have resorted to substitution of steelwork and rebars with new resistant to corrosion materials.

Gas concretes weigh a fifth of normal concretes but have less resistive load to normal concretes. About half the capacity of reinforced polymer fibers has much higher tensile strength than steel. This study's major objective is to analyze the hybrid structural behavior of these two materials within sandwich concrete panels.

This study strives to examine this structural behavior within these frameworks:

A: determining the parameters on the features of the hybrid material out of these two materials

B: determining various strength parameters of hybrid structure

C: determining various kinds of rupture at different loadings.

Research significance:
Autoclaved aerated concrete (AAC) is an ultra-lightweight concrete with a distinct cellular structure. It is approximately 1/5 the weight of ordinary concrete with a dry bulk density ranging from 0.4 to 0.8 g/cc and a compressive strength ranging from 2 to 7 MPa (290 to 1015 psi). 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. Detailed information on porosity, pore sizes, and other material characteristics can be found in Caijun and Fouad (2005). High precision block units of unreinforced AAC can be used in wall construction: load-bearing and non-load-bearing walls. Currently, this material is reinforced in the middle with expensive steel to reduce corrosion. Reinforced AAC elements are in the form of panels for roof and floor decks, exterior walls, and lintels. A comprehensive testing program at the University of Alabama at Birmingham (UAB) by Snow (1999) and Dembowski (2001) revealed the behavior of reinforced AAC. The floor panels and lintels were tested by four-point bending, and the wall panels were concentrically or eccentrically loaded to failure. Some of the results that are interesting to this research are as follows:
1. The load at first crack or the cracking load ranged, on average, 30% of the failure load for the floor panels and lintels;
2. For the floor panels, Snow (1999) reported all the failure modes to be brittle, sudden, and in shear. Dembowski (2001),however, observed all failure modes to be brittle. Snow (1999) also noted that for the floor panels, the steel does not even begin to yield when the ultimate load has been reached; and
3. For the wall panels, Snow (1999) observed a brittle and a sudden failure localized at the top of the panels. Dembowski (2001), however, described a failure due to the concrete shell around the reinforcement mat cracking randomly at the top or bottom of the panel under the axial load. Dembowski (2001) also stated that there were no signs of steel buckling. Moreover, according to Snow (1999), the steel has a very little role to play apart from holding the AAC together. The first cracking load is always very small and the load-deflection curves show negligible ductility. The structural behavior of hybrid carbon fiber-reinforced polymer (CFRP)-AAC panel systems is presented in this paper. It is anticipated that the experimental results presented herein will be a first step toward the long-term goal of providing a practical method to predict deflections, stress, and ultimate load, with the intent of developing tools for the design of CFRP-AAC panels for building construction. Fiber-reinforced composites are currently being used to repair or strengthen reinforced concrete bridges and other structures. Therefore, it is proposed herein that because AAC is ultra-lightweight in nature and FRP is so stiff and has a high specific strength (that is, strength divided by weight per unit volume), the two could be used together to form hybrid structural panels. Cost-effective semi-automatic vacuum assisted resin transfer molding (VARTM) processing will be used to reduce the processing time due to the construction and surface preparation efforts. In addition to improving strength and ductility, the reinforcement of the AAC panels with fiber-reinforced polymer (FRP) composite skins is also expected to enhance durability performance leading to reduced maintenance costs of structures. Moreover, because FRP is noncorrosive, there would be no corrosion problems for the hybrid panels, as is the case with steel-reinforced AAC; and the AAC would be protected from harsh environments due to the protective FRP skins.same time carries the shear stress., the idea is to manufacture the panels numbered in the figure with AAC and CFRP. These panels would be in spans of several feet and they could be easily installed into their required positions. Methods of manufacturing them together from smaller size blocks have to be investigated.

Objectives:
The AAC contributes the flexural compressive strength and is responsible for the bearing capacity of the panels and the CFRP would contribute to both the flexural compressive and tensile strength. The main advantages of the hybrid FRP-AAC panel will be that they would be:
1) ultra lightweight;
2) Versatile for speedy construction;
3) noncorrosive;
4) environmentally protected by CFRP skins; and
5) potentially blast and ballistic resistant.
The main objectives for this investigation were
(1) to assessa 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.the experimental and analytical results presented here would be a first step towards the long term goal of providing a practical method to predict deflections, stress, and ultimate load, with the intent of developing tools for the design of FRP/AAC panels for building construction.

Analytical modeling

Based on the experimental results of FRP/AAC panels, an analytical model was proposed to predict the flexural and shear strengths of a FRP/AAC panels

Assumptions

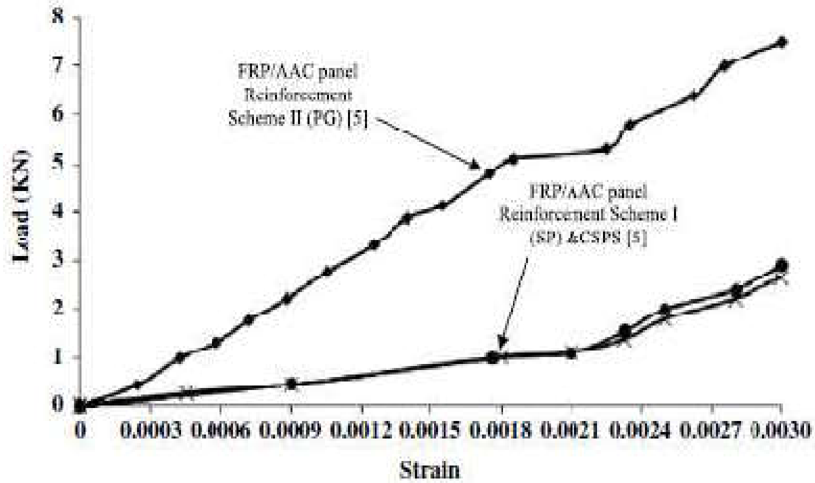
The following assumptions were made in calculating the flexural strength of a section strengthened with an externally applied FRP system:

1. A perfect bond exists between the AAC panel and the external FRP skin.
2. Plane section before loading remains plane after loading, i.e., the strain in FRP reinforcement and AAC is directly proportional to the distance from the neutral axis.
3. The tensile strength of AAC is neglected.
4. The maximum usable compressive strain in the AAC is 0.0018.
5. A bi-linear stressstrain relationship is assumed for the AAC panel.
6. The ultimate capacity is reached when the strain at failure in compression of AAC panel or the strain at failure in tension of the FRP composite skin is attained.
7. The FRP reinforcement has a linear elastic stressstrain relationship up to the failure.

Strain of AAC at failure

According to the previous experimental works done by UAB investigators [4], the FRP/AAC panel loses the linear behavior with an increase in load, and follows a nonlinear behavior after about 0.0018 strain level. This was a unique behavior observed in all of the specimens' results and graphs done by Kotapal [5].

indicates the load versus strain relationship for different configurations of FRP reinforcement. As seen in the figure, the strain in AAC is linear up to 0.0018 for different reinforcement schemes, and the reason for the drastic change in slope following 0.0018 is that the AAC had reached an ultimate strain and formed cracks near the mid-span. After 0.0018 strain, AAC's contribution in the flexural strength is very limited due to the cracking followed by the tension failure. Yet, it acts as a critical separator between the FRP skins providing the much needed integrity for the beam to continue taking up the load and providing flexural strength at the ultimate load level similar to the cracked concrete in a reinforced concrete section. Further, although the contribution of AAC in the flexural strength is assumed as zero in the analysis at the nonlinear level, it has significant contribution for increasing the shear and flexural rigidities of the entire sandwich panel due to its high shear and flexural moduli compared with the core material. Furthermore, it has a good contribution for the shear strength of the panel. In the absence of FRP wraps, it would carry the whole shear stresses acting on the panel. Moreover, its low density and porous structure give AAC excellent thermal and sound insulation properties when used as a core material.



Flexural strength of FRP/AAC section

The analysis of FRP/AAC can be done by internal force equilibrium, computed by determining the stress level in each of the materials. At the equilibrium, the algebraic sum of compressive forces in FRP/AAC panel is equal to the algebraic sum of the tensile forces in FRP-AAC panel at any cross section, i.e.,

$T_{FRP}=C_{AAC}+C_{FRP}$ (1)

But in the inelastic zone, AAC becomes crushed and the strength contribution of the AAC to the FRPAAC composite panel is not significant, as observed in the experimental test. Therefore,in nonlinear (inelastic zone) range the contribution of AAC in compressive forces is considered none, i.e.

$C_{AAC}\cong 0$ (2)

So the equilibrium equation becomes

$T_{FRP}=C_{FRP}$ (3)

To get the location of neutral axis, we have to get TFRP & CFRP first.

CFRP is given by:

$C_{FRP}=b.t_{FRP}.\,\varepsilon_{uFRP}.\,E_{FRP}^{comp}$ (4)

While TFRP is given by:

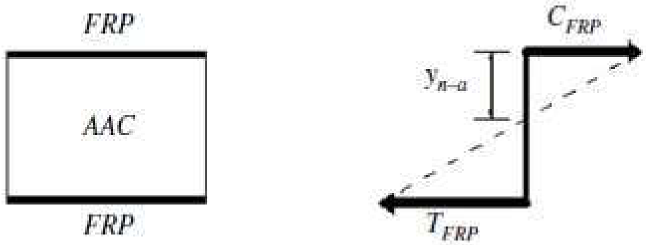
$T_{FRP}=b\,.\,t_{FRP}\,.\varepsilon_{uFRP}\,.E_{FRP}^{Tens}$ (5)

After determining the two forces, the force diagram can be drawn

$y_{n-a}=d.\,(\frac{C_{FRP}}{T_{FRP}+C_{FRP}})$ (6)

Thus, the nominal flexural capacity is given by:

$M_n = T_{FRP}.\,d = C_{FRP}.\,d$ (7)



The stress in the face sheet of the sandwich is given by the following formula

$$\sigma = \frac{PL}{4t(d+c)b}$$ (8)

The average core shear stress equivalent induced at the ultimate load is given by

(9) $$\tau = \frac{P}{2(d+c)b}$$

The maximum deflection in the middle of the span is given by

Δ = bending deflection + shear deflection

$$\Delta = \frac{11PL^3}{768D} + \frac{PL}{8u} \quad (10)$$

$$D = \frac{E(d^3 - c^3)}{12} \quad (c >> t) \quad (11)$$

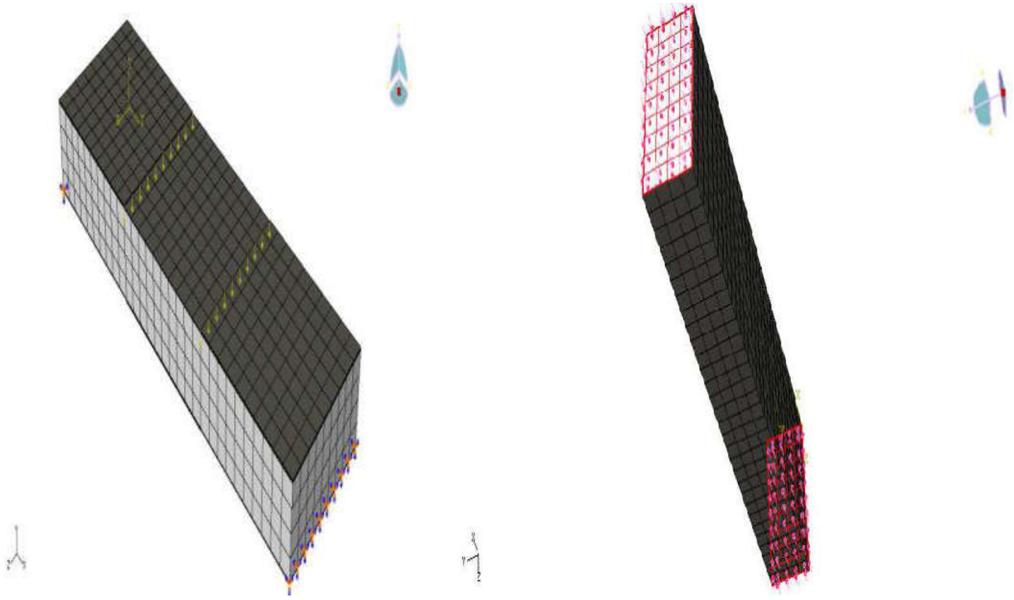
Where the bending rigidity used in the Eq. (3) is given by and the shear rigidity is calculated on the basis of Eq. (12)

$$U = \frac{G(d+c)^2}{4c} \quad (12)$$

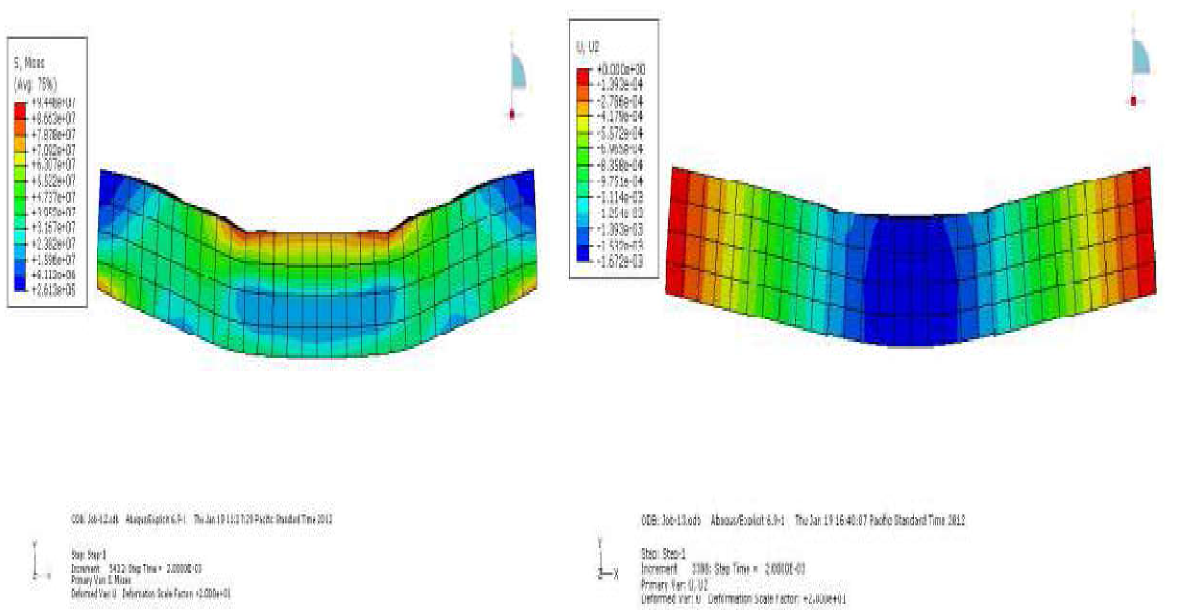
Please note that shear deflection is considered due to relatively low span-depth ratio (l/d) (l/d = 8) and low shearmodulus of the AAC core.

Test setup

To characterize the structural response of the hybrid FRP/AAC panels, the specimens were subjected to a four-point bend test. The flexural tensile strength was determined by a modified version of the ASTM C 393 ``Standard Test Method for Flexural Properties of Sandwich Constructions''. The load was applied at a uniform rate of 0.635 mm/min. The 267 kN Tinius Olsen machine was used to conduct all of the tests. An electronic dial gauge was placed at the mid-span of the section to record the mid-span deflection and the strain gauges were hooked up at the mid-span as well as the shear span to record the strains. shows a schematic for the four- point test for the proposed panels.

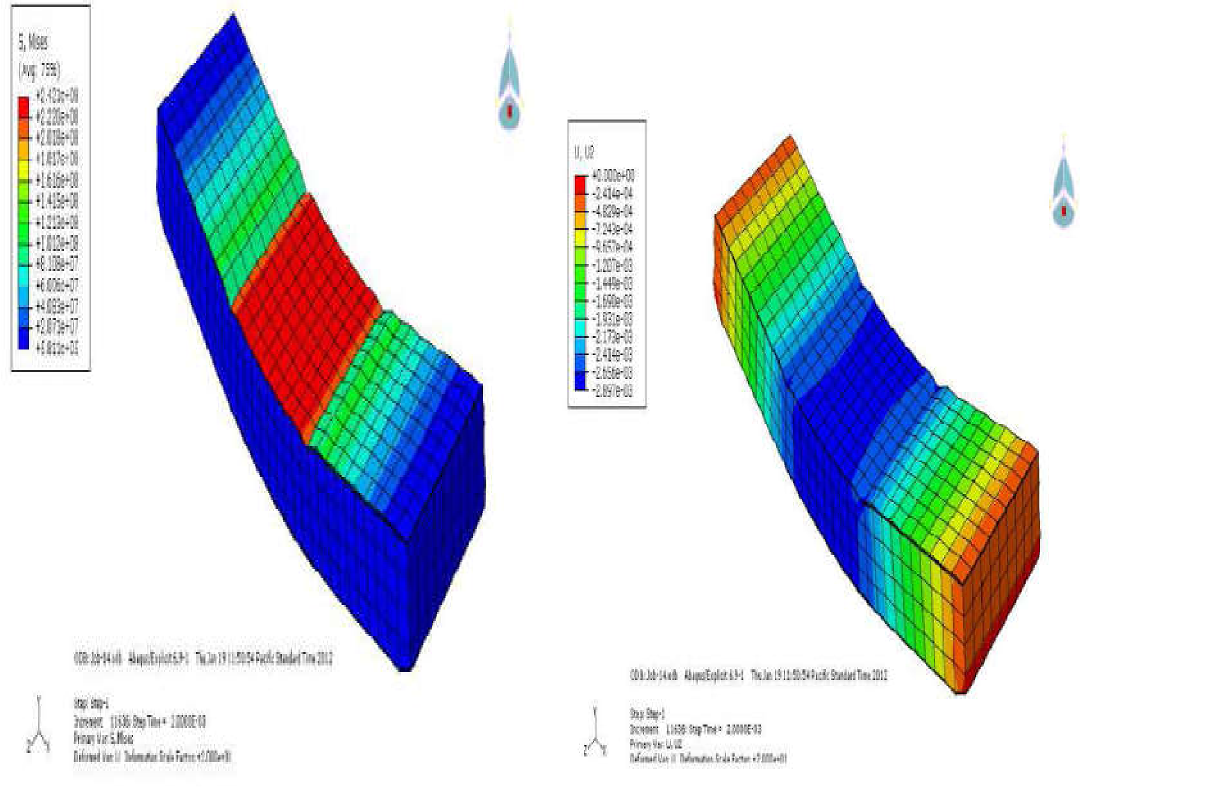


EXPERIMENTAL RESULTS
SPS panels
The SPS panels were strengthened in both flexure and shear. Specimen SPS1 had the highest load carrying capacity for this reinforcing scheme. The maximum deflection at midspan was 1.86 mm, and the sample failed by crushing at the support In spite of crushing at the supports, the panel remained intact and no visible signs of damagewere observed. Specimen SPS1 also shows high stiffness whencompared with the other panels and a significant amount of ductility. The maximum ductility in this category, however, was shown by SPS2. It should be noted that the SPS3 panel was processed using a similar reinforcing scheme as SPS2 but used the hand lay-up process. The better performance of SP1, SP2, and SP4 over SP3 could be attributed to the processing advantages of VARTM over the hand lay-up. As evident from. the superiority of VARTM is clearly proven as the appropriate method for processing. All the panels after failure, however, remained intact and showed very little signs of damage in contrast with the SP panels. Table 4 summarizes the results. Although Specimen SPS4 was expected to record the maximum load and SP2 (with 200 mm shear wrap) was expected to perform better compared with SP1 (with 175 mm shear wrap), the results did not indicate that due to the premature delamination caused by the fabrication flaws. On average, however, the flexural strain induced at failure was 40% of the CFRP ultimate strain and 10% higher than the SP panels.



DB panels

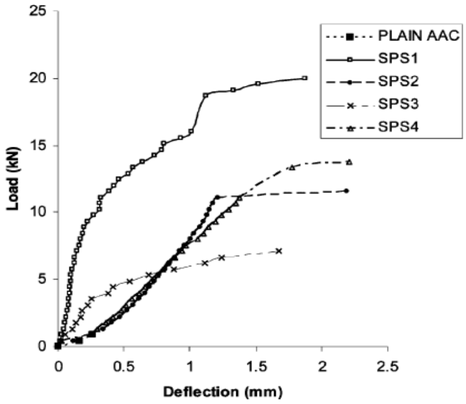
The DB panels were also strengthened for shear as well as flexure. The main objective in this case was to evaluate how successfully the discrete AAC blocks could be bonded to the FRP to process full scale CFRP-AAC structural panels., it was observed that, apart from a minimal joint dislocation in Panel DB1, it was intact and also recorded a load of 17.8 kN, which by all standards satisfies thedesired objective of structural panels. DB1 also recorded the maximum deflection of 2.3 mm and showed excellent ductility as well as stiffness, particularly in the last stages of loading. Moreover, the load capacity of this specimen showed a sudden increase after reaching a deflection of approximately 2.3 mm, which could be attributed to the compression hardening (due to cell collapse of AAC) and tension stiffening of CFRP once the joint dislocation was stabilized. Apart from a joint
dislocation, there were no other signs of visible damage. The flexural strain induced at failure in DBs was almost 47% of CFRP ultimate strain. DB2, on the other hand, showed a lower load carrying capacity and stiffness as compared with the DB1 due to a premature crushing failure in the support. All the hybrid elements of FRP-reinforced AAC exhibited ductility as shown in Table 4. The ductility ratio μ is defined
as the ratio of the ultimate deflection Du at a given load level to the deflection at the yield stage Dy (that is, μ = Du/Dy). Alternatively, one may use other physical parameters that represent ductility but are much easier to obtain. For example, support rotations or the midspan deflection ratio (ratio of midspan deflection to the clear span length) is used frequently and also used in this study

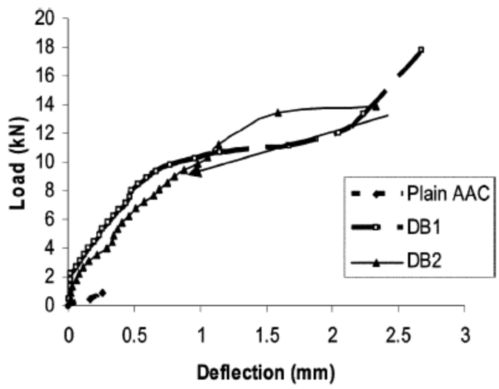


SUMMARY AND CONCLUSIONS

As expected, there is a considerable increase in the load capacity and ductility of the CFRP-AAC panels compared with plain AAC panel. Most of the CFRP-AAC panels (especially the shear reinforced) remained intact even after the ultimate load had been reached with no visible damage. The fact that panels from discrete blocks (DB1 and DB2) stayed intact even at made failure showed that the bigger panels could be formed from joining of discrete blocks into a panel by using the same technique. Most of the load-deflection curves showed a ductile behavior of the panels that indicates that the CFRP-AAC combination is synergetic in nature. As can be seen from the results, the plain AAC recorded an ultimate load of 0.9 kN and the SPS1 panel recorded an ultimate load of 21 kN, which points to the fact that thereinforced AAC panel is 23 times stronger than the unreinforced one. Following is a brief summary of results:

1. Considerable increase in the flexural capacity of the hybrid panels over the plain AAC. Because the premature AAC shear failure is prevented or delayed, their ultimate deflection is also significantly increased, which included a shear deflection in the order of 25% of total deflection;
2. Overall AAC bonds very well with the CFRP provided the processing is done well and the sample properly compacted and adequately cured. The structural capacity of the panels, however, is significantly affected by the reinforcing schemes with the CFRP skin;
3. The strains in the CFRP varied linearly with the applied load reaching up to 0.7% (47% of the ultimate strain) following shear cracking and before onset of failure. Provided that shear failure is further delayed, much higher strain in FRP could be achieved; and





4. The system of reinforcing has to be optimized for cost consideration factors, and VARTM proves to be an effective way of processing the panels as hand lay-up consistently demonstrates lower strength and numerous bonding problems. The biaxially-reinforced larger panels certainly fulfill the objective considering the size of the panel. There also seems to be significant ductility in the response of the panels. Also, it is easier to wrap around the panel with biaxial CFRP. One of the most significant results obtained during this project was the development of an FRP-AAC lintel that could carry the same load as an existing AAC steel-reinforced beam. The designed FRP-AAC lintel occupied 27% less volume and weighed 30% less than its steel-reinforced equivalent. The higher performance of the FRP-AAC lintel produced, combined with its inherent corrosion resistance, enhanced ductility and toughness, and comparative cost far exceeds the low strength and brittleness of plain AAC. It should be noted that although initial project costs were very similar when compared with the use of steel-reinforced AAC (Khotpal 2004), the life-cycle expectancy and maintenance costs were not taken into account and can ultimately give competitive advantage to FRP-AAC over steel-reinforced AAC. Moreover, GFRP could be used instead of CFRP, which would be much cheaper.

TABLE- Summary of all results

Table 4—Summary of all results

Sample No.	Processing technique	Failure modes	Ultimate load, kN	Ultimate mid-deflections, mm	Predicted ultimate deflections, mm	Ductility ratio = deflection/span
Plain AAC	NA	Flexural cracks	0.9	0.30	0.31	0.0005
SP1	Hand lay-up	Shear cracks	12	1.86	1.92	0.0032
SP2	Hand lay-up	Shear cracks and delamination	9.3	1.82	1.49	0.0033
SP3	Hand lay-up	Discontinuous shear cracks	8.0	1.75	1.14	0.0031
SPS1	VARTM	Crushing at supports	20.5	1.87	1.72	0.0032
SPS2	VARTM	Crushing with partial shear	11.6	2.19	1.85	0.0037
SPS3	Hand lay-up	Shear cracks	8.0	1.65	1.85	0.0029
SPS4	VARTM	Crushing at supports and also delamination	11.6	2.21	2.19	0.0036
DB1*	VARTM	Joint dislocation	17.8	2.56	2.92	0.005
DB2	VARTM	Partial delamination with joint dislocation	14.5	1.96	2.67	0.0041

*DB samples have 175 mm long shear wraps from edge going over joint.
Note: NA = not available.

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