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EXPERIMENTAL STUDY ON CFRP-ALUMINUM ALLOY COMPOSITE PIPES UNDER AXIAL COMPRESSIVE LOAD

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ABSTRACT

An innovated element, Al(aluminum alloy) pipe wrapped with CFRP (carbon fiber reinforced polymer), is presented for large-span structures and special structures in favor of their common advantages of light-weight and corrosion-resistance. Outside CFRP layers can enhance strength and stiffness of Al pipes for compression, while Al pipes provide convenient and strong connections between elements. Two sets of composite pipes were tested. Twelve specimens in Set 1 are short pipes, whose bearing strength increments with CFRP layer numbers varying were investigated. And ten specimens in Set 2 with large slenderness and different CFRP layer numbers were tested to investigate their buckling load-capacity. It was shown that the bearing strength and the buckling strength were enhanced significantly to the pure Al pipes. Their stiffness and deformation capacity were improved also.

KEYWORDS

CFRP, aluminum, composite pipe, axial loads, buckling

1. INTRODUCTION

Al (aluminum alloy) is a light-weight, long-endurance material widely used in many engineering fields The research on Al structures for bridges and buildings has developed all over the world since 1930s (Mazzolni, 1985). However, Al structures are limited for its low elastic module which is about 1/3 of steel although the strength is almost same as the common steel. Hence, the concept to combine FRP (fiber reinforced polymer) with high module and Al was proposed to improve Al element performance. FRP has found its applications in civil engineering and is gradually becoming a common structural material in recent 20 years (Ye and Feng, 2006). Comparing with aluminum alloy, FRP has higher tensile strength and elastic modulus in fiber direction, which can be used to enhance performance of Al elements. However, the performance of FRP in transverse and shear is weak. The strengths ratio between the two directions can be up to 25 and 5 respectively to tension and compression (Feng and Ye, 2002). It is resulted in that the high strength and the high stiffness of FRP can not be transferred through the joint without significant weight penalty where various major stress directions occur. If the FRP components are laminated structures, delamination may appear at the joint (Qian and Ye, 2004) .The limitation for joints makes the FRP structure design complicated and difficult, which restricts the full utilization of its high strength and stiffness. It is favored that the combination of FRP and Al will counterbalance this as the connection between Al members is convenient and effective. Therefore, FRP-Al composite structures are presented for large-span structures and special structures. The FRP tubes and the aluminum elements in latticed structures can be taken place by the FRP-Al composite elements. The kind of composite structures has been widely used in aviation industry, like the construction of commercial airplanes, military airplanes and spaceships. F-22 fighter, manufactured by Lockheed Martin, is a typical composite structure which is composed of 39% titanium alloy, 24% aluminum alloy and 39% FRP. And its tail fin is manufactured by aluminum alloy honeycomb core and CFRP stressed-skin structures (Harris et al, 2002). Automobile actuating arms made of CFRP-aluminum alloy composite, can not only reduce the weight of rods, but also improve the strength and stiffness of rods (Lee et al, 2004).

As a typical example of the new conceptual composite elements in structural engineering, CFRP-Al composite pipes under compressive load, which is the most common case in spatial truss structures, are investigated in this paper. CFRP sheets were wrapped and adhered on out-surface of Al piped in longitudinal and transversal alternately. The longitudinal direction fiber is utilized to improve stiffness, strength and stable bearing capacity of Al pipes. The transversal fibers can provide a confinement and prevent the local buckling. The more effective connections between elements than pure FRP components' can be inherited from Al pipes. Thus, the common merits of FRP and Al, light-weight and anti-corrosion, can be utilized but their shortcomings separately may be overcome. In order to investigate the axial compressive behaviors of CFRP-Al composite pipes, two sets of specimens, twelve in Set 1 and ten in Set 2, were tested. The pipes were analyzed by finite element software. The theoretical formula based on Euler Theory were presented and compared with the results of tests and FEA. A design approach for CFRP-Al composite pipes in compression was suggested.

2. EXPERIMENTAL PROGRAM

T6061-T6 Al circular pipes with an outside diameter of 49.7mm and a nominal thickness of 3.1mm were used. The mechanical parameters are obtained by short column compression tests and tensile strength tests respectively as listed in Table 1. From table 1 it is evident that the yield strains and stresses both in compression and tension are quite close to each other. Since during investigation all the components are in compressive state so all the analytic parameters are taken from the stocky column tests in compression. The CFRP were wrapped on the outside surface of the Al pipes, which were treated by sand blasting and cleaned. The unidirectional fiber sheets made of T30 carbon fiber and epoxy resin were laminated layer by layer. The elastic parameters of the CFRP laminates were obtained by tensioning the one-layer plates with different fiber orientations: 0, 90 and 45, according to *Test method for tensile properties of oriented fiber reinforced plastics* (Chinese Standard GB3354-82), as listed in Table 2.

Table1: Aluminum Alloy and Mechanical Parameters

Test	σ_y (MPa)	ε_y	$f_{0.2}$(MPa)	$\varepsilon_{0.2}$	E (MPa)	ν
Compression	259	3881	291	6224	69800	0.36
Tension	270	3965	291	6317	70300	/

Table2: CFRP Laminate Mechanical Parameters

E_1（MPa）	E_2（MPa）	G_{12}（MPa）	ν_{21}
7.15×10^4	3.37×10^3	1.53×10^3	0.36

Table3: Set 1-Short Pipes

Specimens	Al Pipes Outer Diameter - Thickness (mm)	CFRP Thickness (mm)	CFRP Ply
SACP-1,2,3	49.7 - 3.0	/	/
SACCP1-1,2,3	49.7 - 3.0	1.4	$[0/90]_1$
SACCP2-1,2,3	49.7 - 3.0	2.4	$[0/90]_2$
SACCP3-1,2,3	49.7 - 3.0	3.7	$[0/90]_3$

Table4: Set 2-Long Pipes

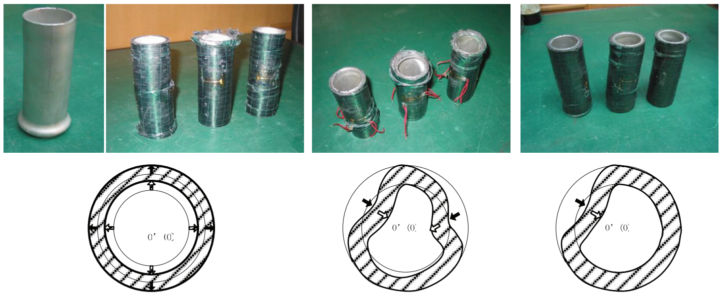
Specimens	Length (mm)	Al Pipes Outer Diameter - Thickness (mm)	CFRP Thickness (mm)	CFRP Ply
ACCP60-0	950	49.7 - 3.1	/	/
ACCP60-2	950	49.7 - 3.1	2.7	$[0^o/90^o]_2$
ACCP60-3	950	49.6 - 3.0	3.5	$[0^o/90^o]_3$
ACCP70-1	1100	49.6 - 3.1	1.5	$[0^o/90^o]_1$
ACCP70-2	1100	49.6 - 3.0	2.7	$[0^o/90^o]_2$
ACCP70-3	1100	49.7 - 3.1	3.5	$[0^o/90^o]_3$
ACCP120-0	1950	49.7 - 3.1	/	/
ACCP120-1	1950	49.6 - 3.0	1.5	$[0^o/90^o]_1$
ACCP120-2	1950	49.6 - 3.1	2.7	$[0^o/90^o]_2$
ACCP120-3	1950	49.6 - 3.1	3.5	$[0^o/90^o]_3$

Two sets of specimens were tested. Set 1 which is 12 short pipes with the length of 150 mm is to investigate the axial compressive loading capacity of composite elements. According to the layers number and the ply orientation the specimens can be divided into four groups as listed in Table 3, including a group of controlling specimens without CFRP named SACP and three groups of CFRP-Al composite pipes named SACCP. Set 2 includes 10 long specimens divided into three groups by slenderness ratio as listed in Table 4, in which two pure Al pipes of ACCP60-0 and ACCP120-0 act as the controlling specimens.

3. TEST RESULTS

3.1 Set 1: Short Pipes

The controlling specimen, SACP, was loaded increasing linearly with vertical displacement before reaching the yield strain of aluminum. After yielding, the end of the pipe began bulging outward, and the transverse deformation kept on increasing until its failure state reached along with a decrease in the load resistance. An elephant-foot buckling appealed as shown in Figure 3. And some tiny longitudinal cracks can be found on the surface near the pipe end. The composite specimens, SACCP1, SACCP2 and SACCP3, show the similar loading failure process with SACCP besides the cracking sounds started emitting always when the pipes closed to the yield load and continued to the rupture of the carbon fiber. There was no obvious bulging, and the yield load and the maximum load rise with the increase of CFRP reinforcement. For SACCP1, two cross layers CFRP wrapped, the failure mode after Al yield is same as SACP without CFRP as the CFRP layer can not provide enough lateral confinement to restrict the lateral expansion of aluminum near the pipe end. But the confinement effect on the aluminum pipes is enhanced to make the ultimate failure mode after Al yield transferred with the increase of CFRP layer amount: SACCP2 were concaved inner and bulged a little on the opposite side; and there were concavity and no obvious bulge in SACCP3. In the test there was no debonding observed at the interfaces between Al and CFRP. The failure modes are shown in Figure 1.



(a) SACP and SACCP1 (b) SACCP2 (c) SACCP3

Figure 1: Failure Modes of Pipes in Set 1

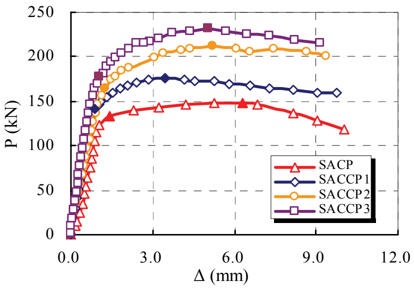
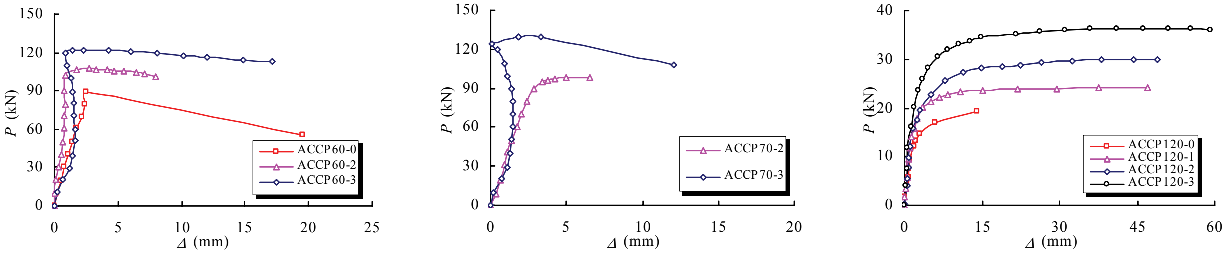


Figure 2: Load-deformation Relations of Set 1

At the same time, the yield loads and the ultimate loads rise almost linearly to the CFRP layer amount increase: the mean yield loads of SACCP1, SACCP2 and SACCP3 are 119%, 139.8% and 150% of SACP respectively, the maximum load capacity are 119.8%, 144% and 154.6% respectively. Figure 3 shows the axial load and the vertical displacement relations obtained from the tests. The values of the curve are taken as the mean of three specimens. It also can be seen that the stiffness of the pipes increase slightly with the increase of CFRP layers before yield and increase considerably after yield. Therefore, the CFRP reinforcements have two different contributions to the composite pipes: the longitudinal fibers enhance the pipe's load carrying capacity directly, and the annular fibers supply the radial restriction and change the failure modes after yield which resulted with the increase in the load carrying capacity indirectly.

3.2 Set2 : Long Pipes

All long pipes in Set 2 under the axial compressive load buckled integrally before Al yield. The lateral displacement in the middle of pipes is not obvious but goes up quickly when a certain axial load arrives. ACCP70-1, the first specimens in Set 2, tested on a ball and socket support at the ends which restricted the ends from free rotation in the test and is a not a hinge. After it, the setup was developed into hinge supports. The relations between the axial load *P* and the lateral displacement *Δ* for each slenderness group are shown in Figure 3 except for ACCP70-1. It can be found that the maximum load capacity can be enhanced obviously with the increase of CFRP layers. The bending rigidities of ACCP60 and ACCP70 decrease quickly after buckling because Al yield come immediately, while ACCP120 shows a slow degradation rate.



(a) ACCP60 Group **(b) ACCP70 Group** **(c) ACCP120 Group**

Figure 3: Load-lateral Displacement Relations of Set 2

4. CONCLUSIONS

Based on the tests of the CFRP-Al composite pipes under axial compressive load, the following conclusions can be drawn.

(1) There was no debonding found between CFRP layer and Al in tests. CFRP-Al composite is an effective concept to build axial compressive elements.

(2) The bearing strength of CFRP-Al composite pipes can be improved considerably which rise with the increase of the CFRP layers. It comes from two parts: the longitudinal fibers enhance the longitudinal and flexural stiffness and strength directly; and the annular fibers provide the radial restriction to change the failure mode.

(3) The stable strength of CFRP-Al composite pipes can be improved considerably which rise with the increase of the CFRP layers.

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