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Experimental Investigation on Cold-Formed Steel Foamed Concrete Composite Wall under Compression

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Abstract**—**A series of tests on cold-formed steel foamed concrete (CSFC) composite walls subjected to axial load were proposed. The primary purpose of the experiments was to study the mechanical behavior and identify the failure modes of CSFC composite walls. Two main factors were considered in this study: 1) specimen with pouring foamed concrete or without and 2) different foamed concrete density ranks (corresponding to different foamed concrete strength). The interior space between two pieces of straw board of the specimen W-2 and W-3 were poured foamed concrete, and the specimen W-1 does not have foamed concrete core. The foamed concrete density rank of the specimen W-2 was A05 grade, and that of the specimen W-3 was A07 grade. Results showed that the failure mode of CSFC composite wall without foamed concrete was distortional buckling of cold-formed steel (CFS) column, and that poured foamed concrete includes the local crushing of foamed concrete and local buckling of CFS column, but the former prior to the later. Compared with CSFC composite wall without foamed concrete, the ultimate bearing capacity of spec imens poured A05 grade and A07 grade foamed concrete increased 1.6 times and 2.2 times respectively, and specimen poured foamed concrete had a low vertical deformation. According to these results, the simplified calculation formula for the CSFC wall subjected to axial load was proposed, and the calculated results from this formula are in very good agreement with the test results.

Keywords**—**Cold-formed steel, composite wall, foamed concrete, axial behavior test.

I. Introduction

CFS walls have been widely used in low-rise residential and commercial building over the years because of the light weight, easy installation, and other advantages such as environmental characteristics and recyclability [1]-[3], but as the main vertical load-bearing member is not suitable for framing a growing number of multi-story buildings in recent years. Foamed concrete (FC) has primarily been utilized as a void insulation material and it is possible to use LFC as structural load bearing material in low load bearing systems such as walls in low-rise residential buildings. Based on the performance of CFS and FC, a new type of composite wall namely CFS FC composite wall (CSFC composite wall) is proposed by combining the CFS and FC.

CSFC composite wall is considered to a multi-function high-performance composite wall, because of high axial bearing capacity, low thermal conductivity, light weight, industrialized construction and environmental characteristics, which could be suitably applied on the modern multi-function building. CSFC composite wall mainly adopts two different materials: CFS and FC. The FC and CFS system sheathed with straw boards are combined organically by using the specific construction technique of pouring FC into the CFS system from the top of wall. This construction technique makes FC and CFS construct an integrated structure, which bears jointly axial load and increases the axial bearing capacity of CSFC composite wall. Due to the filling effect of FC, it effectively prevents the channel of CFS from occurring the three type of failure mode, which are shown in Fig. 1 [4]. Therefore, CSFC composite wall is suitable for constructing multi-story and multi-function buildings, even high-rise buildings. CSFC composite wall structure, one of the important CFS composite structures for the realization of multi-story or high-rise story buildings, has a good momentum of development.

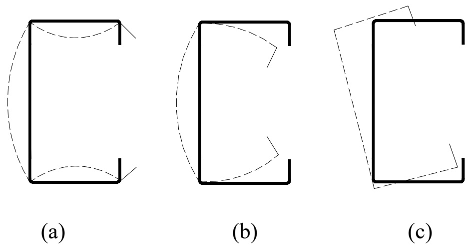

Fig. 1 (a) Local buckling, (b) Distortional buckling and (c) Flexural buckling for CFS column

The existing studies mainly forced on the traditional CFS composite wall without pouring FC and the composite panel system consisting of two outer skins of profiled thin-walled steel plates with lightweight FC core [5], [6]. To the author's best knowledge, no research had been conducted on CSFC composite wall. Thus, it is necessary to carry out fundamental research on the mechanical behavior and identify the failure modes of CSFC composite wall. The study involved experimental investigations on CSFC composite wall and the influencing factors considered were pouring FC or not and different FC density rank (corresponding to different FC strength). Full scale tests were performed. The axial bearing capacity and failure modes under the tests were observed and compared. Based on these results, the simplified calculation formula of the CSFC wall subjected to axial load was proposed.

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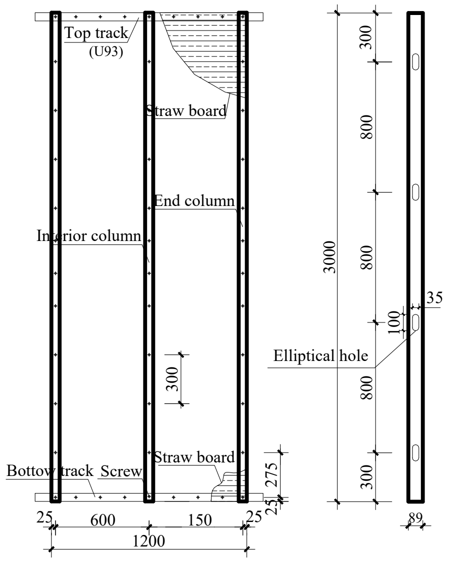
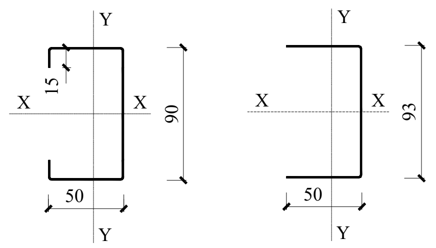
II. Experimental Investigation

A. Test Specimens

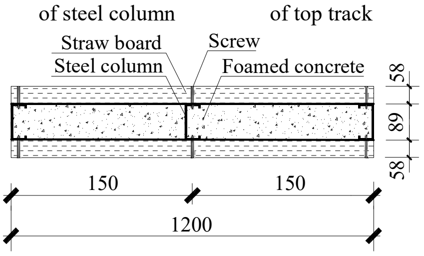
The experimental program was based on three full-scale CSFC wall tests with different assemblies. Fig. 2 shows the configuration details of the specimens. As shown in Figs. 2 (a) and (e), the dimensions of all test specimens were 3000 mm (length) × 1200 mm (width) × 205 mm (thickness). Table I summarizes the different test specimens in the program.



(a) Details of specimen steel frame (b) Elliptical holes of steel column



(c) Section dimension of steel column (d) Section dimension of top track



(e) Sectional view of specimen

Fig. 2 Details of specimen configurations

The steel frames included lipped channel section columns (that is lipped C-channel column) and plain channel section tracks. The lipped channel section column is C90, and the plain channel section tracks is U93, whose dimensions are shown in Figs. 2 (c) and (d). Both columns and tracks were fabricated from a galvanized steel sheet with a minimum yield strength of 345 MPa. The column distance of the steel frame was 600 mm. The steel frames were assembled with 4.8 mm diameter and 19 mm long self-drilling wafer head screws. An edge distance of 25 mm was maintained in these fields like specimen edges. The specimens were sheathed with 3000 mm×1200 mm×58 mm straw board, all of which were attached to the frames using 4.8 mm diameter and 80 mm long bugle head drywall screws as shown in Figs. 2 (a) and (e). A screw distance of 150 mm was maintained in these fields like specimen edges; another screw distance of 300 mm was maintained at the mid column of specimen. The FC was poured into the interior space between two pieces of straw board of the specimen, as shown in Fig. 2 (e).

TABLE I
Parameters of Specimens

Specimen No.	Height×Width *(mm)*	Steel type	FC density rank
W-1	3000×1200	C90	—
W-2	3000×1200	C90	A05
W-3	3000×1200	C90	A07

The specimens W-2 and W-3 were processed in laboratory on the same day so that the FC core would have the same design strength. The FC used in this study was made from ordinary Portland cement, polypropylene fiber, silica fume, water and stable foam. The ratios for material's composition were that the cement–polypropylene fiber–silica fume ratio was 1:0.3%: 10%, and the water–cement ratio was maintained at 0.4.

The pouring FC in specimens served the main purpose of restraining the distortional buckling of steel column and increasing the bearing capacity of specimens. FC is a type of porous concrete, which is produced by mechanical mixing of foam prepared in advance and blended with the cement mixture composed of cement—polypropylene fiber–silica fume matrix. Foam is prepared in a special equipment called foam generator and later mixed by using special mixer. By controlling the dosage of foam, the density of foam concrete was 200-1600 kg/m^3, which can be achieved for application as structural material. FC could be used in composite action with steel, which has high ductility and thermal insulation performance. Therefore, FC with the density from 500 kg/m^3 to 700 kg/m^3 was chosen as an infill material for the present study.

As shown in Fig. 2 (b), the elliptical holes of steel column and top track were beneficial to FC construction. FC was poured vertically similar to the direction of loading, and the test samples were naturally cured in the indoor climate of the concrete lab. The composite wall specimens were tested at the 28th day after casting. Six FC cubes and six prisms were also cast on the same day that the composite walls were made.

B. Material Properties

To obtain the material properties of CFS column, three tensile coupon specimens were made from the same batch of CFS used for the test specimens. And that was taken from three different positions of the CFS column; one from the top, another from the mid, and the last one from the bottom. The material properties of the CFS were determined from tensile coupon tests according to GB/T 228.1-2010 [7]. The material properties of CFS obtained from coupon test are shown in Table II. The average yield and ultimate stress of the sheet obtained are 390.6 MPa and 475.1 MPa, respectively, and the Young's modulus is 210 GPa.

TABLE II
PROPERTIES OF COLD-FORAMED STEEL

Specimen no.	Thickness (mm)	Yield strength f_y (MPa)	Ultimate strength f_u (MPa)	Young's modulus E_s (GPa)
Specimen 1	0.9	393.9	477.6	217.1
Specimen 2	0.9	391.4	476.2	214.3
Specimen 3	0.9	386.5	471.5	198.6

To obtain the material properties of FC, six cubes and six prisms were made for each batch of FC. The cubes (100 mm×100 mm×100 mm) and prisms (100 mm×100 mm×300 mm) were tested on the same day of testing the composite walls (about 60 days). The material properties of the FC were determined from pressure tests according to JG/T 266-2011 [8]. The material properties of FC obtained from coupon test were shown in Table III. The average compressive strength of cubes and prisms of A05 grade FC at the 60^{th} day is 3.3 MPa and 2.9 MPa, respectively, and the modulus of elasticity is 0.32 GPa. And those of A07 grade are 6.4 MPa and 5.6 MPa respectively, and the modulus of elasticity is 0.60 GPa.

TABLE III
PROPERTIES OF FC

Specimen type	Density ρ(kg/m^3)	f_{cu} (MPa) cube	f_c (MPa) prism	Modulus of elasticity E_c (GPa)
A05	514	3.3	2.9	0.32
A07	725	6.4	5.6	0.60

III. TEST SETUP

The schematic diagram of the test setup is shown in Fig. 3. The specimens were loaded in axial compression according to GB/T 50152-2012 [9] and ASTM E72-10 [10]. The test was carried out in a universal compression testing machine with a maximum capacity of 500 kN after 60 days of casting (Fig. 3). The tests began with force control followrd by displacement control. The top and bottom of the specimens were ground flat prior to testing so as to ensure equal load distribution. A wooden plank is placed on the top and bottom of the specimen. The dimensions of the wooden plank were 1200 mm (length) × 200 mm (width) × 20 mm (thickness). Plaster of Paris was used to ensure the contact between mating surfaces. This wooden plank evenly distributed the load to concrete surface. Above the wooden plank, a highly stiffened distributor II-beam was used for uniformly distributing the load along the width and length of wall.

A number of strain gauges were placed on the CFS column. Fig. 4 shows their locations on a sample. In all cases, the strain gauges were at the mid-height (h/2) of the specimen. In addition to the strain gauges on the sample, the displacement of the distributor II-beam was also recorded to measure axial deformation of the specimen. Two Linear Vertical Displacement Transducers (LVDT 1 and LVDT 2) were used to record the vertical deformations of the specimen, which were placed at top of the distributor II-beam.

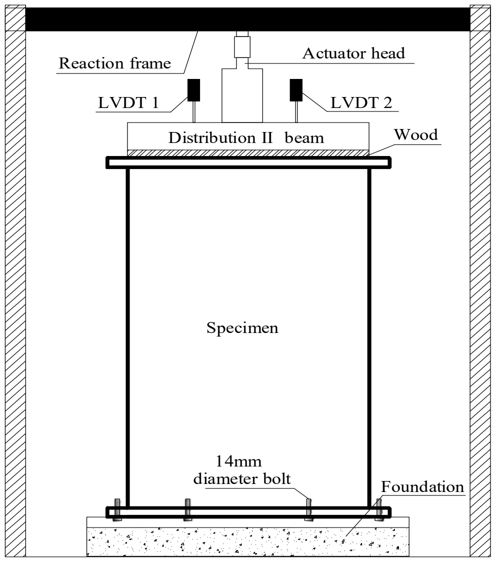


Fig. 3 Test setup for specimens

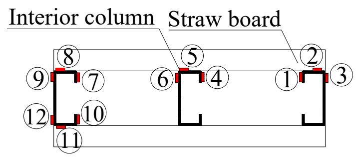


Fig. 4 Arrangement of strain gauges

IV. FACTOR STUDY

Two main influencing factors were considered in this study: 1) specimen with pouring FC or not and 2) different FC density rank. The interior space of the specimen W-2 and W-3 were poured FC, and the specimen W-1 has not FC core. The FC density rank of the specimen W-2 was A05 grade, and that of the specimen W-3 was A07 grade, which properties are shown in Table III. In the first influencing factor study, the effect of FC provided to the composite wall was studied. The specimen W-2 with A05 grade FC and the specimen W-1 without FC were tested. In the second influencing factor study, the effect of different FC density rank (corresponding to different FC strength) of wall core used to the composite wall was studied. The specimen W-2 with A05 FC and the specimen W-3 with A07 grade were tested.

V. TEST RESULTS

The test results were summarized in Tables IV and V. Table IV shows the ultimate load of all specimens from the test and the vertical displacement corresponding to the ultimate load. There were the first, second, and third modes of failure in Table V. Results show that specimens with/without pouring FC have experienced the different failure mode. In the case of specimen without pouring FC, failure began with the local bulging of the CFS column's plate (lipped C-channel plate) followed by distortional buckling of the CFS column's plate. However, when FC was used as infill material (that is composite wall core), the composite specimen behaved differently. There was a lower vertical deformation than the specimen without FC core. And failure began in the crushing of FC core followed by the local buckling of the CFS column's plate. The ultimate load of the specimen also increased dramatically when FsC were used as infill material. The test results are discussed in detail in the subsequent sections.

TABLE IV
ULTIMATE LOAD AND CORRESPONDING VERTICAL DISPLACEMENT OF SPECIMENS

Specimen No.	Ultimate load p_{max} (kN)	Vertical displacement D_u (mm)
W-1	84.3	12.0
W-2	216.2	9.6
W-3	273.5	9.4

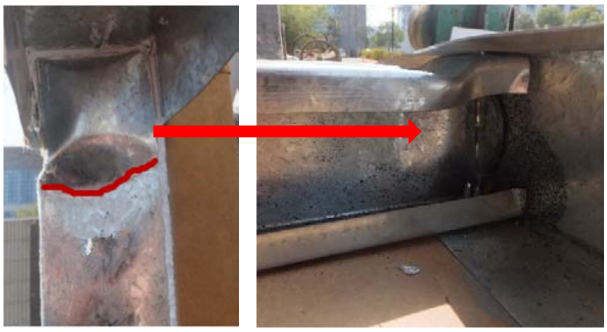
TABLE V
OBSERVED FAILURE MODES OF SPECIMENS

Specimen No.	First observed failure mode	Second observed failure mode	Three observed failure mode
W-1	Local buckling on steel plate	Distortional buckling on steel plate	—
W-2	Brittle failure on FC	Yielding on steel plate	Local buckling on steel plate
W-3	Yielding on steel plate	Brittle failure on FC	Local buckling on steel plate

A. Parametric Study 1: Comparison of Specimens with and Without FC

Tests were conducted on composite wall with FC or not for comparison. Comparison was made between specimens namely W-1 and W-2. Both of the specimens with FC or not behaved differently. For the specimen W-1, failure began with the yielding of the steel column plate followed by local bulging of the steel column plate, and lastly by distortional buckling of the steel column plate. When a load was about 60 kN, yielding on CFS column occurred at the lipped C-channel plate. And the concave and convex deformation appeared on the plate of lipped C-channel column. At a load of 75 kN, local buckling began to develop at the top of lipped C-channel column. At around about 80 kN, distortional buckling of the steel column plate appeared on the position of local buckling. Upon reaching the ultimate load, distortional buckling was fully developed at the top of the wall plate as shown in Fig. 5 (a).

For the specimen W-2, failure began with the local crushing of the FC followed by yielding of the steel column plate, and lastly by local bulging of the steel column plate. When a load was about 67 kN, local crushing of the FC occurred at the top of the composite wall. The increased load of the crushing failure of FC transferred to the steel column and the other FC. At a load of 130 kN, yielding on CFS column occurred at the lipped C-channel plate. And the concave and convex deformation appeared on the plate of lipped C-channel column. At a load of 173 kN, local buckling began to develop at the mid-height part of lipped C-channel column. That indicates FC could confine ranges of deformations and prevent distortional buckling of the steel column plate. Upon reaching the ultimate load, local buckling of the lipped C-channel plate was fully developed at the mid-height part as shown in Fig. 5 (b).



(a) Distortional bucking of W-1 CFS

(b) Local bucking of W-2 CFS

(c) Locak bucking of W-3 CFS

(d) Brittle failure of W-3 FC

Fig. 5 Failure mode of specimens

The results obtained from the tests were plotted in a load vertical displacement graph. From the graph as shown in Fig. 6, the specimen with pouring FC had a higher bearing capacity than the specimen without pouring FC. Compared with the specimen W-1, the ultimate bearing capacity of the specimen W-2 poured A05 grade FC increased 1.6 times. This indicated bearing capacity of the FC and restrictive effect of the FC on lipped C-channel steel column could significantly increase the ultimate bearing capacity of the specimen. For specimens with pouring FC, FC prevented the lipped C-channel steel column from distortional buckling, and shared partial axial load. The specimen with pouring FC has a lower vertical displacement than the specimen without pouring FC. Therefore, the specimens with pouring FC had lower vertical stiffness than the specimen without pouring FC. Pouring FC had great influence on improving axial bearing capacity and vertical stiffness of composite wall.

B. Parametric Study 2: Comparison of Specimens with FC Density Rank

Tests were conducted on composite wall with different FC density rank. The FC density ranks are A05 grade and A07 grade, which compression strength are 3.3 MPa and 6.4 MPa, respectively. Comparison was made between specimens namely W-2 and W-3. Both of the specimens with different FC density rank behaved differently.

For the specimen W-3, failure began with yielding of the steel column plate followed by local crushing of the FC, and lastly by local bulging of the steel column plate. When a load was about 82 kN, yielding on CFS column occurred at the lipped C-channel plate. And the concave and convex deformation appeared on the plate of lipped C-channel column. At a load of 152 kN, local crushing failure of the FC occurred at the top of composite wall as shown Fig. 5 (d). The increased load of the crushing failure of FC transferred to the steel column and the other FC. That indicates FC can resist larger external axial load than lipped C-channel steel column at the early stages of test. At a load of 228 kN, local buckling began to develop at the top of the lipped C-channel column as shown Fig. 5 (c). That indicates FC could confine ranges of deformations and prevent distortional buckling of the steel column plate. Upon reaching the ultimate load, local buckling of the lipped C-channel plate was fully developed at the top of the wall plate as shown in Fig. 5 (c).

The results obtained from the tests were plotted in a load displacement graph. From the graph as shown in Fig. 7, the specimen with A07 grade FC had a higher bearing capacity than the specimen with A05 grade FC. Compared with the specimen W-1, the ultimate bearing capacity of the specimen W-3 poured A07 grade FC increased 2.2 times. This also indicates that the increased axial bearing capacity of the specimen W-3 was benefited from the FC that could bear partial load and constraint effect of FC on lipped C-channel steel column. Compared with the specimen W-2, the axial bearing capacity of the specimen W-3 increased 30%. Results have shown that the increase of FC compression strength was beneficial to increase axial bearing capacity of the specimen, while the increase amplitude of specimen axial bearing capacity was smaller. The specimen with different FC density rank had almost the same vertical deformation. Therefore, the specimens had the similar vertical stiffness.

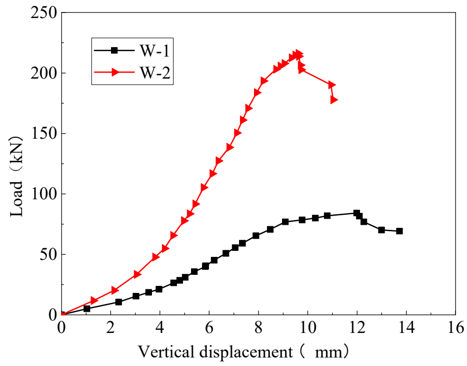


Fig. 6 Load-Vertical displacement curves of specimens

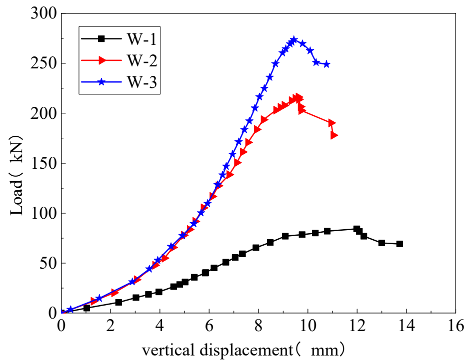


Fig. 7 Load-Vertical displacement curves of specimens

C. Load Carrying Capacity of Composite Wall

As previously described, the panels could be considered to be in composite action and the FC core was able to prevent the CFS column from local buckling. Therefore, the test specimens would be analyzed as a conventional composite wall. Therefore, the ultimate axial bearing capacity of the composite wall, N_u, may be calculated from

$$N_u = N_s + N_c \tag{1}$$

where N_s is the bearing capacity of the CFS column and N_c is the bearing capacity of the FC core. The following sections will discuss how N_s and N_c may be obtained.

Based on current concrete design criterion JGJ 383-2016 [11], the ultimate axial bearing capacity formula may be

$$N_u = \phi\left(N_s + N_c\right) \tag{2}$$

where φ is the stabilization coefficient of the compression member, refer to JGJ383-2016 [11].

Based on the vertical displacement of specimens and Hooke's law, when ultimate load was reached, the compressive strengths of A05 grade and A07 grade FC in the specimens were about 1.1 MPa and 2.0 MPa, which were 0.4 and 0.3 times axial compressive strength of FC, respectively. Therefore, the compressive strength reduction coefficient of FC adopted its average, is 0.35.

Fig. 8 presents that strain values of CFS column in the W-2 and W-3 with FC mostly focused on 1000 με~1200 με, where the corresponding yield strength were 210 MPa~252 MPa. And that of W-1 without FC mostly focused on 400 με~700 με, where the corresponding yield strength were 84 MPa~147 MPa. The yield strength reduction coefficient of CFS column in the specimen with FC adopted the average of numerical range, is 0.6. And that of the specimen without FC is 0.3.

Based on the above analysis of experimental results, the load carrying capacity of the composite wall in axial compression, taking into the compressive strength reduction coefficient of FC and the yield strength reduction coefficient of CFS, can be calculated by:

$$\text{For without FC: } N_u = 0.3\phi f_s A_s \quad (3)$$

$$\text{For without FC: } N_u = \phi\left(0.6 f_s A_s + 0.35 f_c A_c\right) \quad (4)$$

where f_s is the yield strength of CFS, A_s is the area of CFS, f_c is the axial compressive strength of FC, A_c is the area of FC.

Table V compares the calculated and measured composite wall load carrying capacity for all the three tests using the different strength reduction coefficient. It indicated that the calculated results from this formula are in very good agreement with the test results. Hence, it has been proved that the simplified calculation formulas for the CSFC composite wall subjected to axial load have important value in theory and practice.

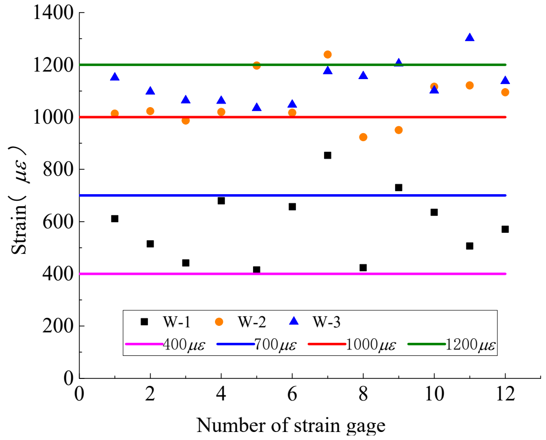


Fig. 8 Strain of specimens

TABLE VI
COMPARISONS BETWEEN PREDICTED COMPOSITE WALL LOAD CARRYING CAPACITY AND TEST RESULTS

Specimen no.	Ultimate load p_{max} (kN)	Calculated load N_u (kN)	$\frac{(N_u - P_{max})}{P_{max}}$
W-1	84.3	81.7	-3.1%
W-3	216.2	198.4	-8.2%
W-5	273.5	283.6	3.7%

VI. CONCLUSION

This paper presents the details of experimental results which were used to investigate the mechanical behavior and identify the failure modes of CSFC walls subjected to axial compression loading. Here, the following conclusions were summarized:

1) The failure modes of composite walls under axial compressive loading changed when composite walls were poured FC. The failure mode of composite wall without FC was distortional buckling of CFS column, and that poured FC includes the local crushing of FC and local buckling of CFS column, but the former prior to the later.
2) Pouring FC was beneficial to increase axial loading carrying capacity of composite walls and to reduce axial deformation. Compared with composite walls without FC, the ultimate bearing capacity of CSFC walls poured A05 grade and A07 grade FC improved 1.6 times and 2.2 times respectively, and CSFC walls which were poured FC had a low vertical deformation.
3) The improvement of FC strength is favorable to improve axial bearing capacity of the CSFC walls, but its effect to improvement of axial bearing capacity is limited. Compared with the specimen W-2 which was poured A05 grade, the axial bearing capacity of the specimen W-3 poured A07 grade increased only 30%.
4) Combined with the analysis of experimental results, Hooke's law and National standards of the code, the simplified calculation formula for the CSFC walls subjected to axial loading is proposed, and it can be found that the calculated results from this formula are in very good agreement with the test results.

ACKNOWLEDGMENT

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