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Behaviour of grout-filled double skin steel tubes under compression and bending: Experiments

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ABSTRACT

The grout is often used to fill the gap between two tubes as binding material in some specific structures, which may actually form a grout-filled double skin steel tube. However, little literature has been found regarding the behaviour of the grout-filled double skin steel tubular (GFDST) member, while the influence of the in-filled grout could be underestimated in the steel-grout composite structure. This paper thus presents an experimental investigation of the compressive and flexural behaviour of GFDST members. A total of 14 specimens are tested, including 8 stub columns, 4 beam-columns and 2 beams. For the axially compressed stub columns, the main test parameter is the hollow ratio of the cross section, and 2 corresponding hollow steel counterparts are designed to study the effect of the grout filling. For the beam-columns, the influences of load eccentricity are analyzed through test results. The failure modes, the strain distribution and the ductility of the GFDST members are studied in order to sufficiently evaluate the performance of the steel-grout composite member. The ultimate strengths of the GFDST members are estimated by the equations of concrete-filled double skin steel tubular members tentatively. It is found that all tested specimens failed in a ductile way, and the stiffness, the ultimate strength and the ductility of GFDST member is improved attributing to the in-filled grout. In addition, the predicted stiffness and strength results generally match well with the measured ones.

1. Introduction

In some offshore structures such as jacket platforms and wind turbine poles, the main leg commonly consists of external tube and internal tube, which serve as outer jacket and pile, respectively. Usually the thickness of the annulus gap is very small, which can only allow materials without any aggregate and with very good workability to be filled in. The grout is often used to fill the annulus gap and serves as binding materials. It actually form a kind of grout-filled double skin steel tube (GFDST), which consists of two concentric-laid tubes, and the grout is filled in the annulus cavity between two tubes, as shown in Fig. 1. The strength and stiffness contribution of the grout may often be ignored or underestimated for conservative purpose since the thickness of the grout is usually very thin in engineering practice [1,2]. However, previous research has found that even very thin grout in-filled might enhance the performance of dual steel tubular structures [3,4]. Better indentation resistance and energy absorption capacities were also confirmed due to the grout composite layer [5]. The safety potential of the structure could therefore be considered for the life extension of existing structures when the effect of grout is properly considered.

A similar type of structure, the concrete-filled double skin steel tubular (CFDST) structure has been used in engineering projects such as transmission poles in land, while the concrete is the in-filled material between two tubes instead of grout [6,7]. The CFDST structure has attracted numerous attentions, and a lot of investigations have been conducted on many aspects such as the short-term static behaviour [8–10], long-term static behaviour [11], cyclic behaviour [12,13], behaviour under fire [14], behaviour under compact and behaviour under various load combinations [15]. In previous research, a hollow ratio χ is often defined to describe the geometric configuration of the cross section, which usually ranges from 0.2 to 0.8 for CFDST members. From previous research it was found that the CFDST structure behaved similarly to that of solid concrete-filled steel tubular (CFST) structure. The outer tube, sandwiched concrete and inner tube could work together well under various loading conditions. Meanwhile, the outer tube confines the sandwiched concrete, and the sandwiched concrete improves the buckling modes of both tubes in contrast. Apart from the experimental research conducted, the numerical investigations were also carried out for CFDST structures. The finite element analysis model was established to study the structural behaviour more thoroughly,

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Nomenclature

A_g	Cross-sectional area of the sandwiched grout, given by $\pi((D-2t_o)^2-d^2)/4$ for GFDST member with circular inner and outer tubes
A_{ge}	Nominal inner cross-sectional area, given by $\pi(D-2t_o)^2/4$ for circular cross section
A_{si}	Cross-sectional area of inner steel tube
A_{so}	Cross-sectional area of outer steel tube
D	Diameter of outer circular steel tube
d	Diameter of inner circular steel tube
E_g	Modulus of elasticity of grout
E_s	Modulus of elasticity of steel
EA_{sg}	Compressive stiffness of GFDST cross section
EI_{sg}	Flexural stiffness of GFDST cross section
e	Load eccentricity
e_L	Load eccentricity ratio
f_g	Compressive strength of grout
f_{si}	Yield stress of inner steel tube
f_{so}	Yield stress of outer steel tube
I_g	Second moment of area of grout
I_{si}	Second moment of area of inner tube
I_{so}	Second moment of area of outer tube
M	Moment
M_u	Ultimate flexural strength
M_{uc}	Calculated ultimate flexural strength
M_{ue}	Measured ultimate flexural strength
N	Load
N_u	Ultimate compressive strength
N_{uc}	Calculated ultimate compressive strength
N_{ue}	Measured ultimate compressive strength
t_o	Wall thickness of outer steel tube
t_i	Wall thickness of inner steel tube
α_n	Nominal steel ratio of the cross section, $\alpha_n = A_{so}/A_{ge}$
Δ	Deformation, axial shortening of stub column or beam-column, deflection of beam
Δ_f	Deformation when load decreases to 85% of ultimate strength
Δ_y	Deformation corresponding to yield strength
δ	Mid-span lateral deformation of beam-column
ε	Strain
ϕ	Curvature
μ	Ductility coefficient
ξ_o	Nominal confinement factor, $\xi_o = \frac{A_{so}\cdot f_{so}}{A_{ge}\cdot f_g}$
χ	Hollow ratio of the cross section, $\chi = d/(D-2t_o)$

where the concrete strength enhancement attributed to the confinement of tube and the steel-concrete interaction between two materials were carefully taken into account. Simplified design methods for CFDST structures were also developed according to parametric analysis by the calibrated numerical model.

Although there are some similarities in geometries of CFDST and GFDST cross sections, the in-filled materials are different between these two structures. Moreover, the hollow ratio of GFDST commonly used in engineering practice is usually larger than that of CFDST structure, which often ranges from 0.8 to 0.92. Up to date the information of the GFDST structure is rather limited, therefore more work should be conducted in this aspect.

This paper investigates some basic behaviour of GFDST members, i.e., the behaviour under axial concentric compression, eccentric compression and pure bending. A series of experiments are carried out for typical GFDST specimens, and the parameters include the type of the cross section, cross-sectional hollow ratio, load eccentricity and etc. The failure modes and the load versus deformation relations are recorded in the test, and the strength, stiffness and ductility of the specimens are analyzed according to the experimental results. The feasibility of current design equations for CFDST structures in the design of GFDST structures is also discussed herein. The main objectives of this study are as follows:

Fig. 1. GFDST used in offshore jacket platform.

- To provide new test data of GFDST stub columns, beam-columns and beams;
- To discuss the strength, stiffness and ductility of GFDST members; and
- To evaluate the calculation methods of the GFDST members.

2. Experimental program

2.1. General description

A total of 14 specimens were designed for the GFDST members, including 8 stub columns, 4 beam-columns and 2 beams. For stub columns subjected to concentric loading, the main parameter was the hollow ratio of the cross section χ, which can be defined as [9]:

$$\chi = \frac{d}{D - 2t_o} \tag{1}$$

where D and d are the outer diameters of outer and inner tubes, respectively; t_o is the thickness of the outer tube. The hollow ratios used for the specimens in the test ranged from 0.56 to 0.92, which is commonly used in engineering practices for the thickness of the grout is usually very thin. Besides, the effect of in-filled grout is taken into consideration directly by setting the hollow double steel tubes without filling grout as counterparts. Large specimens with 1/3 scale of the member in real structures were also designed for comparison. Detailed dimensions of the stub column specimens can be found in Table 1.

For the beam-column specimens, the test parameter was the load eccentricity. The load eccentricity ratio e_L is defined as follows:

$$e_L = \frac{2e}{D} \tag{2}$$

where D is the diameter of outer tube, e is the distance from the loading axis to the central axis of the specimen. Two load eccentricities, i.e. 20 mm and 70 mm, were applied to obtain the column capacity under both axial compression and bending, and the corresponding load eccentricity ratios are 0.29 and 1. The slenderness ratio of beam-columns was 28, which was within the range (28 − 56) of previous research on CFDST beam-columns [9]. Other detailed information for beam-column specimens can be found in Table 1.

For the beam specimens, only one group of specimen was designed