Engineering Structures 160 (2018) 71–84

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Theoretical model for seawater and sea sand concrete-filled circular FRP tubular stub columns under axial compression

Y.L. Li[a], J.G. Teng[b], X.L. Zhao[a,*], R.K. Singh Raman[c,d]

[a] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[c] Department of Mechanical and Aerospace Engineering, Monash University, Clayton, VIC 3800, Australia
[d] Department of Chemical Engineering, Monash University, Clayton, VIC 3800, Australia

ARTICLE INFO

Keywords:
Concrete-filled FRP tube
Confinement
Dilation
Theoretical model
Seawater and sea sand concrete
Axial compression

ABSTRACT

The use of FRP with seawater and sea sand concrete (SWSSC) holds great potential for marine and coastal infrastructure, and concrete-filled FRP tubular columns are among the attractive forms of structural members for such applications. This paper presents a theoretical model for the compressive behaviour of seawater and sea sand concrete-filled circular FRP tubular stub columns. FRP tubes can be manufactured to possess considerable strength and stiffness in the longitudinal direction, so the behaviour of concrete-filled FRP tubes differed substantially from that of concrete columns with an FRP wrap (also referred to as "concrete-filled FRP wraps") which commonly contains fibres only in the hoop direction. Many theoretical models have been proposed for concrete-filled FRP wraps, but very limited work has been conducted on the theoretical modelling of concrete-filled FRP tubes. In the present study, an existing dilation model for concrete-filled FRP wraps is combined with a biaxial stress analysis of the FRP tube so that the effect of the Poisson's ratio of the FRP tube is properly accounted for. In order to predict the buckling of the FRP tube, a maximum strain buckling failure criterion is proposed and is shown to be in reasonable agreement with the experimental results. Moreover, the load carried by the FRP tube is studied, and a simplified model is proposed to determine the load shared by the FRP tube during the entire loading process. Finally, a theoretical model for SWSSC-filled FRP tubular columns is proposed, in which the behaviour of both the concrete and the FRP tube as well as their interactions are explicitly modelled (i.e., an analysis-oriented model). The proposed model gives reasonably close predictions of the existing experimental data.

1. Introduction

In recent decades, fiber reinforced polymer (FRP) has been increasingly used in civil engineering due to its high strength-to-weight ratio and desirable durability performance. One of the applications is in concrete-filled FRP tubular members, in which the FRP tube, with appropriate fiber orientations, can be used to provide strength and stiffness in both the longitudinal and the hoop directions. In such columns, the FRP tube acts as the stay-in-place formwork for concrete casting and provides confinement to the core concrete to enhance its strength and ductility, in addition to serving as the longitudinal and shear reinforcement [1,2]. Due to the absence of steel in such columns, seawater and sea sand concrete (SWSSC) can be used instead of ordinary concrete, leading to FRP-SWSSC hybrid systems, an attractive concept with great potential that was first proposed by the second author for marine and coastal infrastructure [3,4]. The usage of SWSSC can greatly reduce the consumption of fresh water and river sand, which considerably alleviates the resource shortage problem and environmental burden created by marine infrastructure development. This paper forms part of a large research program currently in progress at Monash University [5–9] in collaboration with The Hong Kong Polytechnic University, Southeast University and Harbin Institute of Technology. To facilitate the application of concrete-filled FRP tubular columns in engineering practice, an accurate theoretical model for predicting their behaviour is required.

The key to predicting the behaviour of concrete-filled FRP tubes is the prediction of response of concrete confined with an FRP tube. It is well understood that the confinement provided by an FRP wrap/tube is passive in nature [10]. Passive confinement refers to situations where the confining pressure increases continuously with the lateral strain of concrete, while active confinement refers to situations where the confining pressure is constant throughout the axial loading process. When

* Corresponding author.
E-mail address: ZXL@monash.edu (X.L. Zhao).

https://doi.org/10.1016/j.engstruct.2018.01.017
Received 29 September 2017; Received in revised form 5 January 2018; Accepted 8 January 2018

Nomenclature

A_c	cross-sectional area of concrete
A_f	cross-sectional area of FRP tube
D_i	diameter of concrete core ($=D_o - 2t_o$)
D_o	outer diameter of FRP tube
E_c	elastic modulus of unconfined concrete
E_h	elastic modulus of FRP tube in hoop direction
E_{hsec}	secant modulus of FRP tube in hoop direction
E_l	elastic modulus of FRP tube in longitudinal direction
f_{co}'	unconfined concrete strength
f^*_{cc}	peak stress of confined concrete
f_l	confining pressure
f_{uh}	hoop tensile strength of FRP tube (by split-disk test)
$f_{ul,c}$	longitudinal compressive strength of FRP tube (by compressive test on short tube)
$f_{ul,t}$	longitudinal tensile strength of FRP tube (by tensile coupon test)
I	number of incremental steps
k_1	factor 1
k_2	factor 2
k_3	factor 3
N	load carried by column
N_f	load carried by FRP tube
N_{fu}	ultimate load of FRP tube
N_t	experimental ultimate load
t_o	thickness of FRP tube
$\Delta\varepsilon_h$	hoop strain increment
ε_c	axial strain
$\varepsilon_{c,SG}$	axial strain (from strain gauge)
ε_{cb}	axial strain at tube buckling (predicted)
$\varepsilon_{cb,t}$	axial strain at tube buckling (experiment)
ε^*_{cc}	axial strain at confined concrete peak stress f^*_{cc}
ε_{co}	axial strain at unconfined concrete strength f_{co}'
ε_{cu}	ultimate axial strain
ε_{fu}	axial strain at ultimate load of FRP tube N_{fu}
ε_h	hoop strain
ε_{hb}	hoop strain at tube buckling
ε_{hu}	ultimate hoop strain of FRP tube
ε_l	longitudinal strain in FRP tube
ε_{lat}	lateral strain
η	reduction factor for FRP tube
ρ_K	confinement stiffness
σ_h	hoop stress in FRP tube
σ_l	longitudinal stress in FRP tube
υ_h	Poisson's ratio (hoop tension)
υ_l	Poisson's ratio (longitudinal compression)

the concrete in an FRP wrap (which has negligible longitudinal stiffness/strength) is subjected to axial compression, its lateral expansion is confined by the FRP wrap which is subjected to hoop tension. The confining pressure increases continuously due to the linear elastic stress-strain behaviour of FRP, which is different from the confinement mechanism of concrete-filled steel tube; in the latter, the confining pressure is reasonably constant after the yielding of steel, so the confinement mechanism is close to that of active confinement. The confinement mechanism of concrete-filled FRP tubes is similar to that of concrete confined with an FRP wrap except that the FRP tube, whose longitudinal stiffness/strength is significant, is in a biaxial stress state. Extensive research [11] has been conducted on FRP-confined circular concrete columns [or simply referred to as "FRP-confined concrete" as the concrete in a circular section is under (nominally) uniform confinement] and many stress-strain models have been proposed. These models are generally classified as design-oriented models, which are in closed-form expressions and are easy to use in design, or analysis-oriented models, which employ an incremental numerical procedure [10,11]. Analysis-oriented models for FRP-confined concrete, that are more versatile and powerful than design-oriented models, can potentially be applied to concrete confined by any material [12].

Most of the existing analysis-oriented models for FRP-confined concrete [13–20] were based on an active confinement base model, and the model of Mander et al. [21], with or without modifications, has been widely adopted as this base model. It has been commonly assumed that the prior stress-path of the confined concrete does not affect its subsequent stress-strain behaviour. Among the existing analysis-oriented stress-strain models for FRP-confined concrete, only Fam and Rizkalla's model [15] was developed explicitly for concrete-filled FRP tubes in which the biaxial behaviour of the FRP tube is considered; however, all existing analysis-oriented stress-strain models can be easily adapted to model concrete-filled FRP tubes if the FRP tube does not suffer from local buckling failure.

Based on the authors' experimental observations [5,6], the structural behaviour of SWSSC-filled FRP tubes under axial compression is different from that of concrete-filled FRP wraps: (a) the FRP tube can buckle much earlier than rupture failure due to hoop tension; (b) the dilation behaviour of concrete-filled FRP tubes is affected by the Poisson's effect of FRP tube; and (c) the FRP tube makes a significant contribution to the load-carrying capacity and this contribution should not be ignored. Obviously, as the existing analysis-oriented models for FRP-confined concrete, except Fam and Rizkalla's model [15], were established for ordinary concrete-filled FRP wraps, these models do not account for the factors listed as (a)–(c) in the preceding sentence. Even Fam and Rizkalla's model [15] accounts for only two of the factors, and it does not consider the effect of buckling and post-buckling behaviour of FRP tube. Furthermore, it is found that Fam and Rizkalla's model [15] gives a much lower ultimate load for specimens in the authors' experiments [5,6] if the biaxial failure envelope suggested in [15] is adopted, resulting in inaccuracy in the predicted load-axial strain curves. Therefore, for this simulation exercise on SWSSC-filled FRP tubes, a suitable model is required, especially when the longitudinal strength and stiffness of the FRP tube are comparable to those in the hoop direction.

This paper presents a theoretical model for the compressive behaviour of SWSSC-filled FRP circular tubes, in which an analysis-oriented stress-axial strain model is employed to depict the behaviour of confined SWSSC. Compared to existing analysis-oriented stress-strain models for FRP-confined concrete, the proposed model features improvements mainly in the following aspects: (a) the analysis-oriented stress-strain model presented in Jiang and Teng [17], which was modified from an earlier model proposed by the same group [12], is adapted to consider the effect of biaxial behaviour of FRP tube on the confinement of core concrete; (b) the occurrence of tube buckling and post-buckling behaviour are represented; (c) the contribution of the FRP tube to the axial load-carrying capacity is included. In developing the theoretical model, it is assumed that the behaviour of SWSSC under confinement is the same as that of ordinary concrete, provided the two concretes have the same compressive strength. The limited existing evidence supports this assumption [7,22], whose validity will be assessed as part of the presents study. Finally, the proposed model is verified with the experimental results of the authors and other studies.

2. Experimental data

An experimental database of concrete-filled FRP tubes under axial compression was employed in the present study to support the development of a theoretical model. This database included 12 specimens