Composite Structures 200 (2018) 69–78

Contents lists available at ScienceDirect

Composite Structures

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

Design model of concrete for circular columns confined with AFRP

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ARTICLE INFO

Keywords:
AFRP sheets
Confinement
Concrete columns
Experimental tests
Design-oriented model

ABSTRACT

The advantages of confining reinforced concrete are well-known, making it possible to increase both strength and ductility of structural elements. On this matter, the application of fibre reinforced polymer sheets has been a subject of increasing interest. Various constitutive models of confined concrete have been proposed, the majority of which calibrated with results of experimental tests using mainly carbon fibre composites. In this paper, a design-oriented model is proposed for the prediction of the axial response of confined concrete columns, calibrated exclusively with the results of tests using aramid fibre reinforced polymers. The proposed model parameters were determined based on experimental tests reported in the published literature. The new model is compared with a design-oriented model calibrated with different fibre based composites and with an analysis-oriented model. This assessment was carried out using existing experimental results as well as two specimens confined with aramid fibre composites tested by the authors. The results of the proposed model correlate well with the experimental results, being generally more accurate than the other two models considered.

1. Introduction

The confinement of concrete structural elements with fibre reinforced polymers (FRP), with emphasis on columns, is a well-established concept in the engineering field, resulting in notorious improvement of strength and ductility. Despite all the research developed in the past decades, important gaps remain, regarding, for example, limitations of the existing models on the prediction of the behaviour of elements confined with a specific type of composite, the exception being eventually carbon FRP (CFRP).

A number of constitutive models, regarding stress–strain relationship, have been proposed. The first known studies on confinement were developed by Richart et al. [1], who proposed equations to determine the maximum concrete stress and the corresponding axial strain, based on experimental tests with different confinement solutions. Later, Mander et al. [2] further developed the previous proposal and presented a confinement model for concrete confined with steel hoops. The model developed by these authors is a reference in the research field of reinforced concrete (RC) confinement.

FRP confinement models are usually divided into two categories: models that use an incremental numeric procedure to obtain stress–-strain curves, derived from physical concepts, named analysis-oriented model (AOM) [2–11]); models derived by calibration of stress–strain equations based on experimental results, named design-oriented models (DOM) [12–22]. DOM have the advantage of being simpler than the alternative, from an implementation point of view.

Fardis and Khalili [3] proposed a model capable of describing the behaviour of columns with circular cross-section calibrated for confinement with glass FRP (GFRP). However, this model was defined by adapting the model by Richart et al. [1] for steel. Therefore, it is not capable of adequately representing the elastic nature of FRP.

The AOM proposed by Spoelstra and Monti [4] was developed for the prediction of the stress–strain behaviour of circular columns confined with FRP under monotonic loads. This model is based on the equation presented by Popovics [23] to describe the stress–strain relationship and on the equations proposed by Mander et al. [2] to predict the maximum stress of confined columns. Manfredi and Realfonzo [5] further developed the model by Spoelstra and Monti [4], adapting it for columns with square cross-section. In the latter, the influence of the geometry of the cross-section is accounted for by a parameter defined by the ratio of the corner radius to the side of the column. Also, Manfredi and Realfonzo [5] apply a reducing factor with objectives similar to those of the proposal by Matthys et al. [16], described below. Eid and Paultre [10] proposed a unified AOM, capable of predicting the response of both circular and rectangular cross-section columns. It was developed based on previous work by the same authors, adding the

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https://doi.org/10.1016/j.compstruct.2018.05.094
Received 16 February 2018; Received in revised form 10 May 2018; Accepted 18 May 2018
Available online 22 May 2018

effect of hoops combined with FRP jackets. Jiang and Teng [7] proposed a refined version of previous models, based on the work by their group, which made it possible to improve the predictions of the behaviour of weakly-confined circular columns. The AOM by Rousakis et al. [8] is based on a plasticity model for the prediction of the response of FRP confined concrete, making it possible to simulate both hardening and softening response. Rousakis and Tourtouras [9] proposed a new model for passively or actively confined columns with both circular and rectangular cross-section. Pan et al. [11] proposed an AOM for FRP-confined circular and square columns with preload.

Several DOM have been proposed with the objective of predicting the stress–strain relationship of confined columns. The model proposed by Wei and Wu [12] is based on the work developed by Teng's group [24–26], Harijli et al. [27] and Youssef [28]. This model presents a single set of equations applicable to columns with circular and rectangular cross-section and was calibrated based on experimental results from specimens confined with CFRP, GFRP and aramid FRP (AFRP). The DOM proposed by Rousakis et al. [18] for circular columns was also calibrated for specimens confined with CFRP, GFRP and AFRP. More recently, Ozbakkaloglu and Lim [19] and Sadeghian and Fam [21] have proposed models based on extensive experimental data for various types of FRP systems. These models predict both the confined strength and corresponding failure strain, but they do not model the whole behaviour of confined columns.

Other DOM are based on the Richard and Abbott [29] stress–strain relationship [13–17,20,22]. The DOM proposed by Samaan et al. [13], Saafi et al. [14] and Toutanji [15] were the first models based on the model by Richard and Abbott [29] to be used on columns with circular cross-section. The equations of the model proposed by Samaan et al. [13] were calibrated with experimental results from columns confined with GFRP, while Saafi et al. [14] and Toutanji [15] calibrated the model equations with experimental results from columns confined with CFRP and GFRP. Matthys et al. [16] improved the model proposed by Toutanji [15]. Based on experimental results, these authors observed that the lateral failure strain is less than the ultimate strain of the FRP obtained in uniaxial tests and thus considered a reducing factor. This factor has been adopted in other models. Chastre and Silva [17] also proposed a model based on the Richard and Abbott [29] stress–strain relationship. This model was calibrated for RC columns with circular cross-section confined with CFRP sheets under monotonic load. Faustino et al. [20] adapted the previous model by calibration with experimental results from columns with square cross-section confined with CFRP sheets. The model proposed by Faustino et al. [20] considers the influence of the corner radius in the axial behaviour of columns through the geometric ratio reported by Mirmiran and Shahawy [30]. Following the same methodology, Jesus et al. [22] proposed two DOM calibrated with experimental results of RC columns with circular and square cross-sections confined with GFRP sheets.

Experimental research using columns with circular cross-section [31–41] and with square cross-section [31,32,36–38,42] confined with AFRP sheets has been reported. Nevertheless, as detailed below, aspects of the response relevant for the purpose of the research presented herein were not reported in some cases, mainly regarding the behaviour of the confining composite sheets. For columns with square cross-section, the reported results were not sufficient to calibrate a DOM.

None of the models that predict the entire response of confined concrete mentioned above were calibrated specifically for AFRP. Thus, the research presented in this article is intended to assess the advantages of a DOM calibrated solely with experimental results of RC columns confined with AFRP sheets. For this purpose, the results obtained with the new model are compared with those of an AOM [4] and of a DOM [12].

2. Response of RC columns confined with AFRP sheets

2.1. Experimental tests reported in the literature

In this section, the results of experimental tests of RC elements wrapped with AFRP under monotonic compression found in the published literature are presented.

Referring to specimens with circular cross-section confined with AFRP, all specimens with six or more layers of FRP were not considered, given the decrease of efficiency that may be observed in these cases. Also, specimens with unconfined concrete strength, f_{co}, greater than or equal to 100 MPa, featuring in the tests by Ozbakkaloglu and Akin [40], were discarded. Furthermore, specimens with cross-sections with very small diameter, as is the case of the test campaign performed by Toutanji and Deng [33], were also not considered, given possible scale effects. Rochette and Labossière [31] did not report the axial stress-lateral strain response, nor the axial strain ε_{cc}, corresponding to the concrete strength, f_{cc}. Wu et al. [34] and Wang and Zhang [36] did not report the information required to determine parameters related to the lateral response. The former authors reported the value of the lateral failure strain for only one specimen. Also, Silva [38] and Ozbakkaloglu and Akin [40] did not report the FRP response, and the former author did not report the lateral failure strain of the FRP material. Furthermore, the latter authors performed tests under both monotonic and cyclic loading, but only the results from the monotonic tests were considered in this study. Both Wu et al. [35] and Wang and Wu [43] did not report the lateral failure strain of the AFRP, thus it was not possible to include the results from their studies. Of the tests reported by Vincent and Ozbakkaloglu [41], only those of wrapped specimens, both with and without end plate, were considered.

Regarding specimens with square cross-section, Rochette and Labossière [31] did not report many test parameters, as for the tested circular columns, which is why the study by these authors was not used. Cole and Belarbi [32] did not provide some information on the AFRP behaviour and Wang and Wu [43,44] also did not provide the lateral response of the tested columns. In the latter case, the value of ε_{cc} was also not presented. Silva [38] did not present the lateral failure strain nor the general lateral and axial responses. Wang et al. [42] did not report some information on the lateral response of the column. Also for one of the specimens, the value of the ε_{cc} was not provided.

As a consequence of the above, resulting in lack of experimental results for the determination of some modelling parameters, it was not possible to calibrate the general model presented below for columns with square cross-section.

The relevant characteristics of the tested specimens with circular cross-section used in the study presented herein, regarding geometry and material behaviour, are gathered in Table 1.

D is the diameter of the cross-section, H is the height of the column, ε_{co} is the strain corresponding to f_{co},E_j is the Young's modulus of the AFRP, ε_{ju} is the failure strain and t_j is the design thickness of one FRP sheet.

2.2. Experimental tests performed by the authors

Four confined RC specimens were constructed and tested by the authors (two columns with circular cross-section and two with square cross-section). Each pair comprised a reference unconfined specimen (Figs. 1 and 2 and a confined column (Figs. 3 and 4), with equal material and geometric characteristics.

The tests were performed at a 0.01 mm/s rate on a press testing machine with maximum capacity of 3000 kN. The axial displacements were measured with three TML CDP-50 transducers and the lateral strain response was measured by six TML FLA-5–11-3L strain gauges glued to the FRP on each externally confined specimen.

The characteristics of the S&P A-sheet 120 – unidirectional aramid fibre fabric used – with 290 g/m^2 of fibre weight, as provided by the