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An empirical model for predicting the mechanical properties of FRP-confined concrete

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The mechanism of confining concrete using FRP materials was studied experimentally in numerous works, whereas several models were proposed for the prediction of the mechanical properties of FRP-confined concrete. The first part of this paper is devoted to systematic assessment of the performance of some of the existing models. Since this assessment proves that there is room for more accurate prediction of both strength and ultimate strain of confined concrete, the second part of the paper deals with derivation of an empirical model valid for both circular and prismatic elements. The model adopted by Eurocode 2 for concrete confined by means of hoops or spirals was used as a basis. The validity of the proposed model is checked against experimental results provided by 84 experimental programs (including 785 cylindrical specimens and 289 prismatic specimens). The model proposed in this paper is in good agreement with the experimental results. A set of partial safety factors is proposed for the derivation of design values for strength and ultimate strain of FRP-confined concrete.

Model; Confinement; Concrete; Fibre reinforced polymers

External confinement of concrete is recognized as one of the most efficient applications of FRP. The significance of this subject is confirmed by the numerous experimental researches devoted to the investigation of this mechanism [1–3,5,7–10,12–49,51,52,55–65,67–75,77–81,83–85,87,88,90,91,93–97,99–104]. Furthermore, several models have been proposed with the aim to predict the mechanical properties of FRP-confined concrete (e.g. [5,29,30,32,37–39,50,51,54,86,92,98]). Within the framework of drafting a National Code on Structural Interventions to RC structures in Greece [11], the formulation of design models for various intervention techniques was attempted. Since RC columns designed and constructed according to previous generation codes are expected to exhibit limited ductility, external confinement may contribute to the enhancement of both shear resistance and deformability thereof. Thus, an effort was made to assess the available literature (both experimental data and available models), with the aim to select a design model for FRP-confined concrete. The following steps were taken for this purpose:

(a) Experimental results regarding cylindrical and prismatic elements (either plain or internally reinforced), externally confined using FRPs, were collected. A database was produced including the geometric and mechanical characteristics of each individual test. The available experimental results were critically reviewed and those considered to be unreliable were excluded from the assessment carried out within the present work. The criteria applied for the selection of the specimens are described in the relevant section of this paper.
(b) Models predicting the mechanical properties of confined concrete were subsequently collected and assessed [66]. Those yielding the most accurate pre-

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g	gross cross-sectional area of the element
	diameter of cylinder
	modulus of elasticity of FRP
	height of the element
	width of the section of prismatic element
bL	diameter of longitudinal steel bars
bw	diameter of steel hoops
c	compressive strength of unconfined concrete
f_{c}^{*}	compressive strength of confined concrete
$f_{\mathrm{c},k}^{*}$	characteristic value of compressive strength of confined concrete
	tensile strength of FRP
f_{j}'	effective tensile strength of the FRP
y	yield strength of steel
	length of the section of prismatic element
	number of FRP layers
	radius of the rounded corners of prisms
	spacing of FRP strips
′	width of FRP strips
w	spacing of steel hoops
	thickness of the FRP
α	effectiveness of confinement
α_{n}	in-section coefficient of effectiveness of confinement
α_{s}	in-height coefficient of effectiveness of confinement
$\alpha\omega_{\mathrm{w}}$	effective confinement ratio
$\alpha\omega_{\mathrm{w,FRP}}$	effective confinement ratio due to the composite material
$\alpha\omega_{\mathrm{w,hoops}}$	effective volumetric mechanical ratio due to the steel reinforcement
γ_{Rd}	partial safety factor
γ_{FRP}	coefficient depending on the type of fibres of FRP
$\varepsilon_{\mathrm{cu}}^{*}$	strain at ultimate stress of confined concrete
$\varepsilon_{\mathrm{cu},k}^{*}$	characteristic value of ultimate strain of confined concrete
σ_2	lateral confining pressure
ω_{w}	volumetric mechanical ratio of confining reinforcement

diction of strength and ultimate strain of confined concrete were retained for further assessment. In the following step.

(c) More detailed assessment of the selected models was carried out. To this purpose, the ratios of "experimental to predicted compressive strength" and "experimental to predicted ultimate strain" were calculated for each individual specimen. Statistical data (mean value, standard deviation, coefficient of variation and covariance) of these ratios were also calculated. Taking into account that (i) the assessment of the models has proven that further improvement is possible and (ii) that it would be desirable to derive a unique design model, applicable both for circular and rectangular sections, in the final step.

(d) A new empirical model was developed. It is based on the model adopted by the Eurocode 2 [6] for confinement of concrete by means of steel hoops. The model is described in this paper; its results are compared with the experimental data of the database. Finally, a set of partial safety factors is suggested allowing for the proposed expressions to be used within design codes.

For the assessment of existing models, as well as for the development and calibration of the proposed model, a large number of published experimental results were collected and evaluated. Thus, 785 tests on FRP-confined cylindrical specimens (702 of them without internal steel reinforcement, and 83 specimens provided with internal confinement, as well) and 289 tests on FRP-confined prisms (200 of them made of plain concrete and 89 specimens with internal steel hoops, as well) were collected. The specimens cover a wide range of values for several parameters, as shown in Table 1.

As mentioned previously, 1074 test results were included in the database for further use in assessing models that predict the strength of confined concrete. Since in some experimental works, ultimate strain values are not given, the number of the respective data is smaller than for strength (900 specimens approximately). Among those specimens, 670 were used for the assessment of the models. In fact, detailed study of experimental results has shown that a number of them should preferably not be taken into account. A series of criteria were set to allow for a sensible selection of test results to be further evaluated. The criteria applied in order to exclude some of the experimental results from further evaluation are listed here:

(i) Premature failure due to other mechanism than rupture of the composite material (e.g. when insufficient overlapping length of the FRP sheet was provided or when slender specimens failed in bending).
(ii) Height to sectional dimension ratio smaller than 2.0.
(iii) Incomplete tests due to insufficient capacity of the testing machine.