CYCLIC COMPRESSION OF JACKETED REINFORCED CONCRETE COLUMNS

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ABSTRACT

Retrofitting reinforced concrete (RC) columns jacketed by carbon fibre reinforced plastics (CFRP) is one of the most frequent strategies to increase the life of damaged structures in civil engineering. This study focuses on the experimental research on the deformation during cyclic uniaxial compression of jacketed columns. Damage mechanics is used to interpret experimental data and initiate the second phase of this research.

The experimental studies of jacket effects on the strength and macro-ductility of the column concrete were conducted on 27 circular columns of 750-mm height and 150-mm diameter. Both CFRP and RC were utilised as well as different spacing of stirrups. All tested specimens were macroscopically identical.

Analysis of available data obtained for low values of the aspect ratio, λ=height/diameter, typically $\lambda=2$, raises considerable doubts on the generalisation of those results. Besides known shortcomings of such scaling for compressive tests based on which failure modes are to be analysed, the relative stiffness of the outer composite shell vs. concrete appears overestimated. This is a serious objection that the present study avoided by selecting an aspect ratio $\lambda=5$ for the tests reported herein.

The preliminary conclusion based on the experiment data on CFRP reinforced concrete columns subjected by cyclic compression suggest that the spacing of stirrups affects the strain localisation threshold. The primary objective of the developed continuum damage mechanics model, based on the thermodynamics of dissipated deformation processes and fracture mechanics, is to provide physical underpinning of the process of damage evolution.

1. Introduction

Reinforced concrete columns strengthened by CFRP display obvious advantages, but require further studies both experimental and analytical to establish reliable models for better engineering. Compression tests have shown that large strength and ductility enhancements become possible, but many earlier data are based on cylinders of small diameter vs. thickness of composite wrap and/or for low aspect ratio, typically 2, raising substantial doubts on the conclusions on failure modes. Adequate jacket stiffness is crucial, since lower values made jacket useless whereas very high values make the rupture very brittle. A reasonable compromise that avoids these pitfalls, e.g. [1-3], was attempted using H=750mm and D=150mm throughout the tests.

Results on loading of RC columns confined with FRP are scarce due to the complexity of interaction of between the confinement provided by stirrups to the concrete outer layer and the influence of the stiffness of the FRP shell. Extrapolation from confinement provided by steel reinforcement to that due to FRP is very dubious. Pressure provided by FRP jackets increases continuously till rupture, in association with their linear-brittle constitutive law, while yielding of steel transverse reinforcement induces a different pattern of response.

Models that assume a constant radial pressure simulate the case of steel transverse reinforcement, given that such steel yields and produces a constant confining pressure proportional to the yield stress, area and spacing of the hoops. A better model used in study considers the increasing confining stress due to the actual dilation of the concrete core and fits better the concrete confined by a linear elastic shell. Correlation between confinement and current dilation can be deduced from an incremental model by record increment load, evaluate dilation and calculate confinement pressure and state of stress. Hoppel et al. [4] proposed a linear elastic relation between the hoop strain in the shell, the confining pressure and the axial stress in the concrete. Mirmiran and Shahaway [5] submitted an incremental method, based on a cubic relation relating the change in radial strain with the axial strain. The coefficients of the expression were generated from the unstressed and the ultimate jacket failure and considered a variable Poisson's ratio for the enclosed concrete according to Elwi and Murray [6]. The variable Poisson's ratio was obtained from unconfined concrete coupons and the confining pressure calculated from the jacket hoop modulus, geometry and radial expansion of the core. A constant pressure confinement model is used to predict the concrete axial stress and results have been considered reasonable for jackets only with hoop fibres, low axial stiffness and low Poisson's ratio in axial direction.

Available results on cyclic loading of concrete exist for over 30 years, e.g. at Rice University [7], as well as on confinement provided by steel reinforcement, leading to results and models [8-12] documented and used with success in existing Codes.

However, data are scarce for the case of specimen confined by FRP with the inner core reinforced by stirrups (RC) and subjected to axial cyclic loading. Added to the mentioned factors that make studies harder for loading of RC columns confined with FRP, i.e. contribution of stirrups, concrete outer layer and the FRP shell itself one has to account for the load-unload effects, interpret and explain results.

In order to attain these objectives, tests were made on 27 circular columns, of 750 mm-height and 150 mm diameter, jacketed with CFRP, under axial cyclic compression. Columns without jackets were also used for comparison, illustrating plain concrete behaviour. Results for these cylinders with longitudinal and transverse steel reinforcement are also reported elsewhere in detail. Representative results are described in the text and micromechanics considered only for the interpretation of results.

2. Material Parameters

Concrete, tested in standard cubes, had an average cylindrical strength f_{cm}=37.7Mpa; though, for design equations, values based on cylinders of 750mm were used in tests. Concrete columns were either of plain concrete, or were reinforced longitudinally with 6ϕ6mm or both longitudinally and transversely. In the latter case, stirrups ϕ3mm were placed at s=5, 10 or 15cm. The sample of columns consisted of 11 columns confined with 2 plies of CFRP. The elastic modulus of tested epotherm resin was E=1768 MPa, ultimate tensile strength σ_{tu}=23.7 MPa, strain at maximum force 4.99% and ultimate strain 13.53%. Parameters of Replark 30 carbon fibres were E=230GPa, σ_t= 3400MPa, t_{ply}=0.167mm. Laboratory tests data were E=210GPa, σ_{tu}=3371MPa, strain for maximum force 2.8% and ultimate strain 3.0% for coupons with 2 plies of CFRP.

3. Test Data

Three specimen are selected for the initial part of this communication, due to their clear rupture away from plates and completeness of data, hereafter identified as C3, C4, C26.

This choice allows the comparison of plain concrete with columns jacketed with two layers of CFRP, the latter either under monotonic loading or cyclic loading; all the reported specimen without steel reinforcement. The values of f'_{co}, ε_{co}, which correspond to maximum unconfined stress and corresponding strain in concrete, were respectively 32.2 MPa and 0.2%; f'_{cc} maximum confined stress in concrete; ε_z is vertical strain and ε_r maximum circumferential strain. For identification, C3 is unconfined, plain concrete, whereas C4 and C26 are externally wrapped with two layers of CFRP. Only the loading on specimen C26 was cyclic. The increase of maximum stress f'_{cc} was from 32.2 to 73.6MPa for C4 and to 81.0 MPa when loading was cyclic. Axial strain increased from 0.20% to 1.20 and 1.03%, respectively. Recorded hoop strain appeared reliably recorded for specimen C4 where it was found 0.74%.
A comparison of the results for the three cases in terms of $\sigma-\varepsilon$ curve is depicted in Fig.1. Similar data were obtained for glass fibre wraps. Elastic parameter of the material acquired from FYFE Corporation was E_c=27.6 Gpa. The maximum stress was 552 MPa and the ultimate strain 2.0 %, based on the composite thickness per ply of 1.2954 mm. According to laboratory measure the ultimate strain was ε_u=3.75% .

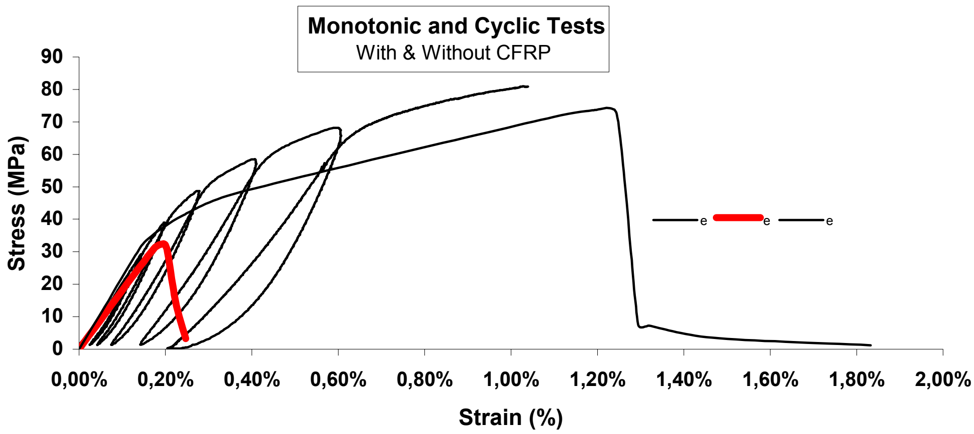

Fig. 1 – Unconfined column and confined under monotonic load and cyclic load (CFRP)

Results for specimens C22 and C27, wrapped with 3 layers of GFRP according to techniques recommended by FYFE, are plotted in Fig. 2, and compared with plain concrete. The behaviour of columns wrapped with CFRP (2 plies) and GFRP (3 plies) for cyclic loading can be compared in Fig. 3.
The influence of transversal steel reinforcement on results, as well as the importance that wider spacing of stirrups confers to the jackets was also examined. Preliminary results suggest that the importance of jacketing is greater when stirrups spacing increases. As mentioned above these results will be reported in a later text.
For CFRP strengthening, the monotonic loading curves were found to be below the envelope for static cyclic loading, for all three different cases of stirrups (5,10 and 15 cm apart). The part of axial strain curves when ε_z is approximately 0.2%, after concrete failure, are consistent to increases of the ratio $|\varepsilon_r/\ \varepsilon_z|$ that is often referred as the Poisson's ratio. The volumetric strain, $\varepsilon_v = 2\varepsilon_r+\varepsilon_z$, for cyclic loading, that increases for

large deformations, is associated to the deformation between the post-rupture of the concrete core and the failure of the RC columns.

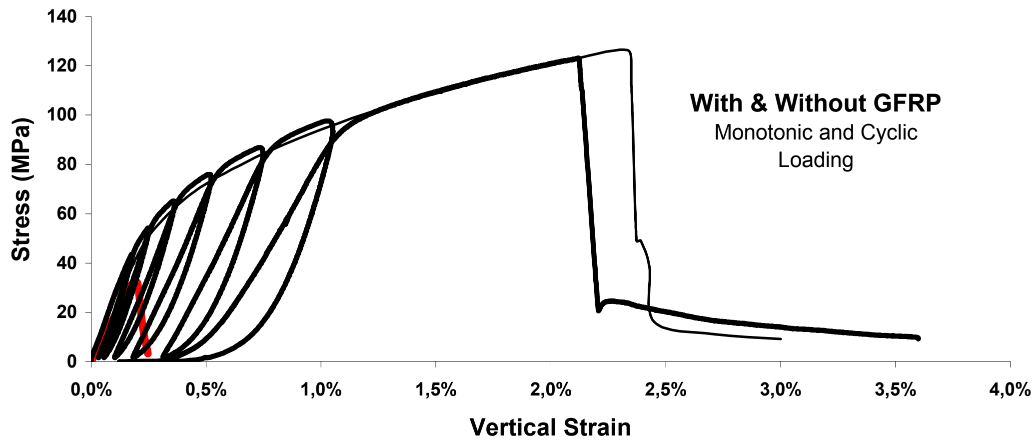

Fig. 2 – Unconfined column and confined under monotonic and cyclic load (GFRP).

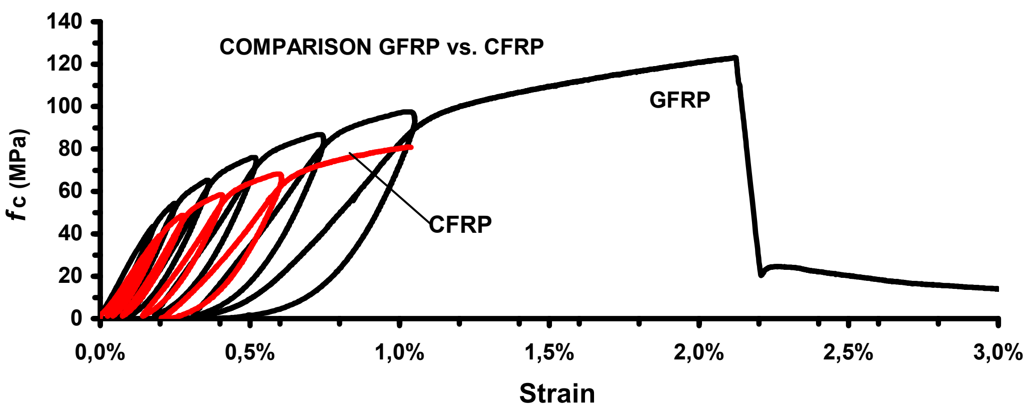

Fig. 3 – Stress-strain curves for confined columns subject to cyclic loading

4. Analytical Model

The macroscopic normal stresses in laterally confined concrete column subjected to quasi-static increased axial direction are all positive. Hence, the cracks are, at least in beginning, only nucleated and propagated in the plane of maximum shear stress. Useful models are discussed in [14]. However, these models can be used only when the material is statistically homogeneous, i.e. in the hardening phase of the deformation, which is also the failure when the applied stresses are controlled.

A continuum model for the FRC columns was developed by authors, that can be generalised to take in consideration column size on failure and seems to be rather useful. A 3-dimensional micromechanics model would be very complex but still possible. Using the assumptions from [4] the micromechanics models the models will be quasi-two dimensional which will minimise the computational aspects of the model. Similar to [15] the ring shaped regions starting from radius zero to the external surface are elastic, process zone of increasing damage in concrete, zone in which the concrete is comminuted into smallest particles and the jacket zone which can be divided into elastic and plastics parts. Some stresses at the interfaces between two zones of different stiffness may be discontinuous. The stress discontinuity can be derived from the mass and momentum conservation equations [5].

Further tests and analytical modelling will interrogate the impact of composite jackets on the safety and on increased damage capability of the columns. The present small contribution to this goal indicates answers to some questions and rises new questions. The need for more precise micro-scale test data is one of the most important requirements that must pursued, in order to create needed conditions to explore further the potential of micromechanical modelling with a better precision.

5. Acknowledgments

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