Quantifying the Compressive Ductility of Concrete in RC Members through Shear Friction Mechanics

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Abstract

This thesis contains a series of journal papers in which the compressive ductility of concrete in RC members has been quantified through shear friction mechanics.

Firstly, the size dependent stress-strain models for unconfined and actively confined concrete are derived based on the fundamental mechanics of shear friction theory. At this stage, the shear friction properties, that is the relationship between the shear stress, normal stress, crack widening and interface slip across the sliding plane, are not specifically required. It is shown how the stress-strain from cylinder tests of one specific length can be modified to determine that for any size of cylinder. Moreover, it is shown that the proposed approach can be used to make existing generic stress/axial-strain relationships size dependent and these size dependent relationships can be directly used to determine the corresponding size dependent stress/lateral-strain relationship. Being mechanics based, size dependent stress-strain models reduce the reliance on vast experimental testing as only one size of specimen needs be tested to obtain stress-strain relationships for all sizes.

Secondly, the shear friction properties, that is the relationship between the shear stress, normal stress, crack widening and interface slip across the sliding plane is derived and presented in a generic form suitable for application. These generic shear-friction material properties are then used to simulate and quantify the shear-sliding behaviour of initially uncracked concrete generally obtained directly from relatively expensive tests. In addition, it is also shown how these shear-sliding capacities can then be used to quantify the shear capacity of RC beams without stirrups and without the need for size factors as the mechanics based approach automatically, through mechanics, allows for member size.

Thirdly, the generic shear-friction material properties derived in Chapter 3 are used to simulate passive confinement in FRP confined cylinders. Importantly, two distinct cylinder failure modes have been identified and examined: that of the circumferential wedge that is common in standard cylinders with aspect ratios of 2:1; and that of the single sliding plane that occurs at higher aspect ratios. It shows the mechanics solutions for the influence of specimen size, that is both diameter and height, on the stress-strain relationship of axially loaded FRP confined concrete cylindrical specimens and how small scale FRP wrapped specimens suitable for compression testing can be designed so that the stress/strain relationship of the full scale member under pure compression can be extracted from those of the small test specimen.

Finally, a series test of steel tube confined concrete columns is designed to verify the accuracy of the size effect expressions proposed in previous chapters. Importantly, it shows that because the standard material test always adopts small scale 2:1 aspect ratio specimens, the majority failure mode in material test specimens is the circumferential wedge failure. Consequently it is for this wedge failure mode that most axial-stress/global-axial-strain relationships are developed. However, similar to the specimens studied in this test program, the aspect ratio of most practical steel tube confinement columns is more than 2. Hence only in a minority of cases does the circumferential wedge failure occur in practice. Therefore, the empirical or semi-empirical equations developed from small scale concrete specimens are not truly representative of the actual behaviour of full-scale columns which have aspect ratios markedly different from the 2:1 ratio most commonly tested.

Statement of Originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or any tertiary institution to Yongjian Chen and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Yongjian Chen Date

List of Publications

Oehlers, D.J., Visintin, P,. Zhang, T., Chen, Y., and Knight, D. (2012). "Flexural Rigidity of Reinforced Concrete Members Using a Deformation Based Analysis." Concrete in Australia, 38(4), 50-56.

Chen, Y., Visintin, P., Oehlers, D.J., and Alengaram, U. (2014). "Size dependent stress-strain model for unconfined concrete." Journal of Structural Engineering, 140(4), 10.1061/(ASCE)ST.1943-541X.0000869.

Visintin, P., Chen, Y., and Oehlers, D.J. (2014). "Size dependent axial and lateral stress strain relationships for actively confined concrete." Accepted for publication by Advances in Structural Engineering on 05/06/2014.

Chen, Y., Visintin, P., and Oehlers, D.J. (2014). "Concrete shear-friction material properties: derivation from actively confined compression cylinder tests." Submitted to Advances in Structural Engineering on 26/03/2014.

Chen, Y., Zhang, T., Visintin, P., and Oehlers, D.J. (2014). "Concrete shear-friction material properties: application to shear capacity of RC beams of all sizes." Submitted to Advances in Structural Engineering on 26/03/2014.

Visintin, P., Chen, Y., and Oehlers, D.J. (2014). "Simulating the behaviour of FRP confined cylinders using the shear friction mechanism." Submitted to ASCE Composites for Construction on 10/10/2014.

Chen, Y., Visintin, P., and Oehlers, D.J. (2014). "Extracting size dependent stress/strain relationships from FRP confined concrete cylinders for varying diameters and heights." To be submitted to Composite Structures.

Chen, Y., Visintin, P., and Oehlers, D.J. (2014). "Test of Steel tube confined concrete columns." Text in Manuscript.

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Introduction and General Overview

The axial-stress/axial-strain behaviour of concrete under compression is crucial in determining both the strength and ductility of reinforced concrete members. In this thesis, it is shown that concrete deformation due to compression is both a material property and a shear-friction mechanism and that by taking into account both of these deformations a size dependent stress-strain relationship can be derived.

This thesis contains a collection of manuscripts published, accepted or submitted to internationally recognised journals. Each of the chapters 1 to 4, which are titled according to the research objective, contain: an introduction explaining the aim of the chapter and how the work fits into the overall objective; a list of manuscripts contained within the chapter; and finally the presentation of each manuscript.

Chapter 1 introduces the fundamental mechanisms of the developed segmental deformation approach for the generic analysis of reinforced concrete (RC) beams incorporating: a size-dependent stress-strain model to simulate the concrete wedge formation associated with concrete softening; and residual strain partial-interaction (PI) theory to directly simulate the effects of tension-stiffening as the internal bonded reinforcement pulls from the crack face. This background paper shows the overall project of our research group of which this thesis mainly focuses on the analysis of size-dependent stress-strain models.

Chapter 2 contains two journal papers which use the mechanics of shear friction theory to simulate the formation and displacement of sliding planes as concrete softens and then derives size dependent stress-strain models. The first paper extracts size dependent strains at the peak stress from 380 published tests on unconfined concrete and then uses it in existing curve fitting models to produce size dependent stress-strain models for unconfined concrete. The second paper has reanalysed 692 published test results on confined concrete to provide size dependent stress/strain relationships for both axial and dilatory strains in both the ascending and falling branches and for a wide range of confinements. The new approach in these two papers considerably reduces the amount of testing required for new concretes as only one size of specimen is required to be tested for obtaining stress-strain relationships for all sizes.

Chapter 3 focuses on the shear-friction material properties across potential sliding planes, that is the relationship between the shear stress, normal stress, crack widening and interface slip across an initially uncracked concrete sliding plane. It shows how the shear-friction material properties can be quantified from relatively readily available and inexpensive compression tests, and then presented in a generic form which is directly applicable for the papers in Chapter 4.

Chapter 4 consists of three papers that show the applications of shear friction properties proposed in Chapter 3. The first paper shows how these shear-friction material properties can be used directly to quantify the shear-sliding capacity and also how these shear-friction material properties can also be used to analyse standard shear-sliding tests in order to extract more accurate shear-sliding capacities. It is then shown how these shear-sliding capacities can be used as the failure criteria to quantify the shear capacities of reinforced concrete beams. The main aim of the first paper is to show that the use of mechanics and shear-friction material properties can not only quantify apparently diverse behaviours such as the shear capacity and flexural ductility but also reduce the cost of developing new RC products and in developing more accurate and less conservative design rules. In the second paper, two distinct cylinder failure modes have been examined: that of the circumferential wedge that is common in standard cylinders with aspect ratios of 2:1; and that of the single sliding plane that occurs at higher aspect ratios. Importantly, from this is shown that although each mechanism is defined by the same shear friction material properties different stress strain relationships result and this may explain some of the scatter of test results. In the third paper, mechanics solutions have been developed to show the influence of specimen size, that is both diameter and height, on the stress-strain relationship of axially loaded FRP confined concrete cylindrical specimens using shear friction theory. Due to the capacities of the testing machines, it is often quite difficult to test large or full-scale FRP wrapped specimens under pure compression in order to extract their axial-stress/axial-strain relationships. The third paper shows that through the mechanics of shear friction, how small scale FRP wrapped specimens suitable for compression testing can be designed so that the stress/strain relationship of the full scale member under pure compression can be extracted from those of the small test specimen.

Chapter 5 is the experimental work for steel tube confined concrete of which the test data can be used to verify the axial and lateral size expressions proposed in Chapters 2 and 4 respectively. It also shows that the proposed expression of the sliding angle α that is dependent on the confinement stress and proposed in Chapter 2 of this thesis has a very good correlation with the experimental results. Importantly, as the standard material test always adopts small scale 2:1 aspect ratio specimens, the majority of the failure modes in material test specimens is the circumferential wedge failure and from which most axial-stress/global-axial-strain relationships are developed. However, similar to the specimens studied in this test program, the aspect ratio of most practical steel tube confinement columns is more than 2, so only in a minority of cases does the circumferential wedge failure occur. Therefore, the empirical or semi-empirical equations developed from small scale concrete specimens are not truly representative of the actual behaviour of full-scale columns which have aspect ratios markedly different from the 2:1 ratio most commonly tested.

Chapter 6 shows the concluding remarks of this research. The applications of size dependent models and shear-friction material properties for passively confined RC members provides a novel technique in simulating what is actually observed in practice. The generic approach proposed in this thesis can easily be repeated and updated by following researchers for new types of concrete.