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Incremental collapse threshold for pushout resistance of circular concrete filled steel tubular columns

T. Aly [a,*], M. Elchalakani [b], P. Thayalan [a], I. Patnaikuni [a]

[a] Department of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, VIC 3001, Australia

[b] Dubai Mens College, Higher College of Technology, Dubai, UAE

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ABSTRACT

This paper presents the results of a series of pushout tests using static loading (SL) and variable repeated loading (VRL) on concrete filled steel tubular (CFT) circular stub columns. The main parameters examined in this paper were the strength and age of concrete and the loading protocol. Under SL tests, the interface bond strength in CFT columns filled with normal strength concrete was found to be higher than that with high strength concrete. The SL test results showed that the interface bond strength varied from 0.41 to 0.85 MPa but from 0.33 to 0.66 MPa under VRL tests. A lower bound for the incremental collapse threshold of the pushout resistance of 70% of the static collapse load was empirically derived. Also an expression of the average growth of slip per loading cycle was empirically derived and recommended for design purposes. A comparison between the bond strength of the columns obtained from the present and previous test results, and available design codes is presented. Two newly derived bond strength limits were experimentally obtained and proposed for the design of structures subjected to either predominantly static or predominantly cyclic loading.

1. Introduction

The use of concrete filled steel tubular columns (CFT) for the construction of building structures, bridges and warehouses has become widespread in recent decades. In composite columns, steel–concrete interface bond plays a major role in the regions of end connections where force transfer takes place. In practice, beams and slabs are connected directly to the steel sections of the composite columns. A portion of the forces and/or moments have to be transferred from the steel to concrete for the column to act compositely. Forces may be transferred between the steel and concrete by mechanical shear connectors and/or by bond between the steel and concrete [1].

Lutz and Gergely [2] had identified three different characteristics of shear resistance between steel and concrete namely, mechanical resistance, chemical bonding and frictional resistance. The mechanical resistance is considered to be negligible when the steel surface is smooth and chemical bond ruptures when there is an excessive interface slip. Therefore, the major contribution to the residual bond strength could be attributed to the frictional resistance resulting from the interface pressure between steel and concrete. Furlong [3]; Johansson and Gylltoft [4] concluded that the actual bond strength has little or no significance in relation to the performance of composite columns, provided that the steel and concrete areas at the column ends are loaded simultaneously, which is difficult to fully achieve on site. Kilpatrick and Rangan [5,6] carried out a limited experimental study into the significance of bond between the steel tube and infill concrete upon the behaviour on composite columns. On the other hand, Hunaiti [7,8] tested 135 battened composite specimens and found that the bond between steel and concrete is likely to be affected by several factors including age and size of the specimen, curing and temperature. He concluded that the age of concrete is a major factor of bond reduction and reported that the bond strength at the age of one year is about 30% of that at the age of three weeks. Roeder et al. [9] studied the bond stress capacity and distribution along the interface of circular members. They concluded that concrete shrinkage, which depends upon the characteristics of the concrete, diameter of the tube and the interface condition can be detrimental to bond stress capacity. They found that the bond capacity, which is interrelated with slip at the steel concrete interface, decreased when the tube diameter and or the diameter-to-thickness ratio increased. Experimental testing of uncapped circular CFT beams under static [10] and under cyclic loading [11,12] showed that bond has insignificant effect on the moment–curvature response.

Eurocode 4.2 [13] bridge design code specifies that bond strength is 0.3 MPa and 0.55 MPa for completely Concrete Encased Sections (CES) and for circular Concrete Filled Tubes (CFT) respectively. However, Eurocode 4.1 [13] specifies 0.6 MPa for CES and 0.4 MPa for CFT. Wium and Lebet [1,14], reported that the

* Corresponding author. Tel.: +61 399259975.
E-mail address: tarek.aly@rmit.edu.au (T. Aly).

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Notations

CFT	Concrete Filled Tubes
f_{cu}	Concrete cylinder compressive strength at the 28 days SL Static Loading
VRL	Variable Repeated Loading
P_{sp}	Static collapse load, kN
P_{IC}	Incremental Collapse load, kN
P_{i+1}	Maximum load level at $i + 1$% of load range ($= P_{sp} * (i + 1)/100$), kN
P_i	Maximum load level at i% load range ($= P_{sp} * (i)/100$), kN
G_i	Growth of slip/cycle at i% load range, (mm/cycle)
G_{i+1}	Growth of slip/cycle at $i+1$% load range, (mm/cycle)
G	Growth of slip/cycle, (mm/cycle)
P	Actual pushout load level, kN
P_{co}	Completed pushout load level, kN
P_{sp}	Static pushout collapse load, kN
$\tau_{SL,peak}$	Static pushout peak strength, MPa
$\tau_{SL,res}$	Static pushout residual strength, MPa
$\tau_{VRL,peak}$	Cyclic pushout peak strength, MPa
$\tau_{VRL,res}$	Cyclic pushout residual strength, MPa

bond strength specified in Eurocode 4.1 [13] has to be verified for safe designs. They found lower shear resistance values than those found in the design codes for large embedded steel sections. The Australian bridge design code AS 5100.6 [15] recommends that shear connectors should be provided where the shear stress, due to ultimate design loads, would otherwise exceed 0.4 MPa for both CES and CFT. The British bridge design code BS5400 [16] recommends that shear connectors should be provided where the shear stress, due to ultimate design loads, would otherwise exceed 0.6 MPa for CES or 0.4 MPa for CFT. The series of pushout tests carried out by Shakir-Khalil and Hassan [17] indicated that the bond strength given in BS 5400 [16] is not always achieved. It was reported that the repeated loading of two cycles at three load levels had no noticeable adverse effect on the failure load of the specimens [18,19]. Al-Rodan [19,20] reported a study on comparison between BS5400 and Eurocode 4.1 for calculating the capacity of CFT columns. The study points to potentially large differences between the capacities as computed from these two methods. Nezamen et al. [21] showed that static pullout bond resistance of CFT columns is reduced by 35% after 20 fully reversed cycles.

The inconsistency in the above reported results show that further studies on bond strength behaviour are needed to evaluate simple and feasible design methods for end connections in composite members. In the literature, there are little studies on bond strength and the incremental interface slip behaviours of CFT circular columns subjected to VRL tests.

Previous work has been carried out to study the behaviour of CFT columns by the authors [22]. In this paper, pushout tests were carried out on 14 CFT specimens to study the bond strength particularly the incremental slip behaviour subjected to cyclic loading. The diameter of the steel tubes was 114 mm which may be considered small from a practical viewpoint. This limitation is important because past research has shown that bond stress is largely influenced by this diameter, since larger diameters typically have smaller bond stress because of shrinkage issues [1,14,17]. The specimens had diameter-to-thickness ratio of 35.72 which may be considered less than those used in construction as the reinforcement ratio is relatively high and of the order of 11%. The main variables considered in the study were the strength and age of concrete and the loading protocol. A comparison between the bond strength of the columns obtained from the present and previous test results, and available design codes is presented. Two newly derived bond strength limits were experimentally obtained and proposed for the design of structures subjected to either predominantly static or predominantly cyclic loading.

2. Experimental investigation

2.1. Test program

A total of 14 pushout tests were carried out on CFT column specimens of 450 mm height with approximately 400 mm steel–concrete interface length to study the interface bond behaviour under SL and VRL protocols. Pushout specimens were cast using 7 different mixes comprising normal ($f_{cu} < 50$ MPa) and high strength concrete ($f_{cu} > 50$ MPa). Two nominally identical specimens were constructed from each mix, one for the SL series and the other for the VRL series. The SL tests were carried out on 7 specimens from 7 different mixes to obtain the pushout force interface slip behaviour, including the maximum pushout force with the corresponding slip and the residual force. The VRL tests were performed on the remaining 7 specimens whereby the load ranges for each specimen were calculated using the maximum static pushout force of the companion specimen assuming that the behaviour of the specimens from each mix is the same. The changes in interface slip deformation in different load ranges for every cycle of the loading were obtained to study the interface slip behaviour and to obtain the incremental collapse (IC) limit under such loading.

2.2. Material properties and concrete mixtures

The steel tubes considered in this test program were circular hollow sections of outer diameter of 114.3 mm and a wall thickness of 3.2 mm. It is made from Grade 350 cold-formed black structural grade steel. The tubes were as received from the mill and the surfaces were not treated. The steel tubes were cut to the required size and delivered by the supplier. Fourteen pushout specimens of 450 mm height with approximately 400 mm steel–concrete interface height were cast using seven different mixes A, B, C, D, F, G and H. The concrete mixes were formulated from three main batches with different water cement ratio (w/c) and cement content as shown in Table 1. The 28-day compressive strengths (f_{cu}) of all mixes ranged between 40 and 80 MPa. Pakenham Blue Metal (Old Basalt) crushed type coarse aggregate with a maximum size of 12 mm was used. The coarse aggregate was tested and found to have a specific gravity of 2.95 and an absorption rate of 1.2%. Lyndhurst washed fine sand was used as the fine aggregate. It was tested and found to have a specific gravity of 2.65 and an absorption rate of 0.5%. A slump of 80±10 mm was achieved for all mixes using various amounts of high range water reducing admixtures. All the aggregate weights shown in Table 1 are in the saturated surface dry condition.

Nine Concrete cylinders were prepared for each mix, size 100 mm diameter and 200 mm height. The specimen moulds were filled in two layers and compacted using a vibrating table. The specimens were demoulded after 24 h and placed in a water tank in a vertical position. Prior to testing, the specimens were removed from the tank and cut to 150 mm height using a saw to get a smooth surface. At the age of 28 days, the specimens were loaded at a constant displacement rate of 0.25 mm/min to determine the compressive strength of concrete (f_{cu}). The average measured f_{cu} values for the 7 mixes are discussed in Section 3.