Journal of Constructional Steel Research 81 (2013) 35–43

Contents lists available at SciVerse ScienceDirect

Journal of Constructional Steel Research

Load-reversed push-out tests on rectangular CFST columns

Xiushu Qu [a], Zhihua Chen [a,*], David A. Nethercot [b], Leroy Gardner [b], Marios Theofanous [b]

[a] School of Civil Engineering, Tianjin University, Tianjin, 300072, PR China
[b] Department of Civil and Environmental Engineering, South Kensington Campus, Imperial College London, SW7 2AZ, UK

ARTICLE INFO

Article history:
Received 4 February 2012
Accepted 3 November 2012
Available online 29 November 2012

Keywords:
Concrete-filled steel tubes (CFST)
Interface bond strength
Interface condition
Load-reversal
Macrolocking
Microlocking
Push-out test

ABSTRACT

Load-reversed push-out tests have been carried out on 6 rectangular concrete-filled steel tubular (CFST) columns with the aim of investigating the nature of the bond between the concrete infill and the steel tube, the contribution of each bond stress component (i.e. chemical adhesion, microlocking and macrolocking) and the development of macrolocking within four half-cycles of loading. The contribution of microlocking to the total bond strength was obtained from the comparison between the ultimate strength of normal specimens and lubricated specimens, which also revealed the detrimental effect of lubrication on the bond strength. The macrolocking contribution was obtained from the comparison between the ultimate strength achieved in the first half-cycle of loading τ_{u1} and the ultimate strength achieved in the third half-cycle of loading τ_{u3} of the non-lubricated specimens. The developed bond mechanisms were explained and details of the interface bond stress distribution were obtained from the recorded axial strain gradients in the steel tube. Finally, the concept of a critical shear force transfer length was introduced, and its implications on practical design discussed.

1. Introduction

Concrete-filled steel tube (CFST) compression members have attracted considerable attention from both practising engineers and researchers owing to their favourable structural properties and significant financial advantages over their structural steel or reinforced concrete counterparts that make them well-suited for structural applications. The steel tube confines the concrete infill thus enhancing its strength and ductility, whilst the concrete core delays the onset of local buckling of the tube wall, particularly for RHS and SHS. Hence the resulting composite columns possess high strength, stiffness and ductility thereby leading to smaller column sizes and to larger lettable areas particularly in the lower storeys of multi-storey buildings [1]. Moreover the steel tubes act as permanent formwork for the concrete and can support significant construction loads before the hardening of the concrete thereby speeding up construction times and lowering the cost. The slenderness of the steel tubes and the strength of the concrete infill utilised in practical applications vary from one country to another [2], with the majority of the research being directed towards relatively thick-walled tubes filled with normal strength concrete, whilst thin-walled tubes filled with high-strength concrete have received less attention [3]. Traditionally CFST have employed square, rectangular and circular hollow sections (SHS, RHS and CHS respectively) or even octagonal hollow sections [4,5], whilst, more recently, concrete filled elliptical hollow sections (EHS) have been introduced [6,7].

Key to the satisfactory structural response of CFST is the effective shear stress transfer from one material to the other (i.e. composite action) particularly in regions of geometric discontinuity of the structural members, where bond stress demand is the greatest [2]. Composite action may be achieved via the natural bond between steel and concrete, similarly to the bond between steel reinforcing bars and surrounding concrete, or with the aid of shear connectors of various forms, including structural bolts [8–10], Hilti nails [9], threaded bars [10], self-taping screws [11] and tab stiffeners [12].

Early research on the bond strength in circular CFST was conducted by Virdi and Dowling [13] who performed push-out tests on stocky CHS filled with concrete of various grades. They examined the effect of various parameters on the bond strength, such as the age, strength, compaction and curing conditions of concrete, the interface length, the tube size and various surface treatments and concluded that the most significant factor contributing to the bond strength is the mechanical keying between steel and concrete. Morishita et al. [4,14] tested CHS, SHS and octagonal hollow sections filled with concrete to investigate the effects of cross-section shape and concrete grade on bond strength. They reported that concrete-filled CHS display increased bond strength compared to SHS and octagonal cross-sections and that high strength concrete results in decreased bond strength compared to normal strength concrete for CHS due to increased shrinkage. Similar observations regarding the effect of the concrete grade on bond strength were also made elsewhere [8,13], and have also been attributed to the higher shrinkage

* Corresponding author. Tel./fax: +86 22 27403736.
E-mail addresses: quxiushu@bucea.edu.cn (X. Qu), zhchen@tju.edu.cn (Z. Chen), d.nethercot@imperial.ac.uk (D.A. Nethercot), leroy.gardner@imperial.ac.uk (L. Gardner).

0143-974X/$ – see front matter. Crown Copyright © 2012 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jcsr.2012.11.003

associated with increased concrete strength. The bond strength achieved by different cross-section geometries was also investigated by Shakir-Khalil [8] and the superior bond strength achieved by CHS compared to RHS was attributed to the more effective confinement pressure exerted by the CHS as evidenced by the friction marks which were distributed uniformly around the CHS, whereas friction marks due to confinement pressure were only observed in the corner regions of the RHS specimens. Moreover, the diminished bond strength observed for the larger tested specimens compared to the smaller ones, was attributed to the more pronounced effect of concrete shrinkage for large cross-sections. A detailed study on the effects of shrinkage and tube dimensions was reported by Roeder et al. [2], who also highlighted the effect of pressure of the wet concrete and internal surface irregularity of the tube on the bond strength at the concrete–steel interface for filled CHS.

The influence of tube interface on bond strength was studied by Tomii et al. [5,15], who tested CFST with checkered internal walls, Shakir-Khalil [8], who compared the bond strength achieved by lubricated and non-lubricated concrete-filled RHS and CHS specimens and Kilpatrick and Rangan [11], who investigated various interface conditions. Other investigations have studied the influence of cyclic shear force [16], cyclic push-out force [17], concrete compaction [18] and utilisation of expansive cement [19], whilst the effect of elevated temperatures on bond strength has also been investigated [20]. A detailed summary of relevant past experimental programmes is given in [21].

Based on the findings of the aforementioned research, the main parameters affecting the bond strength are the cross-section shape [2,4,8,9,14,20], interface roughness [2,5,8,11,13–15], variations in internal tube dimensions [13,20], concrete age [13,17,20], compaction [13,18] and shrinkage [2,4,8,13,14,19] and cross-section dimensions [2,3,8,20]. There seems to be a lack of consensus regarding the effect of interface length on bond strength, since bond strength seems to increase with interface length according to [20], whereas changing the interface length did not have a direct effect on the maximum bond strength of specimens according to [8,13]. Similarly, discrepancies regarding the effect of concrete strength can be found in the literature with some researchers finding that higher concrete grade leads to increased bond strengths [19,22], whilst others observed the opposite trend, due to the increased shrinkage associated with higher concrete strength [3,4,8,13,14], particularly for CHS, where the reduction in confining pressure due to shrinkage is more pronounced.

In addition to studies of ultimate interface bond strength, the mechanisms contributing to it have also been assessed. Virdi and Dowling [13] identified two distinct components contributing to the bond strength apart from chemical adhesion, namely microlocking and macrolocking. Microlocking is defined as the keying between the concrete and the roughness of the steel surface, whilst macrolocking refers to the resistance to movement of the concrete core along the tube–concrete interface due to the manufacturing tolerances associated with the internal tube dimensions. The same bond mechanisms have also been identified for RHS [8,23].

The response of a CFST subjected to push-out forces is qualitatively depicted in Fig. 1, where the contribution of the three components of bond strength at the various stages of loading is shown in terms of an idealized force–slip curve. The bond due to chemical adhesion and microlocking has to be broken for slip to occur, whereupon macrolocking is activated. Chemical adhesion and microlocking govern the initial linear part of the curve and contribute mainly to the attainment of the maximum bond stress, whereas macrolocking determines the residual bond stress that remains at the end of the bond stress–slip curve. The stress–slip curve can assume three different shapes as discussed in [20], depending on the relative contribution of macrolocking upon the loss of bond. It may display a maximum followed by a falling branch, a maximum followed by a falling branch, which raises again at large slips, or display no maximum at all, as was the case for all tests reported in [13].

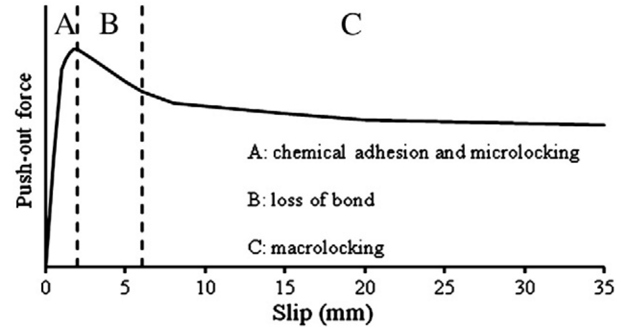

Fig. 1. Idealized response of push-out specimens.

Recent research to investigate the contribution of microlocking to the interface bond stress has been conducted by Chen et al. [24], who assessed the contribution of microlocking by comparing the ultimate average bond stress achieved by normal and lubricated specimens similarly to previous investigations [8,13]. Based on the test results reported in [13,24], the ratios of microlocking to bond stress are 32%–75% for circular CFST specimens, 10%–20% for square CFST specimens, and 10%–50% for rectangular CFST specimens, respectively. In [8] it was observed that lubricated (i.e. with reduced effect from microlocking) specimens attained approximately half the ultimate bond stress of the non-lubricated ones. However, studies into the contribution of macrolocking are rather limited and warrant further investigation.

The main objective of this paper is to assess the contribution of the various components of the bond strength (i.e. chemical adhesion, microlocking, macrolocking) in the case of concrete filled RHS with the focus being on the contribution of macrolocking. Six rectangular CFST columns have been tested using the load-reversed push-out test method with one specimen lubricated at the interface. Details of the interface bond stress distribution through four half-cycles of loading are given. The microlocking contribution is derived from the relative ratio of bond stress between the normal specimens and the lubricated specimen, recorded at the first loading stage. The macrolocking contribution is obtained by comparing the ultimate bond stresses from the first and third half-cycles of loading. Based on the test data, the effect of interface length and concrete strength on the interface bond strength of rectangular CFST columns was also investigated, supplementing previous research in this area. Finally, the critical shear force transfer length was studied to provide guidance for practising engineers.

2. Experimental study

2.1. General

A total of six rectangular CFST specimens were prepared and tested under load reversal. Table 1 provides a summary of the test specimens. Specimens CP1–CP5 had essentially similar properties. Specimen CP6 was slightly longer and was filled with concrete of slightly higher strength. The specimen length was selected such that the specimens behave essentially as stub columns with no influence from member slenderness, whilst still including a representative distribution of initial geometric imperfections along the length, thus allowing macrolocking to develop. The interface length was selected as the nominal specimen length less approximately 60 to 80 mm to allow an adequate space for the concrete core to displace inside the specimens. The interface length of specimens CP1 to CP5 was maintained at approximately 700–750 mm, whilst the interface length for specimen CP6 was 843 mm. For CP5, lubrication was used in the form of butter at the concrete–steel interface to study the loss of microlocking. The section labelling convention is shown in Fig. 2.