Steel to Concrete Bond Transferring in CFST Columns connected to Beams through the Concrete

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Abstract. An important innovation in structural design in the last thirty years has been the use of steel-concrete composite columns, with particular diffusion of tubular profiles. These elements are known in the technical Literature as concrete filled steel tube (CFST) and the metal profiles that characterize the external jacket are usually circular, square or rectangular.

A relevant issue that must be considered is the transfer of shear stresses by adhesion between steel and concrete in composite columns. The problem of adhesion, and thus its formulation, depends primarily on the type of technology used to connect beams to columns. In particular, two different models can be produced: the first case where the beams are connected only to the metal external jacket of the pillar (i.e. steel beams connected with bolted flanges to the column), and the second where beams and columns are connected also in the concrete matrix (i.e. the case of beams in steel-concrete technology, or traditional reinforced concrete beams).

International Standards, regarding the problem of adhesion in jacketed columns, only referee to the first connection type, giving a constant value for adhesion coefficient along the transferring length, with no dependence to the size of the section, and indicate transferring lengths independently from the type of beam-to-column connection and the shape of the section. In the Paper are hence proposed expressions that quantify the fundamental values that govern the action transfer mechanism by adhesion in CFST, such as the transfer length, the perimeter of the active transfer and the shear stress distribution, as a function of the slenderness ratio and of the type of connection adopted. All this has been carried in order to produce a model for the estimation of bond stresses for the second of the two construction system mentioned above.

Introduction

Composite columns made with a rectangular (RCFT) or circular (CCFT) external steel jacket are commonly used for the realization of structural systems that combine the versatility of the metallic structure during the provisional phase and of the performance characteristics of the composite structure during operation. Columns can be connected to beams in two different ways: if the frame is metallic the column is usually characterized by lateral flanges or plates that connect steel beams by bolts; otherwise if the frame is made of concrete or composite structure the column can be realized with opening in the jacket that allow to create a r.c. connection. The paper focuses on this second kind of pillars, that is characterized by the windows in the node , where the horizontal structural elements are connected.

It seams obvious that in this case the floor loads are not transferred straightly to the steel jacket, but they are transmitted into the beam-column connection joint. The focus of the paper is hence the transmission of loads from the concrete to steel by adhesion inside the jacket. A stress limit and a length of stresses transferring will be identified and the transmission capacity between the materials by adhesion will be verified. Appropriate evaluations regarding the shape of the column section and regarding the perimeter of the stress transfering will be given.

State of the Art

General Considerations on Adhesion Mechanisms in CFST

Standards such as Eurocode 4 [1] and Italian Technical Decree NTC [2] assume that there is perfect interaction between steel and concrete. The limit suggested for verification of the sliding stress is $f_{b,lim}$ =0.55MPa for circular sections filled with concrete and 0.40MPa for rectangular sections, while the length of the transfer of stresses is taken as two times the size of the cross section. If the steel jacket is not able to transfer axial loads to the concrete, or vice versa, local tensions generate premature yielding or local instability of the metal profile. For this reason, the mechanism of adhesion must be carefully taken into account in the design with a better approach of the one given by the two standards, evaluating:

- the sliding stress f_b;
- the transferring length L_b;
- the interface perimeter for the tensions exchange p_b

In the following, general consideration will be given for bending and axial load situation in order to underline important aspects that must be taken into account.

Slippage under Bending Conditions

The problem of adhesion between steel and concrete in the pillars jacketed is relevant because the pillar must be able to guarantee its elastic capacity and hence plastic, without significant sliding between the confined core of concrete and the steel jacket. The collaboration of the two materials in a composite sections must be ensured through a mechanism of shear stresses transferring that takes place by natural adherence between materials. This shear adhesion develops through phenomena of chemical type and static friction, both depending on the roughness and on the cleaning of the contact surface.

In RCFT or CFST the core concrete is a confined concrete, hence it improves bending-axial performance of the element. The concrete in tension however, being cracked, provides no mechanical contribution and then, the transfer of forces between the two materials takes place only by friction. As example, the slip between steel and concrete in composite columns carried by bending loads, reached in recorded tests at ultimate loads [3], is given in Table 1.

Table 1. Maximum slip records in bending test [3]

SPECIMEN	CB12	CB13	CB15	CB22	CB31	CB33	CB35	CB41	CB45	CB52	CB53	CB55
MAXIMUM SLIP (mm)	0.7	3.9	2.1	0.5	0.6	0.9	0.8	1.0	0.9	0.3	0.2	0.4

In none of the proposed experiments significant slippage between the concrete core and steel jacket can be appreciated. When slippage is not significant, so when it is lower than 0.5 mm and 1 mm, the maximum moment is reached in the specimen. As example Fig. 1 shows the normalized Moment – slip curves for all strain gauge used in the CB41 in [3].

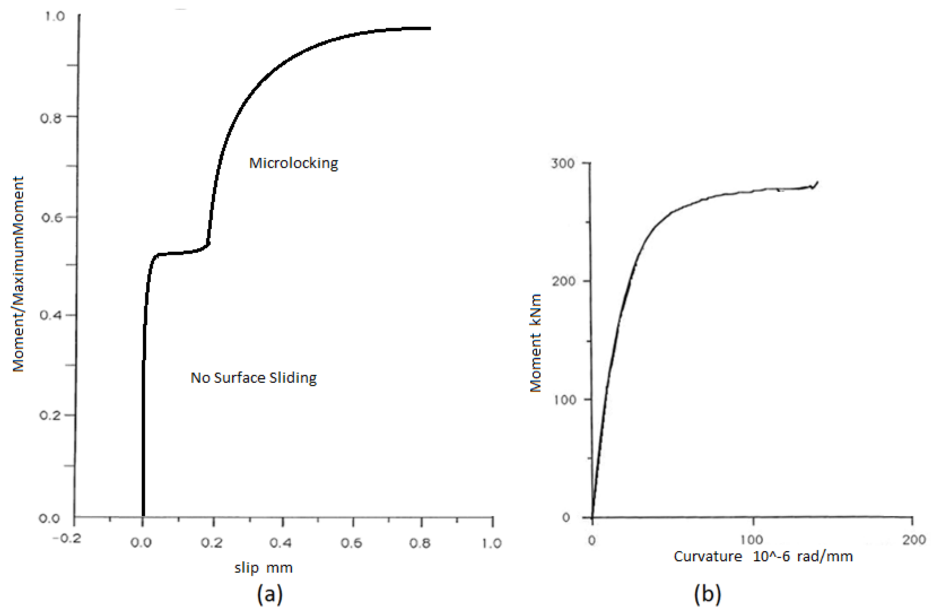


Figure 1. Slip vs normalized Moment curves (a) and Moment Curvature relationship (b) in test CB41 [3].

Curves in Fig. 1 are normalized to the ultimate theorical moment, hence since ultimate resistance is always reached, it can be concluded that the slippage between steel and is negligible even when it happens before reaching the maximum moment. In any case, for a moment applied equal to 50 % of the ultimate moment of rupture, it can be assumed that there is no surface sliding.
It can be considered that the contribution of chemical bonding is active up to a value of the limited moment. Once this bond that can be considered brittle is broken, there is a sudden jump of relative sliding, where the initial mechanism of chemical adhesion disappears and a new mechanism related to friction develops, which is named microlocking.

The simple comparison between the behavior of Fig. 1 (a) and (b) leads to the outline of the following conclusions:

- before reaching the ultimate moment any jumps or interruption in the Moment-curvature curve that can be caused by any loss of grip is evident;
- in correspondence of the sliding jump registered in strain gauge at 50% of the ultimate moment, any discontinuity of the moment-curvature is shown.

Slippage under Axial Load Conditions

First of all it is important to qualify the available tests, in order to establish the possibility of correlate the type of test carried with the practical situation. A large number of studies conducted by some researchers have been performed through push-out tests. This type of test provides an important theoretical evaluation of the sliding stress f_b obtained by dividing the ultimate load supported, for the contact area. Axial Push-out test is here proposed because it is the simplest and the best way to simulate the load transmission in the examined connection.

Push-Out Test – Sliding Stress Evaluation

Experimental studies on the adherence in filled tube columns have been conducted mostly using push-out test [4], [5], [6], [7], [8], [9], [10]. The push-out test (Fig. 2) consist of applying a compression force which tends to push the concrete inside the steel jacket.

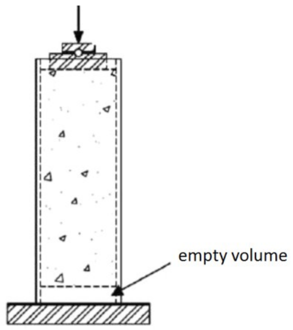


Figure 2. Push-out test setup.

The volume of air below the base plate is necessary in order to transfer of the entire action to the steel jacket, giving the reliability of the fully the capacity of collaboration for adhesion. Using strain gauges it is possible to determine the deformation of the pipe and the displacement of the inner concrete core, evaluating the slip compared to the variation of the load imposed.

The shear resisting stress due to adherence is calculated as:

$$f_b = \frac{N}{p_b H_b} \quad (1)$$

Where N is the axial force, p_b is the perimeter of the shape, H_b is the interface area high.

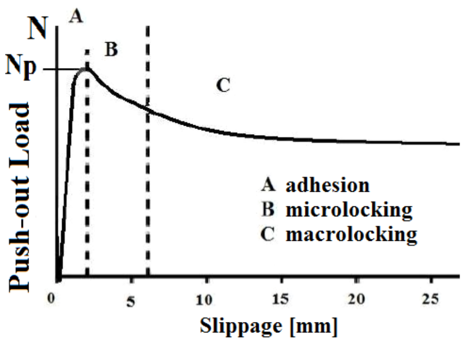
In this type of test, in addition to the evaluation of the average adhesion resistance, it is possible, by studying the force-slipping curve, make some considerations about the resistant mechanisms related to adherence. In this sense, the mechanisms of resistance are attributable to:

- Adhesion that is caused by chemical adherence between concrete and steel; as seen it is a fragile mechanism, which is active only in the early stages of loading. This phenomenon is present only in case there is contact between the surfaces of the materials and for this reason depends on the proportion of water and cement and is linked to shrinkage of concrete;

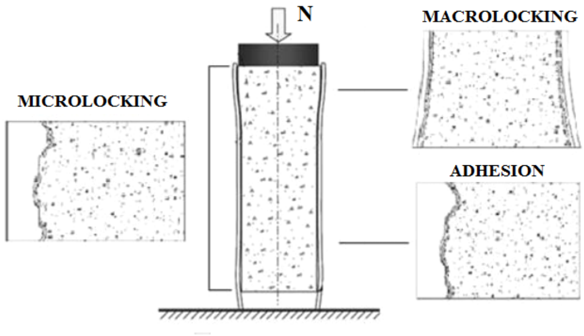
- Friction force that becomes active when adhesion forces fail and the force transferring depends primarily on the roughness of the interface surface; this existing mechanism is said microlocking.;

- Wedge effect that begins when all the concrete core is in motion, i.e. when the micro-bonds and local friction fail. A large scale system of friction is hence generated caused by dimensional irregularities of the steel jacket, that tend to avoid concrete displacements. This mechanism is called macrolocking.

From the tests analyzed in the research, the following factors that affect adherence are identified. The geometry of the section is a determining factor: for the pillars with circular sections, said CCFT adherence is higher compared to the pillars with rectangular section, said RCFT; sections of larger dimensions show lower adherence, because of the shrinkage of the concrete; the class of concrete strength and the strength of steel have no particular influence on adherence. Observing the typical push-out curve as in Fig. 3, the ascending rigid branch is characterized by very limited dsplacements between the two materials and it is related to the mechanism of adhesion. Once the peak of adhesion is reached (~0,2 mm) and the chemical bond is broken, confined core starts to move inside the jacket: in this curve branch the phenomena of friction between the contact surfaces due to the roughness of the surface begin. In the moment when local rupture phenomena occur for concrete crushing at the interface, new frictional phenomena related to macro-imperfections of the steel jacket start to happen. In this way the concrete core will be restrained in macro-wedge of the jacket that will generate due to buckling of the steel element. This contribution continues until the complete expulsion of the confined concrete and is the only mechanism of adhesion remaining until the ultimate condition.



(a)



(b)

Figure 3. Push-out qualitative curve (a) and resistance mechanisms (b)

Proposed Model - Adhesion Proposal Curve in CFST

Introduction

The transferring of the floor loads from the beam-column joint to the composite column will take place for adhesion between steel and concrete inside the jacket, just below the opening in the joint. The behavior is comparable to the behavior of a push-out test where the load must be transferred partially to the steel jacket to achieve the behavior of a composite section. In order to ensure that no sliding between steel and concrete develops, an adherent resistant force f_b variable along a certain lenght L_b of transmission on an effective perimeter p_b. These three parameter will be explained in the next Chapter.

In the following it will be shown that, as analyzed by C.W .Roeder [7], the adhesion under operating conditions developed for a transfer length that can be considered half of the section diameter and follows an exponential distribution along tube high. This behavior can be used until interfacial plasticization develops, i.e. slippage corresponds to the maximum value of adhesion $f_{b,lim}$, beyond which slippage happens. Hence it can be assumed that the behavior shear-stress vs slippage can be described using an elastic-perfectly plastic relationship, where the linear elastic branch (with k_{slip} slope) is due to adhesion and microlocking, and the second constant branch is due to macrolocking phenomena. Summarizing:

$$\begin{cases} \tau(x) = k_{slip} s(x) & \text{for } \tau(x) < f_{b,lim} \\ \tau(x) = f_{b,lim} & \text{elsewhere} \end{cases} \quad (2)$$

Where $k_{slip} = 17{,}91\ N/mm^3$ is assumed according to J.F. Hajjar et al. [11].

Proposed Model for Stress Distribution of the Transfered Load

From the analysis of the infinitesimal sector of the tube, differential equations can be obtained for the distribution of the adhesion stresses:

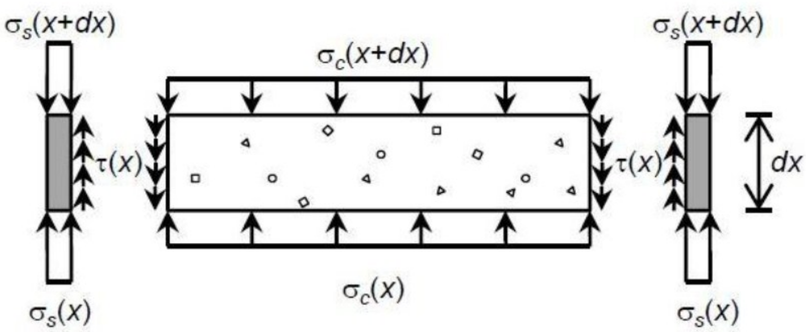


Figure 4. Equilibrium of the infinitesimal column section

$$\Sigma F_c = A_c\sigma_c(x) - A_c\sigma_c(x+dx) - p\,dx\,\tau(x) = 0 \quad (3)$$

$$\Sigma F_s = A_s\sigma_s(x) - A_s\sigma_s(x+dx) - p\,dx\,\tau(x) = 0 \quad (4)$$

giving the following solution:

$$\tau(x) = C_1 e^{-Cx} + C_2 e^{Cx} \quad (5)$$

$$C = \sqrt{\frac{p_b \cdot k_{slip}}{E_C \cdot A_C} + \frac{p_b \cdot k_{slip}}{E_S \cdot A_S}} \quad (6)$$

Where the constants C_1 and C_2 depend from boundary conditions, *Ec* is concrete elastic modulus, *Es* is steel elastic modulus, *Ac* is concrete area, *As* is steel area.

The boundary conditions imposed in order to simplify the problem are based on the results obtained from experimental test. It is firstly assumed that the amount of adhesion at large distance from the point of application of the load tend to zero ($\tau(\infty) = 0$), then $C_2 = 0$.

The second condition is based on the assumption that the load applied to the concrete can be fully transferred in the storey height H_C. This condition give that $C_1 = \frac{N\,C}{p_b(1-e^{-C \cdot H_C})}$. So that finally it is:

$$\tau(x) = \frac{N \cdot C}{p_b(1-e^{-C \cdot H_C})} e^{-C \cdot x} \quad (5)$$

This expression give an undefined length of transferring, but usually the 85-90% of the force is transferred inside the L_b value, already introduced.

Proposed Model - Concrete to Steel Bond Transferring Model

Bond Stress Limit – Sliding Stress $f_{b,lim}$

Factors that mostly influence the adherence performance indicate a close correspondence with geometrical characteristics that are correlated with confining effect of the jacket and the effect of concrete shrinkage; on the contrary, the mechanical characteristics of the materials do not affect adhesion between concrete and steel. For CCFT sections a relationship that depends on the stiffness of the jacket, and consequently to the *D/t* or t/D^2 ratio, is established (where *D* is section diameter and *t* is the jacket thickness). Even the effect of shrinkage/expansion is correlated to that same parameter.

Table 2. Comparison between Test ultimate slip stress and value expressed according to Zhang [12] and Parsley [5] relationships

Author	Specimen	D/t	t/D^2	$f_{b,test}$ [Mpa]	$f_{b,Zhang-1}$	$f_{b,Zhang-2}$	$f_{b,Parsley}$
H. ShakirKhalil[5,6]	X1a	24	0,00035	0,77	0,77	0,74	0,62
	X1b	24	0,00035	0,9	0,77	0,74	0,62
	Y1a	30	0,00022	0,59	0,36	0,47	0,4
	Y1b	30	0,00022	0,58	0,36	0,47	0,4
	Y2a	30	0,00022	0,34	0,36	0,47	0,4
	Y2b	30	0,00022	0,33	0,36	0,47	0,4
	Y3a	30	0,00022	0,37	0,36	0,47	0,4
	Y3b	30	0,00022	0,44	0,36	0,47	0,4
X.Qu [10]	CP1	53	0,00006	0,3	0,05	0,13	0,12
	CP2	53	0,00006	0,27	0,05	0,13	0,12
	CP3	53	0,00006	0,28	0,05	0,13	0,12
	CP4	53	0,00006	0,26	0,05	0,13	0,12
	CP6	53	0,00006	0,32	0,05	0,13	0,12
U.Starossek [9]	S1-S1	24	0,00028	0,68	0,79	0,59	0,5
	S1S2	24	0,00028	0,69	0,79	0,59	0,5
M.A. Parsley [8]	CFT4	32	0,00015	0,29	0,29	0,33	0,28
	CFT3	32	0,00015	0,27	0,29	0,33	0,28
	CFT7	40	0,0001	0,18	0,13	0,21	0,19
	CFT1	40	0,0001	0,18	0,13	0,21	0,19

In the technical Literature different experimental formulas as a function of these parameters are given. In the research the relationships of C.W. Roeder [7], J. Zhang [12] and M.A. Parsley [8] have been analyzed and their expressions have been correlated to the tests of K.S. Virdi [4], H. Shakir-

Khalil [5], C.W. Roeder [7], U. Starossek [9], X. Qu [10], M.A. Parsley[8], on an amount of 57 test database for CCFT, and 19 test database for RCFT. The relationships for $f_{b,lim}$ have been statistically analyzed compared with test results in order to evaluate the expression that better approximates tests (Table 2 for RCFT).

According to this simple statistical evaluation, it can be assumed that the following relationships show the best accuracy:

- for CCFT according to J. Zhang [12]

  $f_{blim} = 196{,}479 \left(\frac{D}{t}\right)^{-1{,}59}$ [MPa] Pearson correlation factor=52%
- for RCFT according to J. Zhang [12]

  $f_{blim} = 42949{,}6 \left(\frac{B}{t}\right)^{-3{,}44}$ [MPa] Pearson correlation factor=89%

Bond Stress Distribution along the Tube – Transferring Length L_b

In order to better understand the adhesion at the steel-concrete interface, the results of the Push-Out analysis conducted by C.W. Roeder et al. [7] is here shown. When the conditions of the interface do not allow slippage (adhesion and microlocking), the stress is distributed exponentially as shown in Fig. 5 , where the adherence is normalized to the compression force and the length is normalized to the diameter D. The maximum value of adhesion is at the top limit of the interface, where the load is applied, and it decays to a value close to zero at a distance of about $0.5\ L/D$.

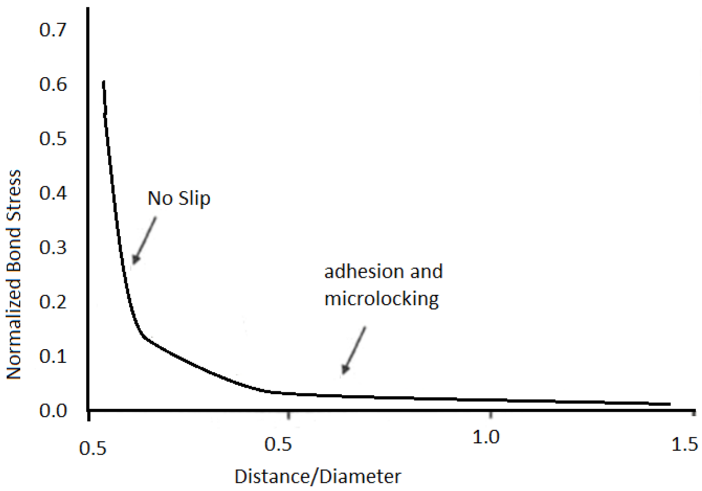


Figure 5. Typical Bond stresses along the height of a circular column CFST

A model for the development of the adherent mechanisms is presented by M.A. Parsley [8] where, from the observation of test result of circular concrete jacketed pillars, it has been given a first uniform stress distribution along the entire perimeter of the interface, that for ultimate limit state length extends for *3,5 D* and a second triangular distribution for serviceability limit state with a length of *0,5 D* involving the entire perimeter interface.

As last information, it must be underlined that slippage must be prevented only for axial load, since when bending moments develop, a local action that improves the local capacity of adhesion starts to act and prevents slippage.

Area of bond Transferring – Perimeter of bond exchange p_b

Only a part of the perimeter of the steel-concrete interface cooperates with bonding between the materials, due to all stiffness differences that can be found in the zones of the steel jacket. Based on observations of the push-out tests and particularly those conducted by H. Shakir-Khalil [5], for samples CCFT, the entire perimeter collaborates in adherence. Otherwise, in sections of RCFT specimens, the rigid parts at the edges better collaborate to adherence. The interaction between the materials also depends on the number of elements converging to the connection; tests on CFST in which only one beam into the connection demonstrate that the load transmitted to the concrete is less, with less involvement of the transmission perimeter. However, it is important to consider that the majority of the connection tests do not come to failure due to slipping, and therefore the loads transferred registered is greater because macrolocking guarantees all the perimeter to collaborate; for this reason, the choice to consider all the section perimeter as resistant it is justified.

Conclusions

This Paper is focused on some of the result of an extended analysis on a wide amount of test carried over the years by many Authors. It provides a simple relationship for the estimation of the bond stress distribution between concrete core and steel jacket along the height of CSFT columns under axial load, carried straightly in the concrete core. For completeness some important information are given on the principal parameters that define the model of force transferring i.e. the adherent resistant limit force $f_{b,lim}$ that must exists on an effective perimeter p_b and the length L_b of transmission.

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