Structures xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Structures

journal homepage: www.elsevier.com/locate/structures

An Analytical Design Method for Steel-Concrete Hybrid Walls

André Plumier [a],*, Dan Dragan [b], Nguyen Quang Huy [c], Hervé Degée [b]

[a] *University of Liege, Belgium*
[b] *Hasselt University, Belgium*
[c] *INSA Rennes, France*

A R T I C L E I N F O

Article history:
Received 2 May 2016
Received in revised form 25 September 2016
Accepted 19 December 2016
Available online xxxx

Keywords:
Composite steel-concrete walls
Hybrid
Columns
Encased sections
Embedded sections

A B S T R A C T

The design of concrete walls or columns reinforced by several encased steel profiles, also called hybrid walls, is similar to the one of classical reinforced concrete, although specific features require adequate design approaches. Experimental research and numerical models demonstrated the feasibility and validity of such structural components, but simple and practical design methods are still lacking regarding their shear resistance. The evaluation of longitudinal shear action effects at the steel profile–concrete interface is a key aspect: research results have been achieved in a more or less recent past for different types of connection but without leading to design conclusions. In this paper, the classical equivalent truss model for reinforced concrete subjected to shear is extended to take into account the contribution of the encased profiles to the shear stiffness and strength. Resulting action effects in the steel profiles, in the concrete and at the steel profile–concrete interfaces are established which allows performing design checks for those three components. In particular, it is evidenced that friction is one of the main component of the resistance to longitudinal shear at the steel profile-concrete interface. It can be directly checked since the proposed method clearly identifies the compression stresses at that location. The validity of the method is assessed by referring to tests results from experimental campaigns in China and in Europe. Some of these tests were carried out without shear connectors welded to the encased steel profiles allowing however achieving the full bending resistance of the element without any apparent problem related to longitudinal shear, like slippage between concrete and steel profile. For some other tests, failure was observed as a consequence of an insufficient shear connection. A detailed assessment of these results shows that the new design proposal is perfectly consistent with all the experimental observations.

1. Introduction

Structural concrete walls are widely used in building structures to provide lateral strength, stiffness, and, in seismic regions, inelastic deformation capacity required to withstand earthquakes. In recent years, steel reinforced concrete (SRC), also called hybrid walls, have gained in popularity. Such walls include steel profiles encased in what for the rest remains a classical reinforced concrete (RC) walls. SRC walls offers the following potential advantages with respect to conventional RC walls: (1) the encased structural steel develops a composite action with concrete, increasing then the compression, bending and shear strength of the walls and reducing the necessary total cross-section area; (2) the steel profiles encased along the wall boundaries increase the deformation capacity and the energy dissipation capacity, these two properties being required for buildings subjected to earthquakes; (3) the encased profiles enhance the weak axis stiffness of the walls and delay the possible out-of-plane buckling failure of wall boundaries; (4) the encased steel profiles can be easily connected with steel and composite steel concrete floor beams that are often used in buildings.

In the past decade, significant experimental research efforts have been devoted to studying the behavior of SRC walls: Wallace et al. [1], Qian et al. [2], Ji et al. [7], Ying et al. [3], Dan et al. [4,5,6]. Design provisions for SRC walls have been included in some leading design codes: AISC 341-10 [8], Eurocode 8 [9] and JGJ 3-2010 [10]. Various types of numerical models have also been developed for modelling RC walls: multiple vertical-line-element models, Vulcano et al. [11], Orakcal et al. [12], fiber beam-column models by PEER [13], and multi-layer shear element models: Miao et al. [14] and Lu et al. [15]. However, although all these tests and numerical models do indeed provide valuable knowledge on the behavior of SRC walls, they don't directly lead to practical design tools. Resorting in a systematic way to a validation by testing or by sophisticated FE models requires indeed a huge investment incompatible with the daily practice of design engineers. Sections 2 to 5 propose an analytical method which allows simple and easy design checks for SRC walls subjected to axial force, bending and shear. Sections 6 to 9 present then a validation of the design method by referring to recent experimental tests. These developments were achieved in the frame of the

---

* Corresponding author.
E-mail addresses: a.plumier@ulg.ac.be (A. Plumier), Dan.dragan@uhasselt.be (D. Dragan), Quang-Huy.Nguyen@insa-rennes.fr (N.Q. Huy), Herve.degee@uhasselt.be (H. Degée).

http://dx.doi.org/10.1016/j.istruc.2016.12.007

Please cite this article as: Plumier A, et al, An Analytical Design Method for Steel-Concrete Hybrid Walls, Structures (2016), http://dx.doi.org/10.1016/j.istruc.2016.12.007

Smartcoco Project funded by the European Commission and dealing with different types of steel-concrete hybrid structures Degee et al. [16].

2. Analysis and resistance of walls subjected to bending and axial force

In a wall subjected to a combination of design axial force N_{Ed} and bending moment M_{Ed}, encased steel profiles are submitted essentially to longitudinal strains. The contribution of the individual bending stiffness of each profile to the global bending stiffness can be seen as secondary. For instance, in the case of the wall section in Fig. 1, the stiffness EI_H of the 3 encased HE120B sections is equal to 5.45×10^{12} N mm^2. In comparison, the wall stiffness EI_{wall} calculated for instance according to Eurocode 4 [17] expression is much greater:

$$EIe_{ff,II} = 0.45E_{cm}I_c + 0.9E_sI_s + 0.9E_aI_a = 2,88 \times 10^{14}\,\mathrm{Nmm}^2 \qquad (1)$$

where subscripts a stand for steel profiles and subscript s for classical reinforcing bars.

The ratio EI_H/EI_{wall} is smaller than 2%. This means that the second moment of area of encased steel the profiles, just like the one of classical reinforcement bars, does not significantly contribute to the global wall bending stiffness, so that the section strength in combined bending and compression can be evaluated by common methods used for usual reinforced concrete.

Besides that, it has been shown by Bogdan et al. [19,20] that the Plastic Distribution Method (PDM), as defined in Eurocode 4 [17] or in AISC2010 [18], and which assumes rectangular stress blocks can also be used.

A subsequent question rises can a steel profile be reduced to a single bar in the model of the cross-section, or is a group of bars required? The second solution is seen as preferable given that a model with a single bar provides only an approximation of the position of the plastic neutral axis of the wall. The modelling of each steel profile by means of two circular bars for each flange and two for the web - Fig. 1 - was proved valid by Bogdan et al. [20] who showed that the interaction curves of axial force N - bending moment M were practically identical for profiles modelled explicitly or by such a set of bars. A modelling with bars was also proved valid for columns with 4 encased profiles.

Yield stress and elongation capacity are similar in encased profiles and standard reinforcing bars, but profiles do not present surface indentations. The bond strength of profiles is 7 times lower than the one of ribbed bars and the difference increases for higher concrete classes. It is shown in Plumier [21] that, although profiles exhibit a larger surface to develop the bond, this does not compensate the low bond strength. This results in the fact that a specific design check is required for encased steel profiles, demonstrating that the longitudinal shear between profiles and concrete can effectively be resisted by an adequate shear connection.

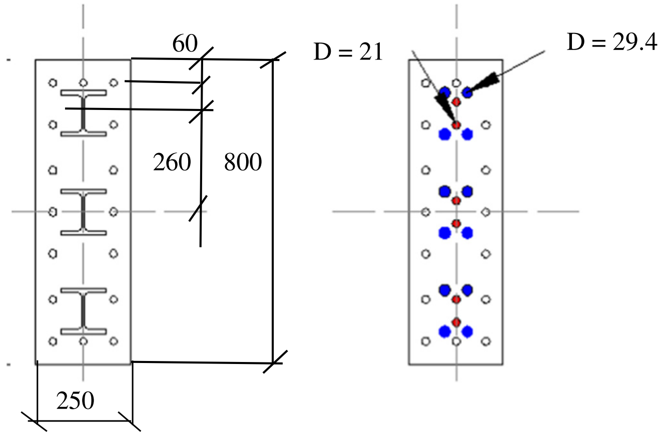


Fig. 1. Wall with 3 encased HEB120 profiles. Left: real section. Right: model with bars diameter $D = 21$ mm for the web and $D = 29.4$ mm for the flanges. Other characteristics: HEB120 height h = width $b = 120$ mm; flange thickness $t_f = 11$ mm; web thickness $t_w = 6.5$ mm. Wall width $b_w = 250$ mm. Longitudinal bars diameter: 20 mm. Ratio of cross-sectional area of encased profile to area of boundary zone 250 × 240 mm: 5.7%.

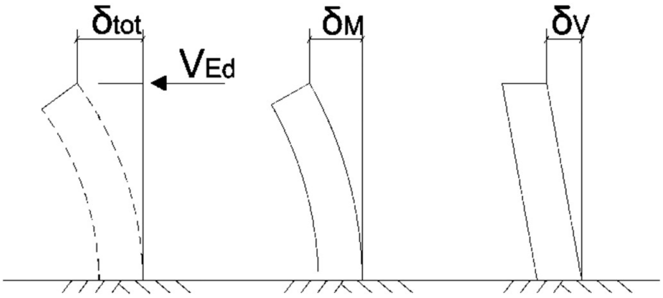


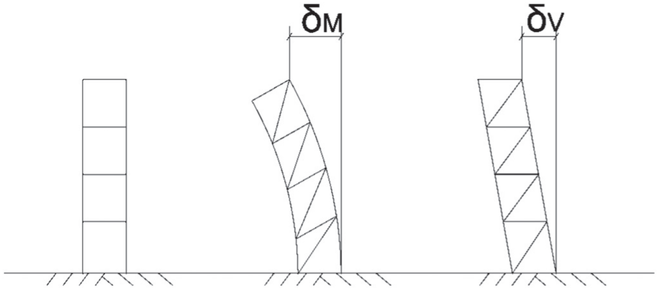
Fig. 2. Components of the deformation of walls.

Moreover, the effect of the shear force $V_a = V_{a,Ed}$ in each profile on its resistance to axial force has to be considered in the evaluation of the wall resistance to combined bending and axial force, see Section 5.

The possibility to define by a straightforward analytical method the transverse shear in each profile as well as the longitudinal shear between steel profiles and concrete corresponding to the applied axial force N_{Ed}, bending moment M_{Ed} and shear V_{Ed} is thus a need for a practical implementation in the daily design practice.

The classical beam theory was the first reference used to establish a complete calculation procedure for beams subjected to shear – Plumier et al. [22,23]. However, this procedure exhibits two drawbacks. First, the classical beam theory is strictly valid only for elements made of a continuous material resisting equally to tension and compression and not subject to cracking, which is in principle not the case of concrete. Second, the method requires the partition of the wall into subdivisions which are either only reinforced concrete or concrete reinforced by encased profiles. In each subdivision, the calculation of the moment of inertia and of a set of first moment of area corresponding to each plane section where shear is calculated have to be made, so that the calculations become long and tedious.

For those reasons, it was decided to develop an alternative analytical method based on the Mörsch truss model – Mörsch [24], this latter being the internationally recognized reference method in reinforced concrete codes like Eurocode 2 [27] or ACI318-14 [30].



a) Hypothesis 1 b) Hypothesis 2

Fig. 3. Deformed shapes of a truss in bending and in shear.

Please cite this article as: Plumier A, et al, An Analytical Design Method for Steel-Concrete Hybrid Walls, Structures (2016), http://dx.doi.org/10.1016/j.istruc.2016.12.007