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Experimental study of the force transfer mechanism in transition zone between composite column and reinforced concrete column

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Abstract

The current EN 1992 provides structured information related to the design of reinforced concrete columns or reinforced concrete column beam connections. On the other hand, EN 1994 gives enough information on the design of composite columns but none of the current codes provide details about a possible transfer zone in the case of usage of RC and composite column solution.
The current study tends to fill the gap between these two norms. In the current experimental campaign, carried out in the frame of the European research program SmartCoCo, it is presented as a calibration method for a tentative design method which has been elaborated by one of the authors based on theoretical strut and tie reasoning.
The objective of the current paper is to present the results of the experiments and aims to validate the theoretical approach for calculating the force transfer mechanism in the transfer zone. The experimental campaign comprises of 4 columns and 4 column-beam connections, all of them being composed by a RC part and a composite. The tests are performed on vertical column, simply supported with a width of 350mm, length of 380 mm and a height of 3850 mm with a regular concrete quality (C25/30).
This contribution describes the test specimens, summarizes their design, presents a selection of the most relevant results from analog and digital measurements and a short interpretation of the obtain results. We concluded from this set of tests that the new design method is able to explain the force transfer mechanism with a good accuracy and can therefore be considered as a suitable solution for designing practical cases.

Keywords: *Concrete reinforced by steel profiles; experimental results; Digital Image Correlation (DIC); composite column.*

1. Introduction

Steel-concrete composite columns made of reinforced concrete with encased hot-rolled steel section are well known since the early 1900 as very interesting resistant and slender compression members. They are generally used as load-bearing members in composite frame structures. The composite structures literature contains plenty of articles presenting the behaviour of composite columns connected to different structural elements like slabs, RC beam or composite beams. The literature and the standards are however not defining nor presenting guidelines or rules regarding the transition zone in a column that would be composite on a part of its height and pure RC on the rest. This type of zones were initially studied within the frame of the INERD (INnovations for Earthquake-Resistant Design) research project [1]. The project had as goal, the development of a solution to mitigate soft storey failures of RC moment resisting frames submitted to earthquakes by locally making them stronger and more ductile thanks to a steel profile embedded in the critical zones of the columns. It was therefore required that the transition zone should not be weaker than the rest of the column. This structural solution was meant to be applicable to concrete moment resistant frames and consisted of enclosing a hot rolled steel profile inside the RC column at the first storey only of the building (i.e. the soft-storey prone level). This additional profile was not considered in the structural design and was only supposed to act as a safety belt activated in case of the earthquake action. The publications about INERD research project [2, 3] proposed design guidelines for the connection between both segments of the column, one being composite and the other one reinforced concrete with appropriate values of shear and bending forces to be transferred, in the presence of beams connected to the column in the transition zone. The local force transfer mechanism between the steel profile and the surrounding concrete in these zones was however not satisfactorily considered. Therefore, a deeper investigation of this transfer mechanism was carried out in the research project SmartCoCo (Smart Composite Constructions) [4]. The final report of this research program includes an analytical approach for the design of transition zones, experimental assessment of elements designed according to this design proposal and numerical simulation to extend the experimental results and achieve comprehensive conclusions. The present paper is mainly going to present the experimental part after a short summary of the proposed design procedure as applied to the test specimens.

2. Design principles of the specimen

The preliminary assessments of the specimens started considering the results and the dimensions of the experimental campaign performed during the INERD project. Therefore, the proposed solution was a regular composite section made out of a HEB140 steel profile, fully embedded in concrete to obtain a 350x380 mm cross-section (Fig.1a). In the attempt to target a specific failure mode of the specimens, namely, failure in the connection zone, it was considered necessary to increase the vertical reinforcement ratio up to 4.35% to ensure the bending resistance of the column. Based on the approach presented by the authors [5] showing that a steel profile can be replaced for the bending verification by equivalent rebars, 4 additional ϕ40 are thus placed in the lower part of the columns, as shown in Fig. 1b. In order to evaluate the possible favourable effect of a beam at the level of the transition zone in the column, some specimens were constituted of an independent column, while some other were including a crossing beam (see Fig. 4). For these, latter the beam was designed as having the same dimensions as for the columns, but a lower longitudinal reinforcement ratio of 1.6%. The beams were finally defined as 400x380mm reinforced by 4ϕ28 rebars (Fig. 1c).

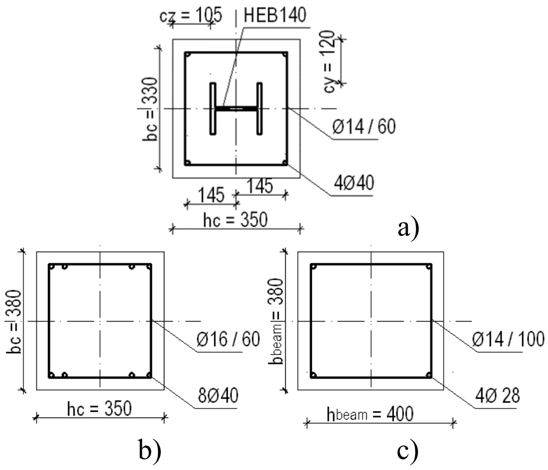


Fig. 1. a) Composite column cross section; b) RC column; c) RC beam.

As a starting point of the design, the action effects in the composite part of the column can be subdivided into a part taken by the steel profile and a part taken by the reinforced concrete (as in Eq.(1-3)):

$$M_{Ed} = M_{Ed,a} + M_{Ed,c} \tag{1}$$

$$V_{Ed} = V_{Ed,a} + V_{Ed,c} \tag{2}$$

$$N_{Ed} = N_{Ed,a} + N_{Ed,c} \tag{3}$$

The part of the internal forces that must be transferred to the pure RC part is thus the component denoted with the subscript "a". Based on the superposition of effects, the diagrams of local shear distribution on the steel profile and the concrete section corresponding to $M_{Ed,a}$ and $V_{Ed,a}$ can be estimated as illustrated in Fig. 2.

The design of the transition zone is then based on a strut and tie model allowing the transfer of this local shear force. Three possible schemes can ensure this transfer: with a strut angle equal to 45º (Fig.3a), smaller than 45º (Fig3b) or larger than 45º (Fig3c).

Based on Eurocode 2 [6] using the resistant design maximum stress at the edge of the nodes, a compression strut resistance can be calculated, further resorting to Eq.(4-5) to calculate the resistance design shear associated to failure of the compression struts.

$$F_{strut} = \sigma_{Rd,max} \cdot b_s \tag{4}$$

$$V_{Rd,s\,\theta=45} = 2 \cdot F_{strut} \cdot \sin\theta \tag{5}$$

Considering that, for each of the schemes, a resistant design maximum stress V_{Rd} can be calculated and the design stress can be obtained using Eq. (6).

$$V_{Rd} = \max(V_{Rd,\theta<45}, V_{Rd,\theta=45}, V_{Rd,\theta>45}) \quad (5)$$

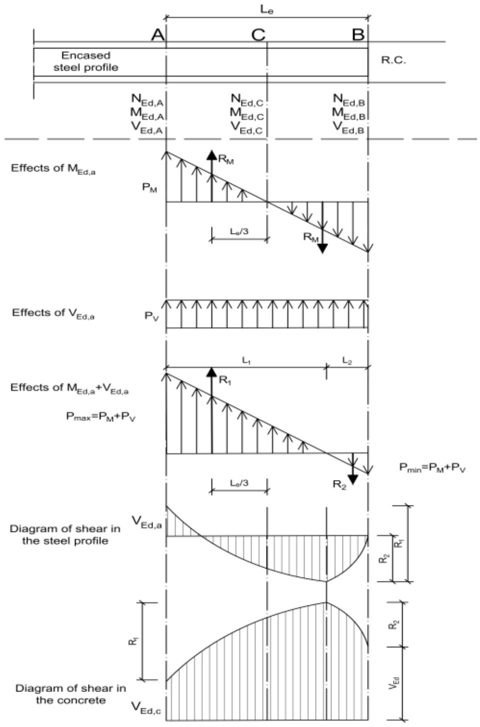


Fig. 2. Pressure and shear diagrams at steel – concrete interface.
Fig. 3.

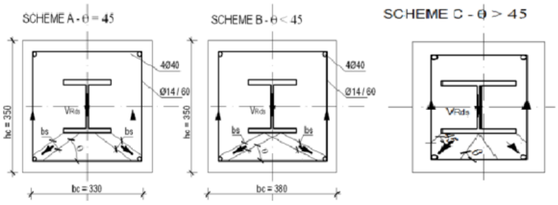


Fig. 4. Possible compression strut development.

3. Experimental campaign

The experimental campaign consists of testing 8 columns based on 2 global systems, namely without and with horizontal beam, each defined by a different positioning of the transition zone with respect to the beam. Each of the 4 configurations is tested with increasing horizontal load at 2 different levels of compression, kept constant during the lateral loading as presented in Table 1.

Table 1. Summary of specimens.

Specimen	Anchorage	Beam	Vert_F(kN)
1a-S-N00	Short	No	75
1a-S-N05	Short	No	300
1b-S-N00	Long	No	75
1b-S-N05	Long	No	300
2-Lb-N00	Long	Yes	75
2-Lb-N05	Long	Yes	300
3-Sb-N00	Short	Yes	75
3-Sb-N05	Short	Yes	300

Based on the configuration and the test setup used during the INERD research project experiments – the testing facility being actually the same – the static scheme of the experiment was a simply supported cantilever column with or without contact point in the case of the specimens that included the horizontal beam as presented in Fig. 4. Fig. 5 shows a picture of the entire setup for the "cross" specimen (i.e. with beam).

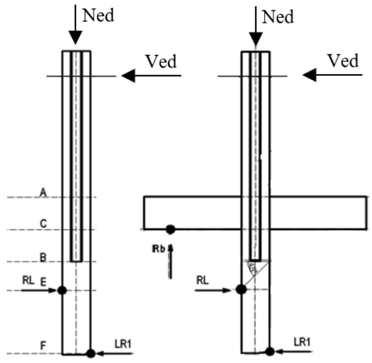


Fig. 5. Static scheme of the experiments.

The specimens were instrumented using a series of 15-17 strain gauges on the steel profiles and tensioned vertical steel rebars at different height in the transition zone. All tests are carried out with a horizontal force increased progressively up to failure or excessive drift. During the tests, a set of 4 load cells were measuring forces R_b, RL, N_{ed}, and V_{ed} from Fig. 4. A total of 6 linear transducers and 3 inclinometers surveyed the displacement and rotation of the tested specimen [7]. The above-mentioned devices are going to be referred from now on as DAQ (Data Acquisition) system.

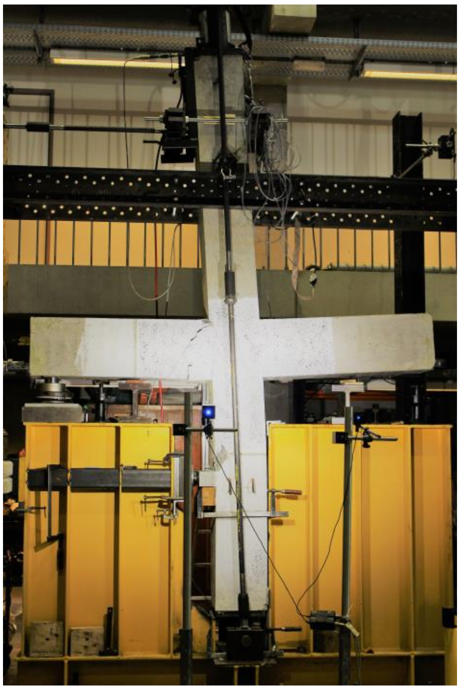


Fig. 6. Overview of the test setup.

The second instrumentation technique used is based on the correlation of consecutive images with a specific load used for processing the concept of deformation mapping. The technique called DIC (Digital Image Correlation) relies on the mathematical correction of the curvature of the image shot by the camera and tracks the movement of each group of pixels trough the set of images. Due to the limitations of the system used for DIC, the surface (approx. 1 m²) chosen to be covered by the monitoring system represents the 15 cm above the node and 50 cm on each side of the node from the beams (Fig. 6).

Fig. 7. Surface surveyed by the DIC system.

4. Results

The analysis of the obtained results was divided in two different parts. One quantitative, based on the measurements obtained from the analog devices (here being included: load cells, linear transducers, inclinometers and strain gauges) and the other one visual-qualitative, based on the processing of the images recorded using DIC technique. A detailed analysis of the results is available in [8]. The following sections illustrate a selection of interesting observations.

4.1. Classical measurements

The general processing of the results from the DAQ system shows that the global behaviour of the specimens is very similar, meaning that the specimens 1A and 1B have the same stiffness independently from the anchorage length of the steel profile (Fig. 7). The same situation is observed for specimens 2L and 3S, with the remark that, as expected their stiffness is increased by the presence of the beam (Fig. 8).

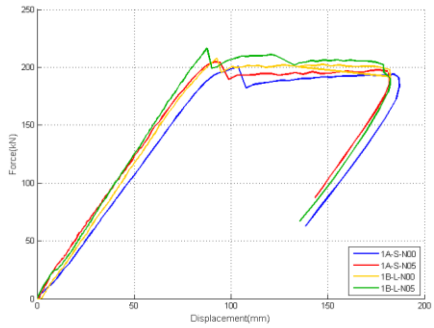


Fig. 8. Force-displacement on column specimens.

The non-consistent curve obtained for the specimen 2LB-N00 is related to an uncontrolled unloading-reloading phase that occurred during the test, associated with a slippage in the setup. Without this slip, the graph would just be similar to the other 2LB specimens.

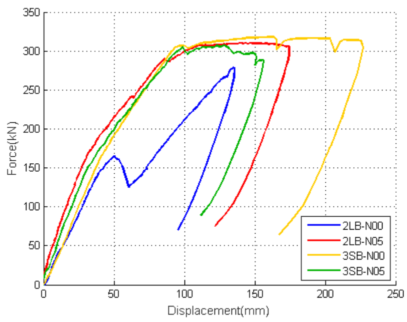


Fig. 9. Force-displacement on cross specimens.

For all the tests, none of the specimens has presented a rupture due to the yielding capacity of the steel profile and steel rebars. Therefore, all the tests where stopped due to the excessive displacement at the top of the specimen, values that reached a drift up to 7%. This also justifies the fact that the transition zone designed according to the methodology summarized in section 3 does not constitute a weak point of the structural system.

In order to investigate further the behaviour of the transition parameter, a relevant measurement is the evolution of the longitudinal strains on the flanges, as given in Fig. 9. The different curves correspond to the respective tension and compression side of the profile (solid and dash lines), P1 being closer to the end of the profile and P3 still the main composite part of the column. As expected, strains are linearly increasing when the external load is increased but, more interesting, these graphs show the decrease of the strain in the profile (i.e. decrease of the bending moment $M_{Ed,a}$) while the global composite moment is still increasing. This justifies the internal force distribution described in Fig. 2 and being the basis of the design method.

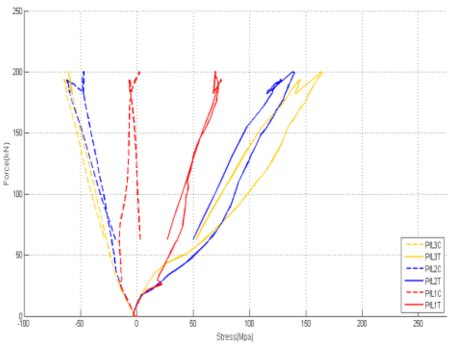


Fig. 10. Force vs Stress in the flanges (T = tensioned; C = compressed) of the steel profile at 3 different heights.

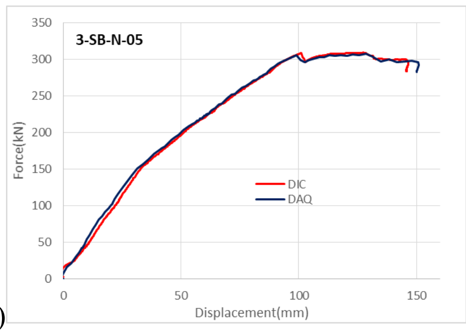
Table 2 compares the maximum expected horizontal loads at failure predicted by the application of the design method vs. the effectively measured values. The table shows that the design method is able to predict in an accurate way the failure loads for the "cross" specimens. The method significantly underestimates the resistance for the pure column specimens with a short profile (i.e. when the transition is rather far from the point where the maximum moment is reached). Otherwise, it seems to underestimate the resistance for the long profiles, when the transition zone corresponds to the location of the maximum bending moment (which corresponds also to the location of the horizontal support). This last observation, coupled with the results in terms of cracking pattern given later on, is likely to let think that there might be a possible interaction between the local transfer mechanism and the mechanism associated to the load introduction at the support. Additional investigations are however necessary to clarify this issue before definitive validation of the proposed design methodology in such an unfavourable configuration.

Table 2. Predicted vs achieved horizontal loads.

Specimen	Predicted horizontal load (kN)	Achieved horizontal load (kN)
1a-S-N00	101.8	200
1a-S-N05	101.8	204
1b-S-N00	303.6	208
1b-S-N05	303.6	216
2-Lb-N00	280.2	278
2-Lb-N05	280.2	310
3-Sb-N00	316.7	318
3-Sb-N05	316.7	308

4.2. Digital Image Correlation technique

The first step in the use of this processing technique consists of an initial comparison of the results with the ones obtained by analog measurements, considered much less environmental sensitive. The comparison of the top displacement (Fig. 10a) and the beam-end displacement (Fig. 10b) measured by both systems confirms the reliability of the measurements performed using the DIC technology.

a) 

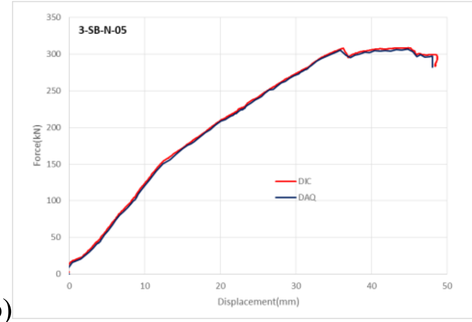
b)


Fig. 11. Force-displacement comparison: a) top b) beam end.

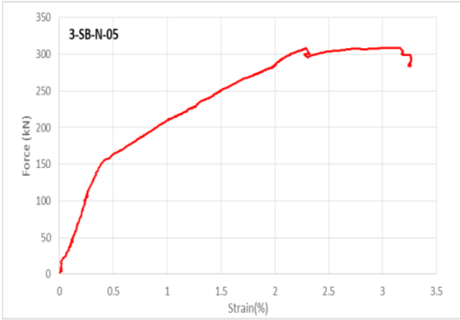


Fig. 13. Force vs Strain on main vertical crack on the beam.

The primary benefit of using the DIC technique is to observe and measure the crack development. It is considered that the crack opening and directions represent the best indication of the struts developed into an element considered as working according to a strut and tie model, as supposed herein for the design of the test specimens. After processing the survey made using the DIC system, a set of cracks that were not visible initially on the specimen can be identified (Fig.11).

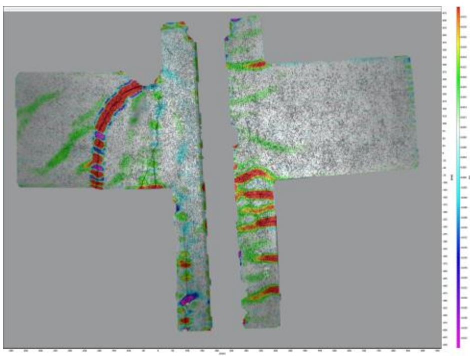


Fig. 12. Strains Syy on specimen 3SB-N05.

It can be seen in the figure that the horizontal cracks are stopping in the same position as the end of the steel profile. Another observation is that the cracks developed on the tension side of the column are less wide in the area with the horizontal beam due to the confinement effect.

According to the chosen proportioning of the beams and columns, it was expected that the beams were going to fail first. This is confirmed by looking at the opening of the vertical crack present in the beam (Fig. 11) and at the equivalent strains on the rebars (Fig. 12).

By observing the crack patterns at the backside of the specimens, one can clearly identify three combined failure modes. In Fig. 13, it is noticed (in the order of their occurrence): (i) a set of vertical cracks due to bending moment on the horizontal beam; (ii) a set of horizontal cracks on the column due to the bending of the column, and (iii) a set of cracks with a inclined directionality spanning from one support point to another, but clearly avoiding the steel profile in the node area.

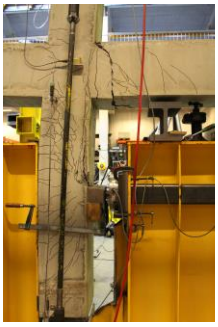


Fig. 14. Crack pattern on specimen 3SB-N00.

It can also be seen that the specimens 1A and 1B are presenting the same crack patterns as 2L and 3S, evidencing the flexural and diagonal cracks and a vertical crack starting from the support point due to the concrete crushing (Fig. 14).

Based on these results, strengthened by the additional strain evolution at crack level given in Fig. 15, it can be concluded that the failure is, as mentioned before, not reached due to pure bending, but due to a combined effect of the bending and the load introduction at the support.

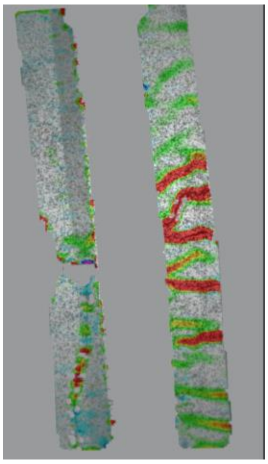


Fig. 15. Strains Syy on specimen 1A-N75.

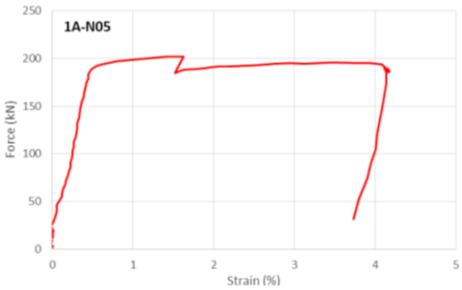


Fig. 16. Force vs Strain of main horizontal crack.

5. Conclusion

The present paper has presented the first results obtained from an experimental campaign aiming at characterizing the force transfer mechanisms in the transition zones of columns composite on a part of their height and made of classical reinforced concrete for the rest.

The main measurements are presented, emphasizing on the crack patterns obtained by a DIC technique.

The results are compared with the application of a tentative design method based on a strut and tie model in the transition zone. This comparison provides a good agreement for situations where the transition zone of the column is located near a crossing beam. The accuracy and safety of the design method is however questionable for a situation without a crossing beam, with an apparently important influence of the interaction of local load introduction with the local mechanisms in the composite-to-RC transition zones. All results however still require a thorough analysis, regarding the measurement on the strain gauges in particular, in order to get a better insight in the involved mechanisms and adjust the proposed design method accordingly.

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