Steel and Composite Structures, Vol. 8, No. 4 (2008) 329-342
DOI: http://dx.doi.org/10.12989/scs.2008.8.4.329

Experimental study of beam-column joints in axially loaded RC columns strengthened by steel angles and strips

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(Received November 22, 2007. Accepted May 2, 2008)

Abstract. The strengthening of reinforced concrete (RC) columns by steel angles and strips (steel cage) is one of various techniques available to increase ultimate column load. Different authors have shown the influence of the beam-column joint on the behaviour of columns strengthened by steel cages. This paper presents an experimental study carried out at the Universidad Politécnica de Valencia with the aim of analysing two different techniques to solve the strengthening close to the joint and the influence on the behaviour of RC columns strengthened steel cages. The ultimate loads obtained in the laboratory tests for these two techniques are compared to that specified by Eurocode 4.

Keywords : RC columns; strengthening; retrofitting; steel cage; beam-column joint; experimental study.

1. Introduction

It frequently happens that RC columns in a building need strengthening. This may be due to problems in the columns themselves (e.g. from using low quality construction materials), requiring the columns to support greater loads than those predicted in the initial structure design (possibly because of a change in the activity for which the building was designed), or as a result of accidents (e.g. fire damage).

There are three principal techniques available for strengthening RC columns: concrete jacketing, steel jacketing and composite jacketing (FRP). One of the steel jacketing variations consists of steel caging (see Fig. 1) and is recognised as being an easily applied and inexpensive technique (Oey and Aldrete 1996).

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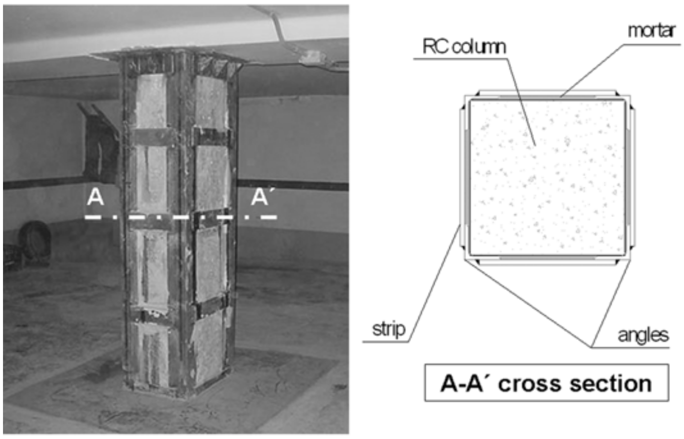

Fig. 1 Example of RC column strengthened by steel angles and strips

Steel caging involves the use of longitudinal angle sections at each corner of the column with transverse steel strips welded to the angles (Frangou *et al*. 1995). The space remaining between the cage and the column is filled with cement or epoxy mortar.

The use of steel caging is a common practice (Tamai *et al*. 2000) and to date has been used in many different countries, such as: the Czech Republic (Cirtek 2001a), Japan (Fukuyama and Sugano 2000), Greece (Wu *et al*. 2006) and Spain (Adam 2007). As Wu *et al.* (2006) indicate, strengthening of this type is fully effective for increasing the strength and ductility of RC columns. CEB-FIB (2003) also testifies to the effectiveness of the method.

As can be gathered from the work of Ramírez and Bárcena (1975), Ramírez *et al*. (1977), Ramírez (1996), Adam (2007) and Giménez (2007), when an RC column is strengthened by a steel cage, a detailed study of the beam-column joint must be carried out, owing to the fact that this element can influence the behaviour of the strengthened column.

Various authors have studied the behaviour of RC columns strengthened by steel caging (Ramírez 1995, Cirtek 2001a 2001b, Calderón *et al.* 2006, Giménez *et al.* 2006, Adam *et al.* 2007). To date, however, no study has been made of the behaviour of the beam-column joint in columns strengthened in this way. Motivated by the need to study the influence of this factor in steel-jacketed columns, the Institute of Concrete Science and Technology (ICITECH) of the Universidad Politécnica de Valencia is at present carrying out research on the subject.

This paper presents an experimental study of beam-column joints in axially loaded RC columns strengthened by steel caging.

2. Mechanisms involved in the behaviour of RC columns strengthened by steel angles and strips

2.1. General

Strengthening columns by means of steel caging increases the ultimate column load. To understand the behaviour of RC columns strengthened by this technique, it is necessary to know the mechanisms involved in increasing ultimate load. With this aim in mind, the following section analyses the load transfer mechanism from concrete column to steel cage by shear stresses, direct transmission loads and the confinement effect in the column produced by the cage.

2.2. Transmission by shear stresses

One of the mechanisms involved in the load transfer to the steel cage is the shear stress transmission through the layer of mortar between column and cage. Part of the load applied to the ends of the strengthened column is transferred to the steel cage in this way. This means that for correct load transmission to occur, close attention must be paid to the contact between column and cage. As described in the previous section, the contact between the concrete in the column and the steel cage is composed of a mortar interface, normally made of cement. Fig. 2(a) shows a scheme of this type of load transmission mechanism.

2.3. Direct transmission loads

Adam (2007) has pointed out that column-cage load transmission can take place through the mechanism known as “direct transmission loads”, based on the transmission of loads through the beam-column joint. Loads may be transmitted to the cage in two ways, depending on the type of strengthening employed in the beam-column-joint zone:

1) If capitals are included at each end of the cage, loads applied to the beam are transmitted to the steel cage through the capitals. Loads from an upper floor of the building are also transmitted to the cage through the beam via the capitals. Fig. 2(a) shows a scheme of how this transmission occurs.
2) If steel tubes are employed through the beam-column joint and welded to the steel cage as recommended by Adam (2007), the loads applied by the upper floors are transmitted to the cage by the steel tubes (see Fig. 2b).

If neither of these elements are included in the beam-column joint, direct load transmission cannot be considered, as shear stress is then the only mechanism involved in transmitting loads to the steel cage.

As stated in Adam (2007), the capitals are easier to assemble than the tubes; however, using the tubes a higher efficacy is obtained for the direct transmission of the loads.

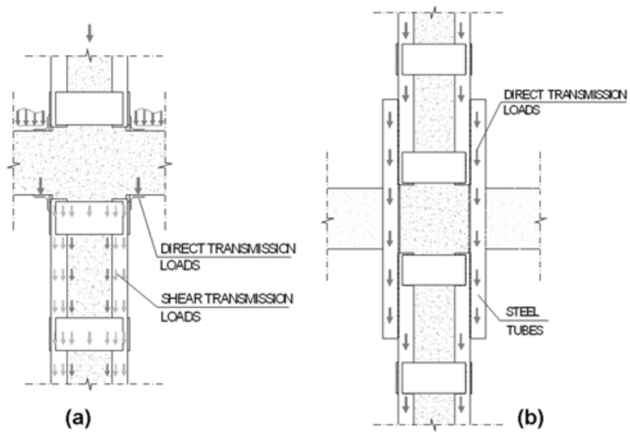

Fig. 2 Load transmission mechanisms

2.4. Confinement imposed by steel caging

When concrete is subjected to triaxial compression its strength increases. The confinement mechanism is thus seen to play an important part in increasing the ultimate load of strengthened columns. Different authors (Cirtek 2001a 2001b, Wu *et al*. 2006) have shown that strengthening composed of a steel cage imposes a considerable degree of confinement on a column, which in turn increases the concrete's compressive strength. This aspect has been demonstrated by Calderón *et al*. (2006), Giménez *et al*. (2006), Adam (2007), Adam *et al*. (2007) and Giménez (2007), in experimental and numerical studies. This confinement mechanism is due to the fact that the steel cage prevents the free transverse dilatation of the concrete in the column caused by the Poisson effect. When columns are subjected to compression, therefore, loads are produced perpendicular to the column axis due to confinement. This confinement pressure will be highest in the area of the cage covered by the steel strips, since these are the zones of greatest stiffness as regards transverse deformation.

3. Specimen characteristics

3.1. General

Specimens were designed with the aim of simulating a building structure zone as can be seen in Fig. 3. They consisted of two lengths of RC column with a central element representing a beam, so that the beam-column joint was situated at the centre of the specimen.

Column cross sections were slightly greater than the minimums allowed by most international codes (Eurocode 2 1991, CEB-FIB 1991). UPN-260 pieces (channel section type, outside depth 260 mm, outside flange width 90 mm, flange thickness 14 mm and web thickness 10 mm) with welded steel plates were attached to the ends of the column lengths to form a type of "steel box" whose objective was to absorb

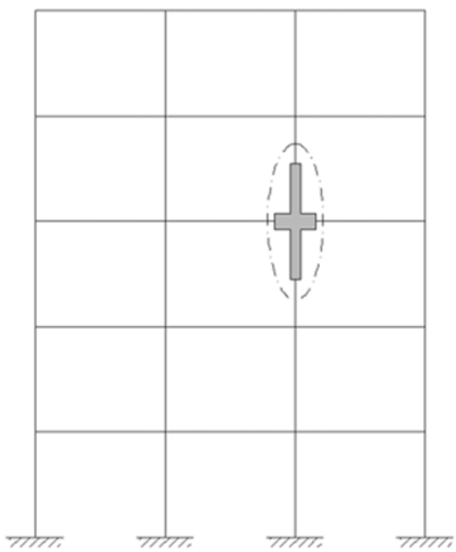

Fig. 3 Structure zone of a building simulated by specimens

the load transmitted by the hydraulic testing machine, in addition to acting as the connecting element with the steel test frame.

Reinforcement in the column lengths coincided with the minimum permitted by Spanish regulations (Ministerio de Fomento 1998) for RC columns and was very similar to that recommended by most international codes (Eurocode 2 1991, CEB-FIB 1991). Beam reinforcement was determined by the normal residential-building slab design requirements. Fig. 4 provides a scheme of the specimen reinforcement in horizontal position.

It should be emphasised that the transverse reinforcement of both column lengths was strongest at the ends of the specimens, with the aim of avoiding possible failure due to the loads applied at these points. The longitudinal reinforcement of both column lengths was welded to the "steel box" at the ends of the specimens (see Fig. 4).

A total of eight specimens were tested, including two specimens without strengthening (named specimens AxL.Ref), to be used as control references. There were two different types of strengthened test specimen with different types of beam-column solution: a) specimen AxL.C (see Fig. 5), where the beam-column joint is solved by means of capitals welded to the steel cage and in contact with the beam; b) specimen AxL.T (see Fig. 6), where the steel cages that strengthened the two column lengths were connected by steel tubes, following Adam's recommendations (2007). A total of three specimens of each type (AxL.C and AxL.T) were tested under axial loading, with the loads applied to the ends of the columns.

3.2. Manufacture of specimens

Specimens were manufactured in formwork specially designed for these tests (see Fig. 7a), and the steel cages were constructed by a team of specialists. Fig. 7(b) shows the construction process of the caging for one of the specimens.

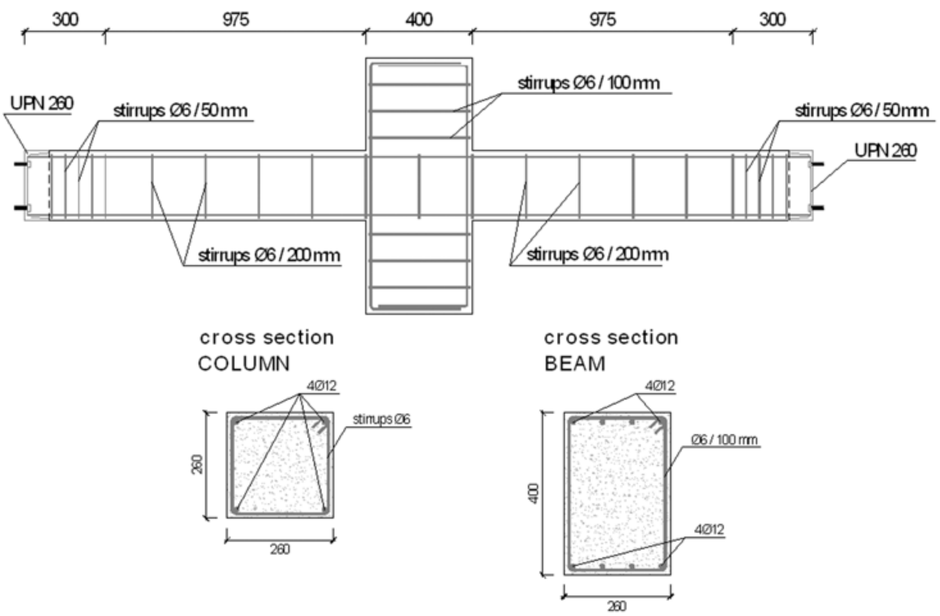

Fig. 4 Specimen geometry and reinforcement

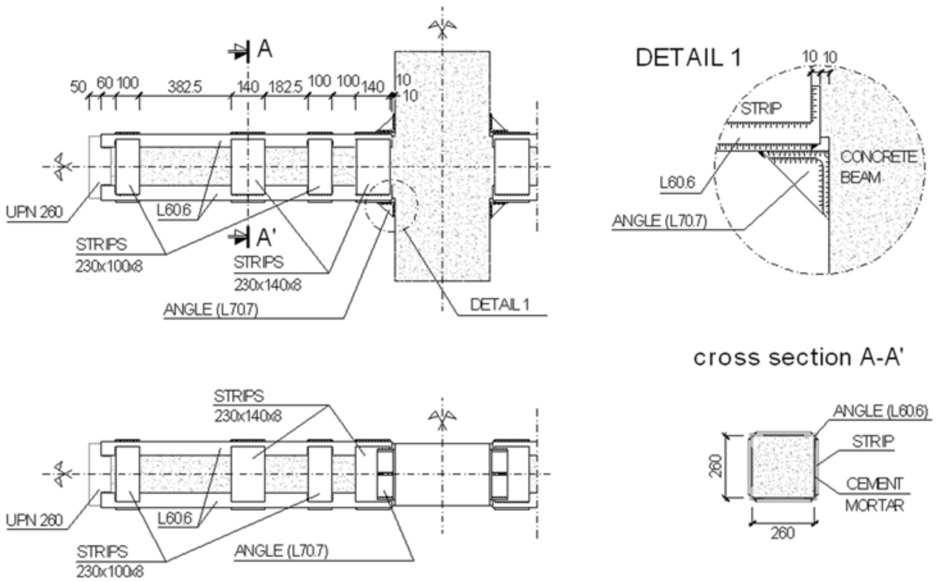

Fig. 5 Specimen AxL.C

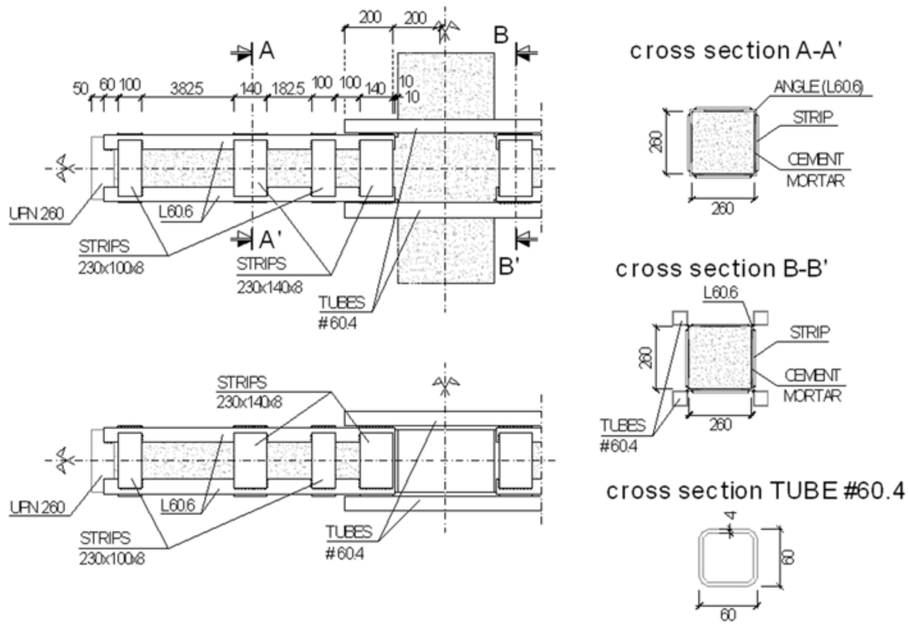

Fig. 6. Specimen AxL.T

3.3. Material properties

The concrete mix used in the columns was designed to simulate a column with low compressive strength in need of strengthening. This methodology was also followed by Calderón *et al*. (2006), Giménez *et al*.

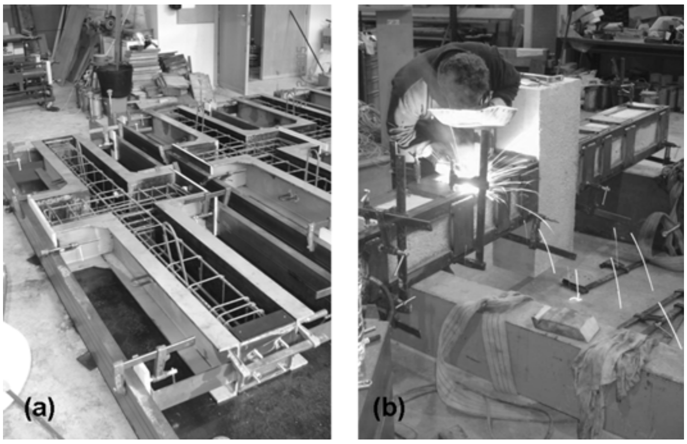

Fig. 7 (a) Specimens contained by formwork; (b) Manufacture of strengthening

(2006), Adam (2007), Adam *et al*. (2007) and Giménez (2007). The concrete mix is given in Table 1.

Compressive strength was determined by the cylindrical specimen tests carried out at the same time as the tests on the strengthened columns. The mean compressive strength value of the concrete used in all the specimens was 11.2 MPa.

The yield stress of the reinforcement steel and the steel cage was f_{ys} = 400 MPa and f_{yL} = 275 MPa, respectively.

The cement mortar between the cage and the column had a cement/sand ratio of 1:2.

3.4. Instrumentation

A total of 26 strain gauges were attached to the AxL.C specimens to measure strain in the cage steel, with four other units in the concrete. 30 gauges were used to measure strain in the steel cages of the AxL.T specimens, with five to take readings in the concrete.

7 LVDTs were used in both specimen types, one of which recorded total shortening and the others recorded slippage between the angles and the cage angle pieces.

Figs. 8 and 9 show the instrumentation used on each specimen. Identification of the elements is as follows:

- A : Strain gauge attached to angle pieces
- P : Strain gauge attached to strips
- H : Strain gauge attached to concrete
- L : LVDT

3.5. Test Procedure

The tests were carried out in a steel frame and the axial load was applied by a hydraulic testing

Table 1. Concrete mix (*kg* per m^3 of concrete)

Cement (CEM II 42.5)	Water	Sand	Gravel
173	173	950	1100

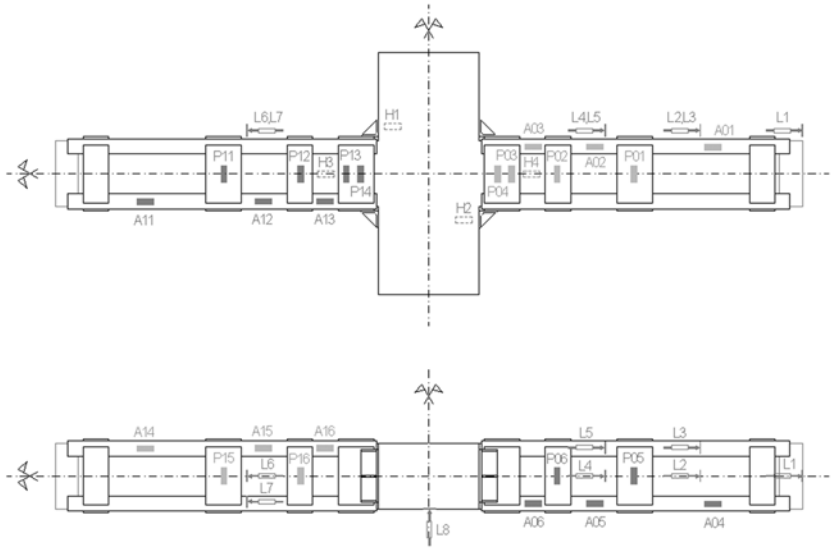

Fig. 8 Instrumentation of specimen AxL.C

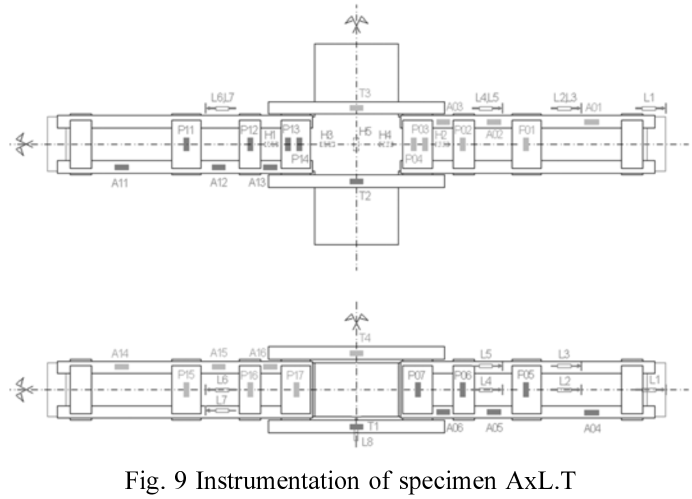

Fig. 9 Instrumentation of specimen AxL.T

machine with a maximum capacity of 2,500 kN. Load was applied in displacement control mode at a constant rate of 0.5 mm/min until failure of the specimen. All the specimens were tested in horizontal position as can be observed in Fig. 10, where a specimen ready for testing is shown.

4. Test results

4.1. General behaviour and failure mode

The mean ultimate load value for the two AxL.Ref specimens was 973.5 kN, failure occurring near to one of the column ends. The mean ultimate load value for the three AxL.C specimens was 1618.1 kN,

Fig. 10 General view of steel test frame with specimen ready for testing

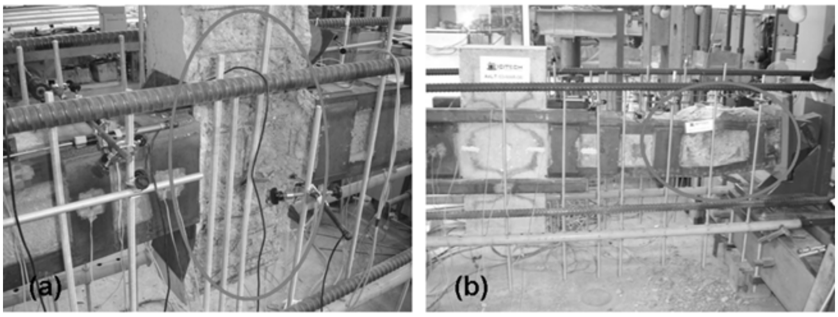

Fig. 11 Failure modes. (a) Specimen AxL.C; (b) Specimen AxL.T

with failure occurring in the beam (see Fig. 11(a)). It can be said that failure in this zone occurred due to a combination of two phenomena:

1) Since the concrete in the beam is subjected to much less confinement than in the zone of the strengthened column, failure of the beam may happen due to the compression transmitted from the column.
2) Part of the compressive load applied by the hydraulic testing machine is transmitted to the beam through the steel capitals in contact with the beam. The failure mechanism may be due to crushing of the concrete in the capital support zone.

The mean ultimate load value for the three AxL.T specimens was 1684.3 kN. Failure of these specimens occurred at one of the ends in the zone between the first and second strips, where confinement due to the steel cage is lowest. Compressive failure of the concrete was detected, also yielding of the angles due to transversal loads on the concrete from the Poisson effect in addition to the axial loading on the angles themselves (see Fig. 11(b)).

Fig. 12 gives the load-shortening curves for the three types of specimen tested (AxL.Ref, AxL.C and AxL.T). It can be seen that the strengthened columns have a considerable increase in ultimate load compared to the non-strengthened specimens (AxL.Ref). In the case of the two strengthened specimens (AxL.C and AxL.T), they present completely different behaviour: the shortening value recorded in specimen AxL.C on failure is of the order of 8 mm, while for specimen AxL.T it is around 12 mm. It can be said that the use of steel tubes contributes to increasing ductility and ultimate load in strengthened columns. This conclusion can also be deduced by comparing the failure modes of the two specimens:

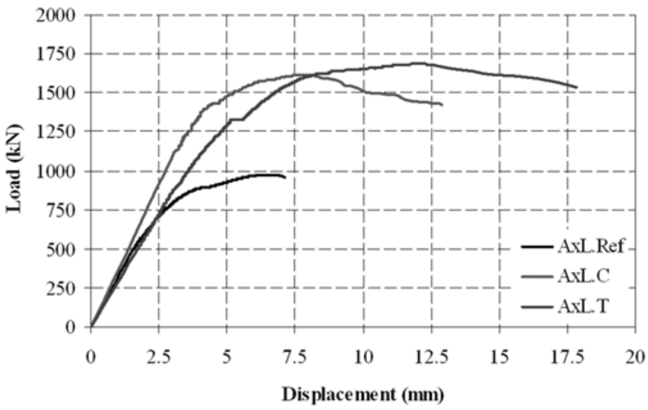

Fig. 12. Load-shortening curves

1) Failure in specimen AxL.T occurs in a confined zone of the concrete, indicating that the failure mechanism is ductile due to the behaviour of the concrete itself when subjected to triaxial compressive loads.
2) Failure in specimen AxL.C is in a zone with low confinement and is caused by a more brittle failure mechanism.

4.2. Slippage between column and cage

In all the strengthened columns (AxL.C y AxL.T) a certain amount of relative slippage was observed between the column and the steel cage. This phenomenon was also observed by Calderón *et al*. (2006), Giménez *et al*. (2006), Adam (2007), Adam *et al*. (2007) and Giménez (2007) for cases in which only column behaviour was analysed.

Fig. 13 includes graphs which compare the relative slippage with the load applied by the hydraulic testing machine. As can be seen in Fig. 13, the presence of steel tubes in the AxL.T specimens considerably reduces relative slippage between column and cage, especially as compared to specimens AxL.C.

4.3. Load distribution between cage and column

From the strain gauge readings it is possible to obtain the load distribution between the column and

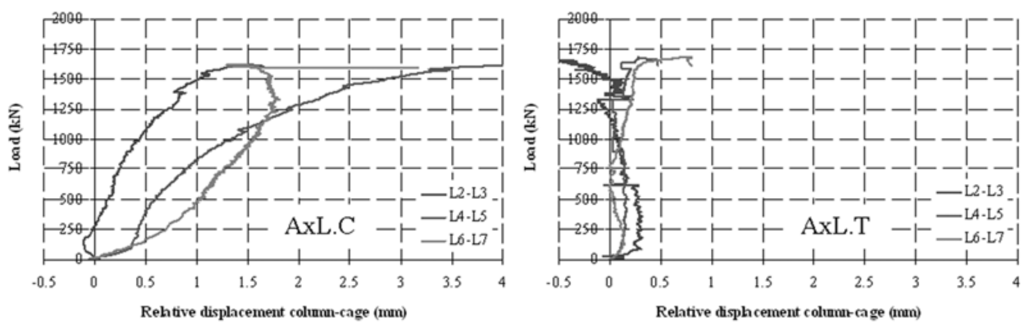

Fig. 13 Load versus relative displacement column-cage (slippage). Specimens AxL.C and AxL.T

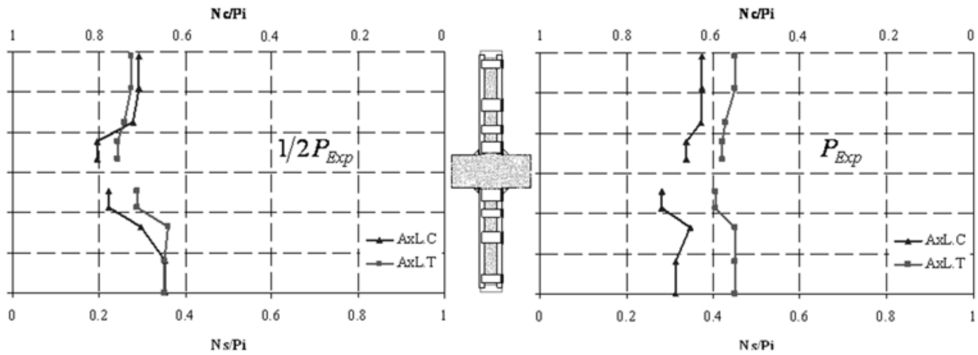

Fig. 14 Load distribution between column and steel cage along column axis

the steel cage throughout the length of the specimens. Fig. 14 shows the load distribution between the steel cage and the column when the load applied by the hydraulic testing machine is 50% and 100% of ultimate load (P_{Exp}). N_c is the load supported by the column, N_s is the load supported by the cage, and P_i is the load applied by the hydraulic testing machine.

As can be seen from Fig. 14, load distribution is more efficient in the AxL.T specimens than in AxL.C, especially when the load applied by the hydraulic testing machine coincides with P_{Exp}. This is due to the presence of the steel tubes connecting the two lengths of column, which contribute to improving load transmission between the column and the steel cage.

4.4. Analysis of confinement imposed by the cage

The confinement imposed by the cage on the concrete column can be quantified by measuring the stress on the strips by the lateral expansion of the concrete due to the Poisson effect. In various numerical studies, Calderón *et al.* (2006), Giménez *et al.* (2006), Adam (2007), Adam *et al.* (2007) and Giménez (2007) verified that the greatest confinement was imposed by the cage in the zones nearest to the beam, since load transmission between column and cage in these zones is not completely effective (see Fig. 14), given that the concrete is here subjected to greater loads than in the rest of the column. The higher the loading of the concrete the greater the lateral expansion from the Poisson effect.

This phenomenon is shown in Fig. 15, which gives the stress recorded in the strips by the two strain gauges (perpendicular to the column axis) in relation to the load applied by the hydraulic testing machine. The confinement imposed by the cage can therefore be quantified in the different zones of the strengthened column. As can be gathered from Fig. 15, confinement is clearly greater in the area nearest to the central beam (strain gauge P06, as indicated in Figs. 8 and 9).

It can be observed that the confinement is greater in the AxL.C specimens than in the AxL.T; this is explained by the fact that the concrete in specimens AxL.C is under a greater load than in AxL.T (see Fig. 14). The greater load increases the lateral dilatation due to the Poisson effect and in turn results in a higher degree of confinement.

5. Analysis of results and comparison with Eurocode 4

As Adam (2007) has shown, the ultimate load of RC columns strengthened by steel angles and strips

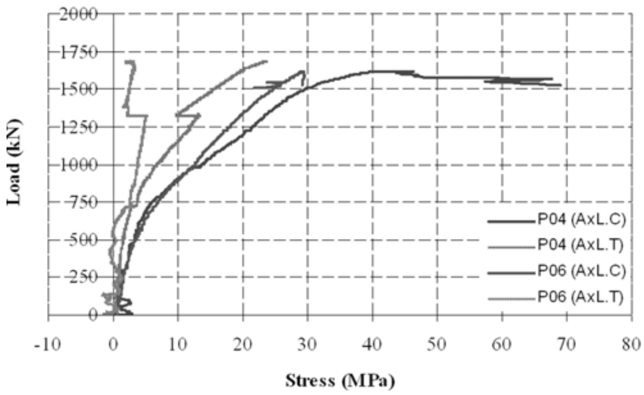

Fig. 15 Load versus stress (in strain gauges placed on strips)

can be estimated from Eurocode 4 (1992), if the possible influence of the beam-column joint on the strengthened column behaviour is not taken into consideration. According to Eurocode 4, the ultimate load of the strengthened column could be expressed by Eq. (1):

$$P_{EC4} = 0.85 \cdot A_c \cdot f_c + A_s \cdot f_{ys} + A_L \cdot f_{yL} \quad (1)$$

where A_c is the cross-sectional area of the RC column to be strengthened, f_c the compressive strength of the concrete, A_s the cross-sectional area of the longitudinal reinforcement of the column, f_{ys} the yield stress of the longitudinal reinforcement, A_L is the cross-sectional area of the angles forming the cage, and f_{yL} the yield stress of the steel used in the angles.

In Table 2 the ultimate load obtained from tested specimens is compared with that obtained from the Eurocode 4. In order to determine the ultimate load according to the Eurocode 4, it should be emphasised that factor 0.85 (reduction of concrete strength) was not taken into account, since the axial load was applied for a short period of time (short-term loading) in the laboratory experiments.

Analysing the P_{Exp}/P_{EC4} ratio included in Table 2, it can be seen that when specimen failure occurs in the column (AxL.T specimens), the ultimate load of the specimens can be accurately calculated by Eurocode 4, the P_{Exp}/P_{EC4} ratio being 0.99. However, when failure occurs in the beams (AxL.C specimens), obtaining ultimate load by Eurocode 4 gives rise to slightly higher values than those obtained in the laboratory tests, with a P_{Exp}/P_{EC4} ratio of 0.95.

It can therefore be said that the presence of steel tubes allows the ultimate load of the strengthened column to be estimated by the Eurocode 4 proposal. If the steel tubes are replaced by capitals in contact with the beam, there is a slight reduction in ultimate load as compared with that obtained by Eurocode 4, due to the fact that failure of the strengthened column occurs in the beam-column joint.

Table 2. Ultimate load of specimens. Comparison with Eurocode 4

	P_{Exp}	P_{EC4}	P_{Exp} / P_{EC4}
AxL.Ref	973.5	-	-
AxL.C	1618.1	1698.2	0.95
AxL.T	1684.2	1698.2	0.99

6. Conclusions

This paper has compared the different behaviour resulting from two different techniques of solving the beam-column joint in RC columns strengthened by steel angles and strips. The work is a continuation of the research carried out by Calderón *et al*. (2006), Giménez *et al*. (2006), Adam (2007), Adam *et al*. (2007) and Giménez (2007).

From the analysis of the laboratory tested specimens it can be concluded that attaching steel tubes to the beam contributes to an improvement in the behaviour of the strengthened column as compared to the case of employing capitals in contact with the beam.

While the ultimate load of the AxL.T specimens (with steel tubes through the beam) can be estimated from the Eurocode 4 proposal, applying this proposal to the AxL.C specimens (with capitals in contact with the beam) would not be appropriate, since the possibility of joint failure could cause a reduction in the ultimate load of the strengthened column.

The capitals at the ends of the column are much easier to assemble than the tubes; however, the latter technique should be considered when capitals could lead to failure at the joint (e.g. joints lacking of reinforcement, low strength concrete, etc.).

Acknowledgements

The authors wish to express their gratitude for the financial support received from the Spanish Ministry of Science and Technology under the research project MAT 2003-08075, co-financed with FEDER funds.

References

Adam, J. M. (2007), "Structural behaviour of RC columns strengthened by steel jacketing", Research Report, Code 1940/66, Universidad Politécnica de Valencia.

Adam, J. M., Ivorra, S., Giménez, E., Moragues, J. J., Miguel, P., Miragall, C. and Calderón, P. A. (2007), "Behaviour of axially loaded RC columns strengthened by steel angles and strips", *Steel and Composite Structures*, 7(5), 405-419.

Calderón, P. A., Giménez, E., Adam, J. M. and Ivorra, S. (2006), "Full scale testing of RC columns strengthened with steel angles and battens", *Structural Faults and Repair-2006*, Edinburgh.

CEB-FIB Model Code 90, 1991. Laussane.

CEB-FIB (2003). "Seismic assessment and retrofit of reinforced concrete buildings". Bulletin no. 24, Task Group 7.1.

Cirtek, L. (2001a), "RC columns strengthened with bandage - experimental programme and design recommendations", *Construction and Building Materials*, 15(8), 341-349.

Cirtek, L. (2001b), "Mathematical model of RC banded column behaviour", *Construction and Building Materials*, 15(8), 351-359.

ENV 1992-1-1 (Eurocode 2), 1991. Design of concrete structures. Part 1: General rules and rules for buildings.

ENV 1994-1-1 (Eurocode 4), 1992. Design of composite steel and concrete structures. Part 1: General rules and rules for Buildings.

Frangou, M., Pilakoutas, K. and Dritsos, S. (1995), "Structural repair/strengthening of RC columns", *Construction and Building Materials*, 9(5), 259-266.

Fukuyama, H. and Sugano, S. (2000), "Japanese seismic rehabilitation of concrete buildings after the Hyogoken-Nanbu Earthquake", *Cement & Concrete Composites*, 22(1), 59-79.

Giménez, E., Adam, J. M., Calderón, P. A. and Ivorra, S. (2006), "Numerical and experimental study of the strengthening of reinforced concrete columns using steel angles and strips", *Proceedings of The Tenth East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-10)*, Bangkok.

Giménez, E. (2007), Experimental and numerical study of axially loaded RC columns strengthened by steel jacketing. PhD Thesis, Universidad Politécnica de Valencia.

Ministerio de Fomento (1998), Instrucción de hormigón estructural. EHE. Madrid [in Spanish].

Oey, H. S. and Aldrete, C. J. (1996), "Simple method for upgrading an existing reinforced-concrete structure", *Practice Periodical on Structural Design and Construction*, 1(1), 47-50.

Ramírez, J. L. (1996), "Ten concrete column repair methods", *Construction and Building Materials*, 10(3), 195-202.

Ramírez, J. L. and Bárcena, J. M. (1975), "Eficacia resistente de pilares de hormigón armado de baja calidad reforzados por dos procedimientos diferentes", *Informes de la Construcción*, 272, 89-98 [in Spanish].

Ramírez, J. L., Bárcena, J. M. and Feijóo, J. M. (1977), "Comparación resistente de cuatro métodos de refuerzo de pilares de hormigón armado", *Informes de la construcción*, 290, 57-68 [in Spanish].

Tamai, S., Sato, T. and Okamoto, M. (2000), "Hysteresis model of steel jacketed RC columns for railway viaducts", *Proceedings of the 16th Congress of IABSE*, Lucerne.

Wu, Y. F., Liu, T. and Oehlers, D. J. (2006), "Fundamental principles that govern retrofitting of reinforced concrete columns by steel and FRP jacketing", *Advances in Structural Engineering*, 9(4), 507-533.

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