BEHAVIOUR AND STRENGTHENING OF RC BEAM-COLUMN JOINTS: EXPERIMENTAL PROGRAM AND FIRST RESULTS OF THE RESEARCH ACTIVITY IN THE FRAMEWORK OF DPC-RELUIS PROJECT (RESEARCH LINE 2)

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ABSTRACT :

The 2005-2008 DPC-Reluis Project, funded by the Italian Department of Civil Protection (DPC), is made up of ten Research Lines (RL). RL 2 specifically focuses on the seismic performance of existing RC buildings and is, in turn, organised in nine different Tasks. In the paper, the design of the research activities being carried out within the Task 7 by the four involved Research Units (RU UNIBAS, RU UNIUD, RU UNISA, and RU UNINA) and some first results are reported. Main objective of Task 7 is to investigate on the experimental behaviour of beam-column joints without or with strengthening, thus providing a contribution to a more reliable evaluation of the seismic vulnerability of Reinforced Concrete existing buildings. To this purpose the main activities carried out have been devoted to design and set up of wide experimental programs on beam-column joints relevant to typical existing RC buildings having different Earthquake Resistant Design (ERD) level, to make a literature review of the state of the art on the subject, to perform numerical simulations based on some analytical models available in literature in order to fully understand the mechanical behaviour. Further, some results of the tests already carried out are reported, analysed and compared in order to understand the failure mechanism and evaluate the seismic performance of joints with and without ERD.

KEYWORDS: Reinforced concrete, existing buildings, beam-column joint, cyclic test

1. INTRODUCTION

The observation of the damage caused by strong earthquakes has highlighted the typical collapse mechanisms affecting Reinforced Concrete (RC) buildings designed for gravity loads only, such as formation of plastic hinges on columns driving to soft storey, shear failure in beams, bar slip, and shear failure of beam-column joints. The capacity design approach provided in modern seismic codes (e.g. in Italy OPCM 3274, 2003 and in Europe EC8, 2003) aims at avoiding brittle collapse mechanisms both in the structural members and in structure as a whole (strong columns-weak beams behavior). In order to obtain local and global ductility, a series of structural details are required in the seismic design, generally absent or inadequate in the existing RC buildings designed without seismic rules. A reliable evaluation of the seismic performance is particularly needed on these buildings, as a fundamental tool in order to select type, technique, extent and urgency of the strengthening intervention (Masi 2003). Many are the factors influencing the structural performances of RC buildings, among them an important role is carried on by the ultimate capacity of the beam-column joints. Some authors performed experimental investigations both on reduced and real scale beam-column sub assemblages (Pampanin et al. 2002) to better understand their behaviour, also for the development and calibration of software models to

be used in non-linear analysis of framed RC structures.
In the frame of the 2005-2008 DPC-Reluis Project made up of ten Research Lines (RL), RL 2 specifically focuses on the seismic performance of existing RC buildings. RL 2 is organised in nine different Tasks. Task 7 is specifically devoted to investigate on the experimental behaviour of beam-column joints without or with strengthening, thus providing a contribution to a more reliable evaluation of the seismic vulnerability of RC existing buildings. In the paper, the design of the research activities being carried out within the Task 7 by the four involved Research Units (University of Basilicata, UNIBAS RU; University of Udine, UNIUD RU; University of Salerno, UNISA RU; University of Naples, UNINA RU) and some first results are reported. The main activities carried out are as follows:

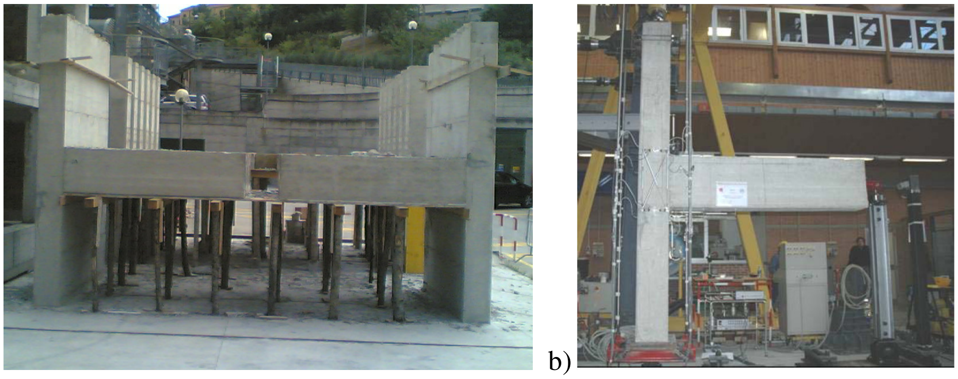
- Design and set up of wide experimental programs on beam-column joints relevant to typical existing RC buildings having different Earthquake Resistant Design (ERD) level, namely joints designed to resist only to gravity loads and joints relevant to structures designed according to the recent Italian seismic code (all RUs).
- Execution and analysis of some tests carried out on full or reduced scale beam-column and base-column joints (UNIUD, UNISA and UNIBAS RUs).
- Numerical simulations based on some analytical models available in literature aimed at the definition of the most appropriate approach to predict the behaviour of RC beam-column joints under combined axial load and seismic actions (UNINA RU).

Specifically, the experimental tests are devoted to investigate the failure mode, the strength and ductility performance, and to verify the damage sequence. These results are, then, correlated to the main characteristics of the beam-column joints under investigation such as ERD level, type of rebar, material properties, axial load values. Some results of the tests already carried out are reported, analysed and compared with the results provided in the literature and by the numerical simulations, particularly keeping in mind a preliminary check on the expressions proposed in the Italian and European seismic codes (OPCM 3431, EC8-3) for the evaluation of the strength and deformation capacities of beam-column RC joints.
Finally, also a literature review of the state of the art on the subject has been carried out by all RUs, based on a wide bibliographic research on the experimental investigations on beam-column joints and on different repairing/strengthening techniques. Particularly, the UNIBAS RU made a state of the art of experimental programs reported in the national and international literature concerning type of test, type of joint tested (i.e. joints with L, T and C shape) and, particularly, observed type of failure mechanism. Main objective of the state of the art was to analyse the correlations between the failure mechanism and the reinforcement detailing (seismic design level), the axial force applied and the loading modality used in the tests. Presently, it is in progress the collection of the available data relevant to experimental programs carried out in many research centres, in terms of geometrical dimensions of the specimens, detailing (amount, position and type of rebars), test apparatus (load applied to column or beam, restrains..) and observed mechanical behaviour (shear-drift law, collapse drift, failure mode). From the experimental results the collapse chord rotation for the beam and column belonging to the specimens is evaluated and compared to that one obtained from the expressions provided in the Italian and European seismic codes (OPCM 3431, EC8-3).

2. EXPERIMENTAL INVESTIGATIONS

A wide experimental program has been designed by the RUs involved in the project, and partially carried out by the UNIBAS, UNIUD, and UNISA RUs.
UNIBAS RU designed and built 26 (13 pairs) external "T" shaped beam-column joints in full scale to be subjected to quasi-static cyclic tests. The joints are relevant to typical existing RC buildings having different ERD level, that is joints relevant to structures designed to resist only to gravity loads and joints relevant to structures designed according to the last Italian seismic code. The experimental program is in progress at the Laboratory of Testing Materials and Structures of the University of Basilicata, Potenza. Presently, experimental tests on 6 specimens have been carried out, all provided with rigid beams (RB type, 300 mm x 500 mm), among which 2 joints designed only to gravity loads (NE type), 3 joints designed for medium seismicity zone (Z2 type) and 1 joint designed for very low seismicity zone (Z4 type). All the joints were provided with deformed bars

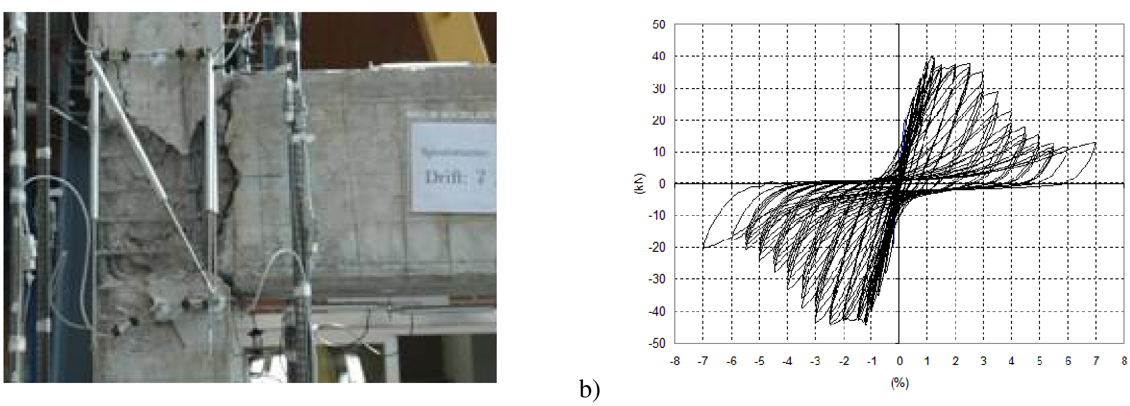
according with the Italian code in effect at the beginning of '70s. The column has cross section dimensions 300 mm x 300 mm. All the tests have been performed up to the total failure as no repair or retrofit interventions were foreseen after the first test. A conspicuous amount of data has been collected in order to study the seismic performance and the observed failure mechanism of the specimens. Before the tests, numerical simulations with fibre finite element software in order to predict the force-deformation law have been carried out.



a) b)

Figure 1 Experimental program at UNIBAS RU: a) outline of specimens, b) test set-up.

Recorded data have been analysed mainly in terms of force-drift laws, amount of energy dissipation, degradation of the secant stiffness, moment-curvature laws, and deformation of the panel zone of the joints. For each test a specific report has been prepared containing information relevant to the specimen under examination (e.g. real position of reinforcing bars compared to the design), main data recorded during the test and relevant analyses (e.g. graphs reporting force, dissipated energy, and other response parameters at increasing drift level). Further, a photographic documentation of the damage pattern evolution observed during the test is reported. Quasi-static tests have been performed with 3 loading cycles for each drift amplitude. Drift values were gradually increased starting from a value equal to 0.25% up to the total failure of the joint. Numerical simulations carried out before the tests provided a good estimation of the values of force and deformation at yielding. Yielding force is about 20 kN for the NE joints, and about 40 kN for both Z2 and Z4 joints as a consequence of the minimum requirements on reinforcement amount prescribed by the Italian code.

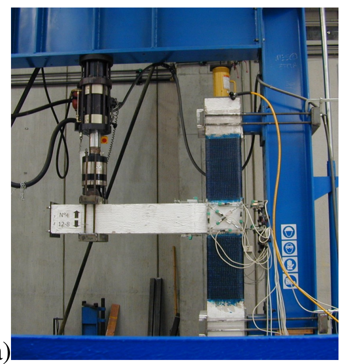


a) b)

Figure 2 Test on a Z2 joint (UNIBAS RU): a) damage pattern at drift=7%, and b) force-drift relationship.

The observed failure mechanism in all the joints showed a wide and heavy cracking in the beam, due to the small amount of the longitudinal reinforcing bars as the beams were not loaded by the floor slabs in the considered building model. Joint failure was generally caused by the tensile failure of the reinforcing bars in the beam. A different as well interesting behaviour was displayed by the test on a Z2 joint (Masi and Santarsiero, 2008), where a wide cracking also in the joint panel and a softening mechanical behaviour (figure 2) was observed, probably due to the reduced amount of the applied axial force (ν=0.1). Drift value (coincident with chord rotation value) at failure in the NE joints is about 3.0%, while in more ductile Z2 and Z4 joints, values

equal to about 4.5% have been detected. Using the code expressions (CEN 2003) ultimate and at yielding chord rotation capacities of the joints have been estimated and compared with the observed experimental values. The first results show that code expressions provide a good estimation of the ultimate chord rotation for the NE joints, while they appear conservative for the joints type Z2 and Z4. On the contrary, chord rotation at yielding is well estimated for the type Z2 and Z4 joints, whereas code expressions provide higher values for the NE joints.
Quite different is the experimental program carried out by the UNIUD RU devoted to the test of four external reduced scale 2:3 beam-column joints (figure 3) provided with smooth bars, which had been retrofitted after a first series of tests. For two of them only the anchorage of the beam bars had been restored by welding threaded bars to the ends of the longitudinal beam bars and bolting them to steel plates placed on the column external surface (as in figure 3b). For the other two joints, besides restoring the anchorage, also vertical and horizontal carbon fiber fabrics had been applied on the column, below and above the joint panel (figure 3a), to oppose to any crack that would had spread from the joint core to the columns. The tests were carried out under imposed increasing cyclic displacements applied to the beam end. Moreover other 2 real scale beam-column joints (figure 4) were built and tested under cyclic deformations. One of these (the former) was tested without retrofitting (figure 4a), to study its behavior; the other one (the latter) was retrofitted before testing. This retrofit was carried out by anchoring the beam bars to steel plates placed on the column external surface, and by applying carbon fiber fabrics to the beam extrados (figure 4b), to overcome the insufficiency of reinforcement for negative moment. After the test on the latter, the former was retrofitted in the same way with, in addition, a fabric wrapped around the beam portion close to the column (figure 4c), to better anchor the fabric applied on the extrados. The efficiency of the retrofit was evaluated in terms of increase of joint strength and ductility.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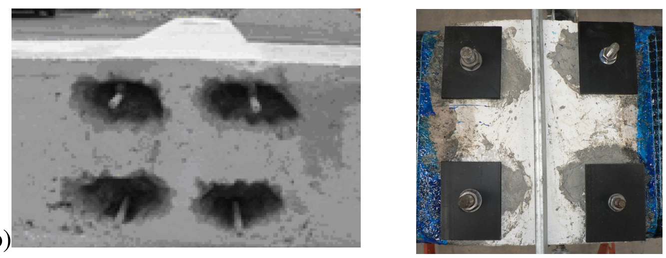


Figure 3 Experimental program at UNIUD RU, joints at scale 2:3: a) test set-up with a joint retrofitted with carbon fiber fabrics, b) retrofit details on the anchorage of beam bars.

As regards the first 4 joints, the restoration of the anchorage of the beam bars proved to be very efficient, since it provided increases in strength up to 300% with respect to not retrofitted joints. Moreover the beam longitudinal bars yielded, with the consequent increase in energy dissipation. The detected structural damages were the crossing crack at the beam-column interface and the slippage of the beam longitudinal bars. The additional carbon fiber reinforcements did not provide noticeable increases in strength, because the cracking of the joint, which would have required the carbon fiber contribute, did not occur. As regards the other two joints, it was observed that the former, not retrofitted, attained low strength values due to the lack of steel reinforcement for negative moment in the beam. As regards the latter, retrofitted before testing, the carbon fiber fabrics applied on the extrados of the beam increased the strength and the displacement ductility, which attained the value of 4. But, successively, the fabric debonded in the zone close to the column and brittle failure occurred. Then the former joint was reinforced like the latter but with an additional wrap near the column to improve the anchorage of the fabric at the top of the beam. This joint attained the same strength and ductility of the latter, because the fabric debonded along the not wrapped portion.
It is well known that also base-joints play an important role in the seismic performance of RC buildings. For this reason, the activities of the UNISA RU were mainly focused on two wide classes of RC joints whose detailing is particularly inspired to the typical solutions adopted in existing structures, although experimental tests were designed also for beam-column joints.

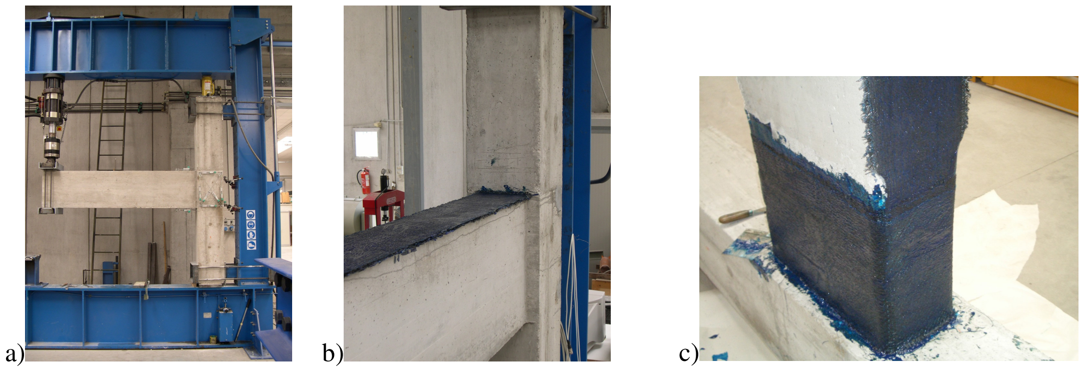


Figure 4 Experimental program at UNIUD RU, joints at real scale: a) test set-up with a joint, b) application of carbon fiber fabric at beam extrados, c) wrapping on beam close to column.

Referring to base-joints, a wide experimental activity has been carried out considering several structural details for steel rebars (smooth or deformed) and various strengthening solutions based on the use of composite materials. In particular 24 full scale RC columns were tested under constant axial load and monotonic or cyclic flexure. The specimens consisted of 300x300 mm square columns having a concrete stub as foundation. Tests were performed on unstrengthened and strengthened columns. The strengthening systems (figure 5a) consisted in confinement by partially wrapping unidirectional carbon or glass layers around the element at the base. On some specimens, in addition to confinement, steel angles were placed in correspondence of the member corners. Steel angles were, in some cases, anchored at the foundation in order to improve the flexural strength and in other cases not anchored. These two solutions were tested in order to verify the behaviour and benefit in terms of strength and ductility. For the beam-column joints, some experimental tests have been designed with the aim of investigating the behaviour of unconfined beam-column joints, and will be carried in the future. The choice of the specimens that will be tested has been done after the study of a wide database of experimental results obtained on beam-column external joints available within the scientific literature. The specimens have been designed according to the technical codes in effect during the '60s and '70s with the aim of reproducing typical dimensions, rebar amount and details common at that time.

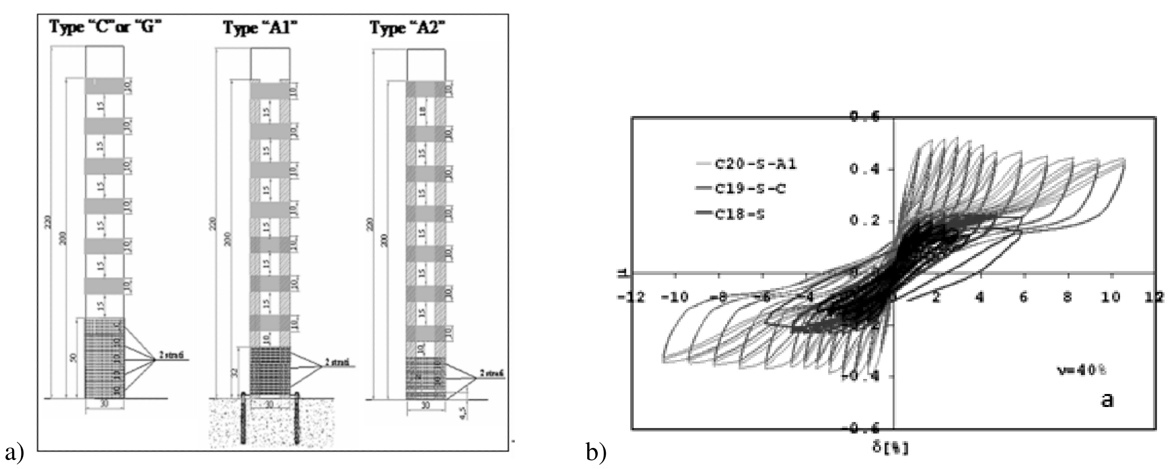


Figure 5 Experimental program at UNISA RU: a) adopted strengthening systems, b) experimental behavior of base-joints having different retrofitting solutions.

Referring to base-joints tested in the research, the following main results have been achieved:

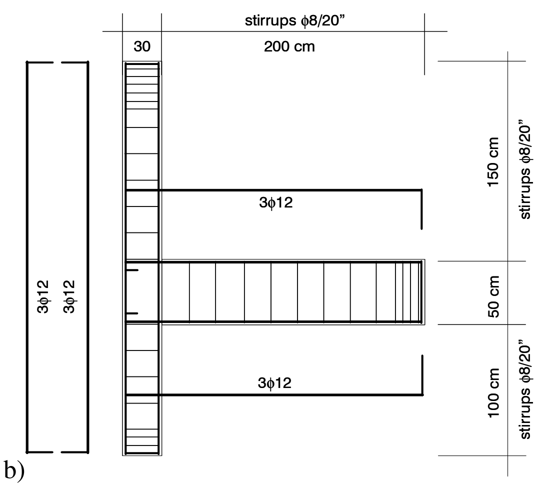
- regardless of the axial load value, the FRP confinement produces significant increases in terms of ductility, especially if a GFRP (glass) jacket is used;

- in case of columns subjected to ν=0.14, the FRP confining system does not provides any gain of the flexural strength; on the contrary, in case of higher values of the axial load (ν=0.40), the action of the FRP system leads to a not negligible improvement of strength;
- the arrangement of the longitudinal steel angles unconnected to the foundation leads to higher ductility levels than those measured for members strengthened by only FRP systems; this ductility gain is lower for columns tested under ν=0.40, even if in these cases the unconnected angles also provide an improvement of the flexural strength;
- when the longitudinal angles are anchored to the foundation the flexural strength of the RC columns significantly increases, but a reduction of the available ductility is observed.

In the figure 5b, for example, a performance comparison under cyclic loading between two retrofitting solutions of columns with smooth bars is reported. In particular the column C20-S-A1 is confined with CFRP and steel angles anchored to concrete stub, the C19-S-C is a column only confined with CFRP while C18-S is an unstrengthen column. The ductility and strength improvement is evident for the C20-S-A1, while the C19-S-C increases only the ductility. These tests were performed under an axial load equal to ν=40%.
The behaviour of beam-column joint is essential to evaluate correctly the seismic global behaviour of a structure and a building in particular. Some mechanisms, namely concrete cracking, longitudinal reinforcement bars slippage, especially in the beams, on one hand are responsible of additional deformability, while on the other hand, they can modify the capacity design assumptions on the connecting structural members (beams and columns) and the joint itself. In order to define the experimental campaign (see figure 7a), the main seismic deficiencies of the existing beam-column joints have been analyzed by UNINA RU performing many parametric analyses (numerical modelling). Specifically, the experimental campaign has been designed to assess the capacity of typical existing beam-column joints and to evaluate the possibility to strengthen the existing joints, as shown in Figure 7b, affected by the typical deficiencies, namely low quality concrete, insufficient transverse reinforcement, low bond quality of the longitudinal reinforcement in columns and beams.

Square external joint	10
Rectangular external joint	10
Design type	Only gravity load
Axial load	ν=0.10, 0.20
Steel type	Plain and deformed bars
Anchorage type	Hook (plain bar), 90° (deformed bar)
Concrete strength	20 MPa
Loading type	Cyclic

a)



b)

Figure 7 Experimental program at UNINA RU: a) characteristic parameters of specimens, b) reinforcement details.

3. NUMERICAL SIMULATIONS

The numerical simulation activity has been principally carried out by the UNINA RU, that worked on the construction of an analytical modelling by using Finite Element DIANA software (de Vitte and Kikstra 2005). The numerical (F.E.M.) parametric investigations allowed to evaluate the typical failure modes and cracking patterns and the impact of the main parameters involved in the formulation of the analytical models for strength predictions available in literature. The numerical activity required the definition of appropriate models to simulate nonlinear behaviour of basic materials (namely concrete and steel reinforcements) and the bond-slip characteristics. The numerical model has been accurately validated based on experimental campaigns available in literature and it has been extended to different test layouts. In particular, the numerical modelling was referred to a specimen tested in the range of an experimental program described in (Zaid et al. 1999). It is a cruciform specimen with column dimensions 300x300 mm and beams having cross section 200x300 mm. The specimen was provided with concrete having fc=28 MPa and reinforcing steel with different yielding stress varying from 390 MPa for the stirrups to 450-470 MPa for the longitudinal reinforcing bars. The detailing was proper of ERD joints. The test was made applying a constant axial load equal to 100 kN.

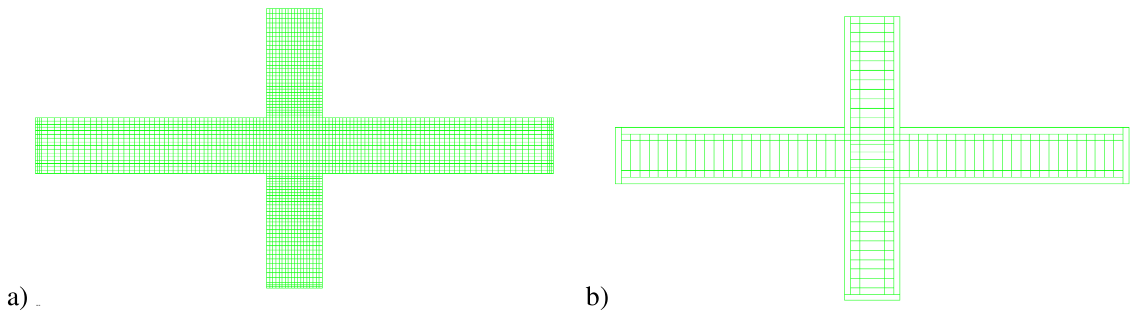


Figure 8 Numerical simulations at UNINA RU: a) adopted mesh of concrete, b) longitudinal and transverse reinforcement.

An accurate numerical analysis (Manfredi et al., 2008) has been performed modeling the several critical aspects on joints behavior using the multipurpose finite-element analysis software DIANA v9.1. Starting from detailed geometric sketches of the tested specimen, the full interior beam-column joint subassemblage was modeled by more than 3,000 eight-nodes, bi-dimensional plane stress elements, based on non-linear material properties. To have a more refined structured mesh close to the joint core, the elements size was biased with a grading factor and decreasing size toward the joint core panel. In Figure 8a is reported the mesh adopted for the concrete material. Numerical results were compared to experimental outcomes and they were found to be in good agreement with the test data.

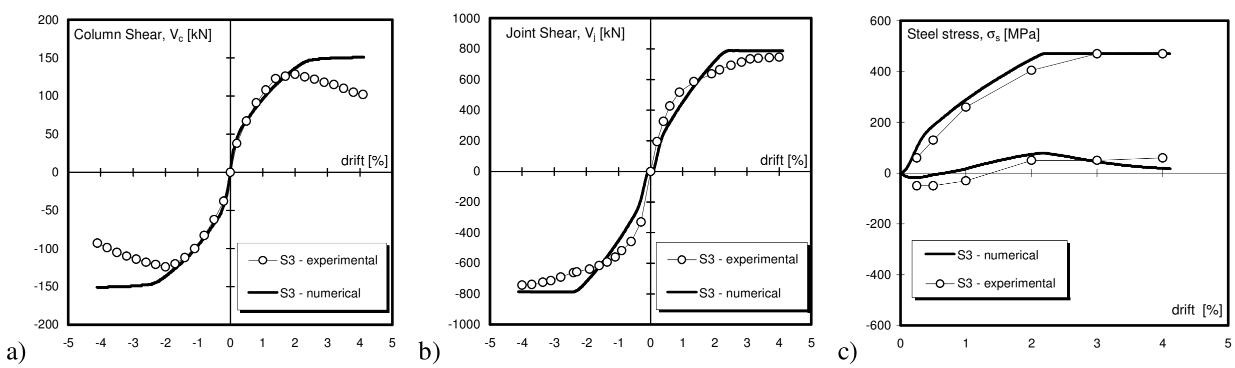


Figure 9 Experimental-Numerical comparisons at UNINA RU: a) column shear, b) joint shear, c) steel stress.

Figure 9a compares column shear-story drift relation. The numerical analysis predicts accurately the ascending portion of the diagram both in terms of shear force and stiffness, while the post peak softening, probably due to the cyclic decay in tested specimen and not simulated in monotonic F.E.M. analysis, was missed. Envelope curves of the joint shear are plotted against story drift in figure 9b. It is observed that relation between joint shear and story drift is very similar to that of the numerical model, even if it was not true in column shear-story drift relation after story drift 2%. Joint shear stress results continuously increasing as story drift increases. Figure 9c compares upper longitudinal bars stress-story drift relation at two opposite column faces of specimens. The numerical analysis predicts quite well the diagrams related to both sides. When the story drift exceeds 3%, yielding of tensile reinforcement in tested specimen beams occurred at the column face. At story drift of 2%, the modeled beam bars showed yielding. It has to be noted that tensile stress is assumed positive. In figure 9c it is clearly noted that the stress in tensile reinforcement is in tension up to the yielding strain, while, when the anchorage resistance attained its capacity, the stress in compressive reinforcement at the right column face shifted from compression to tension. The outcomes of this research campaign confirm the impact of concrete and bond non-linearities on the global and local behavior of tested joint specimen.

FINAL REMARKS

In the frame of the 2005-2008 DPC-Reluis Project made up of ten Research Lines (RL), RL 2 specifically focuses on the vulnerability evaluation and reduction of existing RC buildings. RL 2 is, in turn, organised in nine different Tasks, where Task 7 is specifically devoted to investigate on the experimental behaviour of beam-column joints without or with strengthening. The main activities so far performed in Task 7 are:

- design and set-up of wide experimental programs on beam-column joint specimens with different characteristics (e.g. deformed or smooth steel rebars) relevant to RC frame buildings having different Earthquake Resistant Design level;
- execution and analysis of some tests on full or reduced scale beam-column and base joints (UNIUD, UNISA and UNIBAS RUs);
- numerical simulations based on some analytical models available in literature (UNINA RU).

Although research activities are still in progress some preliminary results have been achieved and shortly reported in the paper.

ACKNOWLEDGMENTS

The work reported in the present paper has been carried out in the frame of the DPC-ReLUIS 2005-2008 Project, Research Line n. 2 “Assessment and reduction of the vulnerability of RC existing buildings” (Task NODI “Assessment and strengthening of beam-column joints”).

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