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EXPERIMENTAL TEST ON A THREE STOREY R.C. FRAME DESIGNED FOR GRAVITY ONLY

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ABSTRACT
The seismic behaviour of reinforced concrete frame systems designed for gravity load only, as typical of the Italian construction practice between the 1950's and the 1970's, is addressed. The results of an experimental quasi-static cyclic test on a three storey reinforced concrete frame system with structural inadequacies typical of pre-seismic code provisions, performed at the Laboratory of the Department of Structural Mechanics of the University of Pavia, are herein presented. Use of smooth bars, inadequate reinforcing detailing (i.e. total lack of transverse reinforcement in the joint region), deficiencies in the anchored solutions (hook-ended bars) and the absence of any capacity design principle resulted in hybrid brittle local and global damage mechanisms. Particularly critical failure mechanisms, with no alternative sources for gravity-load bearing capacity, were observed in the exterior joints. An overview of damage observations and local and global behaviour is provided. Based on the experimental global response, the concept of "shear hinge", due to the joint damage, is also introduced as alternative to flexural plastic hinge and the expected implications on global behaviour are briefly discussed.

Keywords: Existing R.C. frames, Beam-column joints, Damage mechanism, Smooth bars

INTRODUCTION
The seismic response of existing reinforced concrete buildings designed for gravity only, before the introduction of adequate seismic design code provisions, has recently received particular attention through experimental and analytical investigations. As a consequence of poor detailing of reinforcements and absence of any capacity design principle, a significant lack of ductility at both local and global level is expected, resulting in inadequate structural performance even under moderate seismic excitation. Design to an allowable stress philosophy contributes to the uncertainty of the inelastic response. Furthermore, limited information based on experimental results on beam-column subassemblies systems with inadequate design details is available in literature (Kurose [1], Beres et al. [2], Hakuto et al. [3]) while a critical lack of experimental tests on whole frame systems is observed.
As a part of a co-ordinated national project on the seismic vulnerability of existing reinforced concrete frame buildings designed for gravity loads only, as typical in Italy between the 1950's and the 1970's, quasi-static cyclic experimental tests on beam-column subassemblies and on a three storey frame system, 2/3 scaled, have been performed at the Laboratory of the Department of Structural Mechanics of the University of Pavia. This paper will report the results from the aforementioned test on the frame system while the experimental investigations on the beam-column subassemblies are presented in a companion paper (Pampanin et al. [4]). The experimental investigations integrated the information obtained from the previous tests on beam-column subassemblies, confirming the inherent weaknesses

of existing buildings with similar characteristics when subjected to cyclic lateral loads. Brittle local failure mechanisms were observed. Most of the damage concentrated in the beam-column joint panel zone of the exterior tee-joints, which were affected by a particular hybrid damage mechanism, while the tendency to develop plastic hinges in columns put in evidence an unsatisfactory global structural performance of the frame system. Due to interaction of joint shear damage and flexural hinging in beam/column elements, a tendency to develop a hybrid global mechanism was observed. An overview of the hysteretic response, damage level observation, local and global mechanisms is provided, underlining the characteristics of possible sources of damage and failure mechanisms.

EXPERIMENTAL PROGRAM

Frame geometry and reinforcement details

The geometrical and reinforcement characteristics of the three-storey, three bay frame are illustrated in Figure 1. The design recommendations provided by the current national design provisions, integrated by text-books broadly adopted in the engineering practice, available between the 1950's and 1970's (Regio Decreto, 1939, [5]) were followed. Consistently with the old practice, no transverse reinforcement were placed in the joint region. Smooth steel bars, with mechanical properties similar to those typically used in older periods, were adopted for both longitudinal and transverse reinforcement. Beam bars in exterior joints were not bent in the joint region, but anchored with end-hooks. Lap splices with hook anchorages were adopted in the beam bars crossing interior joints as well as in column longitudinal bars at each floor level above the joint region and at the column-to-foundation connection.

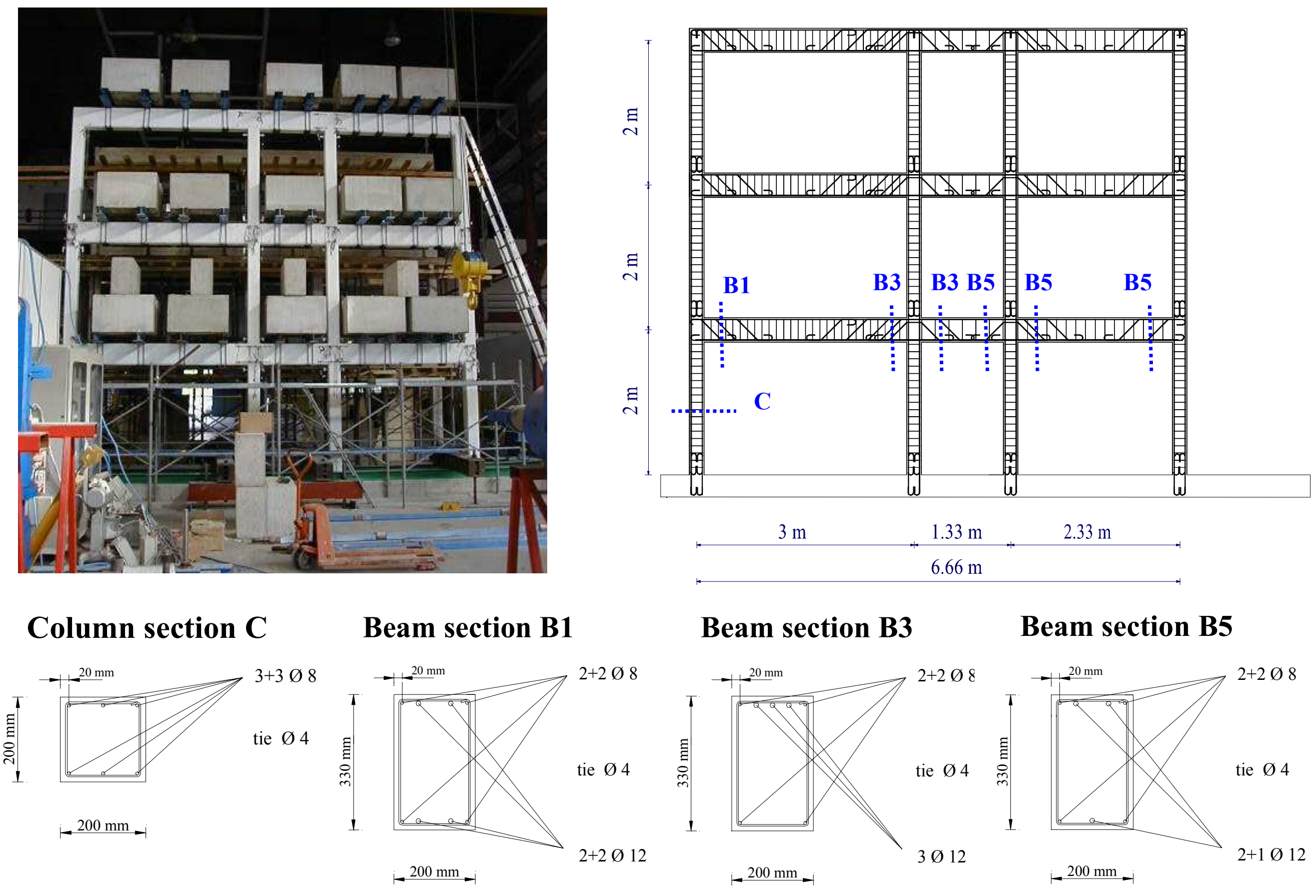


Figure 1 –Test-Frame: elevation view and section properties

Further details on the single beam-column subassembly can be found in the aforementioned companion paper ([4]), where the experimental tests on beam-column subassemblies with similar geometric and mechanic characteristics are reported.

Test set-up

The frame system was subjected to quasi-static cyclic loading at increasing levels of top displacement, applied to the structure using three electro-mechanical actuators connected to the closest beam through a steel level arm (Fig.2). The loading history consisted of a series of three cycles at increasing level of top drift ($\pm$ 0.2%; $\pm$ 0.6%; $\pm$ 1.2%) with one conclusive cycle at $\pm$ 1.6%.

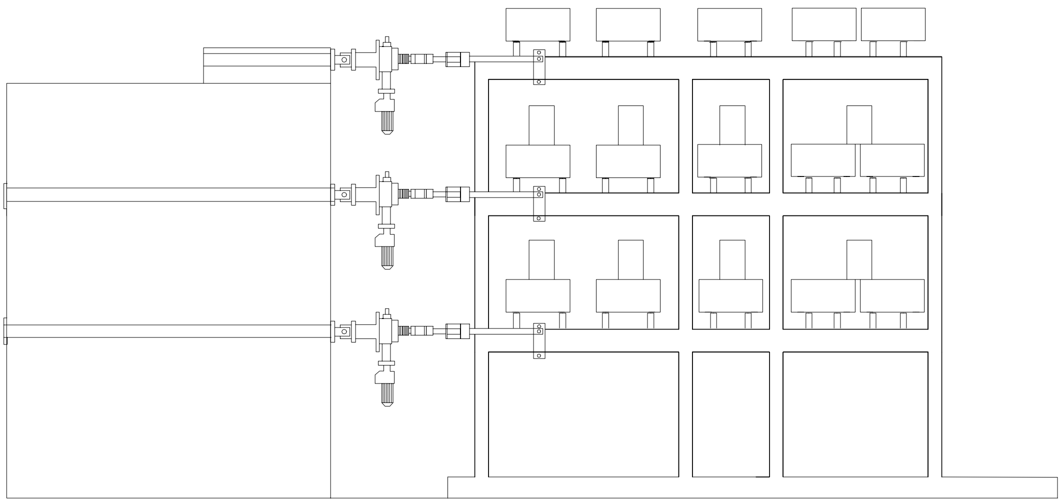
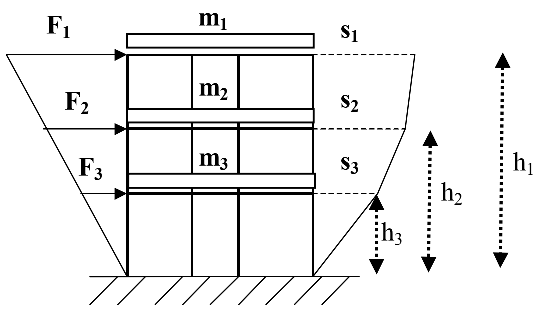


Figure 2 – Test set-up

The application of simulated seismic loads was based on a hybrid force/displacement control: the top floor displacement was directly controlled while maintaining a code-type lateral force distribution, proportional to the mass and to the floor level height, as shown in Figure 3



$$\{\overline{F}_i\} = \begin{Bmatrix} F_{i1} \\ F_{i2} \\ F_{i3} \end{Bmatrix} \qquad \frac{\{\overline{F}_i\}}{F_{i1}} = \begin{Bmatrix} 1 \\ F_{i2}/F_{i1} \\ F_{i3}/F_{i1} \end{Bmatrix} = \begin{Bmatrix} 1 \\ (m_2/m_1)\cdot h_2/h_1 \\ (m_3/m_1)\cdot h_3/h_1 \end{Bmatrix} \cong \begin{Bmatrix} 1 \\ 0.90 \\ 0.45 \end{Bmatrix}$$

Figure 3 – Lateral force distribution

It is worth noting that when dealing with existing frame systems, with strong-beam and weak-column system and tendency to soft-storey mechanism, the structural deformed shape may be expected to abandon, at early levels of drift, the linear distribution assumption.

Although it would have been possible to modify at each loading step the applied force distribution according to the actual deformed shape (similarly to what has been proposed for the "adaptive" pushover [6]), it was decided to maintain a constant ratio among the forces throughout the test, to minimize control problems and instabilities and to provide a simpler but clearer reference for numerical pre- and post-dictions of the results.

EXPERIMENTAL RESULTS

Damage observation

As mentioned, the experimental test on the frame system confirmed the high vulnerability of the panel zone region and the tendency to develop undesirable global mechanisms, due to the absence of an adequate hierarchy of strength. Figure 4 reports the global hysteretic behaviour (base-shear vs. top drift) and the displacement profile at increasing level of top displacement. As shown in Figure 5, the damage mostly concentrated in the joint region (exterior tee-joints) or at the beam/column interfaces with a wide flexural crack as expected due to smooth bars slip. In interior joints no cracks were observed. The exterior tee-joints were subjected to hybrid damage mechanisms, analogous to those observed during the tests on beam-column subassemblies. A “concrete wedge” mechanism (Pampanin [4]) was observed, due to combined effects of inefficient strut mechanism in the joint region after first joint shear cracking (0.6-0.8% top drift) and the stress concentration at the beam bar end-hooks leading to severe damage and local loss of load-bearing capacity.

The combination of smooth bars and end-hook anchorages was therefore confirmed to represent a particular inadequate structural detailing solution.

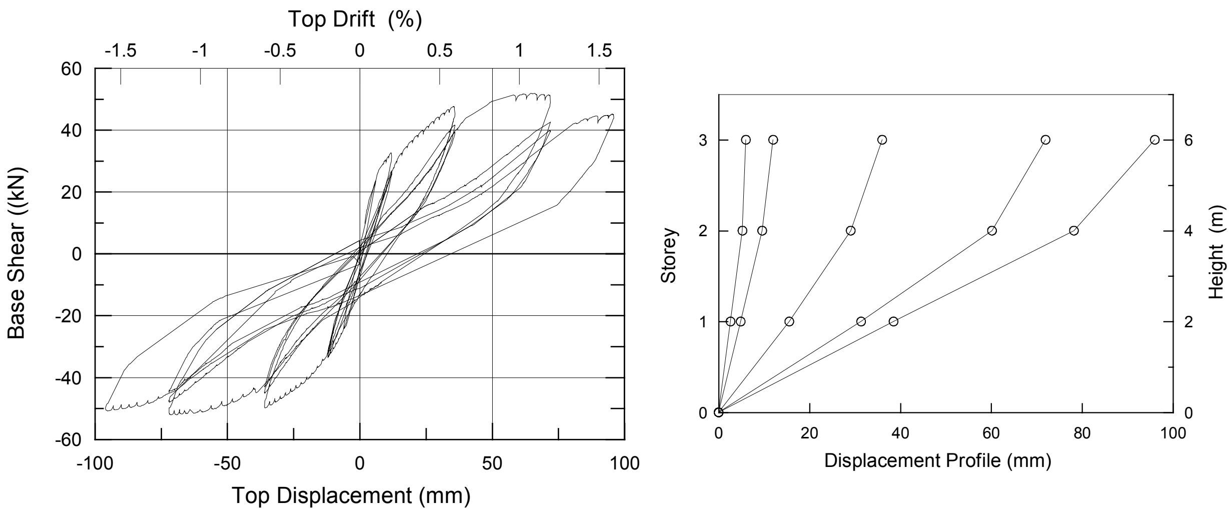


Figure 4 – Global hysteretic behaviour and displacement pattern at increasing level of top drift

Plastic hinge and shear hinge mechanisms

The observed global mechanism presents interesting peculiarities when compared with typical weak-column, weak-beam or combination of the above inelastic mechanisms. The severe damage in the exterior tee-joints (at first level as well as, but more moderate, at second level) combined with the hinging of column base sections at the ground level, would apparently lead to a soft storey-type mechanism. Actually, as evident from the experimental deformed shape shown in Figure 6, a pure soft storey mechanism did not occur at the first floor, while it would have been reasonably expected from preliminary analytical predictions if joint inelastic behaviour had not been considered.

Figure 5 – Damage photo-report at 1.6% top drift

The observed global mechanism, related to joint damage, suggests to introduction the concept of "shear hinge". Fundamental differences with the usual concept of flexural plastic hinge would be related to:

- The structural behaviour activating the hinge (shear instead of flexural behaviour)
- The post-elastic behaviour: while plastic hinge mechanism is typically expected to provide satisfactory ductility capacity, a shear hinge might be characterized by a severe strength degradation

For a given interstorey drift demand, the occurrence of a shear hinge, through shear cracking of the joint region, might lead to a concentration of deformation demand in the panel zone, with significant reduction of rotation demand in the adjacent beam or column critical sections. The interstorey drift demand is thus spread between the storey above and the storey below the joint, somewhat delaying the occurrence of single soft-storey mechanisms. The concept is illustrated in Figure 6, where the observed damage and global behaviour of the three storey frame is adopted as reliable example. The damage observations, combined with the instrumentation readings, confirmed that the occurrence of shear hinges in the first floor exterior joints contributes to significantly reduce the rotation demand in the exterior first floor columns, while higher rotation demand resulted in the interior columns due to the absence of interior joint damage.

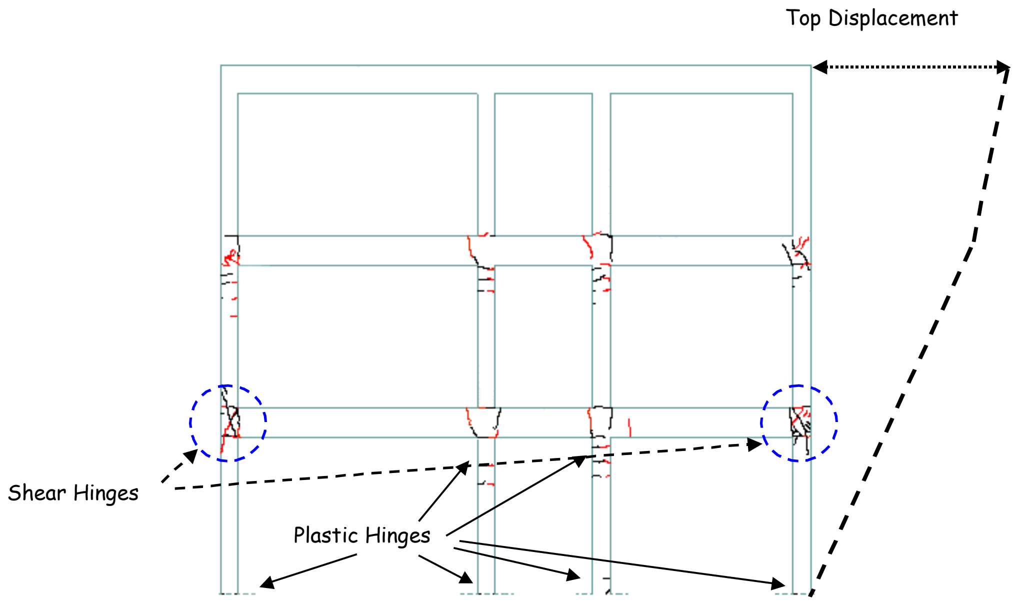


Figure 6 – Global mechanism: plastic hinge and shear hinge (top drift 1.6%)

This apparent favourable effects on structural members is however paid with possible strength degradation (depending on the structural details adopted, i.e. beam bars bent in, bent out or hook-ended, as well as use of smooth or deformed bars) and higher local deformation in the damaged joint panel region. A critical discussion on the relevance of joint damage in the behaviour of gravity load designed R.C. frames can be found in Calvi et al. [7].

PRELIMINARY NUMERICAL ANALYSES

Preliminary numerical investigations on the seismic behaviour of under-designed frame systems confirmed the aforementioned assumptions on the effects of joint damage on the global response. The finite element code Ruaumoko (Carr, [8]) was used for the analyses. The frame model consisted of one-dimensional frame elements with concentrated inelasticity at the critical section interface, defined through appropriate moment-curvature curves based on section analyses. A simplified analytical model was proposed for joint linear and non-linear behavior, consisting of an equivalent moment-rotational spring, which governs the relative rotation of beam and column elements. The characteristics of the spring can be directly derived, based on equilibrium considerations, from the corresponding principal tensile stress vs. shear deformation curve of the joint. For simplicity, no sources for strength degradation in the joint region after first diagonal cracking were considered and the shear hinge mechanisms were thus modelled with elasto-perfectly-plastic or bilinear-with - hardening springs for exterior and interior joints, respectively. Further details can be found in Calvi et al. [7].

The response of two six storey gravity load designed frame systems with and without joint modelling are compared in Figure 7 shows the damage distribution at 1.5% top drift: flexural plastic hinges and the corresponding curvature ductility demands in beam and column elements as well as activation of shear hinge in the joints, corresponding to the occurrence of first diagonal cracking in the panel zone region , are reported. Besides leading to a reduction in stiffness, damage in interior and exterior joints leads to a concentration of angular deformation demand in the panel zone region with significant reduction in ductility demand in the critical interface sections in the adjacent members. Single soft storey mechanism are thus prevented or, more precisely, postponed at higher drift levels.

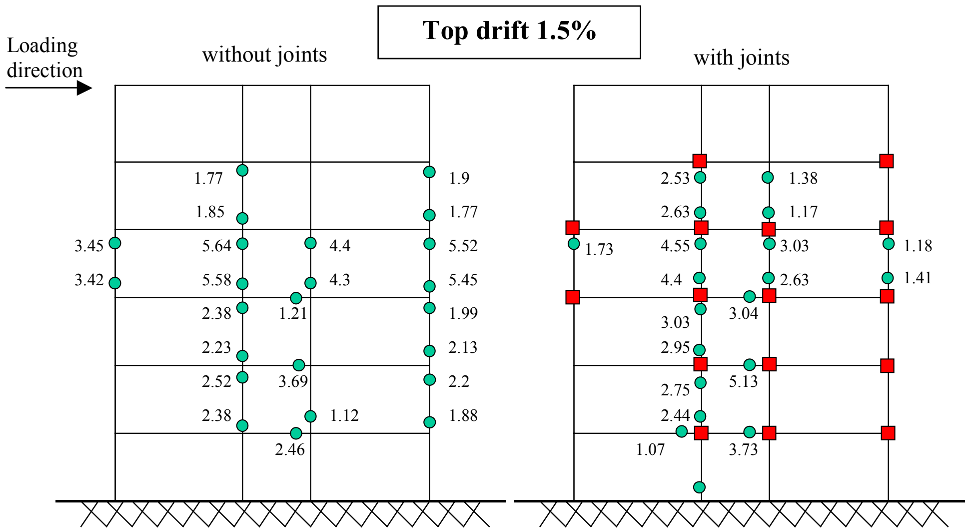


Figure 7 – Comparison of frame model response with and without joint modelling: pushover response on six storey frame; damage distribution

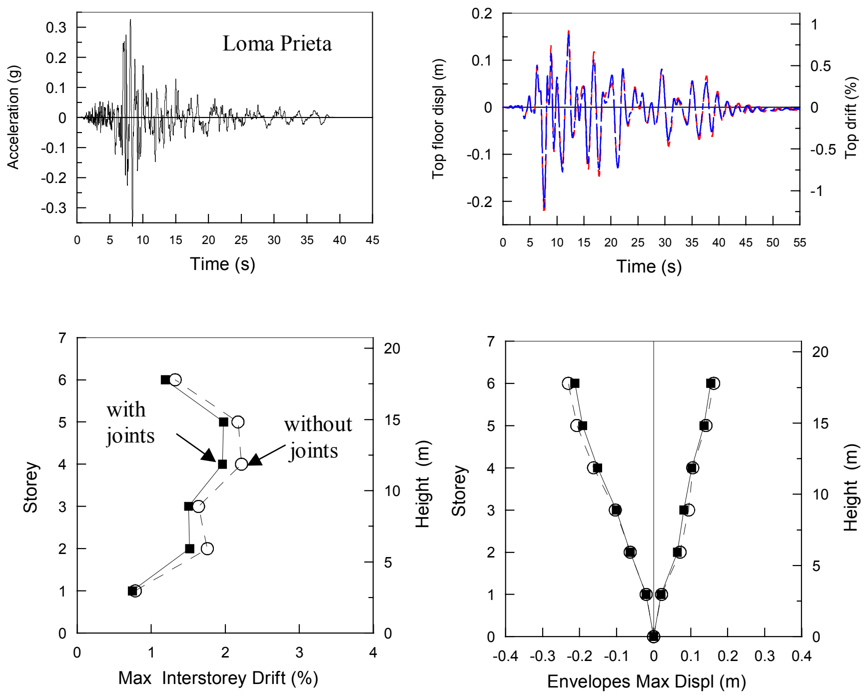


Figure 8 – Comparison of six storey frame time-history response with and without joint modelling
(modified Loma Prieta, 1989, Hollister Differential Array)

The time-history response of the same six storey frames, shown in figure Figure 8, confirms the effect of joint damage in reducing the inter-storey drift demand, while no amplification of maximum global displacement demand is observed.

CONCLUSIONS

The experimental test on a three storey r.c. frame, 2/3 scale, designed for gravity load only confirmed the inherent vulnerability of under-designed frames with structural deficiencies typically adopted in Italy before the introduction of adequate seismic code provisions in the 1970's. The use of smooth bars in combination with end hook anchorage in the exterior joints showed to lead to particularly brittle and undesirable failure mechanism, at both local and global level. The activation of a shear hinge mechanism due to shear cracking in the joint region has been shown, both experimentally and analytically, to modify the global inelastic response, redistributing the deformation demand within the beam-column-joint sub-system. This apparent favourable effect, which can protect or delay soft storey mechanisms, is however paid with high inelastic rotation in the joint region and, depending on the post-cracking joint behaviour (related to the adopted structural details) might result in a sudden degradation with loss of load bearing capacity of the whole frame system.

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