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SEISMIC BEHAVIOUR OF R.C. BEAM-COLUMN JOINTS DESIGNED FOR GRAVITY LOADS

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ABSTRACT
The inherent seismic vulnerability of reinforced concrete beam-column connections designed for gravity load only is herein investigated. Experimental tests on six 2/3 scaled beam-column subassemblies, with structural deficiencies typical of Italian construction practice between the 50's and 70's, were performed under simulated seismic loads. Interior, exterior tee and knee joints, characterized by the use of smooth bars, inadequate detailing of the reinforcement (i.e. total lack of transverse reinforcement in the joint region), deficiencies in the anchorage (hook-ended bars) and the absence of any capacity design principles, were subjected to quasi-static cyclic loading at increasing levels of interstorey drift. The experimental results underlined the significant vulnerability of the joint panel zone region and the critical role of the slippage phenomena due to the use of smooth bars and of inadequate anchorage. A particular "concrete wedge" brittle failure mechanism, due to the interaction of shear cracking and stress concentration at the hook anchorage location, was observed in the exterior specimens. The inaccuracy of traditional shear degradation models for exterior joints in predicting similar damage mechanisms is discussed and possible modifications are suggested.

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

INTRODUCTION
The structural deficiencies of existing reinforced concrete buildings designed for gravity only, as typical of construction practice before the introduction of seismic-oriented design codes in the mid 70's, have recently been recognized. As a consequence of poor reinforcement details and absence of any capacity design principles, a significant lack of ductility at both the local and global levels is expected, resulting in inadequate structural performance even under moderate seismic excitation. Design to an allowable stress philosophy contributes to uncertainty of the inelastic response.
While most analytical and experimental investigations in Earthquake Engineering have focused on the design of new earthquake resistant structures the evaluation of the seismic vulnerability of existing structures is a relatively recent topic, which only in the last decade has been subjected to a significant methodological upgrading. A general lack of information, based on experimental tests on the seismic behaviour of under-designed (or designed for gravity loads only) frame systems or beam-column subassemblies, is therefore observed.
The crucial need of adequate "controlled" information on the behaviour of substandard designed existing structures under seismic loads has been further emphasized, if necessary, by the catastrophic effects of recent earthquake events (India 2001, Turkey, Colombia and

Taiwan, 1999). The tendency of neglecting, in the construction practice, minimum seismic design recommendations provided by standard code guidelines, dramatically increases the percentage of high vulnerable structures within the existing stock.
As 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 before the introduction of seismic-oriented codes in the mid-70's, experimental tests on 2/3 scaled beam-column joints and a three-storey frame system were performed at the Laboratory of the Department of Structural Mechanics of the University of Pavia.
In this contribution, the results from the quasi-static cyclic tests on six gravity-load-designed beam-column subassemblies are presented and critically discussed. The results from the experimental test on the three storey frame are presented in a companion paper (Calvi et al. [1]). Further details on the topic can be found in Pampanin et al. [2] and Calvi et al. [3].

TYPICAL STRUCTURAL DEFICIENCIES OF EXISTING RC BUILDINGS

General lack of ductility rather than inadequate lateral strength has been recognized as the fundamental source of deficiency in seismic performance of gravity load designed existing buildings, as a consequence of total absence of capacity design principles and poor reinforcement detailing (Priestley [4]). At the global level, a weak-column/strong-beam system results, with tendency to develop soft-storey mechanisms. At the local level, inadequate protection of the panel zone region within beam-column joint subassemblies is expected as well as brittle failure mechanisms of structural elements.
Typical structural deficiencies can be related to:

a) inadequate confining effects in the potential plastic regions;
b) insufficient amount, if any, of transverse reinforcement in the joint regions;
c) insufficient amount of column longitudinal reinforcement, when considering seismic lateral forces;
d) inadequate anchorage detailing, for both longitudinal and transverse reinforcement;
e) lapped splices of column reinforcement just above the floor level;
f) lower quality of materials (concrete and steel) when compared to current practice, in particular:
   f_1) use of smooth (plain) bars for both longitudinal and transverse reinforcement,
   f_2) low-strength concrete.

In addition, typical design according to an allowable stress philosophy results in uncertainties on the inelastic response.
In the following research program the design recommendations provided by the current national design provisions adopted in the 50's-70's (Regio Decreto 1939, [5]) were followed. When provisions on structural details were not available, text-books broadly adopted in the engineering practice were followed.

EXPERIMENTAL PROGRAM

Geometry, reinforcement and materials details

Six one-way beam-column subassemblies specimens, 2/3 scaled, were tested, representing the following typologies:

- two exterior knee-joints (specimens L)
- two exterior tee-joints (specimens T)
- two interior cruciform joints (specimens C)

Within the knee and tee typology (Fig. 1 top), the beam longitudinal reinforcement was varied between the two specimens. In the interior specimens (Fig. 1 bottom)., two different anchorage solutions for the beam longitudinal reinforcement through the joint region were adopted: continuous reinforcement (specimen C2) or lapped splices with hook-end anchorage outside the joint region (specimen C4).

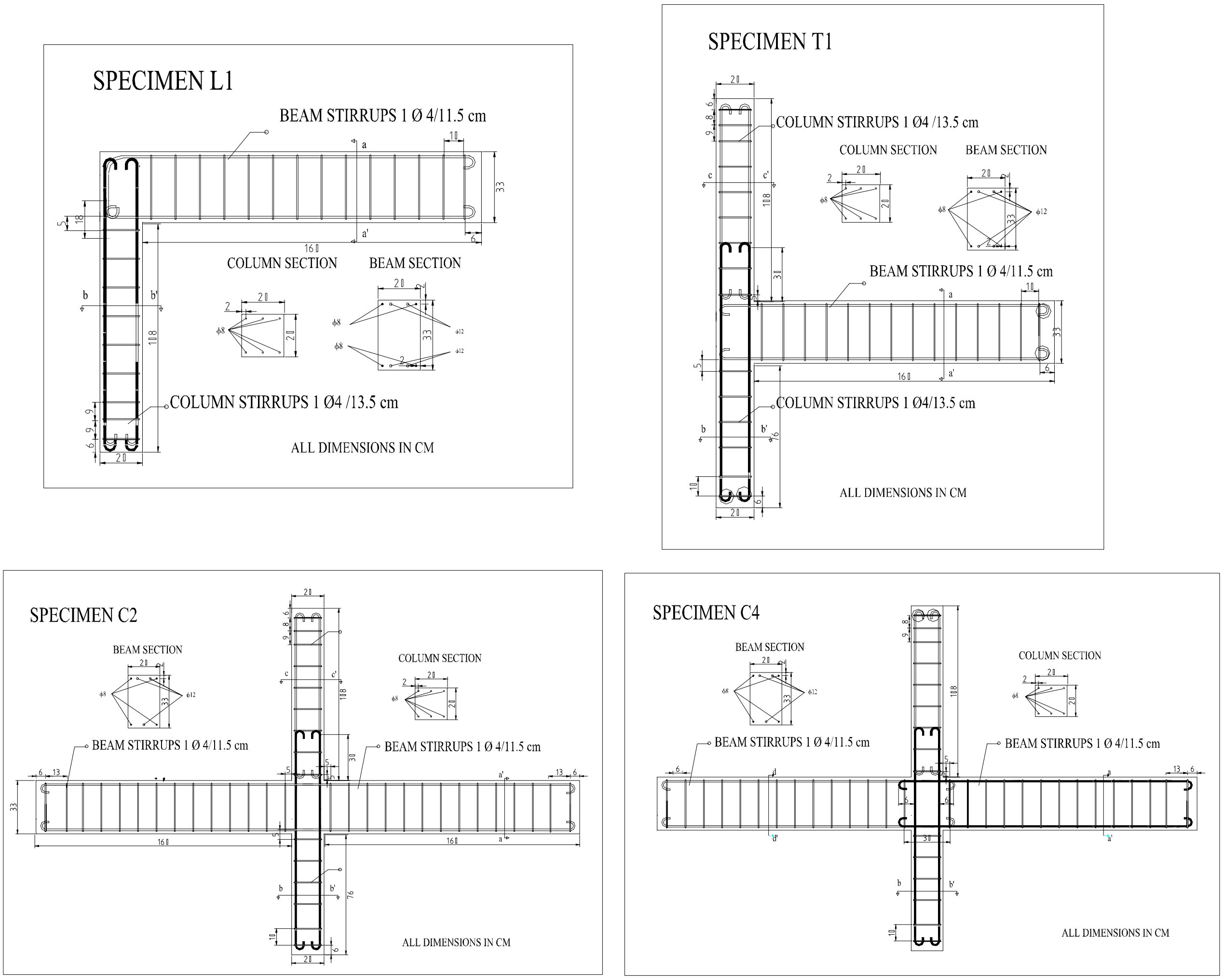

Figure 1 –Beam-column subassemblies specimens

Steel smooth bars, with mechanical properties (allowable stress 160 MPa) similar to those typically used in that period, were adopted for both longitudinal and transverse reinforcements. Table 1 lists the main mechanical characteristics of concrete and reinforcing steel.

Table 1 – Material properties

CONCRETE		**STEEL (longitudinal bars)**	
Cylindric compression strength (MPa)	**Cube compression strength (MPa)**	**Yielding (MPa)**	**Ultimate (MPa)**
Average	*Average*	**Diameter ϕ 8**	
23.9 (0.52)	29.1 (0.64)	385.6 (1.75)	451.2 (3.49)
		Diameter ϕ 12	
		345.9 (2.17)	458.6 (2.17)

Test set-up and loading history

The test set-up for the different specimens was intended to reproduce the configuration of a beam-column subassembly in a frame subjected to reversed cyclic lateral loading.

Figure 2 illustrate the set-up for the different specimens and the applied loading history. Beam and column elements were extended between contraflexure points (assumed to be at midspan of the beams and at midheight of the columns) where pins are introduced. Simple supports at the beam ends were obtained connecting pin-end steel members to the floor. A series of three cycles at increasing level of interstorey drift was applied thought the horizontal hydraulic actuator (100 kN, 250 mm stroke). In order to better reproduce the actual state of stress of beam-column joints during an actual cyclic push-pull test on a frame system, the column axial load was varied during the experiments as a function of the lateral load, alternatively to what typically done in experimental tests on beam-column subassemblies presented in literature. The axial-load vs. lateral-force relationships for exterior and interior joints were evaluated with preliminary pushover analyses on the three storey-three bays R.C. frame system of the co-ordinated research program (Pampanin *et al.* [2]).

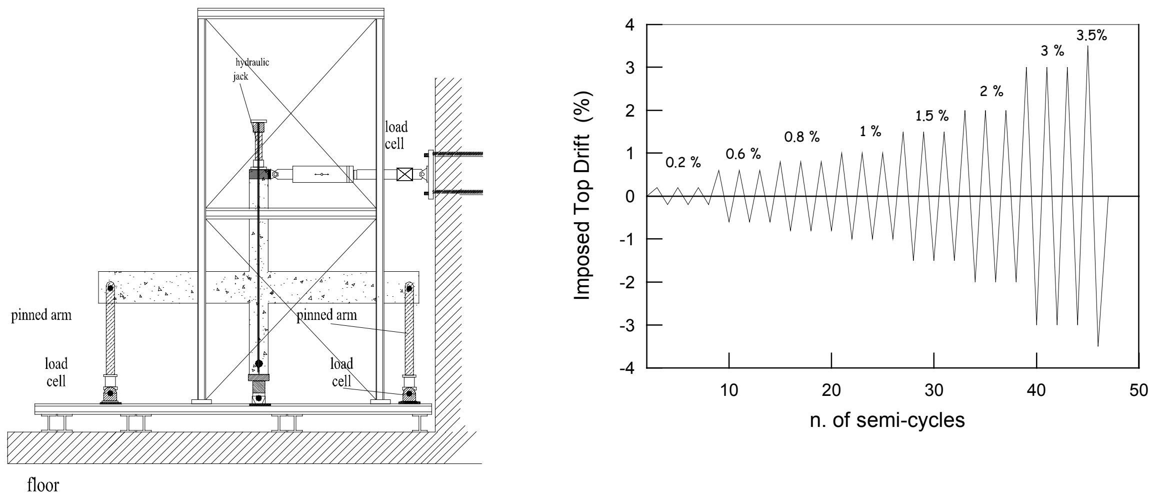

Figure 2 – Test set-up and loading-history

Significant variations of the axial load up to 40-50% (increase and decrease) with respect to the value due to gravity load only were observed. During the tests on the beam-column specimens, a simplified bi-linear relationship between axial and lateral load was adopted. According to the adopted sign convention, positive drift and positive lateral force correspond to a decrease in the axial load. The constant values of axial force due to the gravity loads were 100 kN and 120 kN for the exterior tee-joints and interior cruciform-joints respectively. The axial load was applied by means of a vertical hydraulic jack, acting on a steel plate connected to the column base plate by vertical external post-tensioned bars.
No simulated gravity loads were applied to the beam elements. This must be taken into account when interpreting the results, drawing conclusions on the sequence of events and carrying out a drift-based assessment.

EXPERIMENTAL RESULTS

The experimental results provided encouraging confirmations, from a qualitative point of view, on the capacity of simple analytical tools, based on section analysis and hierarchy of strength principles, in predicting the sequence of events within the beam-column-joint system (i.e. hinging in beam and columns or joint shear cracking). However, significant difficulties in capturing the characteristics of the observed damage mechanisms were encountered.
A significant vulnerability of the panel zone region was shown. Bar slip phenomena, on one side, resulted in marked cyclic stiffness degradation (“pinching” effect in the hysteretic cycle), on the other, guaranteed a pronounced flexibility to the whole subassemblage.

Furthermore, the structural details adopted in the anchorage solutions (bar end-hooks), in combination with smooth bars, represented a fundamental source for hybrid local damage and failure mechanisms, where typical flexural or shear cracking (in beam/column elements or joint panel zone, respectively) interacted with concrete spalling due to concentrated compression force at the end-hook anchorage.

Exterior knee-joints behaviour
The behaviour of the two knee specimens, characterized by different reinforcement, was governed by flexural damage concentration at the column interface. High level of drift (up to3.5%) was reached without significant reduction in strength: this high ductility capacity was provided by the low level of axial load and longitudinal reinforcement ratio as well as by the column bar slip, as evident from the marked “pinching” in the experimental hysteretic behaviour (Fig. 3). At high level of drift a particular local damage mechanisms developed at the top of the joint region, while the cracks at the column interface kept increasing in width. Due to slippage of the column reinforcement and stress concentration at the end-hook. crushing and spalling of the concrete occurred at the top face of the joint (Fig.3).

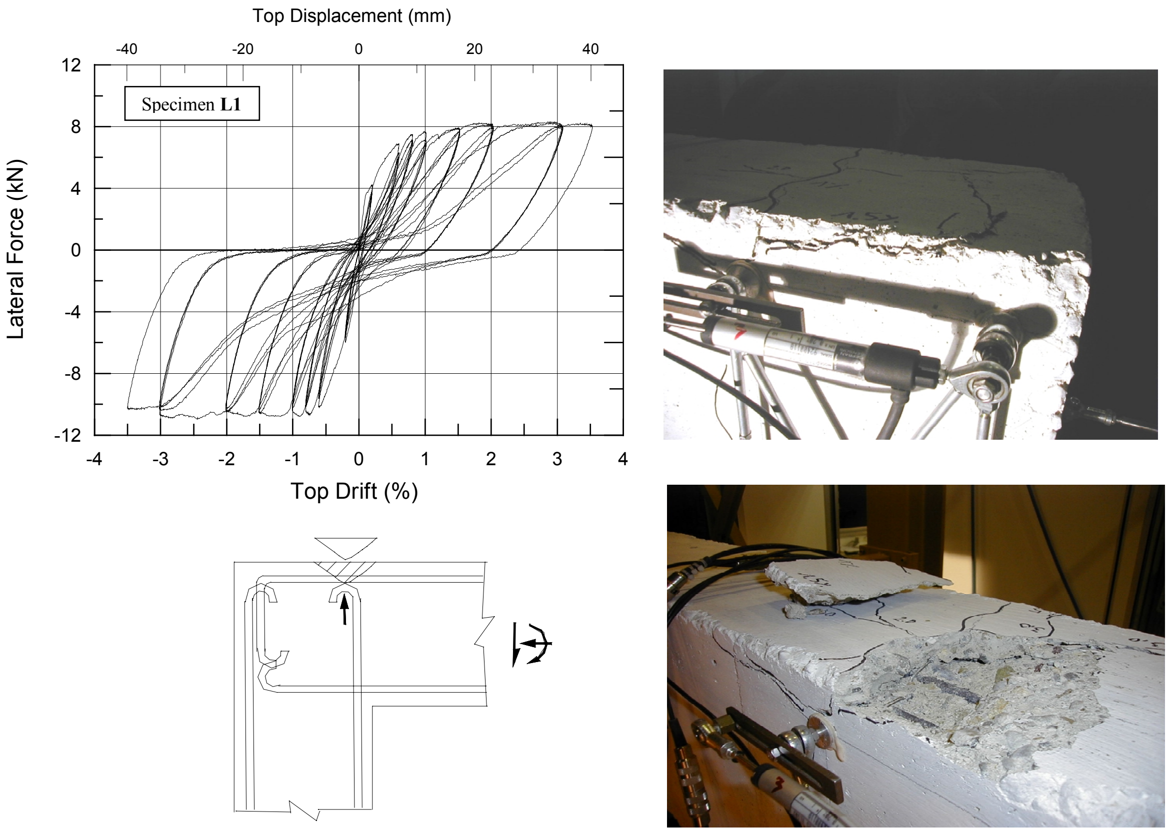

Figure 3 –Exterior knee joint (specimen L1): hysteretic behaviour and damage mechanism

Exterior tee-joints behaviour
The exterior tee-joint specimens showed an analogous particular brittle hybrid failure mechanism: joint shear damage combined with slippage of longitudinal beam bars within the joint region with concentrated compressive force at the end-hook anchorage. As a result, a concrete “wedge” tended to spall off, leading to brittle local failure and loss of bearing-load

capacity (Fig. 4). The observed mechanism presents interesting peculiarities when compared to damage mechanisms typically expected for exterior tee-joint (Fig. 5), depending on the anchorage details adopted: beam bars bent away from the joint or into the joint region. Recent experimental investigations presented by Hakuto et al. [6] on existing joints with substandard reinforcing details, typical of pre-1970s designed moment resisting frames in New Zealand, confirmed the inefficiency of alternative shear transfer mechanism in the joint region, after shear cracking, when beam bars are bent out from the joint. The former anchorage details can not provide an effective node point for the development of the diagonal compression strut mechanism unless a significant amount of transverse column hoops is used immediately above the joint core. Deformed reinforcement bars were adopted during the test.

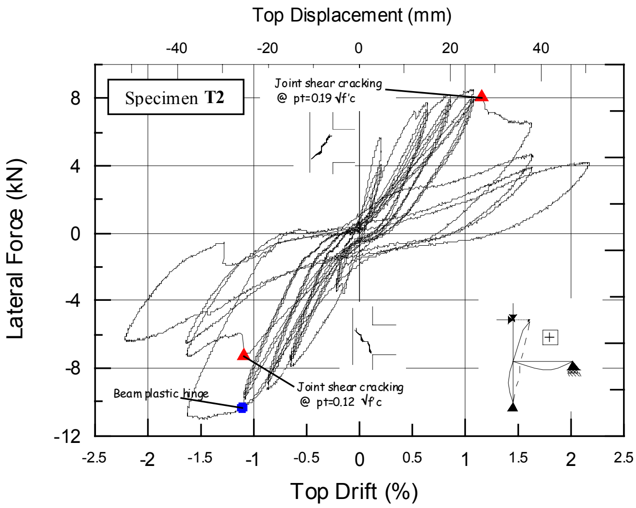

Figure 4- Hysteretic rule and observed damage mechanism in exterior tee-joint

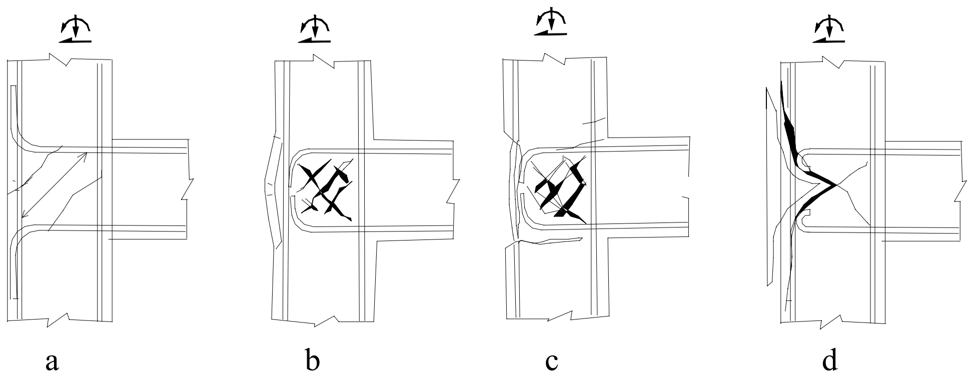

Figure 5- Alternative damage mechanisms for exterior tee-joints :
a) beam bars bent away from joint region;
b), c) beam bars bent in joint region;
d) end-hook anchorage: “concrete wedge” mechanism

Similar qualitative damage mechanism were observed in the tests carried out at the University of Pavia. However, the use of smooth bars in combination with end hook-anchorage played a significant role in modifying the sources of the observed hybrid mechanism. As shown in Fig. 6, due to bond deterioration and beam bar slip at early stages, an additional localized concentrated force at the compressed bar edge acted, after first joint diagonal cracking, in combination with the inefficient strut mechanism, leading to the expulsion of the aforementioned concrete "wedge".

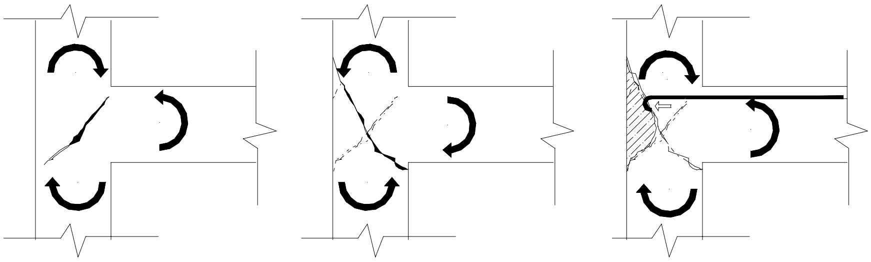

Figure 6 –Development of "concrete wedge" mechanism

Interior joints behaviour
The interior joint specimens showed significant resource of plastic deformation (Fig. 7), even without specific ductile structural details. According to preliminary capacity design considerations shear joint cracking and column hinging were predicted to be relatively close events. The concentration of flexural damage in the column at early stages, thus, acted as a structural fuse for the joint panel zone, which did not suffer any cracking. The anchorage solutions with lapped splices and end hooks (specimen C4).confirmed a superior efficiency as clearly shown in Figure 7. However, a marked pinching was observed in both cases, due to slip of the column longitudinal reinforcement bars. Discussion on the critical implications from beam bar or column bar slip phenomena in interior beam-column subassemblies has been recently proposed by Hakuto et al. [7] and Calvi et al. [3], respectively.

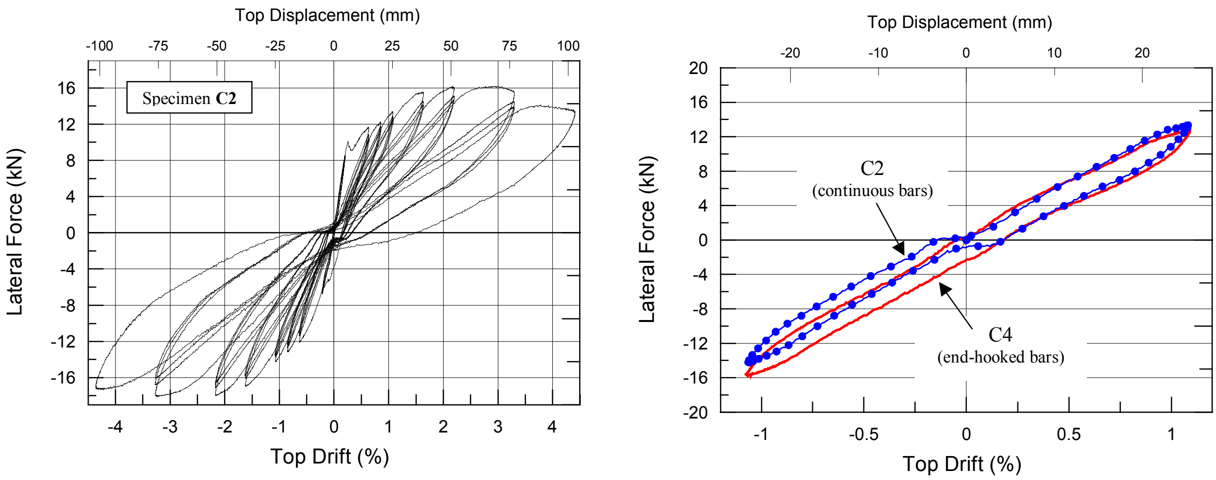

Figure 7 –Interior joints: hysteretic behaviour and comparison of anchorage solutions

STRENGTH DEGRADATION CURVE FOR EXTERIOR JOINTS

The aforementioned peculiar degrading mechanism (named "concrete wedge") in the exterior tee-joints specimens showed a particular brittle behaviour, with a sudden and severe joint shear strength reduction after first diagonal cracking. The combined action, at alternate half cycles, of a concentrated compression force at the beam bar end-hook anchorage and of the diagonal compression strut within the joint region, inhibits any alternative source of shear transfer mechanism within the joint region. The implications, at both local and global levels, can be significant and adequate recommendations are needed for the assessment of analogous under-designed or gravity dominated frame structures.

Joint shear stress is generally expressed in terms of either nominal shear stress (v_{jn}) or principle compression/tensile stresses (p_c, p_t). Although it is commonly recognised that principle stresses provide more accurate indications, considering the contribution of the actual axial compression stress (f_a) acting in the column, current code provisions tend to limit the nominal shear stress v_{jn} expressed as function of concrete tensile strength $k_1\sqrt{f'_c}$ (i.e. ACI 318-95 [8] and similarly EC8 [9]) or concrete compressive strength $k_2 f'_c$ (NZS 3101:1995 [10]), being k_1 and k_2 empirical constants.

Typical strength degradation models available in literature (Fig. 8) and based on research on poorly designed joints (Kurose [11]; Hakuto et al.[6]; Priestley [4]) recognises the inherent vulnerability of exterior joints without transverse reinforcements in the joint region. Recent comprehensive tentative degradation models, suggested by Priestley [4] according to a displacement based assessment procedure, for exterior and corner joint in terms of principal tensile stress p_t as a function of subassemblage drift level or joint shear deformation are illustrated in Figure 8 and compared with the experimental evidences. It is important to underline that literature models refer to experimental investigations on specimens with deformed reinforcement bars.

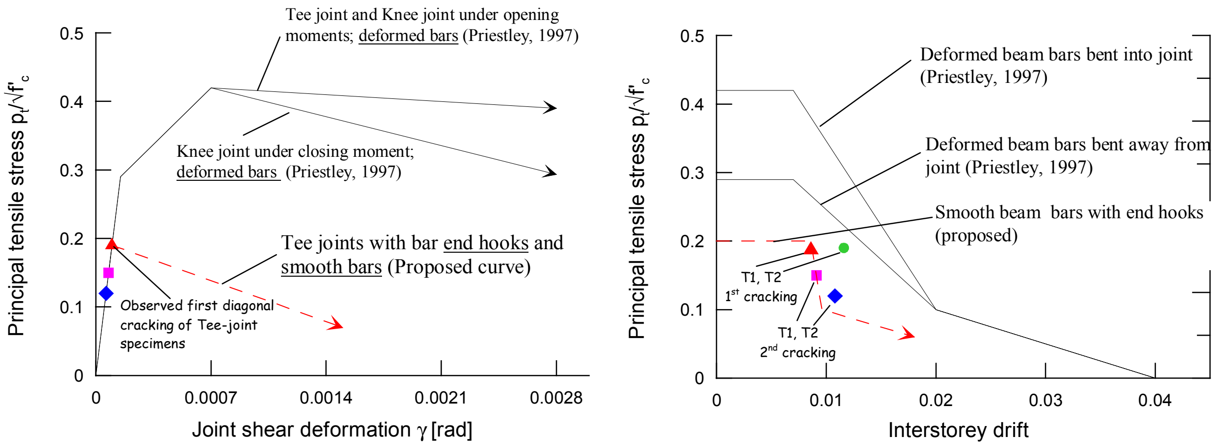

Figure 8 –Strength degradation curve for exterior joints

It is evident that the behaviour of the tee-joint specimens tested is similar to the case of beam bars bent away from the joint region. In this condition, joint failure is suggested to initiate at a principal tension stress $p_t = 0.29\sqrt{f'_c}$ (MPa). Higher principle stress levels, which result to a progressive severe diagonal cracking in the joint region up to $p_t = 0.42\sqrt{f'_c}$, cannot be achieved by through of an hardening behaviour, since alternative transfer mechanism sources are not allowed, as opposite to the case of exterior joint with beam bent in the joint region or interior joint where a reliable compression strut can develop.

In the tested tee-joint specimens, diagonal tensile cracking clearly governed and failure was reached due to the aforementioned hybrid mechanism. First diagonal cracking occurred at a principle tensile stress level $p_t = 0.19\sqrt{f'_c}$ while cracking in the opposite direction of loading occurred at significant lower level ($p_t = 0.15\sqrt{f'_c}$ and $p_t = 0.12\sqrt{f'_c}$ for specimen T1 and T2 respectively). The latter strength reduction was expected in the T2 specimen as a consequence of the ductility demand in the adjacent beam element; further considerations are needed for the T1 specimen, since no plastic hinge occurred in the elements. Furthermore, the experimental strength reduction curve after cracking seems to be more relevant showing a faster degradation than what expected from classical models.

At a local level (joint panel zone), the elastic stiffness is correctly predicted, while cracking and high damage limit states are overestimated both in terms of stress and deformation values. Drift limits at a subassembly level for the first cracking are slightly underestimated, as a consequence of higher deformability of the tested specimen due to the use of smooth bars. The limited number of specimens tested does not allow to formulate a reliable alternative degrading curve. However, an approximate qualitative trend of a degrading curve for tee-joint specimen without shear reinforcement in the joint region and with inadequate anchorage details of the beam bars, can be proposed as illustrated in Figure 8 and described as follows:

- $p_t = 0.2\sqrt{f'_c}$ should be considered an upper limit for first diagonal cracking, with significant reduction for second cracking as a consequence of reverse cyclic deterioration (not necessarily associated with ductility demand of adjacent elements);
- the associated reduced joint shear deformation at cracking can be determined following the elastic curve proposed in literature;
- significant and sudden strength reduction might occur after the cracking point without any additional source for hardening behaviour.

It is worth recalling that a correct estimation of strength and deformation characteristics of joint subassemblies might be critical when assessing the behaviour of whole frame systems designed for gravity only. The use of smooth bars demonstrated to represent possible sources not only for higher global deformability, as already well-known in literature (Soleimani *et al.*, [12]; Filippou *et al.* [13]; Paulay and Priestley [14]) but, more consistently, for particular brittle local degrading mechanisms, which are not expected from classical models.

CONCLUSIONS

The results of experimental tests on reinforced concrete beam-column subassemblies designed for gravity only have been presented. Structural inadequacies, as typical of the Italian construction practice before the introduction of seismic code provisions in the mid-70's, were reproduced. The combined use of smooth reinforcing bars with end-hook anchorage, as well as lack of any capacity design considerations, showed to be a critical source of significantly brittle damage mechanisms as in the case of exterior joints, where additional sources of shear transfer mechanisms cannot develop after first diagonal cracking in the joint. An apparent satisfactory level of deformability as well as ductility, due to the combined effects of slippage phenomena and low column reinforcement ratio, were observed in knee and interior cruciform subassemblies, where no joint degradation occurred and column flexural damage dominated the behaviour. Moreover, the comparison of different anchorage solutions for beam-bars in interior specimens showed an higher deformability due to slippage phenomena, without resulting in flexural strength reduction. When considering the overall seismic behaviour of a frame structure, the implications of the aforementioned flexural damage on the overall seismic behaviour might be significant, with soft storey mechanisms being likely to occur at early stages.

Phenomenological explanations of the observed joint damage mechanisms (i.e. "concrete wedge") as well as considerations on joint shear strength and deformation behaviour have been given. Ultimately, suggestions for alternative qualitative degradation curves (based on principle stress levels) for exterior beam-column joints with similar structural deficiencies have been provided.

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