

# MODELLING OF SHEAR HINGE MECHANISM IN POORLY DETAILED RC BEAM-COLUMN JOINTS

Stefano PAMPANIN<sup>1</sup>

Guido MAGENES<sup>2</sup>

Athol CARR<sup>1</sup>

<sup>1</sup> Department of Civil Engineering, University of Canterbury, Christchurch, NZ

<sup>2</sup> Department of Structural Mechanics, University of Pavia, Italy

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## 1 INTRODUCTION

Recent experimental investigations on the seismic performance of existing reinforced concrete frame buildings, designed for gravity loads only as typical of seismic-prone countries before the introduction of seismic oriented codes, underlined a significant vulnerability of the joint panel zone region ([1-4]). Inadequate structural detailing (i.e. total lack of transverse reinforcement in the joint region), deficiencies in the anchorage (use of plain round bars with end-hooks) and the absence of any capacity design principles can lead to the development of brittle failure mechanisms, particularly in exterior joints where additional sources of shear transfer within the joint region cannot develop after first diagonal crack. Local and global damage and failure mechanisms might be significantly affected by the consequent peculiar non-linear behaviour of the joint.

When assessing the seismic performance of existing under-designed or designed-for-gravity-only buildings, an adequate modelling of the inelastic behaviour of the joint panel zone appears, therefore, to be essential. Alternative approaches for modelling the RC beam column joint, ranging from simplified empirical to refined finite elements models, are available in literature ([5-9]). Multi-node or multi-spring macro-models typically require the definition of a high number of input-parameters as well as appropriate constitutive-laws for the materials. The excessive complexity discourages them from being used as predictive tools in extensive parametric numerical studies. Furthermore, due to relatively scarce information based from experimental tests on gravity-load-designed frame systems and subassemblies, there is a general lack of appropriate modelling solutions for poorly designed beam-column joint system.

In this paper, a simplified analytical model for joint behaviour is presented and proposed as a viable tool for extensive parametrical studies on the seismic response of existing frame systems. Based on the experimental results on gravity-load-designed beam-column subassemblies and on a frame system, the concept of a shear hinge associated with the joint damage mechanism is introduced as an alternative to flexural plastic hinging and the observed implications at local and global level response are described. According to a concentrated plasticity approach, an equivalent rotational spring, governing the relative rotation of the beams and columns, is adopted to represent the joint behaviour in the linear and non-linear range. The monotonic moment-rotation characteristics of the spring can be directly derived from equilibrium considerations on the bending moments of the adjacent elements, corresponding to principal tensile stress levels in the mid-depth of the joint panel zone. An appropriate hysteretic rule with "pinching" behaviour to take into account both bar slipping mechanisms or shear cracking in the joint region should be adopted to model the cyclic behavior. Preliminary numerical-experimental comparisons with the cyclic tests on beam-column subassemblies designed for gravity only as typical of the Italian construction practice between the 1950s and 1970s are also provided.

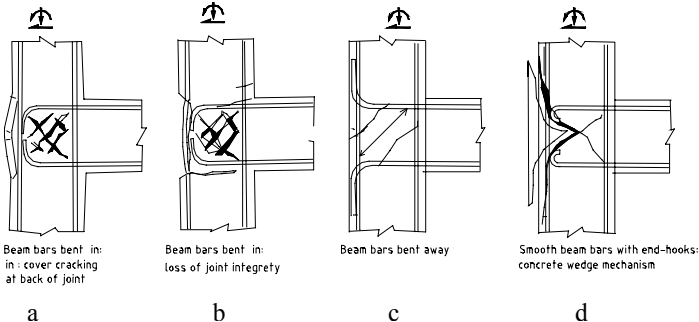
## 2 BEAM-COLUMN JOINT NON-LINEAR BEHAVIOUR

### 2.1 Alternative Damage Mechanisms

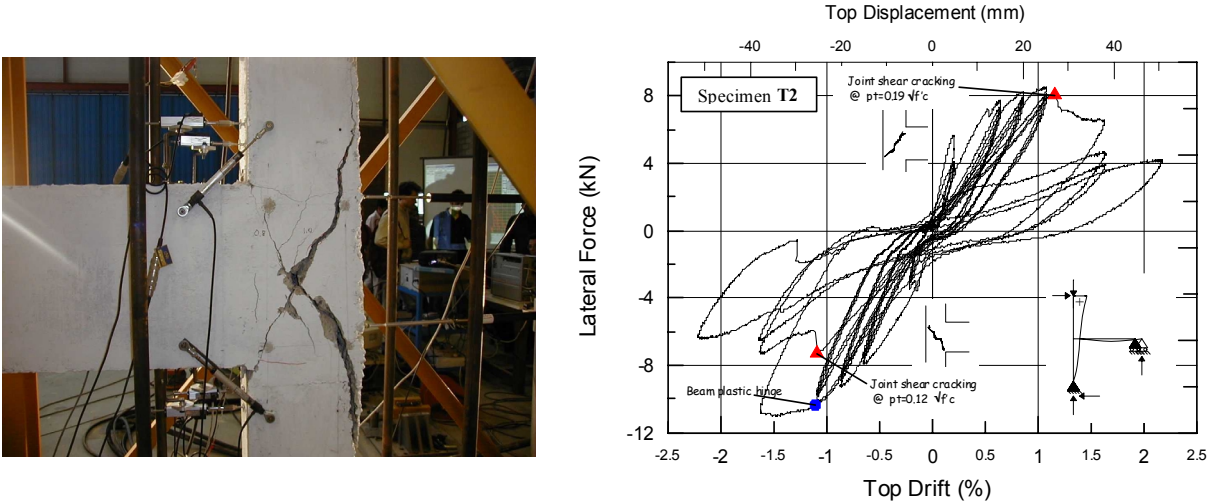
Different damage or failure modes are expected to occur in beam-column joints depending on the typology (exterior or interior joint) and of the adopted structural details (i.e. presence of transverse reinforcement in the joint; use of plain round or deformed bars; alternative bar anchorage solutions). Possible damage mechanisms of exterior tee-joints with no transverse reinforcement (as typical of older construction) in the joint region are shown in Fig. 1. After diagonal cracking, the shear transfer mechanism in the joint region has to basically rely on a compression strut mechanism, whose efficiency is critically related to the anchorage solution adopted for the longitudinal beam

reinforcement. When beam bars are bent into the joint (Fig. 1 a), they can provide a limited resistance against the horizontally expansion of the joint, until the hook opens under the combined action of the diagonal strut and the pulling tension force in the beam reinforcement, leading to a rapid joint degradation. When beam bars are bent away from the joint (Fig. 1c), as typical of older practice in New Zealand and Japan, no effective node point is provided for the development of an efficient compression strut mechanism, unless a significant amount of transverse column hoops is placed immediately above the joint core. A rapid joint strength degradation after joint diagonal cracking is expected. The worst scenario is however provided by the solution shown in Fig. 1d, typical of Italian construction practice, where plain round bars with end hook anchorage were used. As recently shown by experimental tests on beam-column joint specimens and a three storey frame system ([10-12]), the combination of strut action and of a concentrated compression force at the end-hook anchorage, due to slippage of the longitudinal beam bars, lead to the expulsion of a “concrete wedge” (Fig. 2), with rapid loss of bearing-load capacity.

Furthermore, the premature slipping of the longitudinal bars introduces, through a concentrated compression force at the end-hook, an “equivalent” principal tensile stress state in the joint region, which anticipates the joint diagonal tensile cracking.

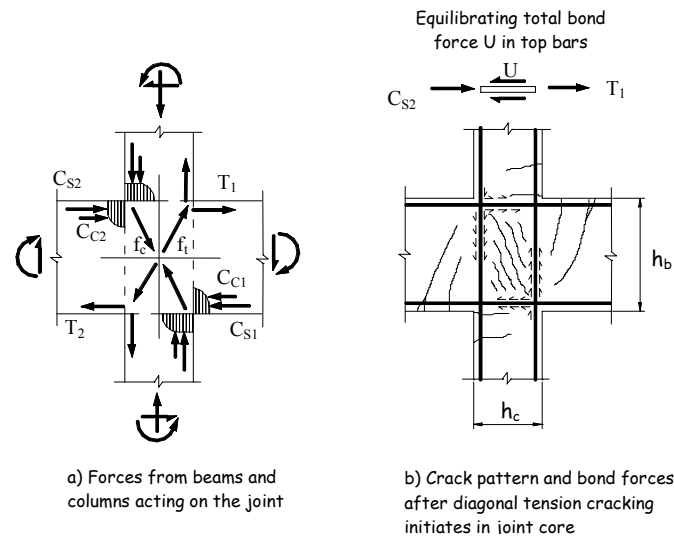


**Fig. 1 - Alternative damage mechanisms for exterior tee-joints:**  
 a,b) beam bars bent inside the joint region (Priestley, [13])  
 c) beam bars bent outside the joint region (Hakuto et al., [1]; Priestley, [13])  
 d) plain round beam bars with end-hooks: “concrete wedge” mechanism (Pampanin et al., [3])



**Fig. 2- Observed “concrete wedge” damage mechanism in exterior tee-joint and experimental hysteretic rule**

Different considerations have to be drawn when referring to the joint damage mechanism and inelastic behaviour of interior beam-column joints. Even when no transverse reinforcement is adopted in the joint region, the shear transfer mechanism is typically supposed to rely on the contribution of a more efficient (when compared to exterior joint) compression strut, assuming perfect bond conditions for the longitudinal reinforcement bars (Fig. 3).

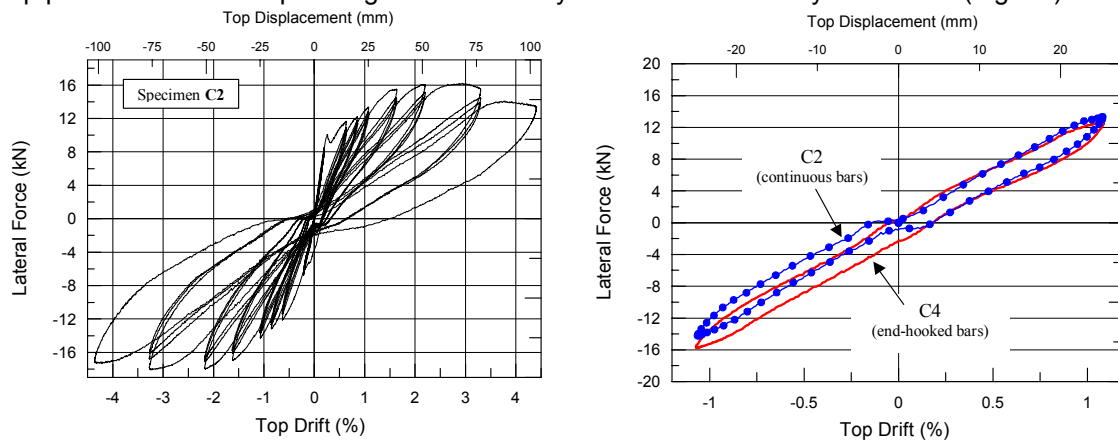


**Fig. 3** - Shear transfer mechanism in interior joint after cracking (after Hakuto et al., [1])

Therefore, after first diagonal cracking and inelastic shear deformation of the joint panel zone, alternative resources for shear transfer mechanism can develop, without significant loss of capacity of sustaining vertical loads, until extensive damage occurs.

However, as anticipated, depending on the structural detailing adopted, the inelastic behaviour under reversed cyclic loading can be significantly different. The use of plain round bars can, for example, lead to a premature deterioration of the bond with a reduction in the flexural capacity and ductility at both beam ([14]) or column ([15]) critical sections. Critical discussion on the effects of bond deterioration in beam-column joint on the hierarchy of strength and on the inelastic mechanism and thus global response of frame systems has been provided by (Calvi et al., [4]). Due to gravity load design, column hinging and joint shear cracking can also be relatively close events: the concentration of flexural damage in the column at early stages could act as a structural fuse for the joint panel zone, showing significant resources of plastic deformation at beam-column subassembly level ([4],[11],[16]), even without specific ductile structural details (Fig. 4a). On the other hand, at a global level, this would result to a concentration of interstorey drift demand, with possible development of a soft storey-mechanism.

Different anchorage solutions in beam or column reinforcement passing through the joint region (i.e. continuous bars, end-hook anchorages or continuous bars), would also determine the amount of slip phenomena with a “pinching” effect in the hysteresis subassembly behaviour. (Fig. 4b).



**Fig. 4** –Interior joints: hysteretic behaviour and efficiency of anchorage solutions (Pampanin et al. [10])

## 2.2 Strength Degradation Curves

The joint shear stress is generally expressed in terms of either the nominal shear stress ( $v_{jn}$ ) or the principal compression/tensile stresses ( $p_c, p_t$ ). Although it is commonly recognised that principal

stresses, by taking into account the contribution of the actual axial compression stress ( $f_a$ ) acting in the column provide more accurate indications on the stress state and thus damage level in the joint region, current code provisions tend to limit the nominal shear stress  $v_{jn}$  expressed as function of the concrete tensile strength  $k_1\sqrt{f'_c}$  (i.e. ACI 318-95 [17] and similarly EC8 [18]) or the concrete compressive strength  $k_2f'_c$  (NZS 3101:1995 [19]), where  $k_1$  and  $k_2$  are empirical constants.

Typical strength degradation models available in literature and based on research on poorly designed joints ([1],[13],[20]) recognises the inherent vulnerability of exterior joints without transverse reinforcements in the joint region. As shown in Fig. 5, joint cracking is generally suggested to initiate at a principal tensile stress  $p_t = 0.29\sqrt{f'_c}$  (MPa). The post-cracking behaviour depends on the availability of alternative sources for shear transfer. Thus a rapid strength degradation is expected to occur when beam bars are bent away from the joint (see Fig.1c), while an hardening behaviour with increase of principal stress levels, up to  $p_t = 0.42\sqrt{f'_c}$  corresponding to more severe diagonal cracking and damage in the joint panel zone, is observed in interior joints where a more efficient compression strut mechanism can developed.

However, it is important to recall that these literature models refer to experimental investigations on specimens with deformed reinforcing bars.

A tentative degrading curve for poorly detailed exterior tee-joints with no transverse reinforcement in the joint region and with end-hooked plain round reinforcing bars, has been recently proposed by Pampanin et al. ([4],[11]). This is based on the aforementioned experimental investigations on beam-column specimens and on a frame system designed for gravity only, and can be briefly described as follows (Fig. 5):

- $p_t = 0.2\sqrt{f'_c}$  should be considered an upper limit of the principal tensile stress for first diagonal cracking, due to the “equivalent” principal stress state introduced in the joint region by the concentrated compression force at the hook anchorage;
- strength reduction is expected to occur after the cracking point without any additional source for hardening behaviour.

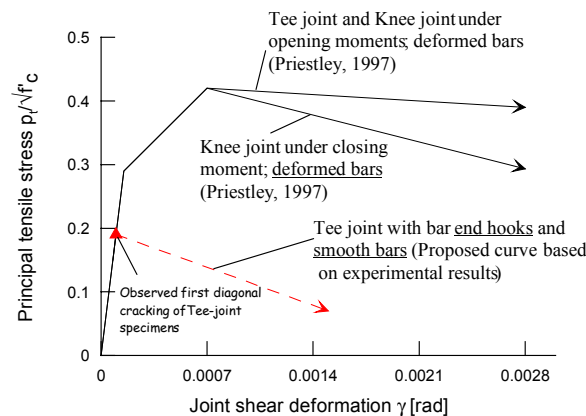


Fig. 5 – Strength degradation curve for exterior joints ([4],[11])

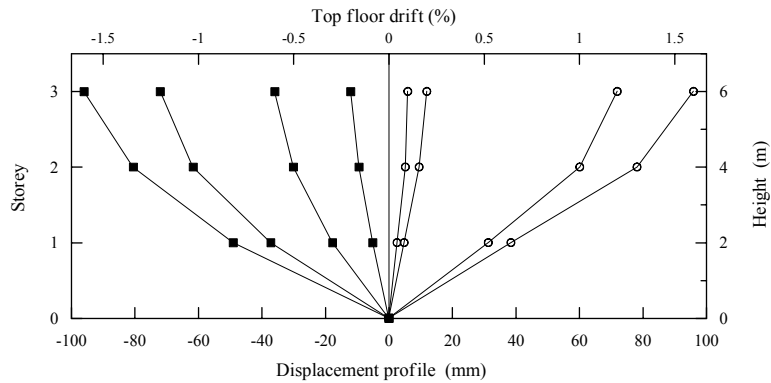
### 3 PLASTIC HINGE AND SHEAR HINGE MECHANISM

#### 3.1 Hybrid inelastic mechanism

The aforementioned experimental tests on gravity load designed beam-column subassemblies and frames provided interesting information on the local and global damage mechanisms. A critical discussion on the effects of damage and failure of beam-column joints in the seismic assessment of frame system has been given by Calvi et al.,([15]).

The observed global response of the three-storey frame system presented interesting peculiarities when compared with a typical weak-column, weak-beam inelastic mechanisms ([10],[12]). Severe damage was observed in the exterior tee-joints at the first storey level as well as, but more moderate,

damage at the second storey level. In addition, as expected, hinging of the column base sections at the ground level occurred. However, as evident from the experimental deformed shape shown in Figure 6, a pure soft storey mechanism did not occur at the first floor, as it would have been reasonably expected from preliminary analytical predictions if joint damage/inelastic behaviour had not been considered.



**Fig. 6** - Frame displacement profile at increasing level of top drift

The observed global mechanism, related to joint damage, suggests the definition of a “shear hinge”. Fundamental differences with the familiar concept of “flexural plastic hinge” would be related to:

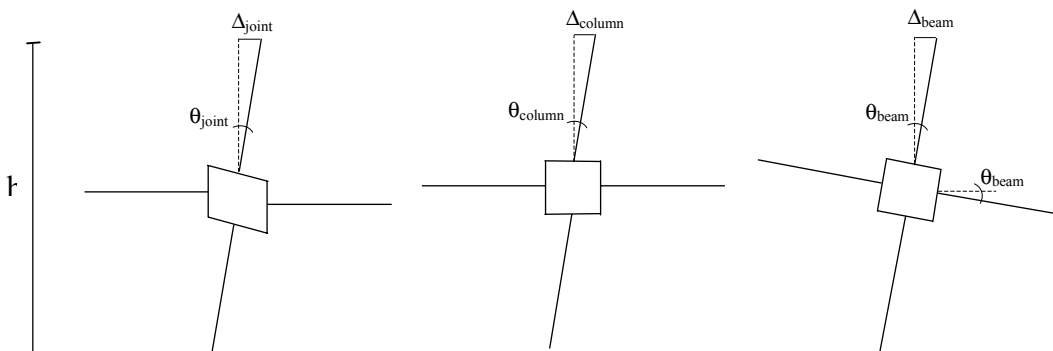
- the structural behaviour activating the hinge: shear instead of flexure;
- the post-elastic behaviour: while a plastic hinge mechanism is typically expected to provide satisfactory ductility capacity, a shear hinge might be characterized by a severe strength degradation;
- energy dissipation characteristic: the shear damage mechanism is not expected to provide a reliable source of energy dissipation under cyclic loading as is the case of a stable hysteresis under ductile flexural behaviour.

As illustrated in Figure 7, the interstorey drift,  $\theta$ , can be looked upon as the sum of contributions provided by the local deformations of the constitutive elements of the subassembly: beams, columns and joint, as follows:

$$\Delta_{tot} = \Delta_{joint} + \Delta_{column} + \Delta_{beam} \quad (1)$$

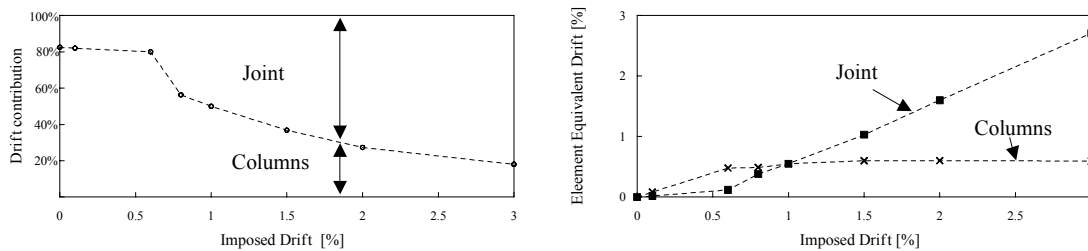
$$\theta_{tot} = \frac{\Delta_{tot}}{h} = \theta_{joint} + \theta_{column} + \theta_{beam} \quad (2)$$

where  $\Delta$  is the interstorey displacement and  $h$  the interstorey height.



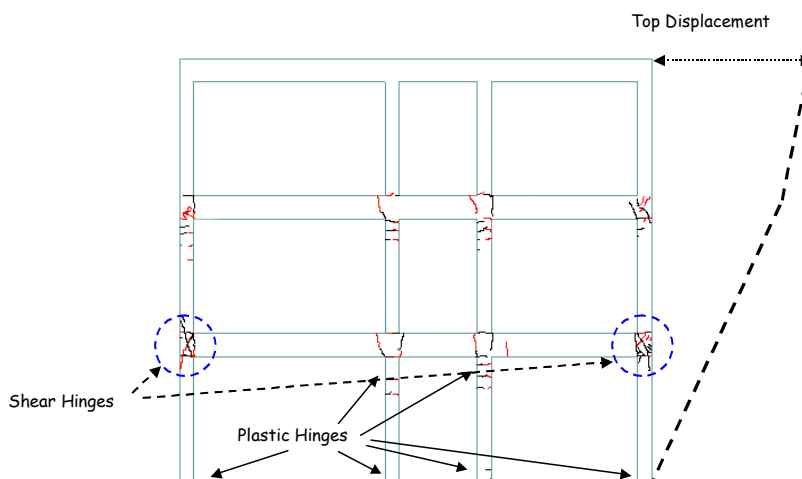
**Fig. 7:** Interstorey displacement/drift contributions by joint, column and beam deformations

Therefore, the activation of a shear hinge mechanism, through shear cracking of the joint region, would lead to a concentration of shear deformation demand in the panel zone, with a reduction of rotation demand in the adjacent beam or column critical sections. Figure 8 shows a numerical example of the members contribution to subassembly drift for the exterior specimen T1 where joint shear damage mechanism (expulsion of “concrete wedge”) governed.



**Fig. 8:** Contributions to interstorey drift: exterior specimen T1 behaviour (numerical)

At a global level, 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 (Fig. 9). An alternative hybrid inelastic mechanism, given by the combination of shear and plastic hinges, has to be defined when dealing with the seismic assessment of under-designed or gravity load designed frames.



**Fig. 9 –** Frame global mechanism: plastic hinge and shear hinge (top drift 1.6%)

This apparent favourable effect on the structural members is however paid for with possible strength degradation (depending on the structural details adopted, i.e. beam bars bent in the joint, bent out or hook-ended, as well as use of plain round or deformed bars) and higher local deformation in the damaged joint panel region. Appropriate limit states based on joint shear deformation need to be defined. Preliminary suggestions, based on experimental observations and numerical analyses with the proposed simplified model will be given in the following sections.

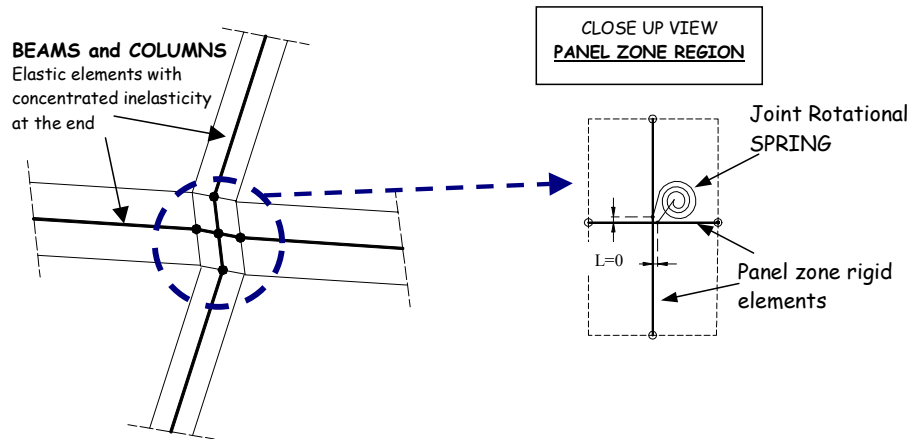
#### 4 PROPOSED ANALYTICAL MODEL: ROTATIONAL SPRING

As shown by the experimental test results and as discussed above, an adequate model of the non-linear behaviour of the joint panel zone should be adopted when evaluating the seismic response of existing under-designed frames. Local and global damage and failure mechanisms can be significantly affected by the peculiarity of the joint behaviour.

Several modelling approaches have been recently proposed in the literature, ranging from empirical methods to finite elements models ([5-9]).

An alternative simplified analytical model for joint behaviour is herein conceptually presented and proposed as a viable and useful tool for extensive parametric studies on the seismic response of such frame systems. An equivalent moment rotational spring, governing the relative rotation of beams and

columns, is adopted to represent the joint behaviour either in the linear and non-linear range. As shown in Figure 10, beam and column elements converging in the joint are modelled as one-dimensional frame elements with concentrated inelasticity at the critical section interface, defined through appropriate moment-curvature curves based on section analysis. The effects of moment-axial load interaction are taken into account for columns. Rigid elements are adopted to model the portion of beam and column elements comprising the panel zone region.

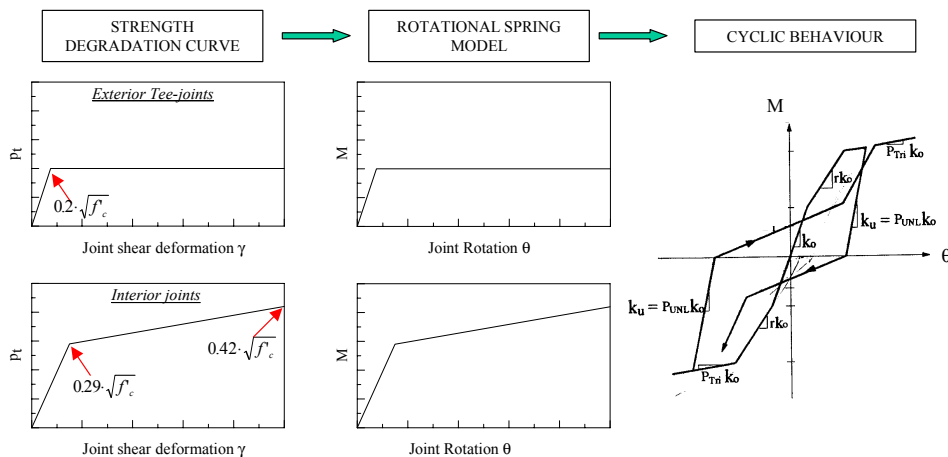


**Fig. 10** – Proposed analytical model for joint behaviour: rotational spring

The moment-rotation characteristics of the joint spring might be directly derived, based on equilibrium considerations, from the corresponding principal tensile stress vs. shear deformation curve (i.e. Figure 5):

- the equivalent joint spring moment corresponding to a defined level of principal tensile (or compression) stress in the joint (first cracking or higher damage level) is taken as the sum of the column moments (equal to the sum of the beam moments);
- joint spring rotation corresponds to the joint shear deformation if a joint shear distortion mechanism is assumed to govern at higher level of deformation (i.e. it is predominant when compared to pure flexural joint behaviour).

According to the aforementioned results, the principal tensile stress at first cracking is defined as  $p_t = 0.2\sqrt{f'_c}$  and  $p_t = 0.29\sqrt{f'_c}$  for exterior joint (with end-hooks and smooth bars) and interior joint respectively. After first cracking occurs, a hardening behaviour until  $p_t = 0.42\sqrt{f'_c}$  is assumed for interior joint, where alternative shear transfer mechanisms can be activated, while elasto-plastic behaviour or an appropriate strength degradation model can be adopted for exterior Tee-joints. The cyclic behaviour will then be modelled by an appropriate hysteresis rule able to represent the “pinching” effect due to slip of the reinforcement and shear cracking in the joint (Fig. 11).

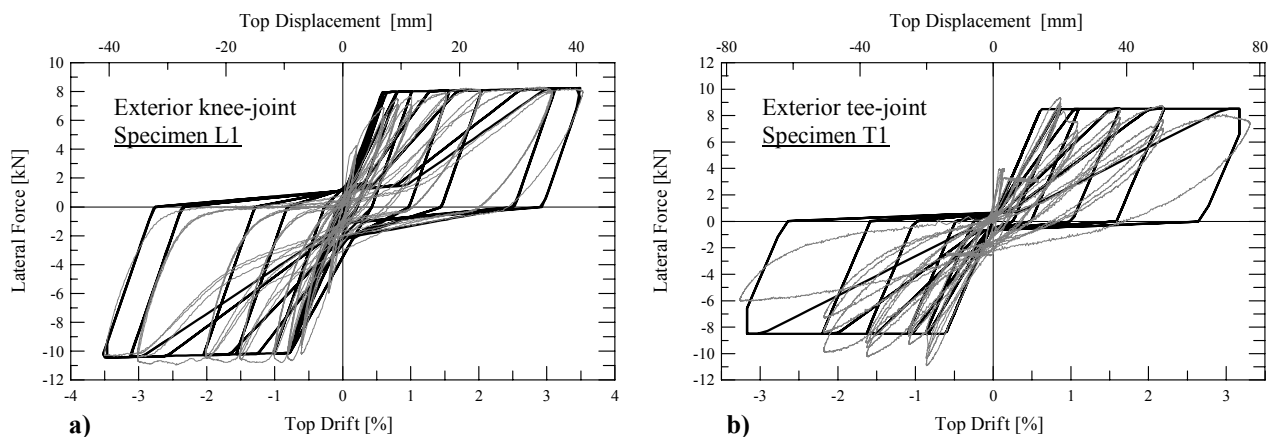


**Fig.11** - Monotonic and cyclic behaviour of the shear hinge model

## 5 ANALYTICAL EXPERIMENTAL COMPARISON

The proposed simplified modelling of the joint non-linear behaviour through an equivalent rotation spring was adopted for preliminary analytical-experimental comparisons. The finite element code Ruaumoko (Carr, [21]) was used for the analyses. An hysteresis rule with pinching behaviour (modified Stewart rule) was assigned to both the joint shear hinge and the adjacent beam and column elements plastic hinge to account for the slip of reinforcement within or outside the joint region as well as for the opening-closing of shear cracks in the joint panel zone region under cyclic loading. Although, at this stage, no strength degradation was taken into account, a satisfactory agreement between the simplified analytical model and the experimental results was observed in both the cases of

- a) “plastic hinge” flexural damage mechanism with slip of the reinforcing bars as in the case of the exterior knee-joint specimen L1 (Fig. 12a)
- b) “shear hinge” joint damage mechanism with slip of reinforcing bars within the panel zone region and expulsion of the concrete cover as in the case of the exterior tee-specimen T1 (Fig. 12b).



**Fig. 12– Analytical –experimental comparison:**  
a) exterior knee-joint, specimen L1; b) exterior tee-joint, specimen T1

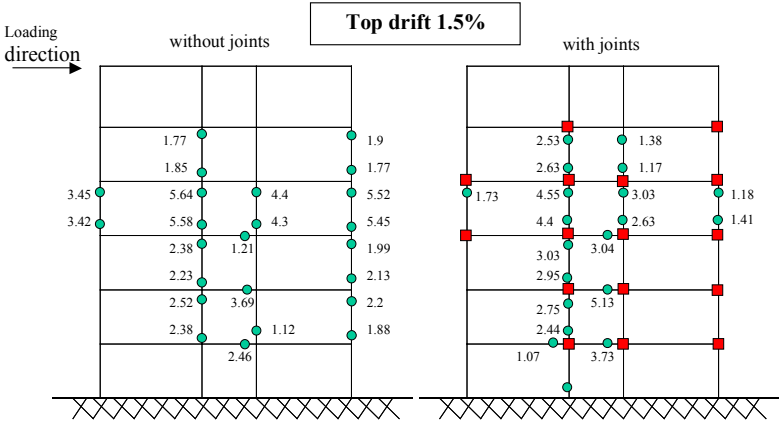
It is worth underlining that the use of the proposed rotational spring model for the non-linear behaviour of the joint panel zone region allows the satisfactory reproduction of the global behaviour of the exterior specimen T1, where no damage occurred in the adjacent beam or column element. Alternative models with non-linear behaviour accommodated only in plastic hinges in the beams and the columns would thus fail in representing the observed behaviour. Based on these promising results, the definition of an improved and refined hysteresis rule with appropriate pinching and strength degradation behaviour to model the joint non-linear behaviour is currently under investigation and development.

## 6 FRAME SYSTEM RESPONSE

Numerical investigations on the seismic behaviour of under-designed frame systems, designed for gravity only according to the Italian code provisions before the 1970's (reported in [15]), confirmed the aforementioned assumptions on the effects of joint damage on the overall frame response and provided additional useful information, complementary to the experimental observations.. The simplified moment-rotational spring, presented above, was adopted to model the joint non-linear behaviour. For simplicity, at this stage, no strength degradation in the joint region after first diagonal cracking nor pinching behaviour in the hysteresis loop were considered. The shear hinge mechanisms were thus modelled with elasto-perfectly-plastic or bilinear-with-hardening springs for the exterior and interior joints, respectively. The response of two six storey gravity load designed frame systems with and without joint modelling are herein compared. Figure 13 shows the damage distribution at 1.5% top drift level: flexural plastic hinges and the corresponding curvature ductility demands in the beams and columns are reported as is the activation of shear hinges in the joints, corresponding to the occurrence of first diagonal cracking in the panel zone region. Besides leading to a reduction in stiffness, damage in the interior and exterior joints leads to a concentration of angular deformation demand in the panel

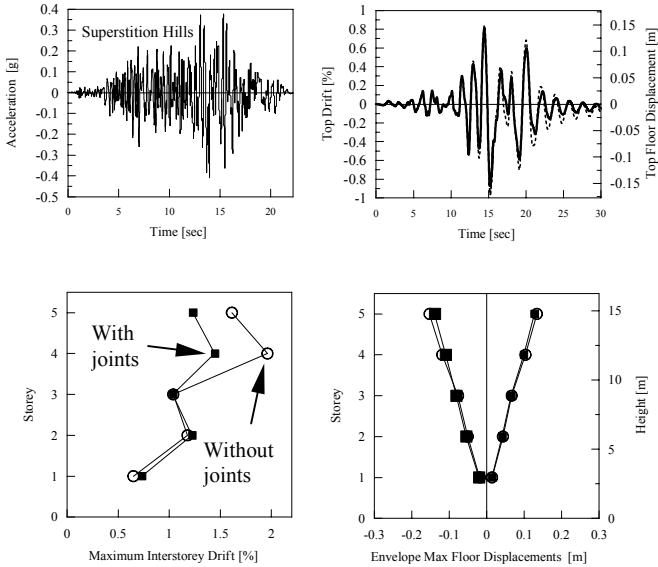


zone region with a significant reduction in ductility demand in the critical interface sections in the adjacent members. A single soft storey mechanism is thus prevented or, more precisely, postponed to at higher levels of drift.



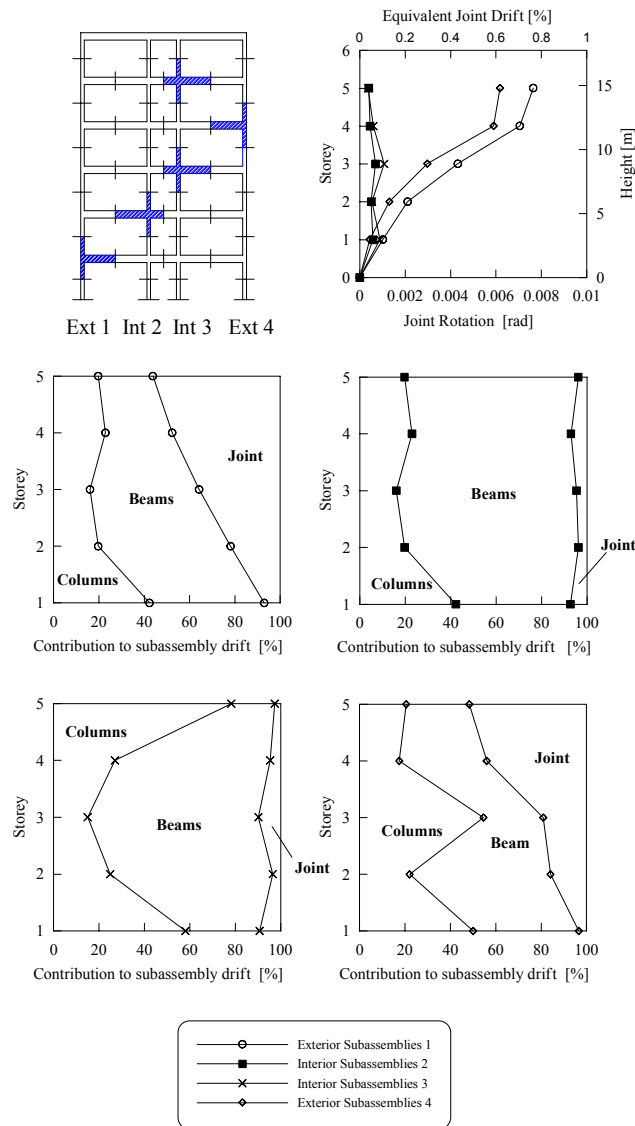
**Fig. 13** – Comparison of frame model response with and without joint modelling: pushover response on six storey frame; damage distribution

The time-history responses of the same six storey frames under a set of earthquake records at different intensity level (average spectrum being compatible with the EQ8 design spectrum with PGA of 0.3 g and medium soil conditions) confirmed the effect of joint damage in reducing the inter-storey drift demand, while no significant amplification of maximum global displacement demand is observed. Figure 14 shows, as example, the response under a single earthquake record. Common trends were found for all the set of records.



**Fig. 14-** Comparison of six storey frame time-history response with and without joint modelling (modified Superstition Hills, 1987)

The role of structural “fuse” of the joint shear hinge mechanism in terms of deformation demand on the adjacent elements is clearly shown in Figure 15, where the contributions of beams, column and joint panel zone to the total exterior or interior subassembly drift are calculated. Also the maximum joint shear deformation demand is evaluated as the main indicator of the damage in the joint region and, thus, of the possible loss of gravity-load bearing capacity.



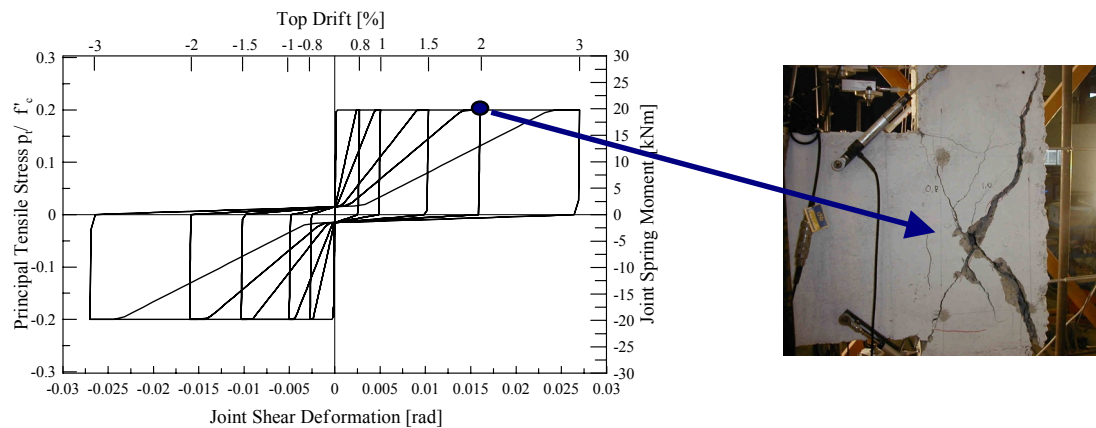
**Fig. 15** – Joint maximum rotation and contribution to subassembly drift (modified Superstition Hills, 1987)

## 7 LIMIT STATES BASED ON JOINT SHEAR DEFORMATION

As shown by experimental results and confirmed by numerical investigations, the positive effects of joint damage in reducing the interstorey drift demand (postponing or preventing a collapse due to the occurrence of a soft-storey) are compensated for by an increased shear deformation in the joint region, which, depending on the structural details adopted (i.e. plain round or deformed bars, beam bars bent into or outside the joint region), could lead to a sudden strength degradation and loss of vertical load bearing capacity. The maximum joint shear deformation  $\gamma$  (i.e. rotation of the spring model) has thus to be checked and compared with adequate reference values corresponding to different limit states.

By comparing the experimental damage observation at increased drift levels with the numerical behaviour of the shear hinge modelling (Fig. 16), limit states based on the joint shear distortion  $\gamma$  (rotation of the simplified models) can be tentatively defined and suggested for exterior tee-joints with substandard details as follows:

- Undamaged (uncracked):  $\gamma < 0.0002$
- Limited damage:  $0.0002 \leq \gamma < 0.005$
- Extensive damage:  $0.005 \leq \gamma < 0.01$
- Critical damage (repairability issues arise):  $0.01 \leq \gamma < 0.015$
- Incipient collapse:  $\gamma \geq 0.015$



Limit State	Subassembly Drift (%)	Joint Shear Deformation [rad]
First diagonal cracking	0.65	0.0002
Extensive Damage	1.0	0.005
Critical Damage (reparability issues)	1.5	0.01
Incipient Collapse	2	0.015

**Fig. 16–** Limit States for exterior tee-joint based on joint shear deformation

Based on the latter considerations, the seismic performance of existing frame buildings, not-seismically designed, can be more correctly estimated, so as to evaluate a reliable damage scenario and define appropriate retrofit strategies. Referring, as an example, to the response of the six storey building (Figs. 14-15), the damage in the exterior joints at the fourth floor provides a significant reduction of the interstorey drift from approximately 2% to less than 1.5%. The occurrence of a soft-storey mechanism with collapse of the entire structures is thus prevented with extensive damage in the joint region. This is still less than the reparability limit, with the maximum joint shear deformation ranging between 0.006 and 0.008.

## 8 CONCLUSIONS

The seismic response of frame systems designed only for gravity loads can be significantly affected by the damage mechanism occurring in the joints. Based on experimental evidence and numerical investigations, the concept of a shear hinge mechanism has been proposed as an alternative to a flexural plastic hinge. The concentration of shear deformation in the joint region, through the activation of a shear hinge, can reduce the deformation demand of the adjacent structural members, postponing the occurrence of undesirable soft-storey mechanisms with consequent collapse of the whole structure. On the other hand, the increase in damage in the joint region, with possible loss of vertical load bearing capacity, depending on the structural detailing, has to be taken into account.

A simplified analytical model for the joint non-linear behaviour has been herein presented, which consists of a rotational spring with monotonic characteristics derived from equilibrium considerations of the principal tensile stress-shear deformation curves. The cyclic behaviour of the joint is represented using appropriate hysteresis rules with pinching behaviour. Satisfactory analytical-experimental comparisons were obtained using the proposed model and adopted to define limit states based on joint shear deformation.

As shown by numerical analyses on the seismic response of existing frame systems designed for gravity-load only, the adoption of a simplified model for joint non-linear behaviour can provide, in combination with appropriate limit states to evaluate the joint damage level, a more accurate estimation of the expected damage and performance of the whole structure.

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