Paper No. 478. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

A NEW SEMI-LOCAL APPROACH FOR THE FINITE ELEMENT MODELING OF INTERIOR R/C BEAM-COLUMN JOINTS

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ABSTRACT

Different approaches for the modeling of reinforced concrete structures supply for diverse needs. As a guide towards the choice of a particular approach, the main features of the three principal families of models developed at the I.N.S.A. of Lyon are presented. On this basis, it appears necessary to construct a semi-local model for the beam-column joint. Towards this aim, a local steel-concrete bond model is developed to be used in a finite element membrane analysis of the joint. The local modeling consequently obtained captures the key phenomena that govern the behavior of the joint, and serves as a starting point for the construction of a more global model. Such a model is developed by formulating and implementing simplifying assumptions on the behavior in shear of the central core. Results of this 'semi-local' model agree very well with the local one, and can be used with any beam model.

KEYWORDS

Reinforced concrete; Finite elements; Beam-column joints; Nonlinear modeling; Cyclic loading.

INTRODUCTION

In comparison with static loading, seismic excitation brings specific needs and added difficulties to take into account. In order to solve the dynamic problem of a strongly non-linear path-dependent structure, it appears necessary to lead deterministic analysis, and thus, to integrate step by step the equilibrium equations. The number of increments then becomes much larger than the one needed for static solutions. Thus the first difficulty concerns the volume of calculations. The frequency content of shaking requires a quality for the displacement field approximation that guaranties that the important vibration modes, and thus the inertia forces, are well described. This constraint, however, is not the most severe. Increased needs also result from the quality expected for an earthquake resistant structure that it should absorb the energy of excitation and dissipate it through material hysteresis: the material model should take into account the degradations induced by the loading history, and in particular it should predict correctly the energy dissipated.

These demands and considerations formulate the problem: improve the prediction tools in order to increase their efficiency (understood as the ratio between the level and reliability of the information on one hand and the computer resources needed on the other hand). This can be achieved by formulating an appropriate reduction of the domain of validity of a model through simplifying assumptions that reduce the volume of calculations during the time integration of the dynamic equilibrium equations.

Three categories of models will be examined, varying from the more general to the particular, as illustrated in figure 1: local, semi-local, and global models.

Local models (Fig. 1a)

These make use of a constitutive material law written in terms of local variables that are independent of the structure's geometry. The parameters of the law have physical meanings and are obtained from standard tests (Merabet 1990). The finite element solution calls for the solution of large systems of equations, the calculation of the law in many points and the integration of stresses in two or three dimensions of space. Data processing tools need also to be developed in order to output the results in a complete form directly usable by designers.

The importance of distortion for short shear walls requires a kinematic approximation that allows the description of warping of the section and a local material law developed for a biaxial state of stress. Although in elastic cases, beam elements that include shear can yield good global results for a shear span ratio up to 1, a local biaxial approach is preferred for three reasons: 1) the calculation effort should not be so different, 2) the results are more complete, and 3) local nonlinearities are likely to contradict the kinematic assumptions justified in the elastic range.

Semi-local models (Fig. 2b)

For slender walls which have geometries closer to beam geometries, the size of the calculations generated by the local approach makes the exploitation of the Bernoulli beam's kinematics in a semi-local approach (Fleury *et al.* 1993) very attractive. Although the concrete law stays local, it is degenerated in one direction, and used with a multilayer, six degrees of freedom beam element. The material's history is followed at a number of points that serve as a support for the integration of the stress (figure 1b). The benefits are: reduction of the number of degrees of freedom and thus of the size of the set of equations; faster calculation of the material law which is uniaxial; alleviation of the integration effort, which concerns only a scalar and is performed on an optimized organization of the support points.

These models, more specialized than the previous ones, offer a good level of local information, in a form more convenient for designers. Its use for slender walls should be considered with precautions, especially where local results are expected (Fleury 96). However, this approach is still most suited for frame systems.

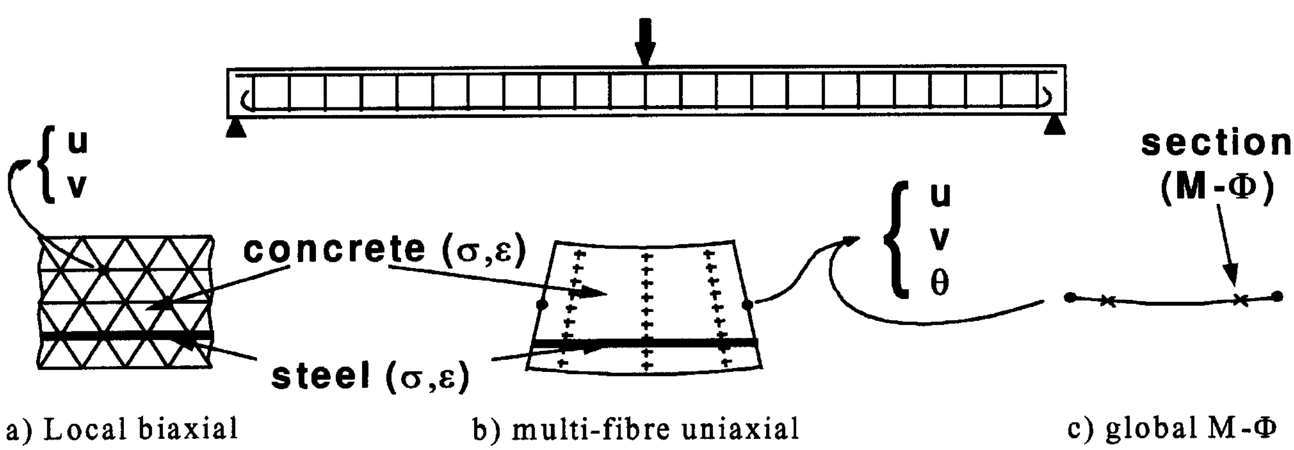

Fig. 1. Different modeling scales

Global models (Fig. 1c)

The relatively high cost of the above analysis leads to the development of global section models, that are even faster, but also more specialized. The only way to reduce drastically the volume of calculations is to suppress one or more directions of integration. This also reduces considerably the number of points at which the behavior law is calculated. The question is then to construct laws that are pre-integrated over the cross section, and written in terms of generalized variables, moment-curvature, for example. The model obtained is very specialized: percentage of steel, section geometry, type, history of loading, etc. In spite of this, and the loss of local information, they offer the advantage of reduced computer time, and an empirical accounting of certain global phenomena produced by local causes that can be difficult to identify and to model, such as the steel-concrete slippage, the cyclic degradations and the effects of shear.

Conclusion

The semi-local and global models have been validated on beams and columns, that is structures that conform well with the assumptions that have lead to their formulation. They have also been used for full size multistory and multibay moment resisting frames (Fleury *et al.* 93, Ile *et al.* 95, Miramontes *et al.* 96). Even if these buildings are indeed composed of linear elements, the connections between these elements violate the Bernoulli's assumptions: beam-column joints are the scene of important distortions, slippage between steel and concrete, and their contribution to the global stiffness and to the energy dissipation may become important. This is well illustrated by Fig. 2 that shows the results of the semi-local model for a beam-column joint tested by DelToro (1988), and from which we can observe that neither the pinching of the hysteresis curves, nor the resistance degradation is well captured. Thus, the reliability of global and semi-local models will be significant only if their semi-rigid connections are correctly modeled. It is then a priority to develop a global or semi-local model for beam-column joints that can reproduce the key phenomena. The same procedure that lead to the construction of the beam models will be followed: on the basis of a reliable local model, simplifying assumptions are formulated, and the modeling is degenerated to the particular case of beam-column joints as usually designed. In order to be reliable, the local model is required to represent correctly the steel-concrete bond when subjected to alternated cycles of high amplitude. The first stage is thus to develop such a local bond model to be used with available and validated local concrete laws (Fleury, 96).

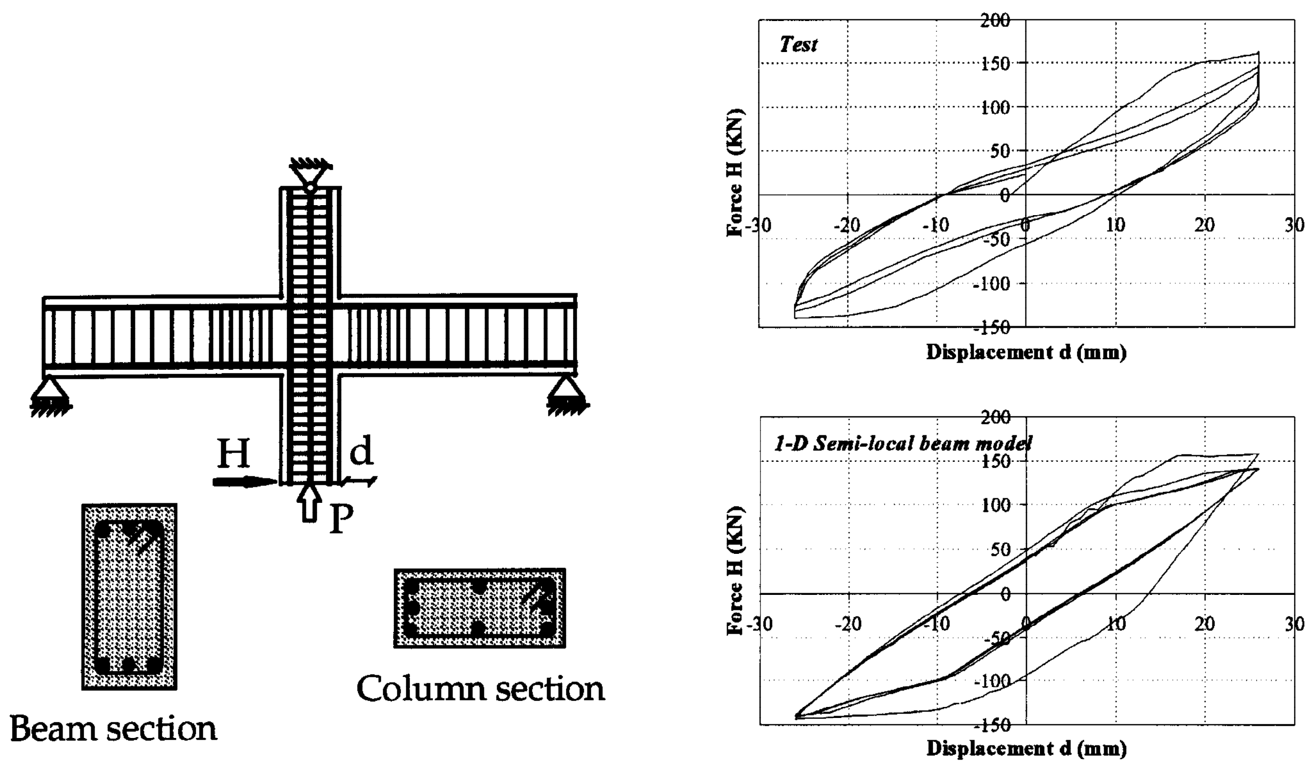

Fig. 2: Semi-local results for interior joint

The material law

The bond model is the one proposed by Eligehausen *et al* (1983) and implemented by Fleury (1996). The identification of its six parameters has to be based on tests that represent the particular boundary problem considered. Twelve parameters must be identified for unconfined regions: six for each direction of loading. The law, presented in Fig. 3 consists in an envelope curve for each direction of loading, an elastic-perfectly plastic unloading, and functions that pilot the evolution of two damage parameters, that affect the envelope curve and the friction plateaus. The unloading modulus (path EG) is unique, while the steel-concrete friction stress following path GI is a function of maximum previously attained slip and of τ_3. If unloading in the opposite direction is continued, the opposite face of the steel ribs comes in contact again with concrete, and the pertaining envelope curve is followed (path IA') and reduced to take into account damage, which is a function of the energy dissipated throughout the loading cycles.

The element

A thin membrane element is used and the Hooke matrix for the elastic material is taken diagonal (orthotropic, with $\nu = 0$). In the direction parallel to the steel, the behavior is considered elastic, with a low Young's modulus. In the transverse direction, the interface is elastic in compression while it has no resistance in tension, allowing the steel in tension to retract freely under the Poisson's effect. Shear resistance is given by the bond law presented above.

Results

This approach has been validated on simple specimens that reproduce the limit conditions present in a beam-column joint in which a steel bar can be simultaneously pulled on one side and pushed on the other. Figure 4 shows the improvement achieved by the bond model of the global force-displacement curve of the same joint presented in Fig. 2. Taking into account the degradation of bond, a better pinching of the hysteresis curves, and a drop in resistance is obtained, that compare well with the experimental observations (Merabet *et al.* 1994). Cycles of higher amplitudes would increase this difference of the two modeling results.

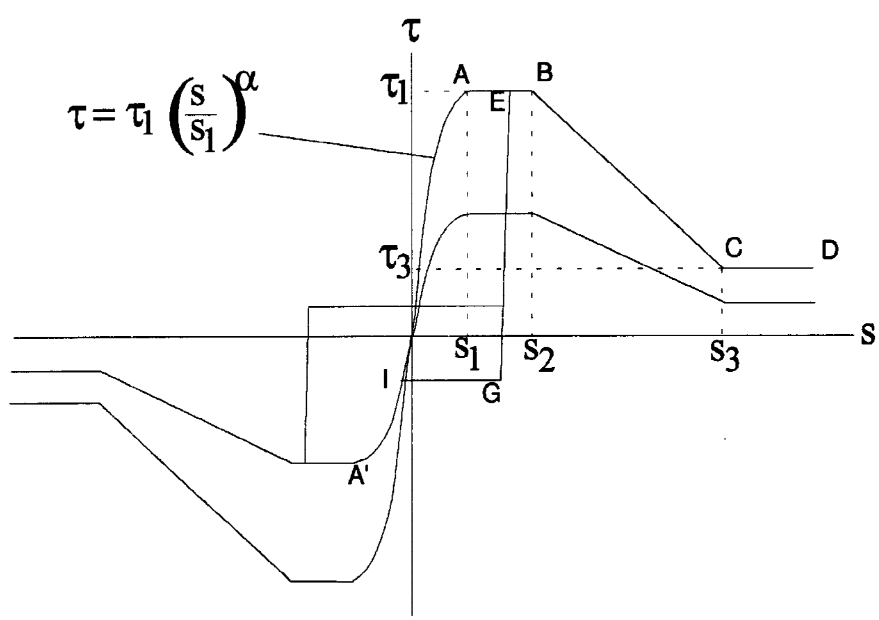

Fig. 3. Cyclic bond law

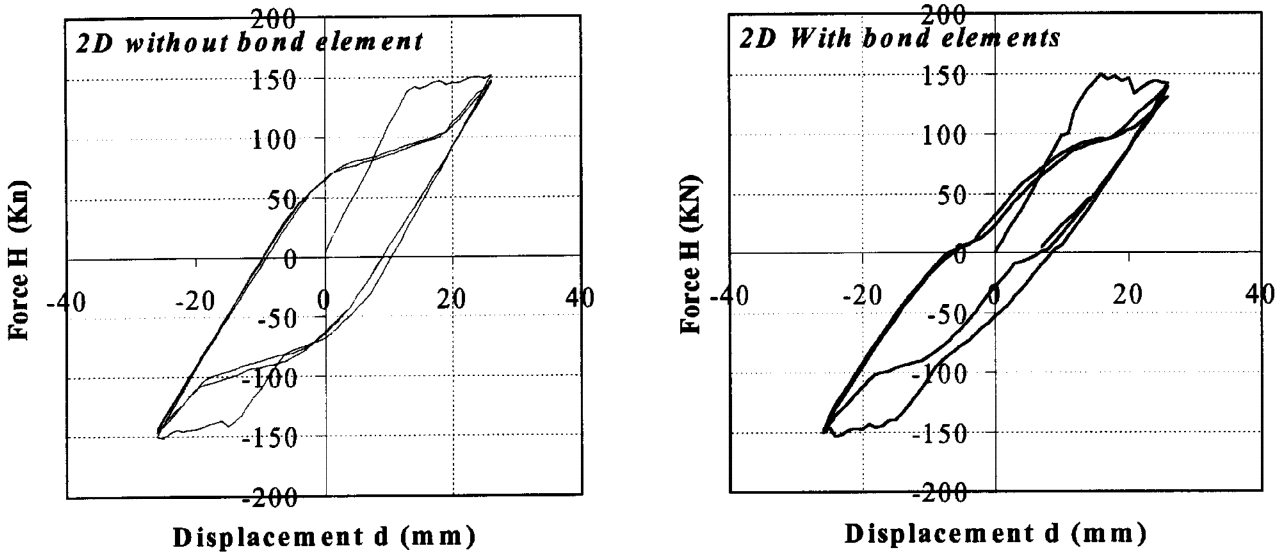

Fig. 4. Comparison with and without bond model.

MODEL FOR THE BEAM-COLUMN JOINT

General

Beam-column joints play an important part in the resistance mechanisms of moment resisting frames in which it is essential that the inelastic regions concentrate in the beams rather than in the columns. Figure 5 depicts the actions on an interior joint after some cycles of increasing amplitudes.

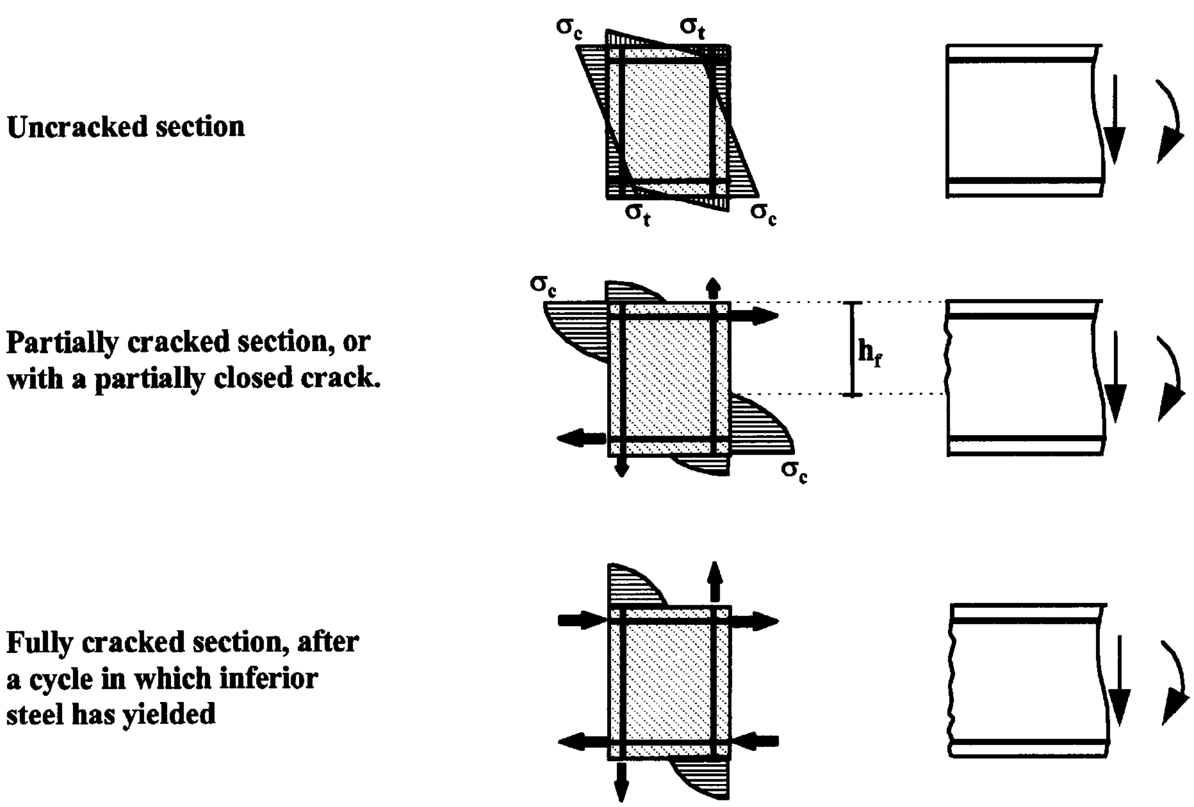

Fig. 5. Actions on the interior joint

To isolate the behavior of the joint itself, its influence at the global level is studied attributing a part of the observed quantity to each phenomena identified: if one follows the load-displacement curve of Fig. 4, it can be considered that the inter-story drift *d* is the sum of the displacements due to: flexure and distortion of the beams and columns, inelastic displacements of the reinforcement at the beam-column interface (Fig 6a), slipping of the bars through the joint (Fig 6a), distortion of the central core (Fig 6b), and dowel deformations of the rebars at the interface (Fig 6c). These modes of deformation coexist, their contribution varies with time, and the mechanisms that produce them are interdependent. For example, the state of bond depends on that of steel (elastic or plastic).

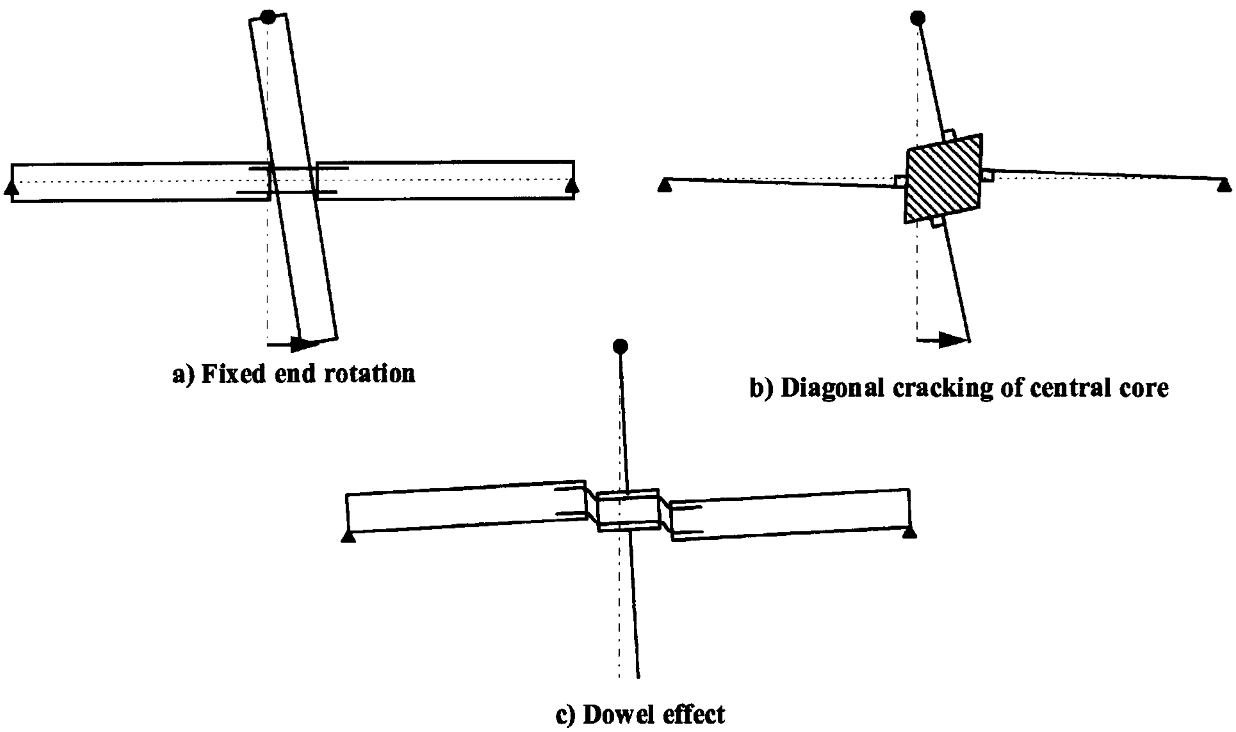

Fig. 6. Contributions of deformation modes.

Modeling

Although certain authors propose a unique global M-θ law to describe the behavior of the joint, it is believed that such an approach is in contradiction with the actual behavior: moments on each face are generally different, and the behavior of the sections on each side of the central core are interdependent through the behavior of the steel-concrete bond in each reinforcement layer. Because the embedment length is small, and bond degrades, one cannot by-pass the resolution of the differential equations of bond.

As a first stage, it is proposed to make use of the following assumptions: 1- plane sections remain plane at each joint face, and 2- uniform distribution of the shear stress in the central core. These assumptions greatly reduce the number of degrees of freedom and integration points. In a second phase, the transmission of the forces to the central core, through bond and beam-column interface needs to be modeled. This necessitates first to solve the differential equations of bond along the rebars across the joint, and second to construct a section model that will yield normal stress distributions over the depth of the interface. To this end, the local bond model and multifibre model presented above are used and connected to the central core through linear relations between the degrees of freedom. The model obtained is schematically presented Fig. 7.

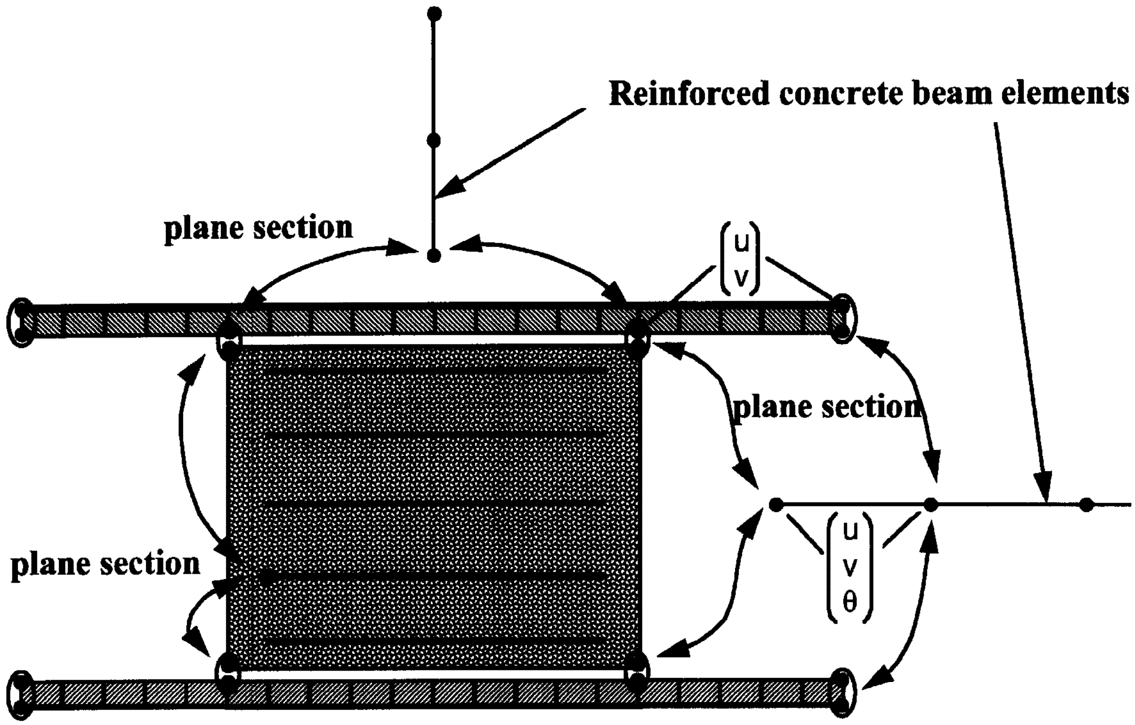

Fig. 7. Proposed 'semi-local' model

The concrete the central core consists of a unique four nodded membrane element. The columns are connected to it by specifying the relation between the respective degrees of freedom. The two nodded membrane bar elements representing the longitudinal steel of the beams are connected to the central core through the bond elements. Constraints are also formulated on the degrees of freedom of these elements which are on the core side, for compatibility with the concrete strains. Outside the core, longitudinal steel is connected to the beams through bond over a given length. Beyond this zone, perfect compatibility exists between steel and concrete. Any kind of model can be used to represent the beams or columns: local, semi-local or global. The beam model used within this length is a plain concrete model (without reinforcement). The assumption of a linear variation of the displacements of concrete along the height of the core is used to connect the stirrups. The longitudinal steel of the columns is not shown on the figure but they are modeled using excentrated membrane bar elements connected to the columns on each side.

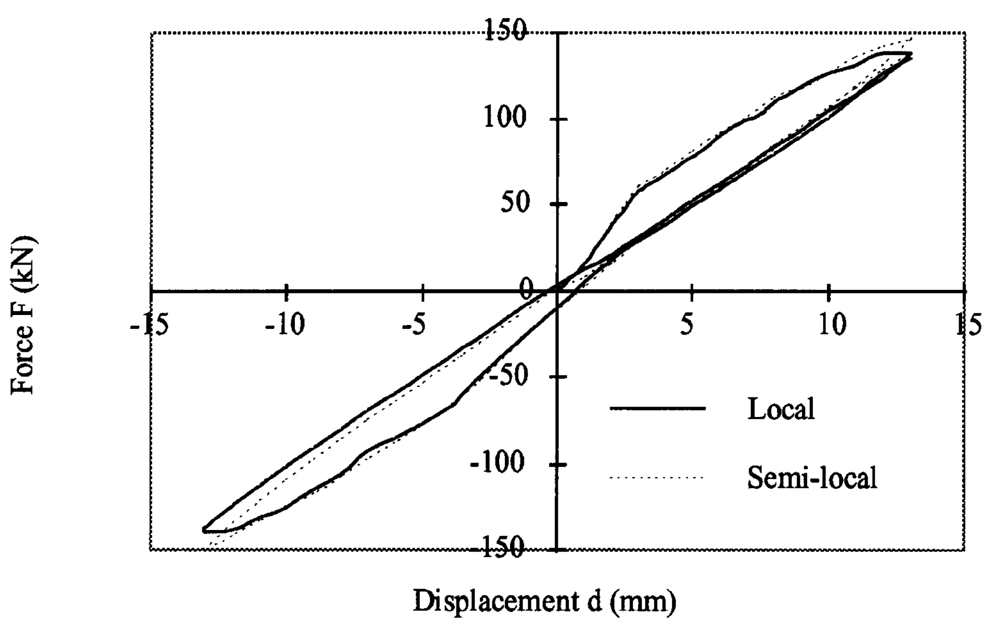

Fig. 8. Local-'semi-local' comparison

Results

The proposed 'semi-local' model has been compared to the local one on the structure tested by Del Toro (1988), presented Fig. 2. The force-displacement curves obtained for each model are compared in Fig. 8 which shows a cycle of 13 mm, in which certain rebars have already yielded. A very good agreement is achieved.

CONCLUSION

The predictions of reinforced concrete structures under seismic loading requires the use of different modeling scales in order to achieve the best efficiency, depending on the characteristics of the structure and of its elements. Multi-fibre and global models are well suited for structures composed of lineic elements, but in order to take advantage of their efficiency, one has to model their connections more accurately, where bond is liable to be subjected to push-pull. The local model for the joint, which makes use of three different nonlinear material models for concrete, steel and bond, is able to capture the key phenomena: distortion and diagonal cracking, steel-concrete slippage, and yielding of steel. On this basis, a more global model is constructed, making use of simplifying assumptions on the shear behavior of the joint core. The global results given by this simplified model agree very well with those of the local approach. The proposed joint model is independent of the models used for the beams and columns, and in particular can be connected to multifibre or global section models. It should then allow to analyze complete multi-bay multi-storey frames more precisely while not increasing drastically the computational effort.

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