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CYCLIC DEGRADATION IN REINFORCED CONCRETE ELEMENTS

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ABSTRACT

In this paper the first step of a suitable model for the cyclic behaviour of r.c. structures is described. Experimental results of cyclic tests on concrete are utilized to set the cyclic constitutive relationship for concrete in compression. Moreover a fiber-model is developed in order to obtain the cyclic behaviour of bending moment-curvature relationship. A comparison of the numerical behaviour of the section to the experimental behaviour of beams tested, allows to evaluate the effectiveness and the future development of the model.

KEYWORDS

Cyclic behaviour, cyclic degradation, damage, fiber model, concrete behaviour, r.c. non-linear analysis.

INTRODUCTION

The monotonic and cyclic behaviour of reinforced concrete structures in post-elastic field is an open problem at the present in terms of experimental results and modelling. Though many theoretical methods for r.c. analysis were proposed [Powell and Campbell, 1994, Park *et al.*, 1987, Taucer *et al.*, 1991], any model is completely reliable in evaluating the structural damage; in fact the two component materials and their interaction have a different influence on the structural behaviour, that depends on the type of element (beam, column, joint) and on the loading pattern. Therefore the development of a reliable model requires experimental results in which the different phenomena are clear and easily explainable.

The experimental program reported in [Cosenza *et al.*, 1994, Manfredi and Pecce, 1994] was carried out at this aim. Simple supported beams were cyclically tested without loading reversal: concrete was always in compression and steel in tension; so steel bars buckling was excluded and bond-slip mechanism was low stressed.

Based on these experimental results a theoretical micromodel is developing; in this model the cyclic behaviour of materials and the bond-slip relationship are explicitly introduced in order to obtain a suitable definition of the element behaviour.
In this paper the first steps of the model are shown: the definition of the materials constitutive relationship and the analysis of the cyclic moment-curvature relation of the cracked section.

The tests described in [Cosenza *et al.*, 1994, Manfredi and Pecce, 1994] are principally influenced by the concrete behaviour in compression because there is not buckling of steel and bond degradation is not much significant. Therefore the first step is the experimental analysis and the theoretical formulation of the concrete constitutive relationship σ-ε for cyclic loading in compression.

Monotonic and cyclic fatigue tests in compression were carried out on concrete cylinders of dimension 15x30 cm using the same concrete of the beams. Fatigue tests were realized imposing N cycles at a prefixed strain: three different levels of strain were considered. The experimental results confirm the typical aspects of concrete behaviour [Gori, 1993, Otter and Naaman, 1989a] that the theoretical model have to take into account. In particular the cyclic behaviour shows that the envelope curve σ-ε substantially coincides with the monotonic curve: in Fig. 1 a cyclic and a monotonic curve are superimposed non-dimenionalized respect to the pick values (σ_0-ε_0). Both the curves are experimental results, but the monotonic one is obtained as the average of 5 monotonic curves. It is worth to notice that after the cyclic history the cyclic and monotonic behaviour are similar.

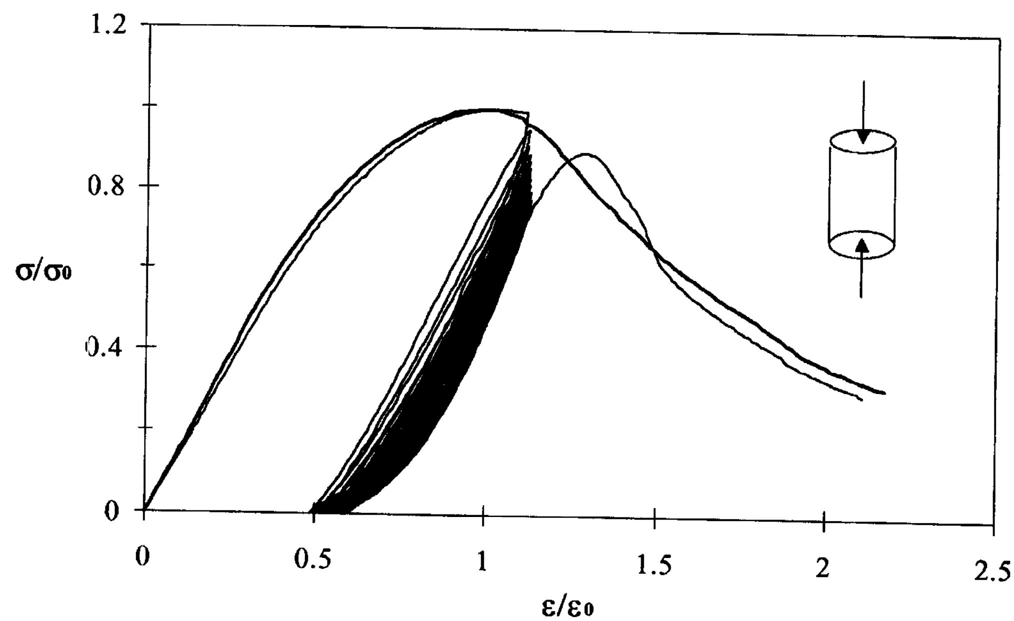

Fig.1 Comparison between cyclic and monotonic experimental tests.

In terms of cyclic damage the stiffness degradation at reloading is negligible but a stress reduction is observed increasing the number of cycles because there is an increment of the plastic strain at the unloading. This degradation cannot be defined as an effective strength degradation because, as already seen, the cyclic curve can return up to the monotonic one [Otter and Naaman, 1989a].

There are many theoretical models that take into account the fundamental aspects of the concrete experimental behaviour [Priestley et al., 1988, Yankelewsky and Reinhardt, 1987], but the most suitable seems the model proposed in [Otter and Naaman, 1989b]. In this case rules for loading and unloading are introduced independent of the monotonic curve; moreover the shape of the relationship can be modified by proper parameters.

In this model two characteristic points of the σ-ε relationship are defined: *the common point* and *the stability point*. The common point is the intersection between the unloading and reloading curve; it can be experimentally defined by means a complete loading and reloading up to the monotonic curve for increasing values of strain. The stability point characterizes a particular degradation phenomenon: in the fatigue tests after some cycles the degradation becomes negligible.

This model is advantageous because the characteristic parameters can be easily evaluated by the experimental results for modelling degradation, plastic strain and hysteretic shape. Moreover it considers the effect of "random" cycles, that other authors have neglected but that is very important for the seismic analysis.

In the following this model [Otter and Naaman, 1989b] is used for the cyclic rules together with the model of [Priestley *et al.*, 1988] for the monotonic behaviour. In this last case the curve parameters are fitted to the experimental results; in Fig.2 the theoretical and the experimental constitutive relationship are reported in dimensionless form: a good agreement is shown.

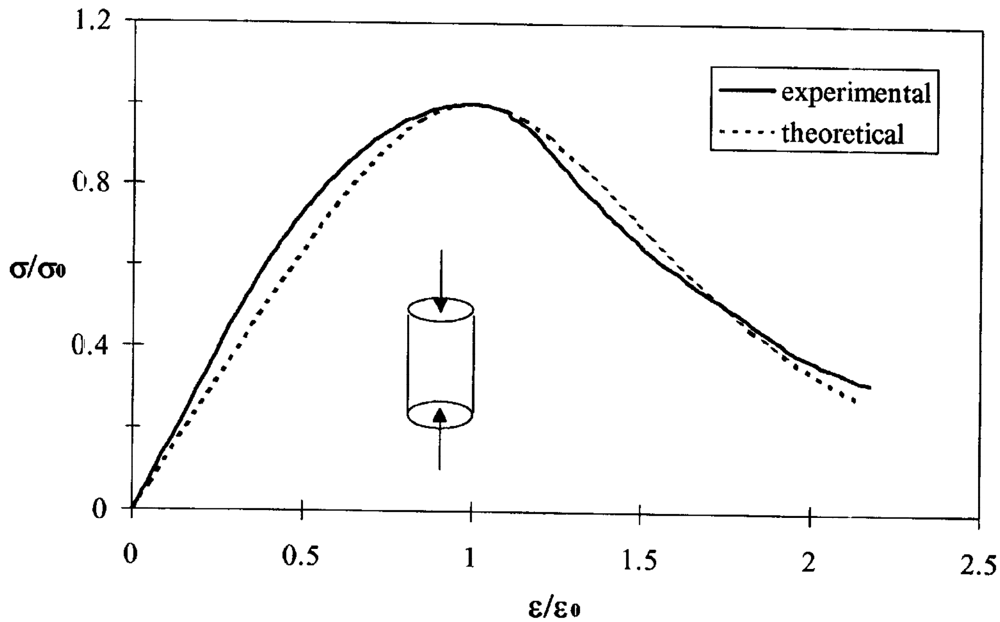

Fig.2 Theoretical-experimental comparison of the concrete monotonic behaviour

The evaluation of the parameters for the cyclic rules is carried out by the minimization of the standard deviation between experimental and theoretical values for the fatigue tests at three strain levels; for each level three equal cylinders were tested.
In Fig.3 the comparison between an experimental and the theoretical cyclic curve is drawn; it shows a good approximation of the model in terms of both the cyclic shape and the strength degradation. This last result is confirmed in Fig.4 where the perceptual strength degradation as a function of the cycles number for the experimental test and the numerical simulation is shown.

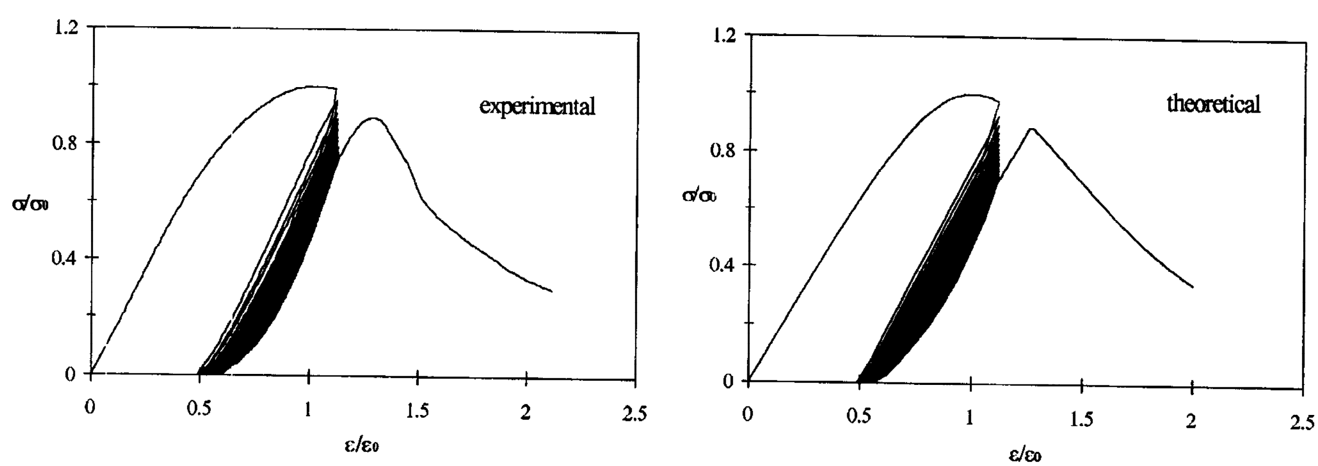

Fig. 3 Theoretical and experimental cyclic behaviour of concrete.

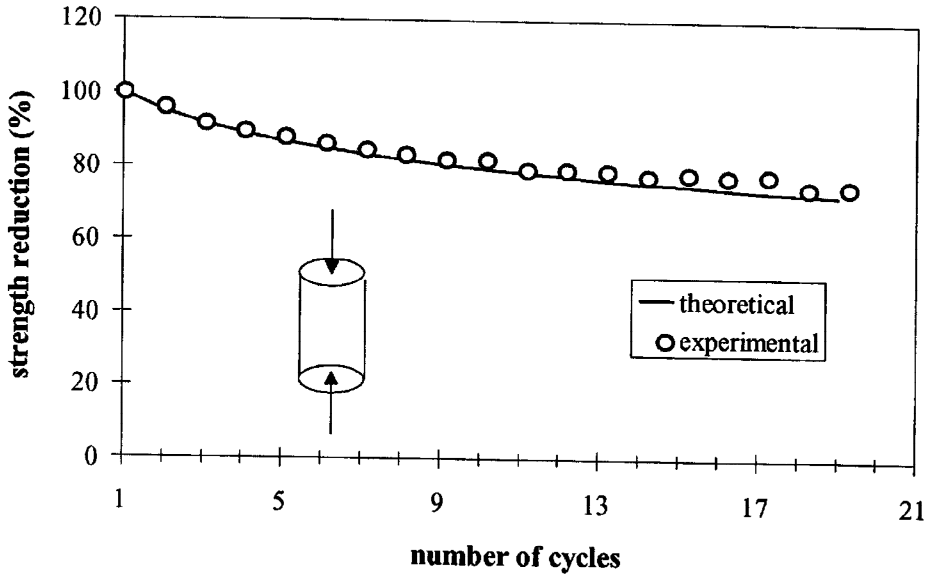

Fig.4 Theoretical and experimental strength degradation.

CYCLIC BEHAVIOUR OF THE SECTION AND THE ELEMENT

The concrete behaviour largely affects the cyclic response of beams, however many other aspects influence the behaviour of the section and of the entire element. For developing the model the results of the experimental tests described in [Cosenza *et al.*, 1994, Manfredi and Pecce, 1994] are utilized; the geometrical characteristics of the beams are reported in Fig. 5. Two types of section were analyzed (type A and type B); the cylindrical strength in compression of concrete is $f_c \approx 40\text{MPa}$ and the yielding stress of steel is $f_y \approx 470\text{MPa}$.

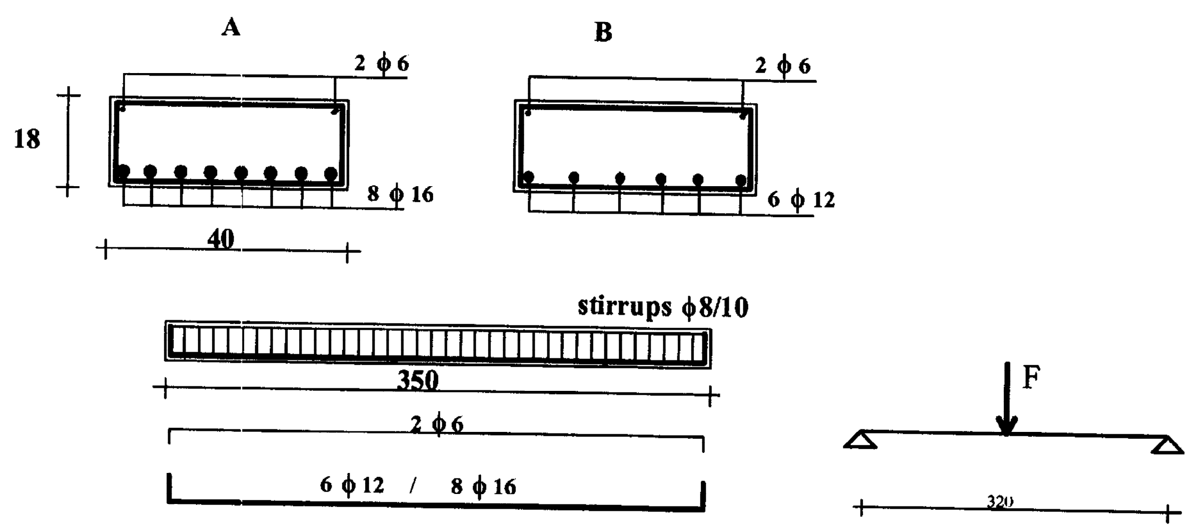

Fig.5 Characteristics of the beams tested.

Two types of test were carried out on the beams: fatigue tests with cycles at three different levels of ductility and cumulative tests. In Fig. 6 the result of a fatigue test is drawn for a beam type B.
The first step of the theoretical model for a monodimensional element is the cyclic moment-curvature relationship of the cross section. During the experimental tests the measurement of the curvature in a section is difficult, and only an average evaluation is possible respect to a prefixed base. Moreover the evaluation is practically impossible for high strains in the post-elastic field both for the reliability of the instruments and the uncertainty of the curvature definition. Therefore in the post-yielding field the measurement was effectuated directly for displacement in the midspan and rotations on the supports.

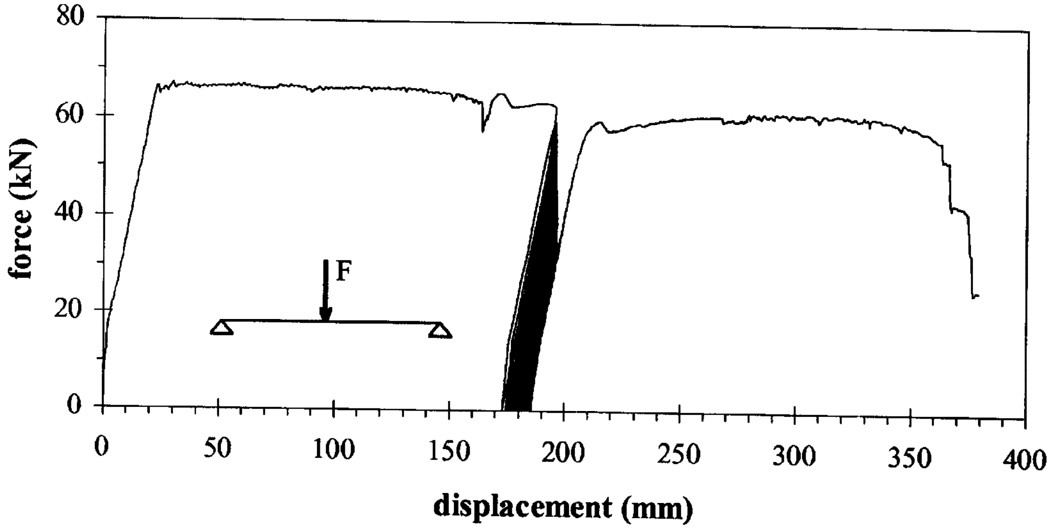

Fig.6 Experimental result of a fatigue test on a beam type B

In this case it is necessary to correlate the global behaviour of the element, in terms of displacement, to the curvature and the strains of the materials in the sections. For this purpose a reliable procedure [Cosenza *et al.*, 1991], that takes into account the steel-concrete bond-slip relationship, is used.

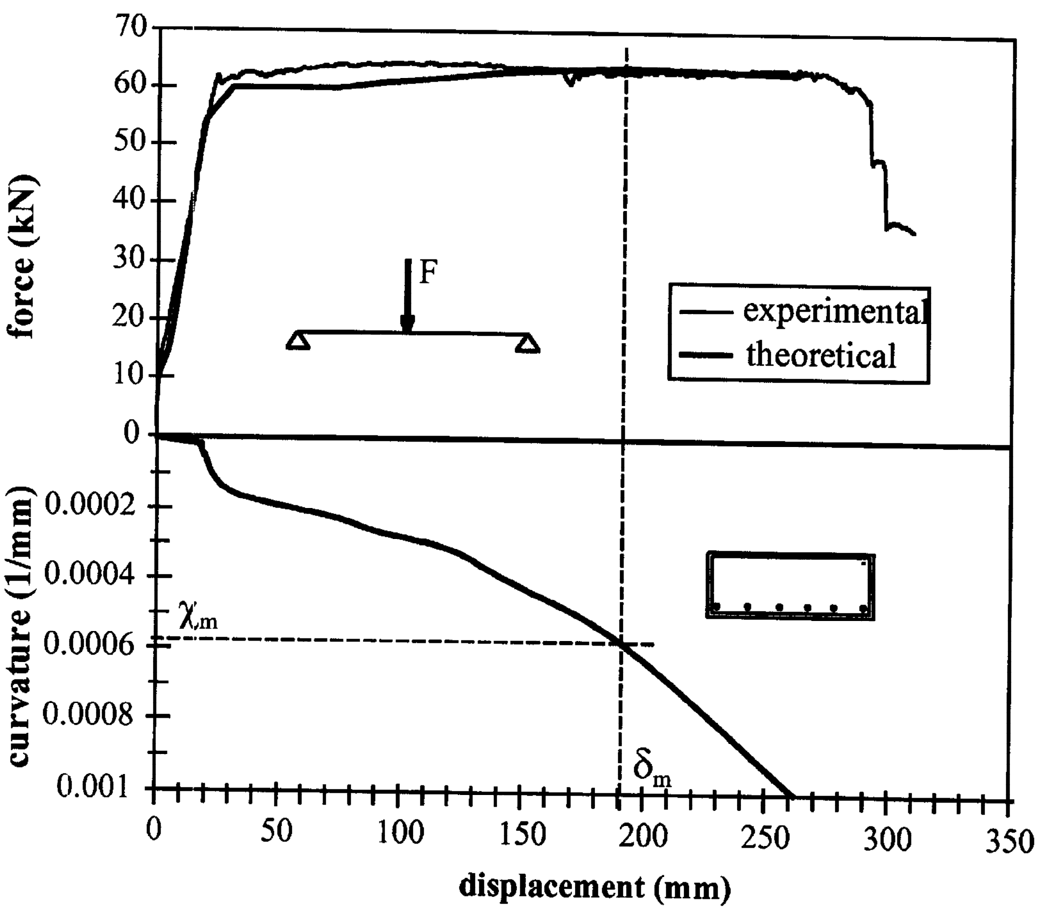

Fig.7 Theoretical-experimental comparison of the monotonic behaviour of a beam type B.

In this numerical simulation the experimental monotonic relationships σ-ε are used for the materials; for concrete the size effect in the post-elastic branch of the σ-ε curve is also introduced, by means the Hilleborg model [Hilleborg, 1989]. This size effect is very important for the behaviour of thin beams, as in this case, because the region of concrete in compression is very small and the concrete ductility results largely increased.

The comparison between theoretical and experimental results for the monotonic behaviour shows a good agreement, as reported in [Manfredi and Pecce, 1995]; an example is drawn in Fig.7 for a beam type B. The numerical analysis of the monotonic behaviour allows to know the curvature distribution along the beam in correspondence with a displacement δ_m; thus the corresponding curvature χ_m in the midspan section is known; therefore the material strains are known and in particular the maximum concrete strain ε_{cm}.
For the theoretical analysis of the moment-curvature cyclic relationship a "fiber model" is developed considering the cyclic rules of [Otter and Naaman, 1989b] for concrete in compression adjusted as described in the previous paragraph, and the model of [Zulfiqar and Filippou, 1990] is introduced for steel; a more complex model for steel [Monti and Nuti, 1992] is not necessary because there are not buckling phenomena in this case.

In order to correlate the theoretical and experimental results, the section behaviour is numerically analyzed for cyclic fatigue histories of the curvature χ_m that corresponds to the beam displacement δ_m, as previous explained, and also the maximum strain in concrete ε_{cm} and steel ε_{sm} are known.
In Fig.8 the moment-curvature relationship is drawn corresponding to the force-displacement history shown in Fig.6; however the curvature-displacement correspondence evaluated for the monotonic load is not completely effective for the cyclic history. In fact when the cycles are imposed the bond degradation, though is low, make the element more flexible than the model can considers; therefore the curvature value decreases when the number of cycles is increased at the same displacement. This effect can be taken into account only introducing explicitly the bond behaviour in the model, however some interesting observations can be carried out by the moment-curvature simulation.

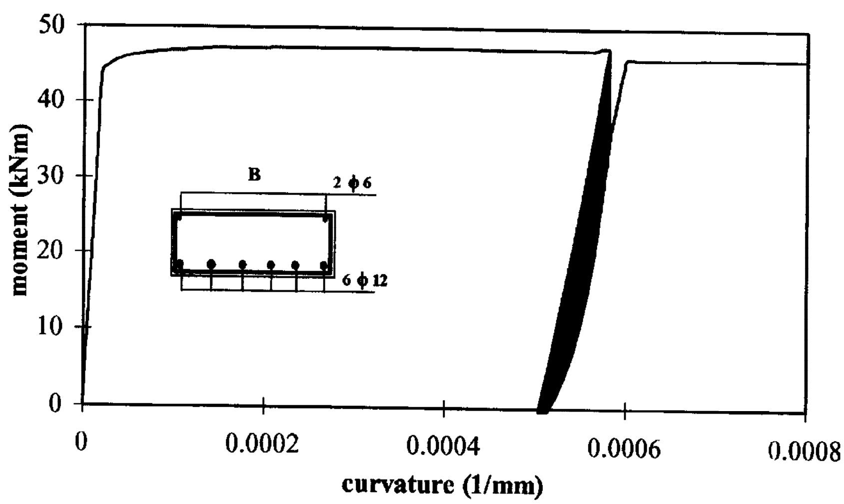

Fig. 8 Theoretical simulation of the curvature cyclic history.

In Fig.9 the strength degradation of the concrete, the section and the beam is drawn each one non-dimensionalized respect to its maximum value, as a function of the number of cycles. For concrete the curve is referred to a cyclic history on the material with a maximum strain of ε_{cm} , for the curvature the maximum value χ_m is considered (Fig.8), for the beam the experimental result of Fig.6 is reported.

The concrete degradation is higher than the section one, because the mechanical behaviour of the section gives a redistribution of stress among the fibers that reduces the concrete cyclic damage. The experimental result shows that the strength degradation of the beam is higher than the section one; in fact other phenomena influence the beam behaviour as bond degradation, shear and local phenomena [Pecce, 1995], that are important for a good assessment of cumulative damage even if are less important than in other cases (i.e. in joints).

In fact this simple case of element and loading pattern shows that modelling has to take into account other aspects as bond, shear and local phenomena in order to fit the cyclic degradation; in fact, even if good constitutive relationships for the cyclic behaviour of materials and a detailed model of the monotonic behaviour are utilized a fiber model is not able to completely simulate the cyclic degradation of beams.

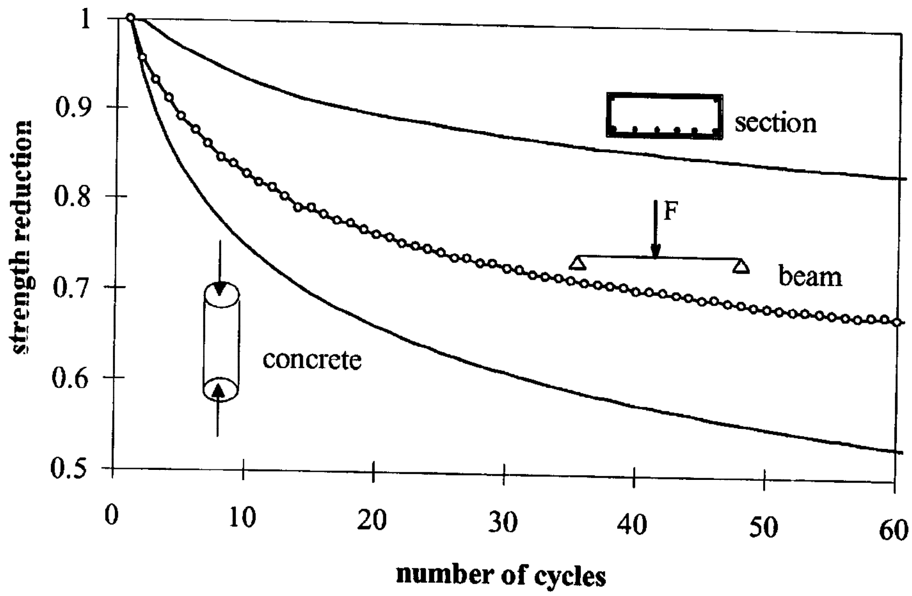

Fig.9 Comparison of the strength degradation among concrete, section and beam.

CONCLUSION

In order to develop a theoretical model for the cyclic behaviour of reinforced concrete elements a wide experimental program was carried out on concrete and r.c. beams.

For the concrete cyclic behaviour a formulation that defines only the loading and unloading rules by means of some parameters, as it is proposed by Otter and Naaman, gives good results; in fact it is possible to set the parameters value by means the experimental results.
The first step of the model has been developed for simulation of the moment-curvature relation setting theoretical constitutive relationships of the materials to the experimental behaviour. The comparison of the numerical simulation to the experimental results of the beams allows the following observations:

- a careful analysis of the monotonic behaviour is necessary to correlate the beam deformations to the sections curvature taking into account the bond-slip relationship especially in the range of large post-yielding strains;

- the cyclic moment-curvature cannot completely simulate the beams degradation, though the material constitutive relationships are set to the experimental results; in fact even if the case of a beam and a simple loading pattern is analyzed the mechanisms of bond, shear and local phenomena influence the global behaviour of the element. The fiber model proposed is qualitative effective for the cyclic behaviour but is less consistent for the cyclic degradation. Therefore for a good assessment of cumulative damage it is necessary to take into account also bond, shear and the other phenomena even if they are low stressed.

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