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Benchmark on the cracking simulation of reinforced concrete ties

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ABSTRACT: This contribution presents a part of the benchmark that was launched during the first year of the French national project CEOS.FR. It consists in modeling the behavior of reinforced concrete ties and in simulating the evolution of the crack opening during loading. Different approaches are compared. The global mechanical behavior is generally well reproduced whereas the simulation of the crack evolution gives encouraging results (appropriate order of magnitude) but needs to be improved.

1 INTRODUCTION

Concrete structures have generally to fulfill functions that go over their mechanical resistance. Many of these functions are related to concrete cracking (durability, tightness or safety for example). Predicting the mechanical behavior but also characterizing the crack evolution (opening and spacing) are thus key points in the evaluation of reinforced concrete structures. That is why a national project, named CEOS.FR (www.ceosfr.org) (Behavior and Evaluation of Special Structures. Cracking and Shrinkage) was launched in France in order to improve the engineering tools and to better estimate concrete cracking. The project is divided in three main themes : “numerical modeling” to develop sophisticated tools in order to provide accurate information about the degradation of the structures, “experiment” aiming at proposing representative, large scale and well instrumented experimental results and “engineering” to propose, from numerical and experimental results, appropriate and adapted engineering tools and rules (or to improve existing ones) to predict cracking of concrete structures. The project covers three types of loadings: monotonic static loads, thermo-hydro-mechanical behavior and alternated loadings.

This paper presents a part of the numerical benchmark that was launched during the first year of the project in order to evaluate the accuracy of the available numerical approaches. This benchmark gathered 10 organisms among the most representative French universities, research centers and companies. This contribution illustrates the results on reinforced concrete ties that were experimented in (Mivelaz 1996) (see section 2.1). This experiment was particularly interesting because some results were available concerning the cracking distribution and opening. The results were analyzed in term of structural (force as a function of the imposed strain for example) but also local behaviors (cracking distribution and evolution of the crack opening).

2 PRESENTATION OF THE TEST AND THE MODELINGS

2.1 *Experimental Concrete ties*

This test case comes from results in (Mivelaz 1996). An experimental investigation was performed on reinforced concrete ties (5m x 1m x 0.42m) (Fig. 1). These ties were loaded in direct tension, with a measurement along the three central meters (the first meter on each side was used to apply the loading). Two types of concrete and 6 reinforcement ratios were tested. For this contribution, only cases R3 and R5 are presented (Table 1).

One of the main interest of this test is the availability, in addition to classical global results, of more local measures, like the position and the opening of the main cracks. As it is exactly the main topic of the project, it was particularly interesting in our case.

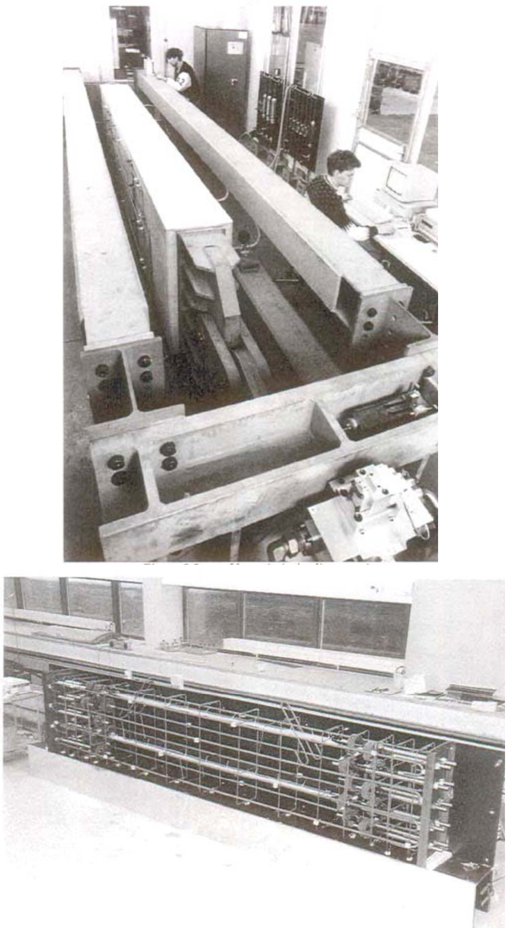

Figure 1. Experimental device for reinforced concrete ties (Mivelaz, 1996).

Armature / Béton	AS1 ρ = 0.60% 2 nappes Ø 20 s = 250 mm	AS2 ρ = 0.57% 2 nappes Ø 16 s = 167 mm	AS3 ρ = 0.86% 3 nappes Ø 16 s = 167 mm	AS4 ρ = 0.86% 2 nappes Ø 16 s = 111 mm	AS5 ρ = 1.15% 2 nappes Ø 16 s = 83 mm	AS6 ρ = 1.15% 3 nappes Ø 16 s = 125 mm
Béton IBAP	R1	R2	R3	R4	R5	
Béton EDF			E3	E4	E5	E6

Figure 2. Reinforcement ratios for the reinforced concrete ties. Only cases R3 and R5 are presented in this contribution (Mivelaz 1996).

2.2 *Presentation of the Constitutive Laws*

The benchmark on the reinforced concrete ties was performed by six teams. For the sake of simplicity, the models will not be described in details in this contribution. The main points of the modeling are mentioned below. Each team will be referred by the name of its laboratory as follows :

- "3SR" : isotropic damage model combined with a non local integral regularization technique (Pijaudier – Cabot & Bazant, 1987) to avoid mesh dependency. The constitutive law is the one developed in its initial form by Mazars (1984). For the cracking properties (spacing and opening), a post-processing technique has been designed which is based on a comparison between the results of the continuum simulation and a discrete approach (Dufour et al. 2008)
- "LaSAGeC" : isotropic damage model combined with plasticity (Fichant et al. 1999) and an energetic regularization technique (Hillerborg et al. 1976). The cracking properties are obtained by a post-processing approach based on the definition of a cracking strain computed from the total and the elastic strains, and the calculation of an isotropic parameter related to the size of the finite element
- "LCPC" : isotropic damage model associated with a decomposition of the strain into a deviatoric and a spherical part (Richard et al. 2008) and with sliding. "LCPC" response is divided in two parts : the first one considers a perfect bond between concrete and steel reinforcement ("LCPC-perfect"), whereas the second one introduces a constitutive law for the steel-concrete interface (Drucker-Prager criterion) ("LCPC-interface").
- "LMT" : the team proposes two approaches to represent the structural behavior of the structure. The first one is based on the isotropic damage model proposed in its initial form by Mazars (1984) ("LMT-cont"). The calculations are local. The second one consists in a discrete approach (Delaplace & Desmorat, 2007) where the material is described through Voronoi particles combined with Euler-Bernoulli beams ("LMT-discr"). The beams are modeled with a elastic – fragile behavior. With this modeling choice, the cracking properties are directly obtained from the relative displacement between the particles on each side of the crack discontinuity
- "Oxand" : fixed smeared crack approach (Cervenka 2005) combined with the crack band theory to avoid mesh dependency (Bazant & Oh, 1983). From this model, the crack width is calculated as a total crack opening displacement within the crack band, using the crack opening strain equal to the strain normal to the crack direction in the cracked state after the complete stress release.

Even if the proposed models are generally based on the continuum mechanics theory, they cover a representative range of approaches : from damage to plasticity and from continuum to discrete methods. Moreover, they generally include a regularization technique to avoid the well-known mesh dependency effect due to the use of softening constitutive laws.

It has to be noted that a perfect bond between steel and concrete is considered in the simulation, except for one participant who takes into account the evolution of the steel-concrete interface ("LCPC interface").

Finally, the main objective of the national project is treated, as the majority of the simulations also includes numerical tools to characterize the crack properties (spacing and opening especially). They are generally based on some post-processing from the distribution of internal variables or strains.

2.3 *Modeling Choices*

This section presents the significant modeling choices (Table 1). For the geometry, the potential symmetry of the problem is taken into account by some of the participants. The simulation is performed in 3D, 2D plane stress or using multi-fiber approach.

Table 1. Modeling choices for the simulation of the concrete tie.

Team	Geometry (symmetry)	Model	Initial heterogeneity
"3SR"	1/1	2D (plane stress)	initial distribution (strain threshold)
"LaSAGeC"	1/4	3D	initial distribution (young modulus)
"LCPC"	1/2	multi-fiber	-
"LMT-cont"	1/2	3D	1 initial crack band (0.95.E0)
"LMT-discr"	1/1	3D	material properties
"Oxand"	1/4	2D (plane stress)	initial crack bands (0.9.E0)

As the loading triggers homogeneous solicitations (uniaxial tensile stresses), the initial heterogeneity of the material has to be included in the model if some localizations want to be obtained. Two techniques were chosen to include this heterogeneity :

- the first one supposes one (or two) initial damage band(s) by decreasing the initial young modulus (by 5 or 10 percent) locally. The main drawback of this approach is to presuppose the location of the first cracks, before the simulation.
- the second one proposes an initial distribution of a material property (young modulus or strain threshold) around its average value. This distribution directly introduces the spatial heterogeneity in the material, without any hypothesis on the position of the first cracks. The example of the initial distribution of the young modulus ("LaSAGeC") is given in Figure 3.

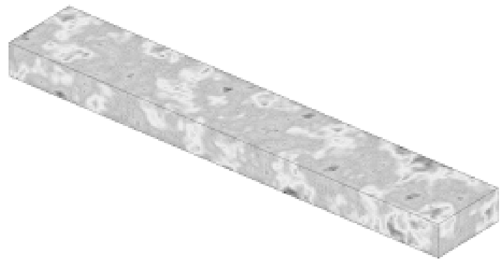

Figure 3. Initial distribution of the Young modulus ("LaSAGeC").

It is to be noted that for the majority of the participants (except "Oxand"), the initial material properties given in (Mivelaz, 1996) and obtained from classical uniaxial tests, were changed to fit the experimental response (uniaxial tensile strength especially). It was also mentioned in (Mivelaz, 1996) and asks the question of a "size effect" concerning the material parameters that have to be chosen for the constitutive law.

3 SIMULATION RESULTS

3.1 *Simulation of the Global Behavior (case R3)*

Figure 4 and Figure 5 illustrate the evolution of the force as a function of the average strain in the tie (case R3).

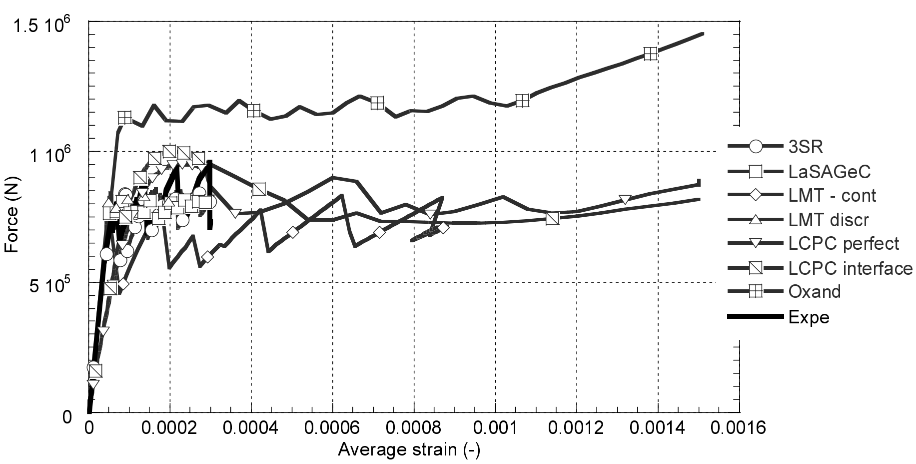

Figure 4. Force as a function of the average strain. Evolution on the total loading.

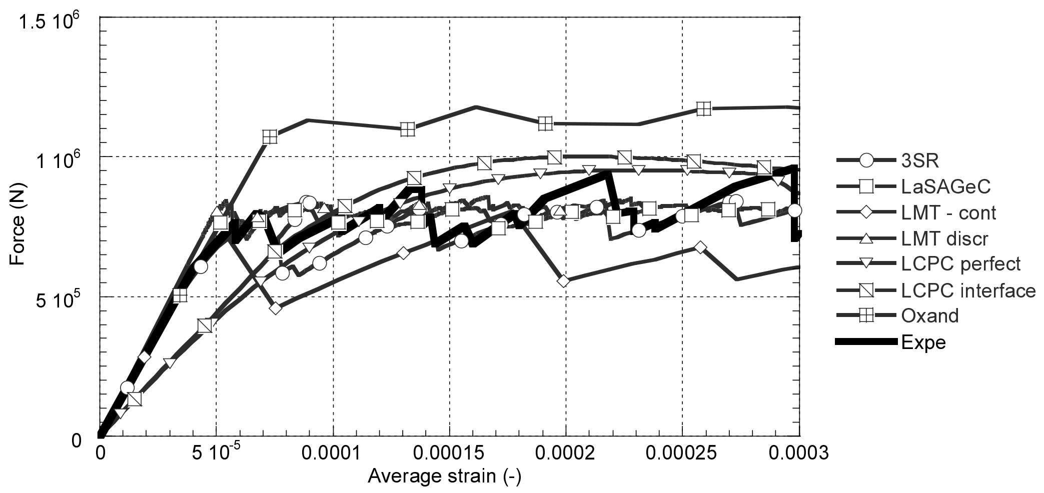

Figure 5. Force as a function of the average strain. Zoom on the first part of the curve.

The elastic phase, at the beginning of the loading, is correctly reproduced, except for one simulation. Globally, the force – strain behavior is in agreement with the experiment, with some partial unloading which are related to the formation of cracked bands. The maximum force measured during the first part of the loading is also well reproduced. It is interesting to notice that, for this simulation and the modeling approach proposed by "LCPC", there is no significant difference between the results taking into account, or not, the steel – concrete interface.

The introduction of the initial heterogeneity through a spatial distribution of a material property seems to give appropriate results without introducing any additional hypothesis on the location of the first cracks.

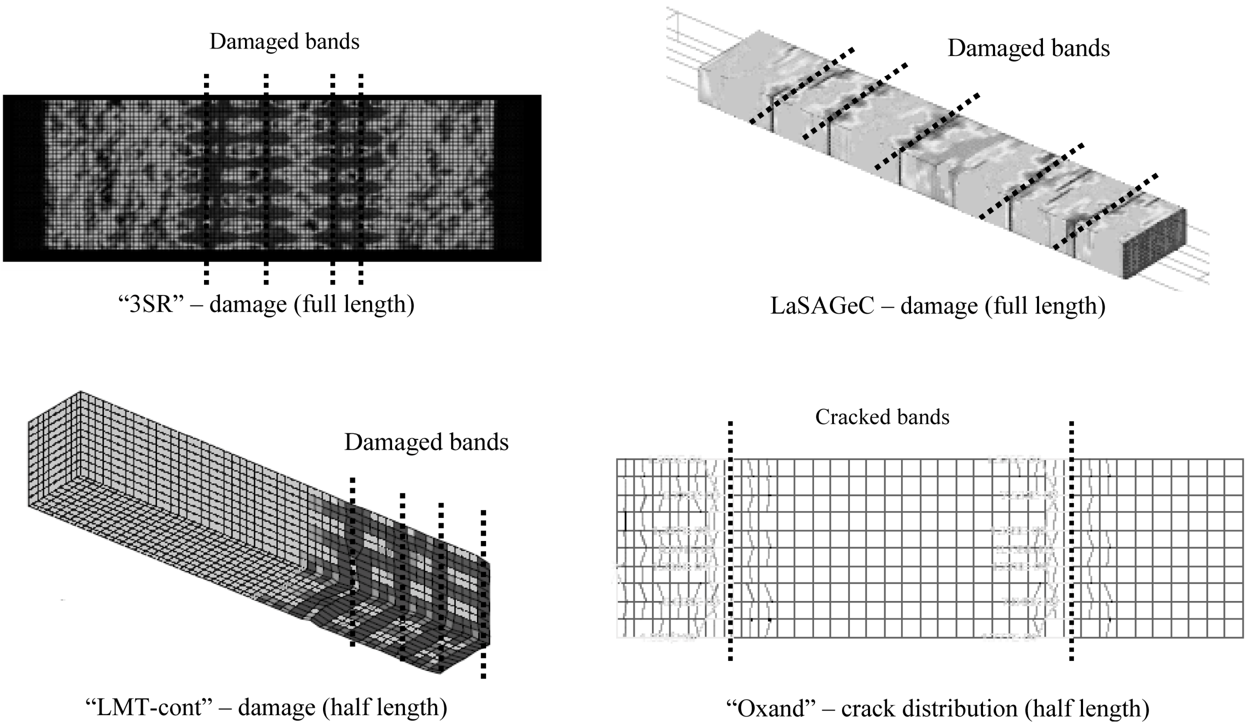

Figure 6. Characterization of the mechanical degradation (average strain = 0.3 0/00).

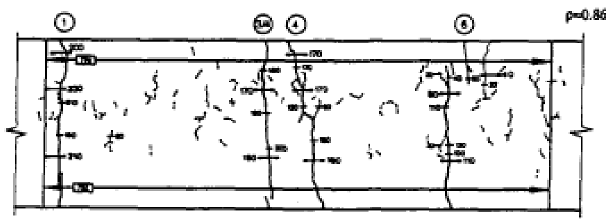

Figure 7. Experimental crack distribution (Mivelaz, 1996).

3.2 *Cracking Properties (case R3)*

Due to the differences in the models, the mechanical degradation is described by different indicators: continuum approaches use internal variables, like damage, whereas discrete or smeared – crack models propose a direct characterization of the crack (opening). In every case, a localization is observed corresponding to heavily damaged zones (Fig. 6).

The comparison between the experiment and the simulations shows that the crack openings captured by the models are not so far from the experiment. The average strain from which the cracks appear is also correctly represented. Moreover, the different techniques seem to propose more or less the same evolution.

To sum up the different results on this test, Table 2 presents a comparison between the experiment and the simulations on three values: the maximum of the force, the maximum of the crack opening and the crack spacing.

Nevertheless, compared to the experimental crack distribution (Fig. 7), the number of simulated cracks is generally higher than the experimental one.

From these results, the evolution of the opening of the two main cracks as a function of the average strain is proposed. Using the techniques presented in Table 1, the results in Figure 8 and Figure 9 are obtained.

As expected, the maximum forces are in good agreement with the experiment and illustrate the ability of the proposed models to represent the global behavior of this reinforced concrete tie. For the crack properties, the experimental maximum of the crack opening is underestimate by 30 to 50% for the first crack. Finally, the spacing is not fully satisfying, as the models simulate a number of cracks which is generally higher than the experimental one. Nevertheless, given the type of loading and the influence of the initial structural heterogeneity, the relevance of the crack spacing measurement on a single test may be questioned.

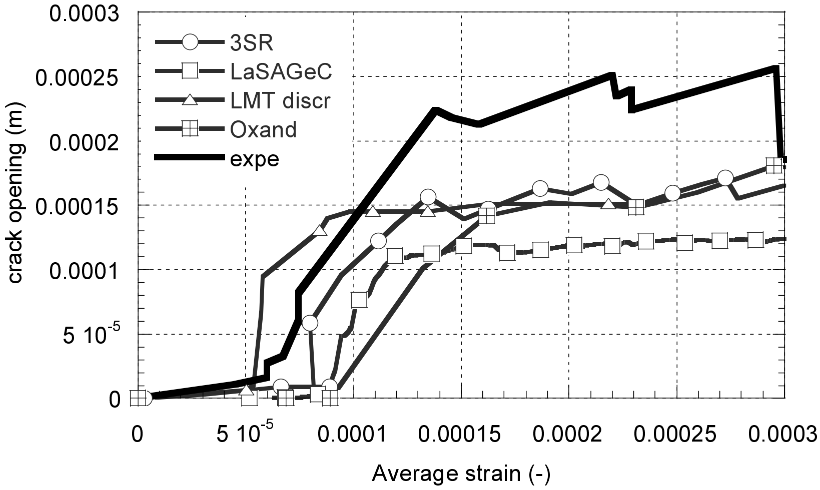

Figure 8. Opening of the first crack as a function of the average strain.

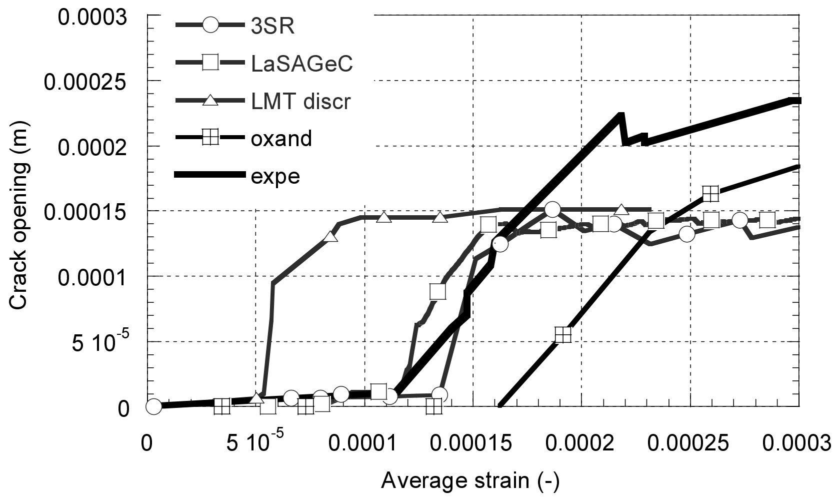

Figure 9. Opening of the second crack as a function of the average strain.

Table 2. Comparison between the simulations and the experiment (for an average strain less than 0.0003).

Team	Force (kN)	Crack opening (µm)	Crack spacing (cm)
"3SR"	835	171	~ 60
"LaSAGeC"	808	126	~50
"LCPC perfect"	950	-	-
"LCPC interface"	1000	-	-
"LMT-cont"	805	-	~ 20
"LMT-discr"	850	150	20 to 50
"Oxand"	1179	181	95
Experiment	960	256	20 - 105

3.3 *Case R5*

To conclude this section, Figure 10 presents the load – strain curve for the R5 case (see Figure 2 : same geometry with a different reinforcement ratio). The global behavior is once again correctly simulated with a general agreement concerning the maximum of the force.

Figure 11 illustrates the evolution of the opening of the main crack. The values are globally in agreement with the experiment: the apparition of cracks is correctly modeled and the order of magnitude is also reproduced, even if some improvements are still necessary to capture the good numbers of localized cracks.

4 CONCLUSIONS

This paper presented part of a benchmark that was performed during the first year of the French national project CEOS.FR. The aim was to evaluate the ability of the existing modeling methods to capture the experimental behavior of a reinforced concrete tie and to provide local information concerning the evolution of the cracking (spacing and opening especially).

The models were generally able to reproduce the global force – strain curve with a correct maximum of the force. Some post-processing methods were also developed to capture the crack-

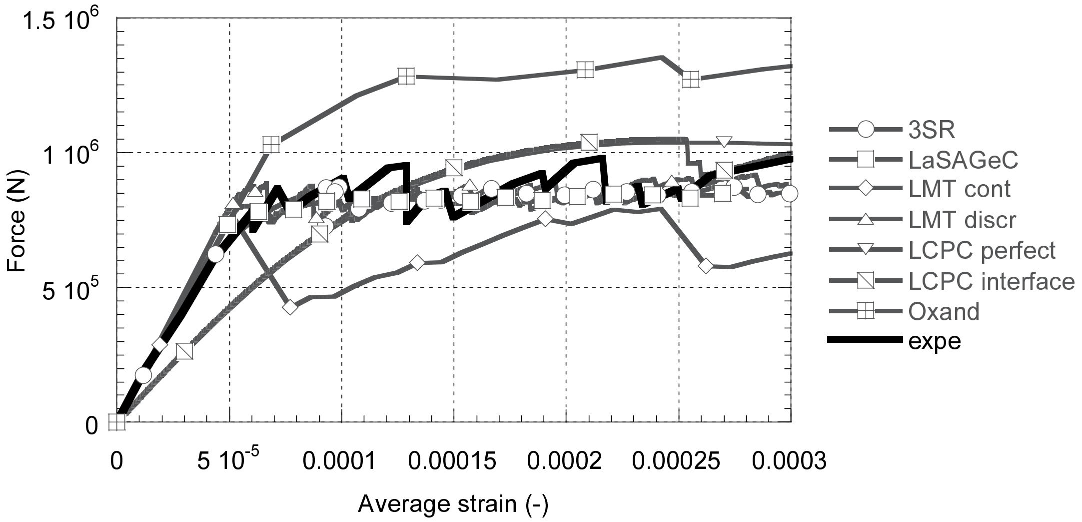

Figure 10. Evolution of the force as a function of the average strain (case R5). Zoom on the first part of the loading.

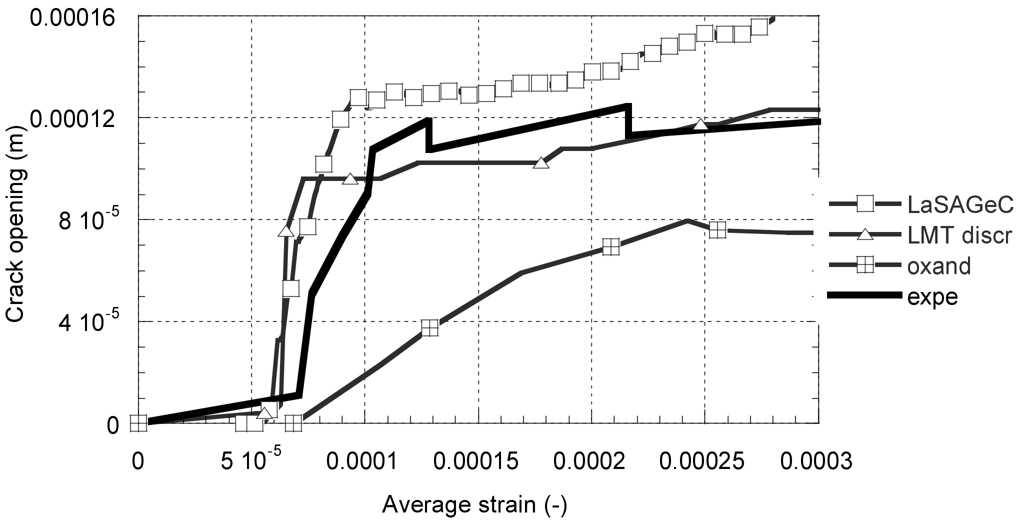

Figure 11. Evolution of the crack opening as a function of the average strain (case R5).

ing. The simulated evolutions of the opening were correct even if the maximum value and the spacing were not in total agreement with the experiment. Nevertheless, this benchmark represents a good starting point for further developments and/or improvements.

Moreover, it asks some questions about the methodology for the simulation of reinforced concrete structures concerning:

- the relevance of the material parameters obtained from uniaxial loading. A change in the tensile strength, compared with the material uniaxial one, was necessary to capture the appropriate value of the peak. It illustrates a "size effect" concerning the material parameters that have to be chosen for the constitutive law.
- Introducing the structural heterogeneity through a spatial distribution of a material property provides interesting results, without introducing any additional hypothesis on the location of the cracks. Nevertheless, some further work is needed to correctly characterize this variability, from experimental results for example.
- The definition of the crack opening has to be chosen carefully as it depends on the position of the measurement and may have different meanings (average, local or maximum values). For example, in our case, no information was available in the experimental report. It may have an influence on the results.
- Finally, even if the simulation proposed by "LCPC" does not seem to underline any difference taking into account, or not, the steel-concrete interface, a perfect relation between the two material is probably not satisfying. The models may be improved in this way to take into account the degradation of the interface.

ACKNOWLEDGMENTS

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