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Damage mechanisms analysis of a multi-scale fibre reinforced cement-based composite subjected to impact and fatigue loading conditions

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Abstract

For several years, Laboratoire Central des Ponts et Chaussées (LCPC) has worked on the development of new cement composites in order to obtain materials sufficiently tough and ductile to be used in structures or structural elements without any other reinforcement that fibres.

Then a multi-scale fibre reinforced cement-based composite (MSFRCC) has been developed and patented. It is principally characterized by a high percentage of fibres, percentage equal to 11% per m^3.

Three fibre dimensions are used in this composite.

In the present article, a qualitative analysis of damage mechanisms of this material under impact and fatigue loadings is proposed.

Concerning impact loading condition, the main conclusions are:

- Apparent *fibre–matrix* adherence, which increases with the loading rate, leads to an increase in material modulus of rupturel, an increase much greater than for all existing cement-based materials due to high percentage of fibres used;
- Mechanical homogenization of composite with loading rate is the result of cracks delocalization during cracking process. This delocalization results from viscous effects generated within the matrix and around the fibre–matrix interfaces.

Concerning fatigue loading condition, the main conclusions are:

- Intermediate fibre length (high percentage of meso-fibres) that is highly and positively involved in material static tensile strength, corresponds to scale of fibre that is sensitive to fatigue loading. As a matter of fact, meso-fibres become rapidly inactive and composite can no longer behave as a multi-scale reinforcement material. Material strength is then greatly affected.
- If the initial cracking state of the material before fatigue loading corresponds to a state of tensile strain that is less than or equal to $1.27\ 10^{-3}$, meso-fibres perfectly play their role with respect to relevant cracks (i.e. meso-cracks whose opening corresponds to their mechanical efficiency domain, that means less than 100 μm), material fatigue behaviour being then good (fatigue rupture after 2 millions of cycles).
- Specimens that did not break before 2 millions of cycles have better residual bending behaviour (gain of 6.5%) than reference specimens (specimens which were not previously loaded in fatigue) This result is the consequence of a morphological modification of cracks due to fatigue loading. Indeed, fatigue cycles lead to a gradual "blunting" of crack tips, cracks that subsequently become less dangerous with respect to their potential propagation.

Keywords: Multi-scale fibre reinforced cement-based composite; Ultra-high compactness cement-based matrix; Damage mechanisms; Analysis

1. Introduction

For several years, Laboratoire Central des Ponts et Chaussées (LCPC) has worked on the development of new cement composites in order to obtain materials that are sufficiently tough and ductile to be used in structures or structural elements without any other reinforcement that fibres.

These materials are the direct application of the "Multi-Scale Fibre Reinforcement Concept" developed by Rossi [1]. The idea is to mix short fibres with longer one to act at the scale of the material (increase of the tensile strength) and at the scale of the

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structure (increase of the bearing capacity and the ductility). Multi-scale fibre reinforced cement-based composite (MSFRCC) is thus obtained.

This patented MSFRCC is principally characterized by a high percentage of fibres, percentage equal to 11% per m^3. Three fibre geometries that are used in this composite.

1. Micro-fibres with a length of less than 2 mm;
2. Meso-fibres with a length of between 2 and 7 mm;
3. Macro-fibres with a length greater than or equal to 20 mm.

Several scientific and technical objectives were considered in the frame of the research related to this material. Hence, several mechanical test campaigns were conducted to study different mechanical behaviours of material (static, fatigue, impact behaviours). Moreover, original tests as a uniaxial tension test [2] and a durability test [3] were developed.

In the present article, a qualitative analysis of damage mechanisms of material under impact and fatigue loadings is proposed. Complete and detailed results (on which this analysis is based) related to experimental studies realized have been presented in previous papers [4,5].

2. Experimental data

Material mix design is presented in Table 1. It should be noted that more than half of total percentage of steel fibres comprises meso-fibres. This fibre dimension is, in the frame of the multi-scale fibre reinforcement concept, important to reach a very high uniaxial tensile strength.

2.1. Experimental results related to impact behaviour

Experimental results, related to strain rate effects on this composite material (tests performed were four-points bending tests [6]) can be summarized as follows:

1. Two domains of rate effects on modulus of rupture exist (Fig. 1): one related to a loading rate varying between 1.25 10^{-4} GPa/s and 1.25 GPa/s (domain 1, intrinsic to material), the other one related to a loading rate between 50 GPa/s and 700 GPa/s (domain 2, not intrinsic to material due to existence of inertial forces).

Table 1
Mix design of CEMTEC$_{\text{multiscale}}$®

Raw materials		Quantities	
OPC	(CPA CEMI 52.5 R)	1050	kg/m^3
Sand	(Quartz 125–400 μm)	514	kg/m^3
Silica fume	(Zirconium)	268	kg/m^3
Superplastizer	(Polyphosphonate — 30%)	44	kg/m^3
Total water		211	Ll
Steel fiber content		897	kg/m^3
Silicate fume/cement	0.255	Superplat/liant	1.02%
Sand/cement	0.573	Air void	2%
Water/cement	0.201	Specific gravity	2.98%
Water/binder	0.16	Fc [MPa]	220

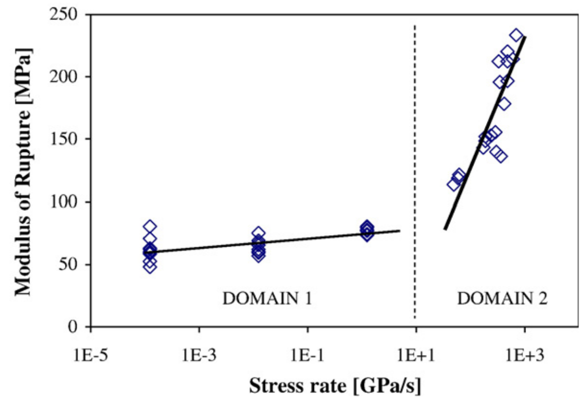

Fig. 1. Evolution of modulus of rupture (MOR) of MSFRCC with loading rate.

2. In the field of rapid static loads (domain 1), relationship between material uniaxial tensile strength and stress rate can reasonably be considered as linear (Fig. 2). Uniaxial tensile strengths are calculated from bending behaviours by using an inverse approach (finite element calculations with an elastoplastic model).The slope of the linear relationship is equal to 1.5 MPa/$\log_{10}$ unit. The value of the slope is clearly higher than that related to others cement-based materials. Indeed, for “common” concrete, including high-performance concretes, this slope is equal to 0.7 MPa/$\log_{10}$ unit [7]. Whereas, for ultra-high-performance fibre reinforced concretes such as DUCTAL®, it is equal to 0.8 MPa/$\log_{10}$ unit [8]. It is also important to specify that, for reference matrix of material studied (without fibres), it is equal to 0.7 MPa/$\log_{10}$ unit (Fig. 2) as for the others non-fibre reinforced concretes.
3. In the field of rapid static loadings (domain 1), the relationship between the pseudo-linear limit of *uniaxial tensile stress–strain* curve (Fig. 3) and stress rate is also linear. The slope of this relation is estimated at 2.25 MPa/$\log_{10}$ unit, a value greater than the one defined above linking the modulus of rupture of the material to the stress rate.
4. A mechanical homogenization of the cement composite (but not of the reference matrix) and a decrease of modulus of rupture scattering with loading rate are observed. Standard deviation (respectively variation coefficient) goes from 9.8 MPa (16%) to 2.8 MPa (3.6%).

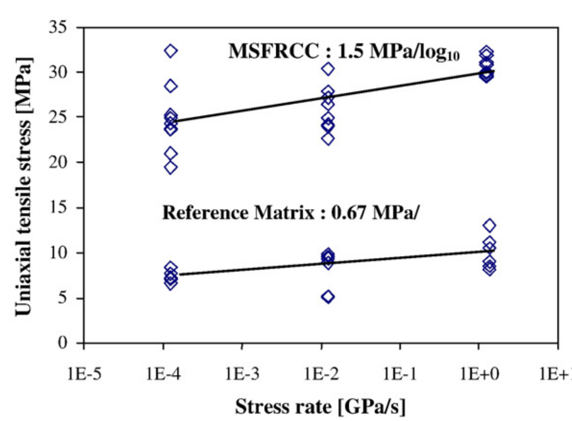

Fig. 2. Evolution of MSFRCC uniaxial tensile strength as a function of stress rate in quasi-static domain of loading.

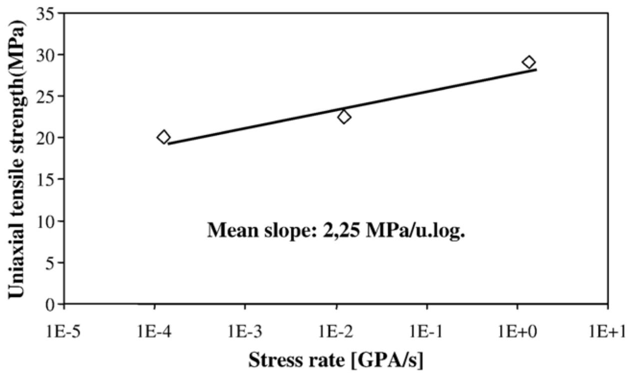

Fig. 3. Evolution of average pseudo-elastic limit related to uniaxial tensile behaviour as a function of stress rate for quasi-static domain of loading.

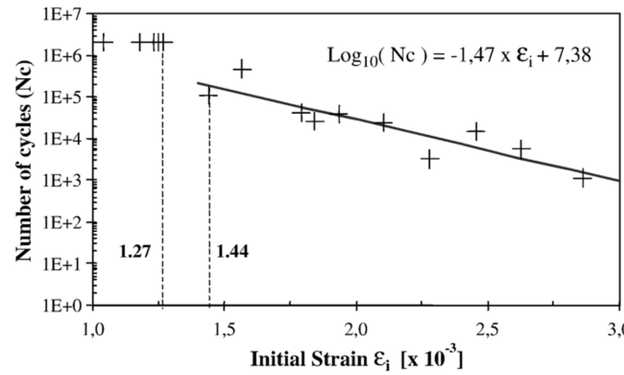

Fig. 5. Number of cycles to rupture versus initial strains.

5. Two main results are noted with respect to evolution of maximum deflection (or ultimate deflection, corresponding to modulus of rupture) according to loading rate:
   – within these two loading rate domains, the ultimate deflection increases with the loading rate;
   – ultimate deflections are lower in domain 1 of loading rates than in domain 2.
6. Young's modulus of specimens increases with loading rates in the domain 1. It goes from 50.6 MPa for a loading rate of 1.25×10^{-4} GPa/s, to 56.9 MPa for a loading rate of 1.25 GPa/s.
7. With respect to domain 2, the experimental system was unable to obtain sufficiently "clean" *stress–deflection* curves to make possible the determination of structural rigidities.

2.2. Experimental results related to fatigue behaviour

Results related to fatigue mechanical behaviour are summarized in Figs. 4–8. They have been obtained by performing four-points bending tests as for dynamic tests evocated before.

Taking into account the fact that real modulus of rupture of specimen tested in fatigue is not known, that scattering on experimental results related to fatigue tests is always important, and that number of specimens tested in fatigue is not enough important, it was impossible to link the level of fatigue stress to the lifetime of specimens (Fig. 4). However, a strong correlation between number of cycles to rupture and initial static strain measured during initial static loading ramp were obtained (Fig. 5).

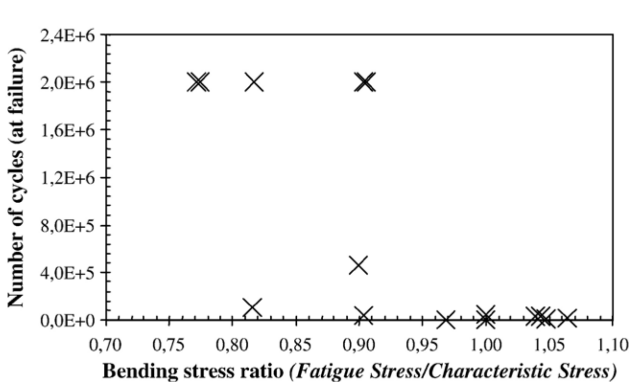

Fig. 4. Number of cycles to rupture versus fatigue stress level (ratio *R*).

This initial static strain is the strain corresponding to the stress reached during static loading (before fatigue loading is starting).

Two examples are then given illustrating specimen deflection evolution according to number of cycles (Fig. 6). One is related to a specimen that reached 2 millions of cycles without rupture, the other one is related to a specimen which led the rupture before 2 millions of cycles. Evolution of cracks appearing during the fatigue tests was also monitored (Fig. 7). Cracks opening related to specimen which reached 2 millions of cycles without rupture was always stabilized.

From the five post-fatigue reloading (in static) curves (obtained with specimens having reached 2 millions of cycles in fatigue), an average behaviour curve was established. This one is compared to the min, max, average, and characteristic curves obtained during static tests (specimens no previously loaded in fatigue, see Fig. 8).

It should also be noted that during static loading which precedes fatigue loading no visible crack appeared, and that several visible cracks appeared afterwards during fatigue cycles.

3. Analysis of damage mechanisms

3.1. Impact behaviour

3.1.1. Matrix behaviour

It is admitted that steel is not rate effects sensitive in stress rate domains described above. Consequently, rate effects in

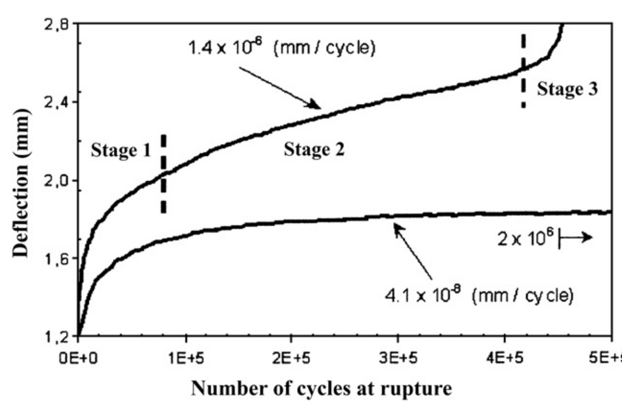

Fig. 6. Evolution of deflection with number of cycles.

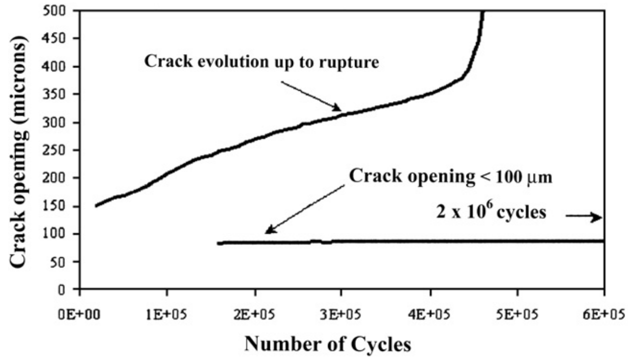

Fig. 7. Evolution of crack opening up to stabilisation.

cement-based composite studied can be principally summarized by those related to matrix and to interfaces between this matrix and steel fibres.

From research conducted at Laboratoire Central des Ponts et Chaussées [7], rate effects related to tension behaviour of cement matrices were quantified and a phenomenological explanation of the physical mechanisms was proposed by Rossi [9].

Thus, rate effect observed on mechanical behaviour of concrete is mainly related, in a certain domain of rates, to the presence of free water in nano-pores of cement paste. So, internal viscosity of material has to be associated only with the porosity of hydrates. Free water in the hydrates porosity acts in a similar manner than Stefan effect, well-known in physics. This Stefan effect can be summarized as follows: when a thin film of a viscous liquid is found between two perfectly flat planes that are moved apart at a speed $\cdot h$, this film exerts an opposing force on plates that is proportional to plates movement speed. This mechanism is taken into account in the following relationship:

$$F = \frac{3\eta V^2}{2\pi h^5} \cdot \dot{h}$$

where

- F is the opposing force,
- η is the viscosity of the liquid,
- h is the initial distance between the two plates,
- $\dot{h}$ is the rate of separation of the two plates ($\dot{h} > 0$),
- V is the volume of the liquid.

Assumption that the free water within the hydrates is the source of a mechanism of this type (when the solid skeleton, assimilated to a network of plates, is subject to tension strains) is made. So, the reason why rate effects are large within wet concrete is understandable.

From concrete cracking process in quasi-static tension [1], viscous mechanism similar to Stefan effect, acts dynamically at two different scales, but in a similar manner:

– *before cracking localization*: consequence of viscous mechanism is first to delay creation of micro-cracks then and, when they are created, to delay their propagation by limiting damage of area preceding micro-cracks tip. These two actions lead firstly to delay localization of micro-cracking and, therefore, to increase load peak, and, secondly, to increase, but weakly, apparent Young's modulus of concrete;
– *after localization*: consequence of viscous mechanism is to block macro-crack propagation following the same principle as for micro-cracks.

In parallel to viscous mechanism activation, inertial forces have no more to be neglected when strain rates generated by dynamic loading reach high values. These inertial forces operate during dynamic loading before micro-cracking stage by opposing all material points movement into specimen, that increases material apparent strength. Then, when micro-cracks are created and propagate, inertial effects are mainly present at cracks tips. A material point on one of lips surface of a recently created micro-crack or of a micro-crack in propagation goes rapidly from a rate of v_1 (before cracking) to a rate of $v_2 \gg v_1$ (after cracking). So, consequence of these inertial forces is to oppose micro-cracks propagation and, thus, to delay cracking localization. Inertial forces also operate after cracking localization phase if macro-crack opening rate remains very high (following the same mechanism as for micro-cracks).

It is clear that, although able to act simultaneously, viscous mechanism and inertial forces are not activated with the same intensity. That depends on loading rate that is applied to specimen.

A simple model [10] based on experimental results indicates that for strain rates inferiors to a critical value around 1 s^{-1}, inertial forces are negligible with respect to viscous effects, and that, for strain rates greater than or equal to this critical value, inertial forces are no longer negligible at all and become dominant from a strain rate of approximately 10 s^{-1}.

3.1.2. Fibres acting on cracking process during dynamic loading

From concrete cracking process in the frame of dynamic loading, steel fibres acting during this process can be analyzed as follows: to act differently in dynamic situation than in static situation, fibres must be the source of additional physical mechanisms (with respect to static loading) having positive or negative effects on the cracking process. In reality, no mention of the existence of physical mechanism having negative effect

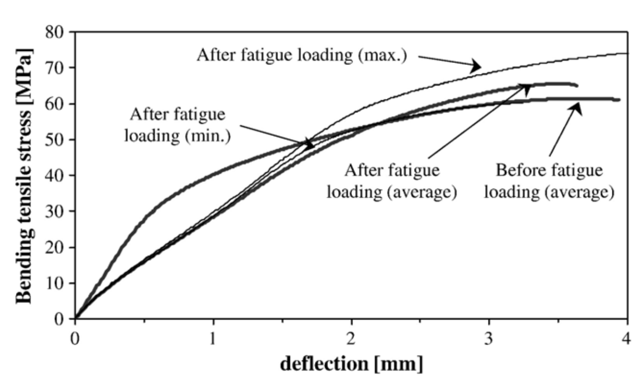

Fig. 8. Static behaviours related to specimens previously loaded in fatigue and to specimens directly loaded in static.

has been found in literature; at the most, authors indicate the relative insensitivity of traditional cement matrices to incorporation of a low percentage of fibres.

Concerning potential positive effects, Rossi [11] proposed two physical mechanisms capable of interacting positively on fibre reinforced matrices strength evolution with loading rate: waves diffraction by fibres and synergetic coupling between fibre and cement matrix.

Experimental study related in this paper did not bring any elements that could validate the first mechanism. Consequently, only the second one is considered in the following analysis.

Synergetic coupling between concrete and steel fibres is closely linked with *fibre/matrix* interface behaviour. The role of fibres is to oppose normal or tangential displacement of micro-crack or macro-crack lips created in the matrix, and therefore to transfer stresses to either side of these cracks. Resulting stresses, according to fibre form and dimensions, can be shear stresses at *fibre/matrix* interface, but also tensile and compressive stresses if fibre has mechanical anchorages such as hooks at its ends, or if it is undulating in shape, or simply if it is not aligned in relation with loading direction. During a pulsed load, cracks lips movement rate is very high, and fibres loading rate (uniaxial tension or bending, according to fibres orientation with respect to cracks) is also high. Fibres, by transmitting stresses to matrix surrounding them, create high strain rates in this matrix. As rate effects related to fibre mechanical behaviour are negligible, only local rate effects in matrix related to steel fibres presence then exists.

For a fibre that acts by adherence, which is the case in MSFRCC studied, stress transmitted by fibre to matrix around it is a macroscopic shear stress. At a finer scale, if matrix endogenous shrinkage restrained by fibre, and matrix microstructure heterogeneity around this fibre, are both taken into account, local tensile stresses are in fact observed. These tensile stresses create micro-cracking (small cracking with respect to fibre dimension) *fibre/matrix* interface. By taking into account what it has been said concerning rate effects on matrix tensile behaviour, it is possible to deduce that, when matrix cracks around fibre, apparent mechanical adherence between fibre and matrix is created. Consequently, fibres are mechanically more efficient in dynamic than in static loading condition, provided, of course, that they do not break, which is the case for cement-based composite studied.

With regards to mechanism described above, it appears evident that greater the number of fibres loaded, so the number of interfaces, higher will be the synergetic effect between fibre and matrix. Firstly, this explains why rate effects within MSFRCC studied are greater than those related to reference matrix, as well as within mono-fibre concretes that clearly contain fewer fibres than MSFRCC. This also explains why rate effects in pseudo-linear domain of MSFRCC behaviour are greater than in its strain hardening domain. As a matter of fact, even fibres quantity acting during pseudo-linear domain is admittedly less than for strain hardening domain, the “weight” (in terms of number) of new interfaces (corresponding to longer fibres) loaded during this strain hardening domain is much lower than that of previously loaded interfaces (number and specific surface of micro-fibres are without comparison with the two others dimensions of fibres). This remains consistent with respect to MSFRCC cracking process which leads to a continuous increase of cracks number as shown in Fig. 9. This process can be schematically divided in three stages:

Stage 1 Development of micro-cracking mainly involving micro-fibres.
At this point, matrix damage is sufficiently diffuse to preserve material rigidity (no apparent decrease of material Young modulus). It is during this stage that most of *fibre/matrix* interfaces are loaded. Logically, it is in this domain that rate effects are mostly expressed.

Stage 2 Propagation of some of micro-cracks (creation of meso-cracks) until they are bridged by meso-fibres.
This bridging permits to loading more the composite, so new micro-cracks appear within the matrix (at same scale as that related to stage 1 of cracking process). Then, number of interfaces loaded increases that

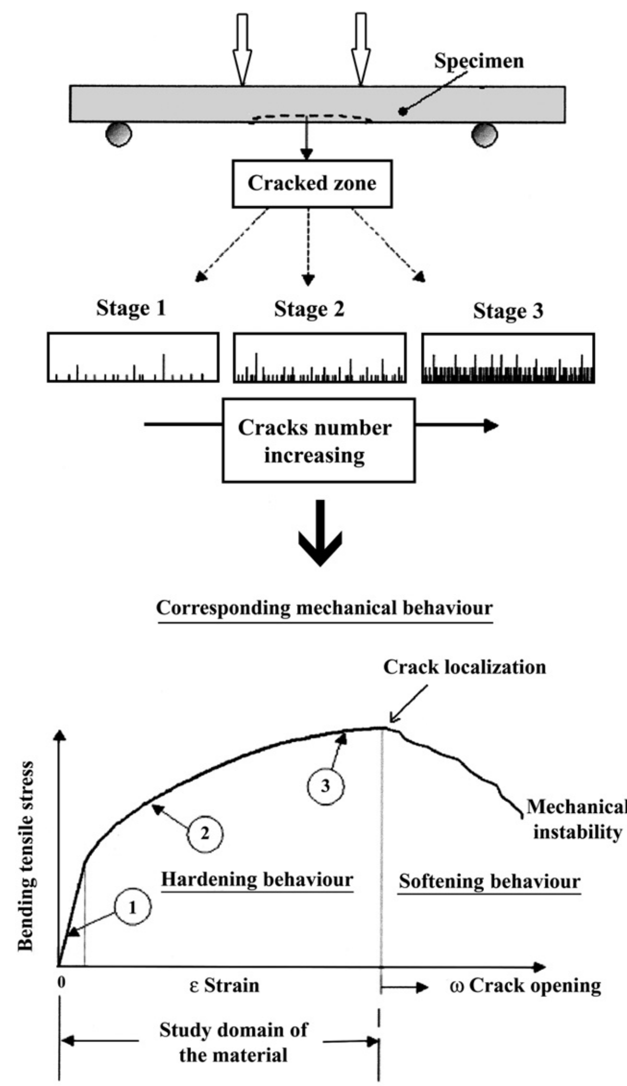

Fig. 9. Schematic diagram of multi-cracking process of a multi-scale fibre reinforced cement-base composite.

leads to appearance of a material strain hardening behaviour.

Stage 3 Propagation of some of meso-cracks (creation of macro-cracks) until they are bridged by macro-fibres.
This bridging again permit to loading more the composite. In a similar manner to Stage 2, creation of new cracks within the matrix is then observed (at micro and meso-scale).

The concepts of micro, meso and macro-cracks used above must be associated with the three fibre geometries used.

The cracking process proposed above is similar to "snowball" effect. It stops with macro-crack appearance at structural scale (than means with a mechanical instability).

3.1.3. Mechanical homogenization

Scattering related to tensile behaviour of cement-based composites is not only due to the presence of local defects in cement matrix (e.g. initial micro-cracks), but also to the spatial distribution heterogeneity of fibres. Mechanical homogenization of cement-based composite therefore consists in eliminating these two "weaknesses".

When a micro-crack is created or is initially present in matrix, it was stated above that viscous phenomena slow down this micro-crack propagation by opposing it. This mechanism therefore makes it possible for other micro-cracks to appear in matrix. Weight of each crack with respect to cracking localization mechanism is therefore lessened and matrix mechanical homogeneity increases. It was signalled above that synergetic effect between matrix and fibre leads to the fact that *fibre/matrix* apparent adherence increases with local stress rate at interface. If a crack propagation favours an area of lower fibre density, fibres encountered by this crack are proportionally more stressed than elsewhere in composite and rate effects on these fibres adherence are therefore greater. Consequently, by more effectively countering cracks propagation when loading rate increases, fibres action cause an increase in probability of creation of other cracks and therefore delocalize cracking with respect to slower loads.

The fact that fibres in fewer numbers "work" better leads to a fibre action homogenization, and, therefore, to a cement composite mechanical homogenization.

3.1.4. Evolution of ultimate strain

Ultimate strain increasing with loading rate is simply explained by an increase of created cracks number (see above), increase leading to an increase of fibres concerned by cracks.

However, the fact that ultimate deflection is less in domain 2 of loading rate than in domain 1, can only be explained by structural rigidifying (i.e. specimen rigidifying) related to inertial forces appearance acting on matrix.

3.2. Fatigue behaviour

It is noted on Fig. 5 that there is a very clear threshold concerning initial strain with regard to number of cycles to rupture. This threshold, which can be called critical initial strain, ϵ_{ic}, is between 1.27 10^{-3} and 1.44 10^{-3}. Beyond this threshold, number of cycles to rupture decreases in a linear manner, on semi-log scale, with increase of ϵ_{ic}, whereas before this threshold, specimens subjected to two millions of cycles do not break. It was also noted that transition between these two fatigue domains is not continuous, but a very clear jump is observed.

Moreover, it was also observed that the lower limit of ϵ_{ic} corresponds to a tensile bending stress of approximately 65% (ratio *R*) of characteristic modulus of rupture, a relatively low value. If tensile bending stress is compared to average modulus of rupture, this ratio drops below 50%. This value is the lower limit for fatigue limits of standard fibre reinforced concretes (mono-fibre reinforcement). All experimental observations related to fatigue behaviour of MSFRCC studied can be summarized as follows:

- material uniaxial tensile strength is mainly provided by the high content of meso-fibres;
- in ultra-high compact matrices, straight and hooked fibres, mainly operate by adherence. Their length of anchorage (even for longest one) is too short to cause their rupture (that is experimentally observed);
- ratio *R* (defined above) which not lead to rupture by fatigue of specimen is relatively low (approximately 0.65);
- there is an ϵ_{ic} strain threshold corresponding to an initial micro-cracking state. This threshold separates two domains of behaviour: one in which material does not break in fatigue, an other one in which number of cycles to rupture linearly depends on static initial strain;
- during static loading that precedes fatigue loading, no visible crack appears whereas a clear network of visible cracks develops during fatigue cycles, that for a loading much lower than average modulus of rupture (62 MPa in this case).

These observations lead to the following proposition concerning damage process of MSFRCC under fatigue loading.

3.2.1. First stage

Initial static loading of MSFRCC specimen introduces an initial micro-cracking state which induces initial strain ϵ_{ic}. This micro-cracking state is related to damage of *fibre/matrix* interfaces, essentially that of meso-fibre. During the following fatigue cycles, development of micro-cracking (characterized by number of active micro-cracks) and damage of *fibre/matrix* interfaces both occur. This micro-cracking induces at macroscopic level a fast increase of deflection and of strain. Micro-cracking of composite becomes quickly stable in terms of number of cracks created since maximum stress applied does not change anymore. Only second process related to damage of *fibre/matrix* interface continues, leading to a deflection rate which becomes lower and lower. Micro-cracks opening previously no visible becomes detectable without propagating significantly. This first damage stage is illustrated in Fig. 10a. It corresponds to a rapid increase of deflection (then of strain) observed during the first cycles (see Fig. 6 — Stage 1).

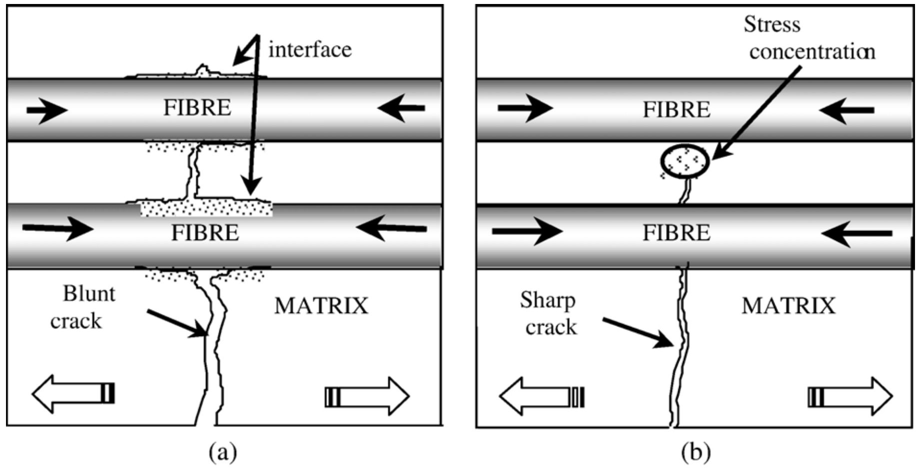

Fig. 10. Cracking appearance in presence of fibres, a) during static loading following a stage of fatigue loading, b) during static loading without previous fatigue loading.

3.2.2. Second stage

With fatigue cycles and crack openings increasing, longest fibres of material (third dimension of fibre) are increasingly stressed and their interface begins to degrade. Fig. 6 shows that there is a crack opening threshold around 100 μm. If this threshold is not exceeded crack opening does not propagate and the specimen reaches 2 millions of cycles without rupture. Otherwise, crack opening continues to increase and the specimen breaks before 2 millions of cycles. This crack opening value must not however be viewed as a triggering level, but rather as an asymptotic level of crack opening only for specimens that show no change in their damage. Indeed, it appears that this opening limit is an intrinsic characteristic of composite related to different percentages and different *length/diameter* ratio of fibres. For specimens that exceeded ϵ_{ic}, crack exceeds the threshold of 100 μm during a transient phase, then reaches a regime in which changes slow down. This threshold does not induce a change in material behaviour (e.g. loss of efficiency of meso-fibres or start of yielding of macro-fibre hooks, as example), but depends directly on initial ϵ_{ic} strain.

This second stage of damage corresponds to stable, slow, and linear increase of deflection in function of cycle number logarithm (see Fig. 6 — Stage 2). It is the illustration and the consequence of multi-scale nature of reinforcement and of material damage as well as the synergy between fibres. Although meso-fibres act satisfactorily, they help the longest ones to maintain crack openings in a domain where these fibres do not suffer a degradation of their interface with the matrix during fatigue cycles. However, if meso-fibres act unsatisfactorily, the longest ones suffer such stress during fatigue cycles that their interface with matrix is gradually damaged, hence a continual increase of crack openings (see Fig. 7) and, consequently, of strain is observed in the specimen.

3.2.3. Third stage

Whereas cracks open gradually during second stage of damage, they finally reach opening values that are incompatible with meso-fibre dimension (in the order of 250 to 350 μm). From this moment, the multi-scale nature of reinforcement ceases and critical crack is only bridged by macro-fibres with degraded interfaces. This opening changes quickly and unstably during the following cycles, terminating with specimen rupture. This comprises the last part of the curve (see Fig. 6 — Stage 3).

This unstable crack propagation must be compared with cracking localization (appearance of visible crack) observed during static test carried out on same material and same specimen dimensions. Crack opening related to specimen rupture lies between 500 and 600 μm and strain is by 20% greater than ultimate strain of material subjected to static loading.

3.2.4. Pseudo-accommodation

Comparison between average static loading curves obtained respectively before and after fatigue loading (Fig. 8) highlights following points:

- MSFRCC specimens subjected to static loading after 2 millions of fatigue cycles show a much lower rigidity than those directly subjected to static loading (without been previously subjected to fatigue loading).
- Average modulus of rupture of MSFRCC obtained after 2 millions of cycles increases about 6.5% compared with what happen when material is directly subjected to static loading. Ultimate strain is, however, slightly lower. Finally, ductility of specimens tested in fatigue (*non-elastic strain/elastic strain*) is clearly lower than that of virgin specimens (no tested in fatigue before).
- Pseudo-linear domain of behaviour related to static loading is greater for specimens that have previously been loaded in fatigue than for those that have not been subjected to this loading.

The first point can be explained easily by the material state of cracking and of damage. 2 millions of cycles created microcracks in cement matrix and a network of visible cracks, due to damage of *fibre–matrix* interfaces, developed in parallel. Logically, this mechanism leads to a loss of specimens' rigidity.

The second notable point concerns modulus of rupture increase. This phenomenon has already been observed by other authors [12] for low levels of fatigue loading (below limit of fatigue) but they did not formulate any explanation that could reasonably account for this phenomenon.

It is proposed here to attempt an explanation by using fracture mechanics theory.

It is known that crack bridging mechanism absorbs a considerable amount of energy and that cracks propagation is lower as fibres reduce the stress intensity factor at crack tip. During fatigue loading, specimens that reached 2 millions of cycles without breaking have the specific feature to contain one or more visible cracks whose opening never exceeds 100 μm (see above). The fact that there is no crack opening evolution could be explained as follows:

– a non-propagation of cracks, because, for geometric reasons, a crack that propagates leads to an increase of its opening;
– a stop in damage of *fibre–matrix* interfaces because an increase in cracks opening should be also observed.

The fact that a crack no longer changes marks a change in the energy dissipation mechanism within material.

In spite of existence of compressive stresses around fibres due to cement-based matrix shrinkage, *fibre–matrix* interface remains a relative weak zone for material. This point is however positive because it allows cracks to deviate by propagating along *fibre–matrix* interface zone (interface debonding).

Most of mechanical energy is therefore dissipated, no longer during crack propagation in matrix, but to amplify debonding along *fibre–matrix* interface. In this way, cracks are probably very blunted at their tip (crack tip which includes damaged *fibre–matrix* interface (Fig. 10a)). Indeed, a sharp crack should propagate in same loading conditions (see fracture mechanics theory).

This explanation is consistent with an increase of pseudo-linear domain of the specimens' behaviour when this specimen is previously subjected to static loading before being subjected to fatigue loading. The fatigue cracks are probably propagated mode widely in the damaged composite than in untested composite (which is conveyed by the loner pseudo-linear domain), but their leading appearance shows a morphology favourable to stress concentrations (stress intensity property).

In following cracking process and mechanical behaviour during static loading are considered in two situations:

– Initial cracking is related to a virgin specimen (no previous fatigue loading).
– Initial cracking (before static loading) is related to a specimen previously loaded in fatigue).

The state of initial cracking between these two situations therefore differs greatly.

Specimen has no cracks in first situation and contains blunted cracks in second one (see Fig. 10a and b).

If from these two initial situations, a same static loading is applied, it is not very difficult to imagine cracking evolution:

– In specimen no previously loaded in fatigue: cracks are not very deep but fairly sharp;
– In specimen previously loaded in fatigue: cracks are deeper but much more blunt.

If static loading is continued, fracture mechanics theory shows that tensile stress concentration at crack tip is much more important when crack tip is sharp than when crack tip is blunted.

Consequently, cracks related to specimen no previously loaded in fatigue have a greater tendency to propagate than those related to specimen previously loaded in fatigue.

This difference in cracking process explains, on one hand why specimen pseudo-linear behaviour in static is greater for specimens previously loaded in fatigue and, on other hand, why modulus of rupture of specimens previously loaded in fatigue is slightly higher.

4. Conclusions

This article presents an analysis of damage mechanisms of a multi-scale fibre reinforced cement-based composite (MSFRCC) with a high fibres content subjected to impact or fatigue loadings.

Concerning the impact loading condition, the main conclusions are:

- apparent *fibre–matrix* adherence, which increases with loading rate, generates an increase in material modulus of rupture, an increase much greater than for all existing cement-based materials due to the use of a high dosage of fibres;
- mechanical homogenization of composite with loading rate results from cracking delocalization, this delocalization resulting from viscous effects generated within the matrix and around the *fibre–matrix* interfaces.

Concerning fatigue loading condition, the main conclusions are:

- intermediate length of fibre (high percentage of meso-fibres), that is highly and positively involved in material static tensile strength, become the weakest point of composite material with respect to fatigue loading. Indeed, cyclic loading greatly damages *fibre–matrix* interfaces which decreases highly efficiency of fibres that operate by adherence as is the case for most fibre reinforced cement composites. Thus, fibres which have a low *length/diameter* ration, that the case for meso-fibres used in material studied, become rapidly inactive and material can no longer behave as a multi-scale reinforced material. Material strength is then greatly affected.
- If initial cracking state of material before fatigue loading corresponds to a state of tensile strain less than or equal to $1.27\ 10^{-3}$, meso-fibres perfectly fulfill their role with respect to relevant cracks (i.e. meso-cracks whose opening is less than 100 μm), and fatigue behaviour of composite material studied is stable (fatigue rupture after 2 millions of cycles).
- Specimens that did not break before 2 millions of cycles have a residual bending behaviour greater (gain of 6.5%) than bending behaviour of specimen directly subjected to static loading. This result is the consequence of a modification of crack morphology due to fatigue loading. Indeed, fatigue

cycles lead to a gradual “blunting” of crack tips, cracks that subsequently become less dangerous with respect to their potential propagation.

References

[1] P. Rossi, P. Acker, Y. Malier, Effect of steel fibres at two stages: the material and the structure, Materials and Structures 20 (1987) 436–439.
[2] C. Boulay, A. Arca, J. Sananes, J.-L. Tailhan, P. Rossi, Comportement mécanique d’un nouveau composite cimentaire à écrouissage positif. II. Comportement en traction uniaxiale, Bulletin des laboratoires des Ponts et Chaussées 243 (2003) 19–30.
[3] E. Parant, Mécanismes d’endommagement et comportements mécaniques d’un composite cimentaire fibré multi-échelles sous sollicitations sévères: fatigue, choc, corrosion, PhD from ENPC, Paris, France, 2003, p. 248, (in french).
[4] P. Rossi, Development of new cement composite materials for construction, Journal of Materials: Design and Applications, vol. 219, Professional Engineering Publishing, 2005, pp. 67–74, part L.
[5] P. Rossi, E. Parant, Mechanical behaviours of a multi-scale fibre reinforced cement composite (MSFRCC) subjected to severe loading conditions, in: Banthia, et al., (Eds.), Proceedings of ConMat’05, Vancouver, 2005.
[6] P. Rossi, A. Arca, E. Parant, O. Laurence, P. Fakhri, Bending and compressive behaviors of a new cement-based composite, Cement and Concrete Research 35 (2005) 27–33.
[7] P. Rossi, Strain rate effects in concrete structures: the LCPC experience, Materials and Structures, hors série, 1997, pp. 54–62.
[8] J. Sercombe, Modélisation du comportement du béton en dynamique rapide — Application au calcul des conteneurs à haute intégrité, Thèse de doctorat de l’École Nationale des Ponts et Chaussées, 1998.
[9] P. Rossi, A physical phenomenon which can explain the mechanical behaviour of concrete under high strain rates, Materials and Structures 24 (1991) 422–424.
[10] P. Bailly, Une modélisation d’un matériau fragile avec prise en compte d’effets dynamiques, C.R. Acad. Sci. Paris, t.318, série II, 1994, pp. 1–6.
[11] P. Rossi, Les bétons de fibres métalliques, Presses de l’École Nationale des Ponts et Chaussées, 1998, p. 309.
[12] V. Ramakrishnan, et al., Cyclic behaviour, fatigue strength, endurance limit and models for fatigue behaviour of FRC, high performance fibre reinforced cement composites 2 (HPFRC 2), in: A.E. Naaman, H.W. Reinhardt (Eds.), Proceedings of the Second international RILEM Workshop, 1995, pp. 103–116.