6th RILEM Symposium on Fiber-Reinforced Concretes (FRC) - BEFIB 2004
20 - 22 September 2004, Varenna, Italy, pp197-218

CLASSIFICATION OF FIBRE REINFORCED CEMENTITIOUS MATERIALS FOR STRUCTURAL APPLICATIONS

Henrik Stang [1], Victor C. Li[2].
[1]Department of Civil Engineering, Technical University of Denmark (DTU), Denmark.
[2]Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA.

Abstract

A great diversity of different cement based fibre reinforced (FRC) materials can be found today either in practical use or under development in research laboratories. These include materials with significantly different material properties as well as materials with very different constituents and structure. At the same time a need for design guidelines for the use of FRC-materials has been widely recognized both by researchers and practical engineers. Design guidelines based on a simple material classification as well as representation of (mechanical) material properties can be considered as a pre-requisite for further advancement of application of innovative FRC materials and for focusing of the research in such materials.

The paper discusses and presents a fundamental classification based on the concepts of (pseudo) strain hardening and tension softening. The paper further sheds light on this classification by describing existing and possible structural applications based on the utilization of the material characteristics in serviceability and ultimate limit state. The classification is further substantiated, by presenting simple engineering representations of the mechanical behaviour in the two cases, suitable for structural design. The representation of mechanical properties is related to test methods and the availability of and requirements to standardized methods is discussed. Durability performance is discussed and the required durability performance testing for each class of material is described along with envisioned results. Finally, the implementation of results from durability in the various types of design approach is described.

Fax: +45 4588 3282
E-mail: hs@byg.dtu.dk

1. Introduction

All structural design can be considered to be design for structural performance, if one defines performance in the broadest sense covering everything from aesthetic requirements, to durability, load carrying capacity, stiffness, price and more. Hence, the end goal of design of materials for structural use is always structural performance.

The need for a holistic approach to materials and structural design has been pointed out recently by Stang and Li [1]. Such an approach would allow for close communication between the materials engineering and structural engineering and lead to higher degree of optimization in the construction industry.

A strong driving force for developing a more holistic approach to materials and structural design is the emerging performance based design criteria and performance based design codes. Performance Based Design Codes (PBDC) shifts from prescriptive requirements in structural detailing (materials and shape) to structural performance specifications. The performance objectives may be specified in terms of operability, repairability, service life, or collapse prevention subsequent to specified load levels and environments. This shift in design codes places a greater responsibility on the structural engineer to ensure that the structural design directly links to an expected outcome in performance. However, because of the removal of the detailed, prescriptive nature of the code, structural engineers have greater flexibility in adopting emerging structural materials in the design and to perform an overall optimization of structural shape and material performance.

The link between structural engineering and materials engineering is established through *materials models* and the associated *material parameters.* The isolated fields of structural engineering and materials engineering have different goals with materials models. In materials engineering materials models are used to understand the relationship between on one hand processes, material composition and micro-structure and on the other hand material performance. In structural engineering materials models are used as one of three sources of input (material performance, structural shape and execution circumstances) for the prediction of structural performance.

In materials engineering the focus is placed on reflecting the material physics governing the material performance. In materials engineering, materials performance can be expressed in many ways. Furthermore the way that materials performance is expressed does not seem terribly important, as long as the performance measure is able to distinguish between significant performance issues.

In structural engineering the picture is very different. Here focus is placed on the structural modelling and the materials model is just one of many elements in this. The materials model is chosen taking into account the material performance in an average sense and the computational tools and their capabilities play a major role in the choice of materials model. Here, the way materials performance is expressed (i.e. the materials parameters, their nature and their number) plays a major role for the structural design process.

A holistic approach where information about materials composition, structure and processing is transferred easily from materials engineering via structural engineering to structural performance requires participation from both the materials and the structural research communities and can only be done if:

1. The materials models have a sound physical background reflecting the materials physics governing their behaviour
2. The materials models are simplified to an extend that they can be included in the structural design process but at the same time reflect the material physics involved

The last point will typically put significant restrictions on the detailing of materials models seen from a materials engineering point of view, since models on the structural level can only treat materials in an average sense. Thus at the end of the day it is the materials models implemented at the structural level that sets the agenda, at least if the synergistic effect of the holistic approach should be achieved.

Finally, the aspect of testing should be mentioned. Information about materials performance is gained through testing. However, there is a difference between testing to understand material behaviour and testing to verify a certain material performance as specified in a structural design using simplified materials models and simplified representation of materials performance, see [2].

The present paper presents a suggestion for materials models representing mechanical behaviour of Fiber Reinforced Cementitious (FRC) materials, primarily in tension. In 1991 Stang, [3] suggested to introduce two classes of FRC materials based on their ability to resist strain localization: "*Roughly speaking, fiber reinforcement is introduced to deal with this tendency* [of the matrix] *towards strain localization. This can either be done by modifying the tendency to localization or by removing it entirely. Since whether or not the material in question has a tendency toward strain localization has major consequences on a structural calculation procedure, it is reasonable to characterize FRC-materials on the basis of their tendency to exhibit* [strain] *localization*". Much work has been done in the past years regarding materials models and testing methods, however the basic distinction between the two fundamentally different material behaviour still stands. In fact the basic distinction has been further emphasized by the continued development of ECC materials [4], which has now completely negated the statement in [3] about FRC materials without strain hardening: "*This group of FRC-materials are typically cementitious steel, glass or polymetric fiber composites with such a high fiber volume concentration (typically 6-14%) that any micro-cracking is stabalized*." Today we know that ECC materials can be designed containing about 2 vol.% fibre and having properties in the fresh state which from a process point of view make them completely equivalent to non-strain hardening or tension softening materials. The implication of near term practical use of strain hardening FRC further emphasizes the need for a clear distinction between the two classes of materials. Various national documents exist linking test methods, interpretation of test results and structural design methods. One of the earliest examples of a consistent approach is the recommendation [5] produced by the Swedish Concrete Association. This recommendation aims at strain softening FRC and is based on the toughness index concept. A series of recommendations for test and design methods for the same type of material came from the RILEM Technical Committee TC 162, [6] -[9], now basing the testing on a fracture mechanical 3-point-bending test specimen with a notch and placing some of the design formulae on a fracture mechanical basis. Recently French recommendations for testing and design have emerged aiming particularly at ultra high performance FRC, [10].

In [11] Li and Stang point to the fact that in cementitious materials and structures there is a close link between durability and ductility. Also it should be pointed out that FRC materials in general undergo aging (i.e. change in ductility over time) and that the aging processes in general are dependent on transport phenomena and thus eventually on cracking. Consequently structural cracking should be evaluated in a structural durability context. Furthermore it follows that material ductility must be evaluated taking cracking and aging into account i.e. material ductility must be evaluated over time under different environmental conditions, since both classes of FRC materials are envisioned to be utilized in their cracked state even in the serviceability limit state. Note that this latter issue represents a major departure from conventional reinforced concrete design where is there is no link between concrete properties and possible cracks; crack widths are only analysed in order to assess and prevent reinforcement corrosion.

2. Mechanical classification: strain hardening and tension softening

Many construction materials, including steel, aluminium, concrete, FRC, wood and polymeric materials show similar behaviour under mechanical loading to such an extend, that it is reasonable to talk about a generic stress-strain curve with features which in principle can be found in all of the materials with varying degrees of importance. Such a generic curve representing the mechanical response under uni-axial stress is shown in Fig. 1. The generic mechanical response contains the following features: a linear regime in which very little permanent micro-structural changes and deformation take place, a nonlinear regime in which permanent micro-structural changes take place in a stable manner i.e. micro-cracking in a uni-axial test under increased stress (strain hardening). In this range a certain permanent deformation is typically introduced (plastic deformation) however, not necessarily. If e.g. the micro-structural change is formation of frictionless micro-cracks the corresponding mechanical response would only show decreasing stiffness and virtually no permanent deformation. Finally, the generic response consists of a regime in which deformation localizes – in a uni-axial test under decreasing stress (tension or compression softening). This final softening part cannot be

Fax: +45 4588 3282
E-mail: hs@byg.dtu.dk

described using strain due to its localized nature but should be described using deformation over the localization zone, as shown in Fig. 1. In general the behaviour in tension and compression are different, however they both contain the same basic elements: linear reversible response, nonlinear irreversible response and deformation localization. The underlying mechanisms for reversible, irreversible and localized deformation can be very different in different materials as can their relative importance. In concrete and other cement based materials the underlying mechanism for permanent deformation is various types of micro-cracking (damage) while the underlying mechanism in metals is dislocation movements. In traditional concrete there is a significant difference between tension and compression (due to the specific damage mechanism observed) and in tension the hardening part is virtually non-existent. In fact, in tension even the softening part is so insignificant that for many years and even today this is ignored in practical design. The presence of a strain hardening regime in tension was elaborated on by Van Mier in [12] where also the similarity of the mechanical response to other materials like glass and metals was pointed out.

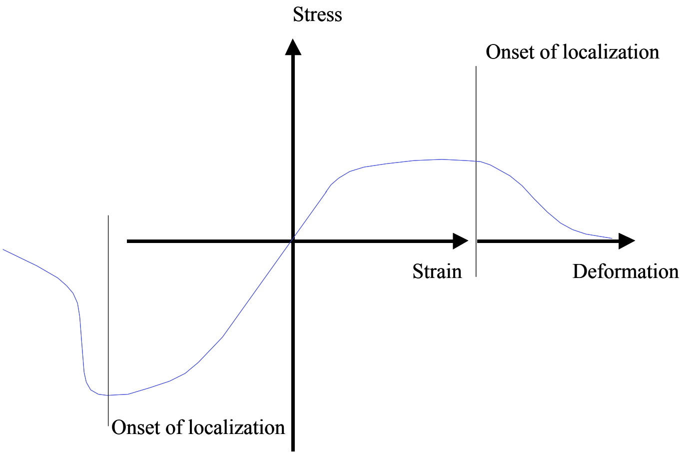

Fig. 1: Generic mechanical response under uni-axial stress.

When dealing with aspects of structural application of Fiber Reinforced Cementitious (FRC) materials it is important to realize that 3 situations can be achieved : 1) tension softening response is so significant that it can be allowed to be taken into account in structural design, 2) the strain hardening portion is significant enough that it can be taking into account in structural contexts, or 3) both the hardening and the softening regimes are significant enough to be taken into account in structural design. Even though it could be argued that the last situation covers the two first (indicating there is really no need for classification) as we will see the difference in structural behaviour is as significant that a classification is still relevant.

2.1 The classification in uni-axial tension

The classification suggested here is based on response in uni-axial tension only i.e. the compressive behaviour is not considered. Though seemingly limited this classification is based on the practical experience that the part of the mechanical response which can be engineered to a significant extend is the tensile part. In FRC materials the compressive part is modified by the presence of the fibers, but not fundamentally changed – i.e in most practical FRC materials – and in plain concrete as well – the compressive behaviour is characterized by some degree of strain hardening while the compression softening part is not taken into account in practical design. Attempts have been made to investigate the influence of compression softening on structural behaviour, e.g. [13] and standardized test methods have been proposed for its determination [14], however to the authors knowledge the field has not yet progressed to a degree where operational test and design methods taking compression strain hardening into account have been proposed.

Thus, the classification suggested here consists of two classes: *(tension) strain hardening FRC materials* and *tension softening materials.* The first is often denoted HPFRCC materials (High Performance Fiber Reinforced Cementitious Composites) – a term which is used synonymous with materials belonging to the (tension) strain hardening materials class in the present text. It should be stressed that the main rationale behind this classification is the behaviour observed on a structural level, see next section. Also it should be noted that there is a gradual transition between the two classes: a certain material exhibiting distinct hardening and softening behaviour might rightly be treated as a tension strain hardening material in certain structural applications (with relatively low requirements for strain capacity) while it should be treated as a tension softening material in other structural applications (where the strain capacity requirements are relatively high).

2.2 Implications for structural use

2.2.1 Tension softening materials

The fact that tension softening FRC materials by definition have a negligible hardening regime and a modified tension softening regime compared to plain concrete indicates that modified mechanical performance of FRC structures can be expected when comparing to plain concrete structures. In general, reduced crack opening and reduced crack spacing can be expected in structural FRC elements. However, the crack pattern as well as the crack openings remains a function of *material performance combined with structural design, including structural size.* Also, the load carrying capacity is increased, typically when structural elements are loaded in bending and where load re-distribution is made possible due to deformation capacity.

2.2.1.1 Bending and deflection hardening.

In the case of a tension softening material, a cross-sectional analysis of the cracked section of e.g. a beam, a pipe or a slab can be carried out describing the cracked section as a non-linear hinge.

The idea of the non-linear hinge model is to analyze separately the section of the structural element where the crack is formed and assume that the rest of the structure behaves in a linear elastic fashion. In order for the non-linear hinge to connect to the rest of the structure, the end faces of the non-linear hinge are assumed to remain plane and to be loaded with the generalized stresses in the element.

It is possible to obtain a closed form solution for the non-linear hinge when using a multi-linear or bi-linear stress crack-opening relationship in combination with the kinematic assumption that the boundaries of the non-linear hinge remain plane while the fictitious crack plane deformation is governed by the stress-crack opening relationship as well as the overall angular deformation of the non-linear hinge and the length of the fictitious crack.

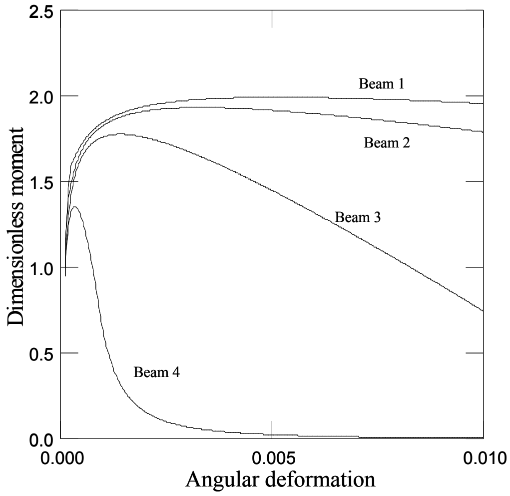

Fig 2. Moment curvature relationships for various beam cross sections with square cross section made from a tension softening material. Beam height ranges from 100 (beam 1) to 10000 mm (beam 4). It is seen how the so-called deflection hardening behaviour behave significantly on structural size. From [18].

In particular a solution for the moment-angular deformation relationship in the case of zero axial force and a bi-linear stress-crack opening relationship was presented in [15]. The complete solution for the bi-linear stress-crack opening relationship including a non-zero axial force can be found in [16].

It is characteristic that the ductility as well as the load carrying capacity are significantly influenced by the shape of the softening curve. A significant hardening behaviour in the moment-curvature response can be observed for certain material performance. This behaviour is sometimes referred to as deflection hardening [17]. It is characteristic, however, that this deflection hardening behaviour is a structural property, and thus depending on structural characteristics such as size, [18]. In Fig. 2. the moment-curvature behaviour of various size beam cross sections are shown for the same softening material.

2.2.1.2 Crack width limitation

One of the major practical applications of tension softening FRC materials is in industrial floor and slabs on grade where the softening response is used to control the temperature, shrinkage and load induced cracking in floors and slabs with various degree of restraint. Strain softening materials are used routinely today for this purpose and in [19] theoretical analysis and experimental verification was presented quantifying the influence of the softening response on the initial shrinkage and temperature initiated cracking of a slab on grade.

Much experimental evidence exists indicating that the softening response of FRC materials also limit crack width in combination with conventional reinforcement. In [20] a fracture mechanical approach was taken to describe the post-peak model for the tensile behavior of FRC: the post-peak stress is assumed to be at a constant level, defining the so-called toughness class of the FRC. Moreover, the interaction between the main reinforcement bars and the surrounding FRC material is taken to be a constant interfacial shear stress. These simplifying assumptions allowed for the development of closed form solutions for the description of the growth of bending cracks in main reinforced FRC beams with rectangular cross-section providing a rationale for the structural use of strain softening FRC for crack control in the serviceability limit state.

Recently, the applicability of tension softening FRC as stiffening and strengthening thin overlay on steel bridge decks has received significant attention, see e.g. [21] and [22]. It has been shown experimentally and through modelling that the softening regime of the FRC material behaviour has major influence on the overall behaviour of the structural composite system and that the maximum load carrying capacity is significantly increased. However, it is interesting to note that the load for which the first crack is formed is almost unchanged. Further it is found that the softening behaviour of the tension softening FRC plays a very limited role in preventing debonding at the FRC-steel plate interface where the FRC crack meets the steel. In order to prevent interface debonding, tension strain hardening materials have to be implemented [22]. See also below.

2.2.1.3 Load carrying capacity and safety

In general the load carrying capacity and deformation capacity of structural elements have been shown to increase, when FRC materials are implemented replacing plain concrete. Thus, potentially FRC has the ability to increase structural safety. To date, however, no design procedure is available taking such effects into account.

2.2.2 Tension strain hardening materials

The tensile strain hardening property of HPFRCC can be elevated to structural system performance through modifications of the behaviour at the structural member level. A variety of such behaviour modifications have been demonstrated over the last several years, and their implications to structural design are being increasingly clarified. In a number of circumstances, field demonstrations have been or are being conducted. In the paragraphs below, we attempt to summarize some of the important behaviour modifications arising from the tensile strain-hardening property, and indicate different structural application scenarios where such behaviours can be elevated to high structural performance. The response of structural members built with HPFRCC based on elastic-plastic material model and on multi-scale damage evolution model implemented in FEM has been successfully simulated, see e.g. [23-24].

2.2.2.1 Damage tolerant under severe loading

ECC has been shown to have high damage tolerance under at least three types of severe loading: cyclic loading, fatigue loading, and impact loading. The damage tolerance of a material refers to its capability to carry additional load even when loaded to beyond the elastic limit. This behaviour is valuable to the performance of a structure in terms of collapse resistance, extension of service life, and minimisation of repair after an extreme event.

The damage tolerant behaviour of ECC was recently summarized by Billington [25] in the context of seismic resistant performance of structures. The anti-spalling of ECC under compression loading, and the ability to close tensile cracks upon unloading was emphasized. As example, an infill ECC panel was observed to be 35% stronger and reach higher drift levels before losing strength than an identically reinforced concrete panel under the same cyclic load. In this and other investigations, sometimes conducted without shear reinforcements (e.g. [26-30]) the ability of ECC to withstand larger imposed load and drifts with significantly less damage compared to normal R/C were demonstrated. Similarly, impact tests based on high velocity projectiles on ECC prismatic panels [31] demonstrated enhanced structural protective performance such as increased shatter resistance with reduction of scabbing and spalling damage, and enhanced energy absorption ability. These performance enhancements are assumed to be directly derived from the tensile strain-hardening characteristics of ECC.

2.2.2.2 Compatible deformation with reinforcement

In conventional R/C, cracking of the concrete implies elastic unloading accompanied by a jump in load demand on the segment of the steel reinforcement crossing the crack. This leads to incompatible deformation between the concrete and the steel. In contrast, ECC maintains compatible deformation with the steel by continued load transfer through the fibres crossing the micro-cracks[32]. Thus commonly observed bond splitting, local re-bar yielding and buckling in R/C can be eliminated. An additional advantage of this phenomenon is that the segment of the steel rebar which undergoes plastic yielding can be extended, resulting in higher levels of plastic energy dissipation in the structural element [27-29]. The compatible deformation behaviour of R/ECC can be extended to FRP rebar. Under severe imposed deformation, the large elastic limit of the FRP rebar keeps the element in quasi-elastic behaviour with negligible permanent member deformation after unloading, while the strain-hardening behaviour of ECC prevents bond-splitting, and therefore protects the FRP from premature local buckling under the compression loading cycle [27-28]. In an experiment of a steel bridge deck stiffened by a layer of ECC [22], compatible deformation of the steel and the ECC under flexural loading was shown to prevent the formation of an interfacial shear crack typically observed in concrete or tension-softening FRC. In the latter case, a macroscopic tensile fracture occurred in the cementitious layer which immediately led to a fast propagating interfacial shear crack. In contrast, the strain-hardening behaviour of the ECC maintained the load continuity in the layer, thus protecting the integrity of the composite bridge deck.

2.2.2.3 Steel/concrete connection integrity

The strain-hardening behaviour of ECC has been utilized as a mechanism to redistribute concentrated loading and thus prevent sudden failure at a critical structural connection where steel and concrete come into contact. In many structural elements, steel and concrete may interact mechanically. This includes, e.g. connections such as shear studs, fasteners, or the joint where a steel beam meets an R/C column in a hybrid structure. The high stiffness and toughness of steel and the high brittleness of concrete typically results in a brittle fracture of the concrete leading to a failure of the connection. Tensile strain-hardening relaxes the high stress at the steel/ECC contact point and allow the load to be carried by a larger volume of material. This effect was demonstrated by Qian et al [33] in a shear stud connection.

2.2.2.4 Elimination of structural size effect

It is well known that concrete being a quasi-brittle material exhibits structural size effect. A ductile material which fully suppresses the fracture failure mode can eliminate size-effect associated with fracture failure. ECC flexural beams have been shown to exhibit no size effect in the size range of 0.175 m to 2.8 m span length [34]. The elimination of structural size effect implies that much larger structures can be built without additional strengthening measures (e.g. steel plates) to overcome size effect and allow larger structures previously considered uneconomical because of size effect to be built.

2.2.2.5 Accommodation of large imposed deformation

In many situations, failure of concrete structures are associated with large imposed deformation rather than high loads. This includes the broad class of repair situations where the repair material is restrained from movement, but undergoes autogenous and/or drying shrinkage. This results in restrained shrinkage cracking and therefore premature failure of the repair. The use of ECC for durable repair has been demonstrated recently on a patch repair of a bridge deck [35] and an earth retaining wall [36]. Another application which takes advantage of the large deformability of ECC is the development of ECC link-slab for replacing conventional joints on a bridge deck [37]. The basic concept is that the ECC link-slab will accommodate all imposed deformation, including those induced by live and environmental loads, thus serving the function of a joint in a continuous jointless bridge deck. Elimination of the convention joint is expected to significantly reduce the amount of maintenance needed for the bridge structure.

2.2.2.6 Structural durability

Li and Stang [10] suggested the elevation of material ductility to structural durability. This concept relies on two levels of protection of the structural element. The first level assumes relies on the tight crack width control of ECC (< 100 μm) which delays the penetration of aggressive agents from reaching the steel reinforcement. Hiraishi et al. [38] showed that the corrosion rate in a R/ECC beam is significantly lower than that of a reference R/C beam preloaded to the same level. The second level of protection afforded by ECC is the prevention of radial crack formation even if the steel rebar corrodes and expands. This anti-spall ability of ECC has been demonstrated in simulated experiments [10, 39].

3. Engineering representation and Test Methods

3.1 Engineering representation

For HPFRCC materials, it seems that an appropriate engineering representation of the tensile constitutive relationship would be an elastic perfectly plastic material model, with a strain cut-off. This model, while conservative, should make structural analysis relatively easy. Thus, HPFRCC materials are suggested characterized though a uni-axial stress-strain diagram as shown in Fig. 3. This characterization involves the following material characteristics: Young's modulus in the linear part, E, a perfectly plastic yield stress in tension, f_y^t, a perfectly plastic yield stress in compression, f_y^c, a limiting strain in tension, $\varepsilon_{\max}^t$ and a limiting strain in compression, $\varepsilon_{\max}^c$. In case the tension softening branch is relevant different representations can be used similar to what is suggested for tension softening materials.

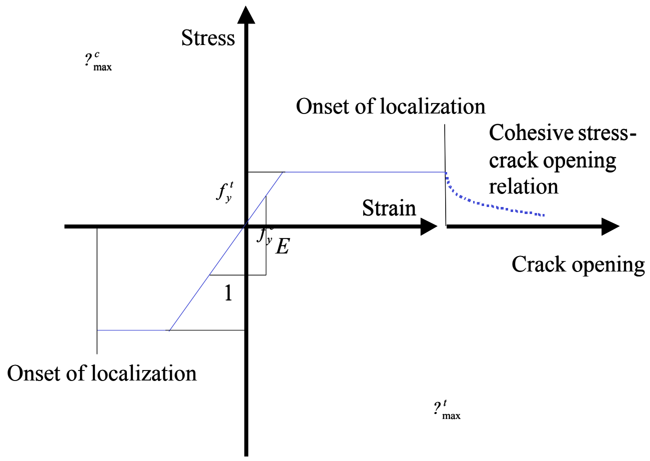

Fig. 3: The mechanical characterization of the tension strain hardening class of FRC materials based on behaviour under uni-axial stress. At the limiting tensile strain, strain localization sets in as indicated in the figure. If material characterization beyond this point is called for in the structural analysis one of the tension softening characterizations used for tension softening materials can be used, see Fig. 5.

Tension softening materials could be characterized by a uni-axial stress-strain diagram as shown in Fig. 4. This characterization involves the following material characteristics: Young's modulus in the linear part, E, a tensile strength indicating the onset of cohesive cracking, f_t, a perfectly plastic yield stress in compression, f_y^c, and a limiting strain in compression, $\varepsilon_{\max}^c$. Here the softening branch is always relevant. Due to the localized nature of the phenomenon, a fracture mechanical approach should be adopted. Here, the fracture mechanical concept of cohesive stress-crack opening relationships or the fictitious crack concept introduced by Hillerborg, [40], [41] is applied.

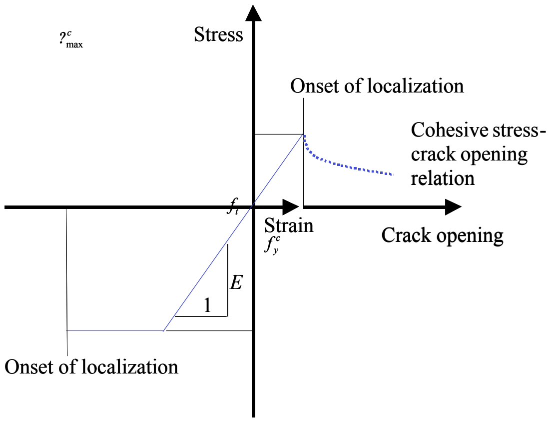

Figure 4: The mechanical characterization of the tension softening class of FRC materials based on behaviour under uni-axial stress. At the tensile strength, strain localization sets in as indicated in the figure. Material characterization beyond this point should be one of the tension softening characterizations shown in Fig. 5.

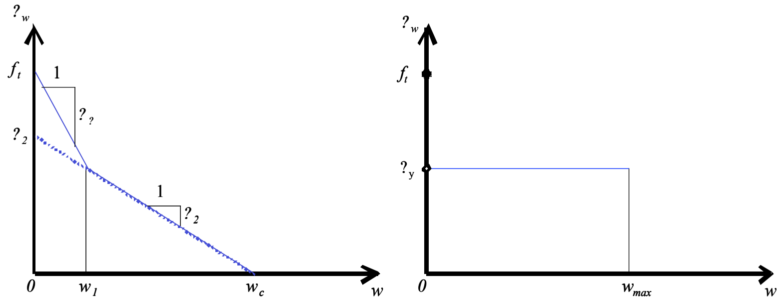

Figure 5: Two practical representations of the cohesive stress-crack opening relationship of either class of FRC material: the bi-linear representation (left) and the drop-constant relation (right). The representations follow the suggestions of RILEM TC 162 [8].

Two practical representations for the tension softening branch are suggested here: the bi-linear and the drop-constant representation, where the latter can be considered as a limiting case of the first case. The two representations are shown in Fig. 5. The representations introduce yet another set of material parameters, four in the case of the bilinear representation and 3 in the case of the drop-constant representation.

Even though from a materials research point of view these representations seem over-simplified, from a practical, structural design point of view the number of material parameters is at the limit: 5 material parameters in the case of tension strain hardening materials without considering softening (growing to 8 or 9 if softening is included) and 7 or 8 for tension softening materials depending of the representation used. Further, from a practical material specification and testing point of view the suggested representations are at the limit.

The tensile strain cut-off in tensile strain hardening materials can be due to either the mechanical strain capacity or it could be adopted based on durability considerations, or both. In HPFRCC, it is understood that micro-crack formation occurs in the non-linear range of the mechanical response. The width of these cracks may increase or remain constant with increasing tensile strain, depending on the specific HPFRCC material. A strain cut-off is used to limit the maximum crack width in the serviceability limit state, either as a result of accounting for material durability limitation and/or structural durability limitation. The specific relationship between tensile strain and crack width must be obtained from a uni-axial tension test, and the limiting crack width must be determined by the nature of the specific HPFRCC material and the service environment in which the material/structure is exposed to.

In the same way the maximum crack opening allowed in serviceability limit state and ultimate limit state analysis of structures made from tension softening materials can be based on durability or structural safety issues or both. The issue of durability is further taken up in Section 4 in this paper.

3.2 Test methods

3.2.1 Tension softening materials

In the case of a tension softening material, the challenges lie in determining the softening behaviour, which essentially is a fracture mechanical property. Thus fracture mechanical methods should be implemented and by now a range of various options are available depending on the degree of detailing necessary and the engineering representation, which is implemented in the structural analysis.

The uni-axial tensile test seems the most direct and logical way of determining the stress-crack opening relationship. Recently, RILEM technical committee TC 162-TDF, ‘Test and design methods for steel fibre reinforced concrete’ published a recommendation for uni-axial testing of SFRC with the aim of determining the stress-crack opening relationship directly [5]. The test relies on the assumption that it is possible to restrain rotation of the crack surfaces in order to make it possible to obtain more or less uniform crack opening over the whole specimen. This concept has been discussed at great length in the literature, but recent studies seem to confirm that the completely or sufficiently restrained uni-axial test specimen indeed does determine the stress-crack opening relationship correctly at least in the case of plain concrete [42].

RILEM technical committee TC162 proposes a 3 point bending test on a test specimen with a notch. The standard specimens proposed has a span l of 500 mm, a height h of 150 mm, a width, b, of 150 mm and a notch depth a_0 of 25 mm. The load P as well as the deflection δ is measured. Optionally, the Crack Mouth Opening Displacement, CMOD, can be measured at a distance d from the bottom of the beam [6]. Recently, it has been shown that it is possible to model the behaviour of a FRC beam with or without a notch with good results using a fracture mechanical approach. This can be done both using non-linear finite elements and an analytical approach introducing a non-linear hinge [15], where the crack is propagating, in an otherwise elastic beam. The approach is discussed at some length in a paper on structural analysis of FRC structures based on fracture mechanics from RILEM technical committee TC162 [7]. The analytical analysis can be based on analytical solutions for the non-linear hinge in terms of moment versus angular deformation relations. Closed form solutions are available for both the bi-linear as well as the drop-constant stress-crack opening relationship [43].

The existence of such relatively simple solutions for the beam test based on fracture mechanics obviously opens up for using the beam test for determination of the fracture mechanical properties, i.e. the stress-crack opening relationship. When detailed information about the stress-crack opening relationship is required a so-called back analysis is needed, because it is not possible based on knowledge of the beam response (load-deflection or load-CMOD) to solve directly for the underlying stress-crack opening relationship. Back analysis is based on a comparison between the observed response and the response calculated with a certain choice of stress-crack opening relationship. This comparison is quantified in terms of an error. The best choice of stress-crack opening relationship can now be determined by minimizing the error. Back analysis for the beam test has been studied extensively for concrete and SFRC. Standard algorithms now exist for inverse determination of the bi-linear stress-crack opening relationships for plain concrete as well as FRC [42, 44].

Recently, the use of the so-called wedge splitting test, see Fig.6 was investigated in detail for testing of tension softening FRC [44]. The wedge splitting test is very simple to conduct and puts only few requirements on the test equipment. Comparisons with 3 point bending tests using inverse analysis were carried out. Further, comparisons with uni-axial tensile tests were carried out. The results from the wedge splitting tests and the 3 point bending tests are in good agreement giving further confidence in the testing and

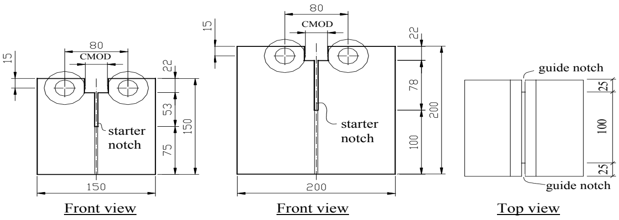

Fig. 6. Geometry of the wedge splitting test specimens used in [44].

inverse analysis approach. The uni-axial testing results diverge significantly from the two other tests primarily due to the different fibre distribution in these specimens.

In the case where the simple drop-constant stress-crack opening relationship has been applied, the expected beam response in terms of either a load-deformation or a load-CMOD relation can be calculated using the analytical model based on the non-linear hinge as outlined above. For a given test specimen geometry, this calculation can be based on the assumption of vanishing tensile strength and a certain value σ_y of the residual stress. Choosing different values for the residual stress, σ_y, a series of curves is produced which can be interpreted as a *verification chart*. Since the influence of the Young's modulus is very weak for practical purposes only a single verification chart is needed for each type of test specimen. The residual stress for a given material can then be determined by simple comparison with the relevant verification chart [2].

1.1.2 Tension strain hardening

There has been some discussion of test methods of HPFRCC materials, (see e.g. JCI Workshop 2002 Committee Report). However, world-wide consensus on a simple, robust and yet meaningful test method remains to be achieved. This is one of the objectives of a new reformulated committee under RILEM (RILEM TC HFC).

It may be useful to consider the specific needs and objectives of target users in developing widely accepted test methods. In general, we envision three groups of potential users. The first group belongs to those who need to conduct on-site quality control in a construction project, much like standard concrete cylinder tests. This group has the objective of verifying that given the execution method applied and on-location environmental conditions (mixing, casting, curing, wind and temperature conditions, etc.), that the HPFRCC material will achieve the mechanical property intended by the material specification for the job. While the material may be assumed to undergo strain hardening, the variability of tensile strength, Young's modulus, and strain capacity must be established and the averaged and standard deviation values recorded. Quality control may involve a large number of sampling in field conditions precluding complicated testing. For these reasons, a simple bending test, with the test curve interpreted for the true tensile stress-strain curve, or at least matching a minimum material class-category, may be suitable.

Another group of potential users of test methods will be material suppliers, including suppliers of fibres and/or pre-packaged material used in making HPFRCC. The objective of this group is to establish the performance of their product, typically in the form of "spec sheets". It seems reasonable to expect this group to have the responsibility and capability of conducting more sophisticated type of testing which can distinguish between a strain-hardening HPFRCC from a tension-softening FRC. It is incumbent for this group to conduct uni-axial tension test for material characterization of HPFRCC.

The last group of potential users of test methods will be researchers. The objective of this group may include the investigation of composite design approaches in achieving strain-hardening behaviour. The goal may be to engineer material microstructures for optimal composite performance. Standardized uni-axial tension test will allow meaningful comparisons of materials or design approaches from different research groups.

From the above, it seems that two types of test emerges – bending test for use in on-site quality control, and uni-axial tension test for material suppliers and researchers.

Four point bending test, in which the mid-span of the specimen undergoes constant bending moment, may be carried out to determine the moment-curvature and/or moment-deflection curves. This type of test is relatively easier to set up and conduct in comparison to uni-axial tension test, and a large amount of experience in bending test has been accumulated in the user community of cementitious materials. The objective of this test for HPFRCC is to use the moment-curvature or the moment-deflection curves so determined to invert for the uni-axial tensile stress-strain curve. This requires a relatively simple material model and a structural analysis technique for the flexural beam. JCI [45] suggested a simplied elastic-perfectly plastic model with a "first crack yield strength" and a tensile strain capacity as the two material parameters as the material model, and a sectional analysis similar to that suggested by [46] to relate the distributed sectional stress and strain to the moment-curvature relationship. The matching of the inverted stress-strain curve from the bending test data [45] demonstrated the viability of this inversion process. Additional work on developing engineering chart(s) to further simplify the inversion process may be useful to make the bending test widely accepted.

It should be emphasized that for the bending test to be meaningful in the present context, it has been assumed that the material will undergo strain-hardening under uni-axial tension, so that the bending test is mainly adopted to constrain the tensile material parameters (such as the "first crack yield strength" and the tensile strain) as part of the quality control process in the field. The bending test is NOT meant to determine whether the material has tensile strain-hardening behaviour or tension-softening behaviour.

Uni-axial tension test, while simple in concept, requires attention to many test details. Amongst these are specimen alignment, and post-crack stability. The latter concern makes testing of concrete or tension-softening FRC particularly challenging, and a variety of methods of stiffening the machine and load-trains have been proposed. However, and at least in this respect, the use of uni-axial tension test for characterizing the properties of HPFRCC is much easier, since these materials do not unload after first cracking, but rather strain-hardens. As a result, no sudden release of energy, and no loss of stability, occurs during the strain-hardening stage up to peak load.

In the previous section, the proper characterization of HPFRCC is discussed. During the inelastic stage characterized simply as pseudo-plasticity, micro-cracks accumulate as inelastic damage spread over a volume of material. Proper testing, therefore, requires that the strain gage be long enough compared with the spacing between adjacent micro-cracks. The "strain" measured would then be interpreted as the smeared and averaged elongation over the gage length. Thus, a minimum requirement for proper strain-measurement in HPFRCC property characterization would be a gage length at least several (say, five times) the averaged crack spacing between adjacent micro-cracks. Otherwise, the measured stress-strain curve will not be representative of the material behaviour. Indeed, if this requirement were not met, it would be doubtful whether the material qualifies as a HPFRCC or is simply a regular FRC. For this reason, it is proposed that the crack pattern should be recorded during testing. At the least, the crack pattern and crack spacing at or beyond peak load, and the gage length used, should be reported in uni-axial tension test of HPFRCC. A special treatment of crack pattern through image analysis has been proposed by Fischer [47].

For ensuring material and structural durability, it is desirable that only a portion of the stress-strain curve be allowed for use in structural design. The cut-off strain value should correspond to an averaged crack width that ensures durability. The relationship between durability and crack width in HPFRCC is a subject urgently requiring research efforts.

To summarize, uni-axial tension test appears to be the most appropriate method of material characterization of HPFRCC, at least for researchers and material suppliers. For the uni-axial stress-strain curve to be valid and useful for structural design, it is recommended that at least the following information be included in a test report:

a. Complete stress-strain curve
b. Crack pattern and crack spacing at or beyond peak load, and gage length
c. Crack opening (averaged over several cracks) during strain-hardening

Because of potential loading rate sensitivity, it is also recommended that the loading rate applied be reported as is commonly done. In addition, the specimen size must be large enough in relation to the fibre length to ensure random orientation of the fibres. The loading boundary condition (pin or fixed) may also have an influence on the material properties measured. These and other considerations are being taken up by committees on standardized testing of HPFRCC set up by professional societies (e.g. JCI DFRCC, RILEM TC HFC).

4. Durability

In a recent European research project [48] the durability of steel fibre reinforced concrete (tension softening type) was investigated. Wedge splitting tests were carried out opening the crack to certain crack widths. At this point the crack opening was fixed and the specimen un-loaded. Subsequently, the specimens were exposed to various types of environmental conditions including outside exposure; alternatively drying and wetting for one week in lab environment; wetting in demineralised or chloride water and drying in CO2 environment. Reference testing was done after 6, 12 and 18 months. To assess the mechanical behaviour, the wedge splitting test were reloaded and the deformation and load carrying capacity compared with the specimen response at first cracking.

This type of testing addresses the fundamental issue of aging of the mechanical properties with time under various environmental conditions particularly the fact that one can expect the aging effect on properties closely related to the presence of fibres to be more significant when the fibres crossing the cracks are directly exposed to the environment. Since as already mentioned it is expected that both tension softening as well as strain hardening materials will be serving in the cracked state it is necessary that exposure tests on pre-cracked specimens be carried out with subsequent determination of the properties of the aged material in order to determine the mechanical response that can be taken into account in various environments. It is by no means a simple task to work out the associated testing specifications, however it is essential that it is done in order to place confidence in the attractive mechanical performance of FRC materials for long term use. It is particularly important considering the fact that the use of these materials potentially represents considerable durability improvement over regular concrete [11].

5. Conclusions and Directions for Future Work

In order for FRC materials to be applied on a regular basis in structures a framework for material models identifying key material parameters needs to be established. Such key material parameters will help the structural designer as well as material suppliers and contractors communicate on a rational basis. It is argued – based on structural performance – to distinguish between two fundamentally different FRC materials: tension softening and (tension) strain hardening or HPFRCC. Through the work of RILEM TC-162 a consistent proposal has been made in this respect for tension softening materials, however there is a strong need to establish a similar consistent framework for strain hardening materials. A simple framework for such materials has been suggested here. It is imagined that such frameworks are supplemented with information about e.g. unloading, fatigue, creep or relaxation and durability.

With the identification of key material parameters naturally follows the need for testing methods. It is advantageous to divide testing methods into at least two categories one related to simple verification of anticipated material parameters and one related to more detailed investigations of material behaviour for the purpose of clarifying the validity of underlying assumptions. Other test methods might relate to application specific properties. For tension softening materials there is growing consensus to apply the 3-point, notched bending test specimen suggested by RILEM, TC-162. Resent work has shown that it is possible both to perform an inverse analysis of such specimens and to use the specimen for simple verification. Similar work has also shown that the wedge splitting test can be used in a similar manner. There is a strong need to establish consensus in regards to test specimens and interpretation methods to be applied in conjunction with HPFRCC materials.

Since it is anticipated that both types of FRC materials to a certain extend will serve in the cracked state during service, and since fibre related aging (or durability) effects potentially are more significant at the cracks where the fibres are directly exposed, it is essential that durability issues are investigated on preferably loaded or at least pre-cracked specimens.

References

1. Stang H. and Li, V.C., “Bridging – Physical and Mechanical Aspects,” DCAMM – Højgaard foundation Summer School Mechanics of Fiber Reinforced Cement Based Composites, DTU, August, 2001.

2. Stang H. Toughness in Testing and Design, the FRC Experience. In: ‘Fracture Mechanics of Concrete Strcutures, Vol. 1’. (eds.) Victor C. Li, C.K.Y. Leung, K.J. Willam, S.L. Billington. Ia-FraMCos 2004, pp. 61-69.

3. Stang, H. ‘Evaluation of properties of cementitious fiber composite materials’, in High Performance Fiber Reinforced Cement Composites, Vol. 1. (eds) H.W. Reinhardt and A.E. Naaman. E & FN Spon, London, 1992. pp. 388–406.

4. Li, V.C., "On Engineered Cementitious Composites (ECC) – A Review of the Material and its Applications," *J. Advanced Concrete Technology*, Vol. 1, No. 3, (2003), pp.215-230.

5. Swedish Concrete Association 'Steel Fibre Reinforced Concrete – Recommendations for construction, execution and testing. Concrete Report no. 4. Swedish Concrete Association, 1995

6. RILEM TC TDF-162 'Test and design methods for steel fiber reinforced concrete. Recommendations for uni-axial tension test' *Materials and Structures*, 34 Jan-Feb (2001), pp. 3-6.

7. RILEM TC TDF-162 'Test and design methods for steel fiber reinforced concrete. Bending test – Final Recommendation' *Materials and Structures*, 35, Nov 2002, pp. 579-582.

8. RILEM TC TDF-162 'Test and design methods for steel fiber reinforced concrete. σ-ε Design Method.' *Materials and Structures*, 33(March 2000), pp. 75-81.

9. RILEM TC TDF-162 'Design of steel fibre reinforced concrete using the σ–w method – principles and applications' *Materials and Structures*, 35 June 2002, pp. 262-278.

10. AFGC - Association Francaise de Genie Civil 'Ultra High Performance Fibre-Reinforced Concretes. Interim Recommendations' AFGC, January 2002.

11. Li, V.C. and Stang, H. "Elevating FRC Material Ductility to Infrastructure Durability" To appear in proceedings of BEFIB 2004, Varenna, Italy Sep. 20-2, 2004.

12. van Mier, J.G.M. "Reality behind fictitious cracks?". In: Fracture Mechanics of Concrete Structures, Vol. 1. (eds) Victor C. Li, C.K.Y. Leung, K.J. Willam, S.L. Billington). Ia-FraMCos, 2004, pp. 11-30.

13. Markeset, G. "Failure of Concrete under Compressive Strain Gradients". Ph.D. Thesis, Department of Structural Engineering, The Norwegian Institute of Technology, 1993:110.

14. an Mier, J. and van Vliet, M.R.A.,'Experimental investigation of concrete fracture under uniaxial compression', *Mechanics of Cohesive-Frictional Materials*, 1(1996), pp. 115-127.

15. H. Stang and J. F. Olesen. On the interpretation of bending tests on FRC-materials. In H. Mihashi and K. Rokugo, editors, Fracture Mechanics of Concrete Structures,

Proceedings FRAMCOS-3, volume 1, pages 511-520, D-79104 Freiburg, Germany, 1998. Aedificatio Publishers.

16. J. F. Olesen. Fictitious crack propagation in fiber-reinforced concrete beams. *Journal of Engineering Mechanics,* 127(3):272-280, March 2001.

17. Naaman, A.E. and Reinhardt, H.W., ‘Setting the Stage: Toward Performance Based Classification of FRC Composites’, In ‘High Performance Fiber Reinforced Cement Composites (HPFRCC4). Proceedings of the Fourth International RILEM Workshop’. (eds.) A.E. Naaman and H.W. Reinhardt. Rilem Publications S.A.R.L. 2003, 1-4.

18. Stang, H., ‘Scale Effects in FRC and HPFRCC Structural Elements’, , In ‘High Performance Fiber Reinforced Cement Composites (HPFRCC4). Proceedings of the Fourth International RILEM Workshop’. (eds.) A.E. Naaman and H.W. Reinhardt. Rilem Publications S.A.R.L. 2003, 245-258.

19. Olesen, J.F. and Stang, H., ‘Designing FRC Slabs on Grade for Temperature and Shrinkage Induced Cracks’, In ‘Fibre-Reinforced Concretes (FRC) BEFIB’ 2000’, (eds.) P. Rossi and G. Chanvillard. Rilem Publications S.A.R.L. 2003, 337-346.

20. Olesen, J.F., ‘Cracks in reinforced FRC beams subject to bending and axial load’, In: ‘Proceedings of The Fourth International Conference on Fracture Mechanics of Concrete and Concrete Structures, Cachan, France’, (eds.) de Borst et al., Swets & Zeitlinger, Lisse, 2001, 1027-1033.

21. Walter, R., Stang, H., Olesen, J.F., Gimsing, N.J., ‘Debonding of FRC Composite Bridge Deck Overlay’, In ‘Brittle Matrix Composites 7’, (eds.) A.M. Brandt, V.C. Li and I.H. Marshall, Woodhead Publishing Limited, 2003, 191-200.

22. Walter, R. Li, V.C., Stang, H., ’Comparison of FRC and ECC in a Composite Bridge Deck’, To be presented at: 5th International PhD Symposium in Civil Engineering, 16-19 June 2004, Delft, The Netherlands

23. Kabele, P., ‘Linking scales in modeling of fracture in high performance fiber reinforced cementitious composites’, in: ‘Fracture Mechanics of Concrete Structures, Proc. of Framcos-5’, Eds. Li et al., IaFraMCos 2004, 71-80.

24. Kabele, P., ‘Assessment of Structural Performance of Engineered Cementitious Composites by Computer Simulation’, Thesis (Habilitation). (CTU in Prague).

25. Billington, S., "Damage-Tolerant Cement-Based Materials for Performance-Based Earthquake Engineering Design: Research Needs." Proc., FRAMCOS-5, Vail, Colorado, (eds. V.C. Li et al.), IaFraMCos 2004, 53-60.

26. Parra-Montesinos, G., and Wight, J. K. 'Seismic Response of Exterior RC Column-to-Steel Beam Connections,' *ASCE Journal of Structural Engineering*, Vol. 126, No. 10, 2000, 1113-1121.

27. Fischer, G., and V.C. Li, 'Intrinsic Response Control of Moment Resisting Frames Utilizing Advanced Composite Materials and Structural Elements', *ACI Structural J.*, Vol. 100, 2, (2003) 166-176.

28. Fischer, G., and V.C. Li, "Deformation Behavior of Fiber-Reinforced Polymer Reinforced Engineered Cementitious Composite (ECC) Flexural Members under Reversed Cyclic Loading Conditions," *ACI Structural J.*, Vol. 100, 1, (2203), 25-35.

29. Fukuyama, H., Y. Sato, V. C. Li, Y. Matsuzaki, and H. Mihashi, "Ductile Engineered Cementitious Composite Elements for Seismic Structural Applications," CD Proceedings of the 12 WCEE, Paper 1672, 2000.

30. Kanda, T., Watanabe S. and Li, V. C. "Application of Pseudo Strain Hardening Cementitious Composites to Shear Resistant Structural Elements", in Fracture Mechanics of Concrete Structures, Proceedings FRAMCOS-3, AEDIFICATIO Publishers, D-79104 Freiburg, Germany, Oct., 1998, 1477-1490.

31. Maalej, M., J. Zhang, S. T. Quek, and S. C. Lee, "High-Velocity Impact Resistance of Hybrid-Fiber Engineered Cementitious Composites," Proc., FRAMCOS-5, Vail, Colorado, (eds. V.C. Li et al.), IaFraMCos 2004, 1051-1058.

32. Fischer, G., and V.C. Li, "Influence of Matrix Ductility on the Tension-Stiffening Behavior of Steel Reinforced Engineered Cementitious Composites (ECC)," *ACI Structural J.*, Vol. 99, No. 1, (2002), 104-111.

33. Qian, S., Y.Y. Kim, and V.C. Li, "Influence of Concrete Material Ductility on the Behavior of Stud Shear Connection," in Proc., FRAMCOS-5, Vail, Colorado, Eds. V.C. Li et al, IaFraMCos 2004, 1045-1050.

34. Lepech, M., and V.C. Li, "Size Effect in ECC Structural Members in Flexure," in Proc., FRAMCOS-5, Colorado, Eds. V.C. Li et al, pp. 1059-1066, 2004.

35. Li, V.C., "High Performance Fiber Reinforced Cementitious Composites as Durable Material for Concrete Structure Repair," in Proc. of ICFRC Int'l Conference on Fiber Composites, High Performance Concretes, and Smart

Materials, Ed. By V.S. Parameswaran, Pub. Allied Publishers Private Limited, New Delhi, India, pp. 57-74, 2004.

36. Rokugo, K., Kanda, T., Morii, N., Iwata, T., Taki, K., Fujimoto, Y., Nagase, T., Takagi, K., Kunieda M., and Lim, S.C., "Field trial on concrete retaining wall repaired by ECC-patching and performance evaluation through tensile tests of modeled specimens," in Proc. JCI DFRCC Domestic Workshop, Tokyo, Japan, 133-140, 2003 (in Japanese).

37. Kim, Y.Y., Fischer, G., and V.C. Li, "Performance of Bridge Deck Link Slabs Designed with Ductile ECC," Accepted for publication in *ACI Structural J.*, Feb., 2004.

38. Hiraishi, Y., Honma, T., Hakoyama, M., Miyazato, S., "Steel corrosion at bending cracks in ductile fiber reinforced cementitious composites," Proc. of the JCI Symposium on Ductile Fiber Reinforced Cementitious Composites (DFRCC), Tokyo, Japan, 2003 (In Japanese).

39. Kanda, T., Saito T., and Sakata, N., "Tensile and anti-spalling properties of direct sprayed ECC," *J. of Advanced Concrete Technology*, 1(3) (2003), 269-282.

40. Hillerborg, A., Modeer, M., and Petersson, P.E. 'Analysis of Crack Formation and Crack Growth in Concrete by Means of Fracture Mechanics and Finite Elements', *Cem. & Concrete Res*. 6(1976), 773-782.

41. Hillerborg, A., 'Analysis of Fracture by Means of the Fictitious Crack Model, Particularly for Fibre Reinforced Concrete', *The Int. J. Cem. Comp*. 2(1980), pp. 177-184.

42. Østergaard, L. 'Early-Age Fracture Mechanics and Cracking of Concrete – Experiments and Modelling'. Ph.D. Thesis, (BYG•DTU Department of Civil Engineering, Technical University of Denmark. 2003).

43. Olesen, J.F. 'Fictitious crack propagation in fiber-reinforced concrete beams'. *Journal of Eng. Mech.* 127(3): pp. 272-280, 2001.

44. Löfgren, I. Stang, H., Olesen, J.F., 'Wedge Splitting Test – A Test to Determine Fracture Properties of FRC', To appear in proceedings of BEFIB 2004, Varenna, Italy Sep. 20-2, 2004.

45. T. Kanakubo, K. Shimizu, M. Katagiri, T. Kanda, H. Fukuyama and K. Rokugo, 'Evaluation of Tensile Properties for DFRCC -Results of Round Robin Test by JCI Technical Committee', In: 'Proceedings of JCI Symposium on Dutile Fiber Reinforced Cementitious Composites', pp.101-111, 2003.12 (in Japanese)

46. Maalej, M., and Li, V.C., ‘Flexural/Tensile Strength Ratio in Engineered Cementitious Composites’, ASCE J. of *Materials in Civil Engineering*, 6(1994), No. 4, pp. 513-528.

47. Fischer, G., ‘Characterization of Fiber-Reinforced Cement Composites by their Tensile Stress-Strain Behavior and Quantification of Crack Formation’, To appear in proceedings of BEFIB 2004, Varenna, Italy Sep. 20-2, 2004.

48. Lambrechts, A., Nemegeer, D., Vanbrabant, J. and Stang, H., ‘Durability of Steel Fibre Reinforced Concrete’, Paper presented at 6th CANMET/ACI conference in Thessaloniki, 2003.