

Fracture mechanics of concrete: will applications start to emerge?

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Fracture mechanics of concrete has developed into an active field of research in the past decades. It promises a rational solution technique to structural problems in reinforced concrete in the limit state. Numerical tools have been developed on the basis of fracture mechanics theories. The question to be addressed is how much of the early promise, i.e. the promise of a powerful rational numerical tool having predictive capabilities, has come true, and whether additional research is needed in order to further extend the range of applicability of the new tools. Essential for new applications, both at the structural and the materials engineering level seems a combined experimental and numerical approach. Both experimentation and numerical simulation have grown to a level where highly advanced techniques are applied, often too complex and of a scope too wide to be comprehended by a single researcher. Structural engineering applications of fracture mechanics must be sought in problems where the concrete reaches its limit state, and where knowledge of softening becomes eminent. Examples are the minimum reinforcement ratio in reinforced concrete structures, or structural details like anchor pull-out. Other recent developments point towards applications at the material level, where numerical models at the meso-level (particle level) of the concrete are used to develop materials for specific structural applications. At best numerical analyses and testing should be carried out in close cooperation. A meaningful development seems one where the softening response of the material (for example by adding fibres to increase the ductility) is optimised in conjunction with new structural applications. The development of a SIFCON truss systems is a recent example.

Keywords: fracture mechanics, concrete, SIFCON, 3-level approach, fracture energy, meso-modelling, numerical materials science, applications.

Introduction

Fracture mechanics of concrete has developed into an active area of research. The theoretical and experimental challenges are enormous, but the question is whether all these developments lead to useful applications in engineering. After some first trials in the 1960s to apply conventional linear elastic fracture mechanics to plain concrete by, for example, Kaplan (1960), the field has rapidly developed, in particular after the introduction of the Fictitious Crack Model by Hillerborg and co-workers (1976). Where linear elastic fracture mechanics predicts that a crack is immediately stress free up to the crack tip, the non-linear model developed by Hillerborg assumed that a non-linear zone advanced in front of the stress-free crack. In this so-called process-zone stress could still be

transferred, and the best way to estimate the amount of stress transfer was through a uniaxial tensile experiment. In such a test, when it is carried out in stable displacement control, a descending branch or softening branch is measured after a maximum stress has been reached. The softening zone would exactly match the stress transfer over the process zone. Much efforts have been made worldwide to establish the shape of the softening branch in uniaxial tension tests, or in alternative experiments like a displacement controlled three point bend test. In the Stevin Laboratory these initial efforts date back to Reinhardt (1984), but since then many others have addressed these matters, e.g. Van Mier (1986), Hordijk (1991), Van Mier & Nooru-Mohamed (1992), Schlangen & Van Mier (1992) and others. The different approaches have led to an improved fundamental insight in the fracture process of concrete under mode I, but also under combined tensile and shear loadings, e.g. Nooru-Mohamed et al. (1993). Thorough experimentation, not only in the Stevin Laboratory, but also at other laboratories (e.g. Elices et al. (1992)), has shown that a direct and unbiased determination of the softening parameters is a difficult and tedious task. The main task concentrates on separating material parameters from structural effects that inadvertently occur in the softening regime, when the size of the cracks increases and is of the same order of magnitude as the characteristic size of the structure. Thus, size and boundary condition effects become an essential part of the experimental result. One way of addressing these matters seems to apply the so-called 3-level approach to concrete fracture. Behaviour at the macro-level is explained at a lower dimensional level, i.e. the level where the individual aggregates are assumed to be embedded into a uniform cement matrix. In such an approach the aggregates, the matrix and the bond-zone are modelled as a homogeneous continuum. Of course, one might continue to descend the dimensional staircase one level lower, and indeed, consider the structure of cement, which seems particularly of interest when the bond between matrix and aggregate is studied. Using fast digital computers, the meso-level behaviour of concrete can be modelled quite realistically. However, similar as for the macro-level models disagreement exists about the parameters that should be used in the various models. For example, in order to obtain mesh insensitive results, it seems that higher order continuum models should be adopted. However, such models require new model parameters that can only be determined in an inverse way, i.e. they cannot be measured directly in experiments, and more seriously, a sound physical basis is lacking. For simple mode I (uniaxial tension, or opening mode) the problem can be solved, but somehow, the higher order models are not capable of simulating curved crack growth, e.g. Pamin & De Borst (1995). Curved crack growth can however conveniently be simulated using meso-level fracture models based on the lattice technique. The question is, where is space left for applications ? Is the hodgepodge of models, each having their own virtues and deficiencies, not an extreme obstacle for deriving sound and sensible applications ? These questions are addressed in this paper. After presenting the three-level approach to concrete fracture, we will give an overview of parameters needed in the different models of increasing complexity. It will be tried to separate material parameters from model parameters, and to indicate where structural effects blur the direct determination of the material parameters. At the macro-level all efforts point to an experimental set-up where a lower bound for tensile strength and fracture energy can be determined. It seems that the knowledge has advanced to a stage where a standard experiment for the determination of these fracture parameters can be proposed. Crucial in the development of a better understanding of the macroscopic fracture parameters has been meso-level modelling of concrete fracture using a simple but effective lattice model. This development has now led us to propose that

the same numerical technique can be applied – in conjunction with experimentation – to the development of new structural composites. Some issues regarding materials engineering will be addressed in the last part of the paper.

Three-level approach to concrete fracture

The three-level approach, which is commonly used in materials science, was first introduced to fracture of concrete-like materials by Wittmann (1983). Three levels of observations and modelling are distinguished as shown schematically in Figure 1. The levels are the micro-, meso- and macro-level. At each subsequent level more or less detail is recognised in the material structure of the concrete. The most global approach to modelling is the macro-level, where the material is considered as an equivalent isotropic continuum. No material structure is distinguished, and all non-linear behaviour is included in the constitutive law. The advantage from a numerical point of view seems that the structure that is analyzed can be divided in a relatively small number of large finite elements. This tends to reduce the computational effort. Note however, that results from finite element analyses are generally mesh dependent, except when higher order continuum theories are used. Such models lead to new complications that will be mentioned furtheron in this paper.

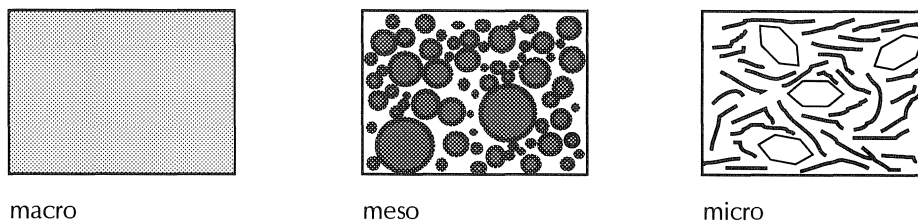


Fig. 1. Concrete material structure: macro-, meso- and micro-level.

The second level of observation is the meso-level. At this scale, 10^{-3} to 10^{-2} m, individual aggregate particles in the concrete are distinguished. The particles are assumed to be embedded in a matrix of cement mortar, i.e. a mixture of cement and fine sand particles. The grading of the sand and aggregates is generally selected such that a dense particle skeleton is obtained. The particles are bonded together through very thin layers of cement. At the macro-level, the response of the concrete under mechanical load can be explained and computed from interactions of the aggregate particles and the cement matrix at the meso-level. The interfacial transition zone plays a major role as it is generally weaker than both the matrix and the aggregate particles. In a meso-level model, the aggregate, matrix and bond zones are represented by a isotropic continuum.

The behaviour of the cement-matrix and the interfacial zone between the aggregates and the cement-matrix can be explained by considering the material structure at the level of the individual Calcium-Silicate-Hydrates (CSH). These particles are rolled up plates of nanometre to micrometre

scale, bonded together through VanderWaals forces. Water between the particles plays an important role, in particular in relation to strength, creep and shrinkage. Of course, the meso-level behaviour of the aggregative material should be studied at the micro-level as well. In general the aggregates consist of heterogeneous rock.

It will be obvious that the structural behaviour at each of these levels requires different types of input parameters. Always it has to be decided at which dimensional level the material is considered to behave as a continuum. For the macro-level model this is done at the level of the structure that is analyzed. In the meso-models, the particles, matrix and bond zones are considered as continuum materials. In the micro-models, the individual cement particles are assumed to be homogeneous and are represented by a continuum. In reality of course, one could further descend the dimensional staircase, and find heterogeneities that contradict the continuum assumption at every level of schematization. In the remainder of this paper we will limit the discussion to meso-level and macro-level modelling only.

Fracture mechanics modelling at the macro-level

In Figure 2a, the softening diagram commonly employed in macro-models of concrete fracture is shown. The behaviour measured from uniaxial tensile tests is depicted. After a more or less linear ascending branch, a slight curvature is measured just before the peak. Beyond the peak, a strongly non-linear descending branch is found. The main characteristics of this descending branch are the steep stress drop just beyond peak, and the long tail. Note that E^* is not the true Young's modulus because a deformation has been plotted along the x -axis. Because of localization in the post-peak regime, a stress-deformation diagram is used in stead of a relation in terms of stress and strain. In the pre-peak regime however, still a stress-strain diagram is used. The physics of the post-peak fracture process can be understood when using meso-level models, and by performing detailed crack detection experiments. During the steep part of the falling branch, a macro-crack traverses the specimens cross-section from one side to the other. The main crack branches are discontinuous, and at the point of overlaps stress can still be transferred. This latter mechanism, often referred to as crack face bridging explains the long tail of the softening diagram, see Van Mier (1991).

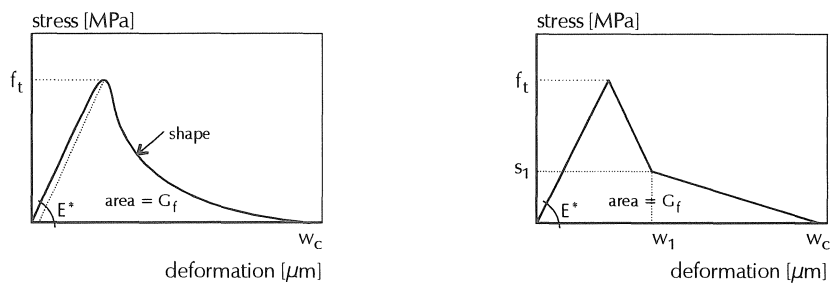


Fig. 2. Stress-deformation diagram from uniaxial tensile tests on concrete (a), and multi-linear representation for computational convenience (b).

For numerical analysis of reinforced concrete structures, preferably, the complete diagram should be known. However, as very clearly pointed out by Elices & Planas (1995), the simplest type of

fracture mechanics analysis requires knowledge of the peak (tensile) strength from experiments on at least two different specimen geometries only. The simplest way of course is to use the same global geometry, and to perform experiments on specimens with different notch depth. A much improved analysis can already be carried out when two parameters of the softening diagram are known, i.e. the peak strength and the first steep part of the tail of the softening diagram. In the most advanced analyses, the complete diagram has to be known, and of course a representative experiment must be carried out. In such analyses, the curvi-linear diagram is often replaced by a multi-linear diagram, for example the variant of Figure 2b. Most researchers would now agree that the steep part of the diagram just beyond peak is most important. The tail part of the curve has a much less significant effect on the behaviour. A simple example of an analysis with a linear softening diagram suffices. This diagram contains two of the most important parameters, namely the peak tensile strength and the first steep branch of the softening relation. In Figure 3, an example is shown of a macro-level analysis of a tooth structure of a beam used for the construction of the Rotterdam metro. Increasing the slope of the softening diagram has a significant effect on the rate of crack growth. The result computed using the diagram with the steepest slope showed the best resemblance to the experimentally observed crack growth. Details in the overall load-deflection diagram of the metro-beam analysis are then still not correctly “predicted”, but this can be explained from neglecting the tail of the softening diagram.

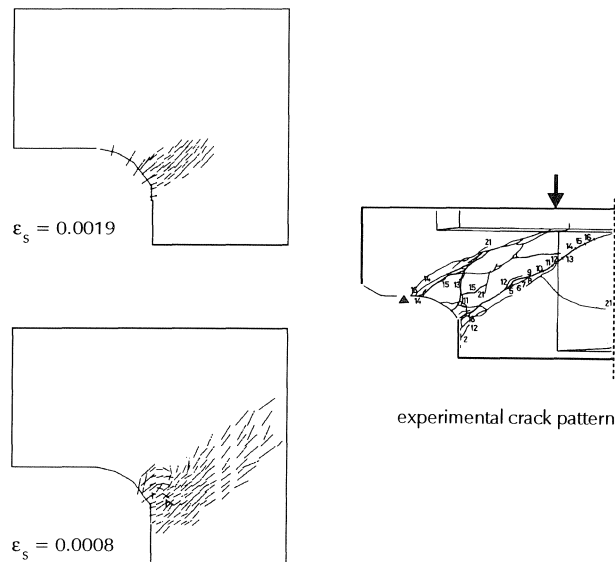


Fig. 3 Analysis of the tooth structure of a beam for the Rotterdam metro. A comparison between experimental and numerical analysis is shown, in particular the fracture patterns at load step 12 ($P = 2092 \text{ kN}$). The difference in crack growth in the analyses is caused by differences in maximum crack-opening in the crack band model used, after Van Mier ed. (1987).

Experimental and numerical difficulties with macroscopic softening

The principle explained in the previous section seems quite simple and straightforward. However, the experiments are far from simple. The softening diagram is found to depend on the size of the structure, Carpinteri & Ferro (1992), but also on the boundary conditions adopted in the tensile experiment, Van Mier et al. (1994). In a series of carefully conducted uniaxial tensile tests on specimens with varying size, Carpinteri & Ferro (1992) showed that the tensile strength decreases with increasing specimen size. However, the fracture energy G_f , defined as the area under the stress-crack opening diagram of Figure 2a, was shown to increase with increasing size. Such observations form the basis for (empirical) size effects laws, e.g. Bažant (1984) and Carpinteri et al. (1995). Because of the empirical nature of such “laws”, extrapolation outside the range of experimental observations is simply impossible. Next to the size effect, the fracture energy and tensile strength depend on the boundary conditions adopted in the experiment. Van Mier et al. (1994) showed through analyses with a lattice model, and through a series of uniaxial tensile experiments between parallel travelling loading platen or between freely rotating loading platen that the fracture energy could decrease by as much as 40% for the latter boundary condition. Figure 4 shows the difference

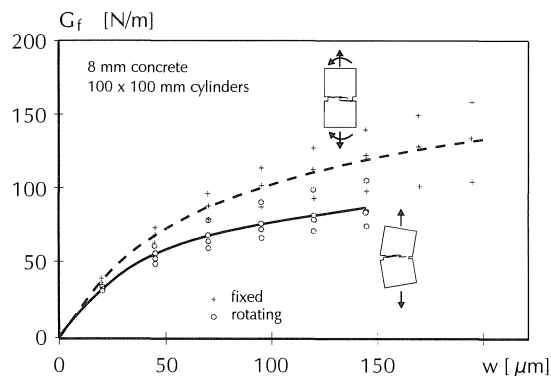


Fig. 4. Dependency of fracture energy on the rotational freedom of the loading platen in a uniaxial tensile test, after Van Mier et al. (1994).

in fracture energy as function of crack opening for freely rotating boundaries and for “fixed” boundaries. The difference will be evident. Moreover, the tensile strength of the specimen decreased when rotating boundaries were used. In addition to these quantitative differences, the shape of the descending branch changed significantly when the boundary conditions were changed (i.e. the rotational stiffness of the loading platen). In more general terms, the softening diagram depends on the flexural stiffness of the specimen-machine system outside the fracture zone. This implies that not only the rotational stiffness of the loading platen, but also the flexural stiffness of the specimen itself is of importance, as for example shown by Hordijk (1991). Differences in the rotational freedom of the loading platen leads to a different crack growth process. When the platens can rotate freely, a single crack-zone traverses the specimen from one side to the other, whereas for

a test between fixed platens two interacting cracks develop from two sides of the specimen (see inset in Figure 4). The crack growth process under fixed loading platens leads to a typical bump in the descending branch, see Van Mier et al. (1994). In summary, from an experimental point of view, size and boundary condition effects have a profound effect on the softening diagram. *In fact, the differences are so large that a unique softening diagram can not be defined.* Therefore we must rely on inverse modelling, using for example the multi-linear approximation of Figure 2b, and find the best fit. It will be obvious that because the diagram cannot be measured independent of the test environment, the early promise of a numerical model having “predictive qualities” should be abandoned. Because the softening diagram must be determined through inverse analysis, some researchers (e.g. Elices et al. (1992)), propose to use not the complicated uniaxial tensile experiment but rather a three point bend test. Note however that the same experimental difficulties that are experienced in the tensile test apply to the bending test as well. Moreover, the tensile strength cannot be measured directly in the bending test, and normal practice is to measure it through the “imperfect” splitting tensile test. Figure 4 suggests a lower bound for the fracture energy in a tensile experiment between freely rotating loading platens. Perhaps the three point bend test could be used as a standardized test, provided of course that the outcome is corrected and tuned to this hinged tensile test?

From a numerical point of view, softening analyses lead to difficulties as well. In conventional finite element analysis (smeared crack model, e.g. Rots (1988)) mesh sensitivity is observed as soon as localization of deformations occurs. The equations become ill-defined. The solution is found in applying higher order continuum theories, e.g. De Borst & Mühlhaus (1991) and Pamin & De Borst (1995). In such models the softening diagram is separated in a “computational diagram” and a term with dimension of length. The latter length scale is referred to as “internal length scale of the material” or “characteristic length”, and cannot be measured directly in an experiment. Gradient theories and non-local models fall in this category. The dependency of the characteristic length on the type of problem that was computed, was shown by Ožbolt (1993) for a non-local microplane model. Of course this situation is highly undesirable, and seems an obstacle in the development of applications of numerical methods in fracture analysis.

It could be argued that much of the problems of continuum models stem from the fact that the discrete nature of the fracture process cannot be captured by smeared models. In contrast, in discrete crack models, such as the model developed by Reich et al. (1993), a crack is modelled as a discrete displacement jump between finite elements. Remeshing is an essential ingredient of such models in order to allow for crack growth independent of the original finite element mesh. It should be recognised of course that discrete models can be used best for solving single crack problems. In some of the programmes interactive use is essential, and issues as defining initial notches from which a crack should nucleate are a rather haphazard undertaking. Finally it should be mentioned that the original purpose of smeared crack models has been the application to problems where *diffuse multiple cracking* would occur, for example in reinforced concrete. The use of the continuum models for discrete fracture problems has started much later, and has grown into a rather large contingent in fracture research of concrete. It is questionable whether this development should continue.

Meso-level fracture models for concrete

The boundary rotation effect that was discussed in the previous section is one of the phenomena that can be analyzed using a meso-level fracture model for concrete. As mentioned before, in a meso-level model, the various phases of the concrete, viz. aggregate, matrix and bond zone, are included directly in the model. Thus, some of the material structure is included in the model, but at a certain level (scale) continuum properties of the constituents have to be assumed. This seems a rather arbitrary procedure because the lower cut-off of material structural elements is chosen freely. In practice it means that a lower cut-off is defined depending on the computational facilities that are available. The computational effort increases substantially in meso-level analysis of concrete fracture. Note that this is also true for higher order continuum models. Quite an interesting development in meso-level modelling (or “numerical concrete”, a term coined by Roelfstra (1989)), who was one of the first to apply meso-level models to concrete) are lattice type models (e.g. Herrmann & Roux (1990)). A lattice model was applied for modelling concrete fracture by Schlangen & Van Mier (1992). In such models, the continuum is discretized into a network of beam or bar elements as shown in Figure 5. The elastic properties of the beams are determined from comparing the solution for the complete lattice with a continuum model. Next, a material structure is projected on top of the lattice, and different properties are assigned to beams (or bars) falling in different parts of the material structure (Figure 5b).

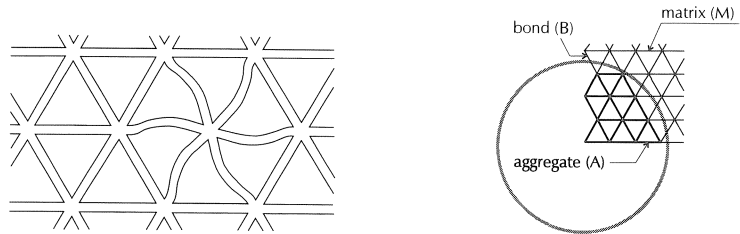


Fig. 5. Regular triangular lattice (a), and projection of material structure (b), after Schlangen & Van Mier (1992).

The “continuum assumption” in the lattice model is made at the level of the individual beams, i.e. the beams are supposedly made of a homogeneous continuum, which in the example of Figure 5b are the matrix, aggregate and bond phases. Schlangen (1995) recently showed that solutions with the lattice model are mesh dependent as well, quite similar to the observations in conventional macroscopic smeared crack models. This would imply that also for meso-level models, higher order continuum theories would have to be used at the level of, for example, the beam elements in a lattice. Quite interestingly, in spite of this pitfall in lattice modelling, the models are quite well capable of simulating curved crack growth under biaxial tension and shear, e.g. Nooru-Mohamed et al. (1993). Curved crack analysis using higher order continuum elements has not been possible to date, as shown clearly by Pamin & De Borst (1995). Again, the reason for this might be that the

continuum formulations is a too coarse approximation of the discrete crack process. Discrete crack models (boundary element formulations) seem much better equipped to simulate curved crack growth under biaxial tension and shear.

Crack patterns are the main issue that are very well handled using lattice type models. Problems are encountered in the load-displacement behaviour, which is generally too brittle. The reason for the increased brittleness has been shown to depend, at least in part, on neglecting the fine details in the material structure (see Schlangen & Van Mier (1993)), neglecting the third dimension (Van Mier et al. (1994)), and by neglecting the large scale porosity in the concrete (Arslan et al. (1995)). Among the other factors which have not been satisfactorily solved to date is the effect of moisture gradients in the material and the related problem of hygral shrinkage cracking. Main advantage of the lattice type models is that no softening is used as a fracture criterion, which is certainly advantageous in view of the experimental problems in measuring a unique softening diagram for concrete. On the other hand, defining the tensile strength of a lattice beam is not straightforward either.

Structural applications?

Fracture mechanics principles are preferentially used in numerical models. Essentially, the stress redistributions from crack growth processes are simulated using such models. An example of structural analysis was already shown in Figure 3, but of course quite specialized knowledge is needed if one is to perform such analyses. On the one hand, the engineer must be familiar with the numerical tools, on the other hand he/she will also have to judge the validity of the material parameters used in the model. In an analysis of a reinforced concrete structure at the macro-level not only the softening parameters, as described before, must be known, but also other parameters like bond-slip relations for the steel to concrete interface and aggregate interlock models should be understood. And of course the behaviour of concrete in compression, which may be of particular interest when the rotational capacity of reinforced beams is assessed. The question to be raised is: how valid are these numerical analyses? Are they really useful in structural design. Or is there a need for fracture mechanics based design rules for model codes? At present, the best application of fracture mechanics seems to be as support tool for research engineers. Thus, not a direct application of the models in construction practice, but rather a somewhat more distant application in research laboratories. In such applications, a good interaction between numerical specialists and experimentalists seems of extreme importance to obtain valuable results. Experiments are used in different manners, as for example sketched in Figure 6 for macro-level fracture analysis of reinforced concrete structures. First of all, the experiments are needed to determine the input parameters (constitutive equations) for the numerical model. Secondly, experiments at the structural (composite) level are needed to validate the model as shown. The application of the numerical model is also two-fold. Firstly, it can be used for a better understanding of the experiment that is carried out for determining the input parameters. Secondly, it is of course applied to extend the experimental range at the structural level.

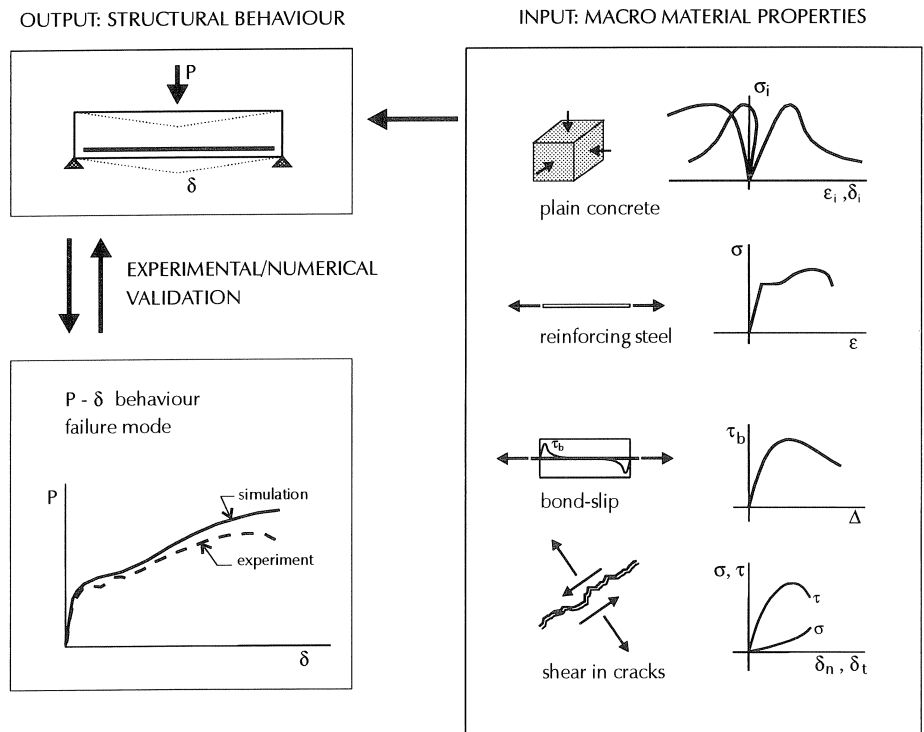


Fig. 6. Concrete mechanics approach at the structural level, after Van Mier (1996).

In summary, three classes of applications can be distinguished. The most "practical" application is of course the use of the numerical problems directly in construction practice. An example is perhaps the analysis of structural details in offshore platforms (see in Mod  er (1995), but the real extent of such applications is not clear. It is estimated that such applications are limited to isolated cases.

The second class of applications is the use of numerical fracture tools for obtaining an improved insight in the behaviour of the structural problem that is studied. The most direct practical result from such applications might be the development of analysis guidelines to be included in model codes such as ACI, CEB and others. This type of application of fracture models is perhaps the most widespread. Research engineers at Universities and research institutes use the numerical tools in such sense. Results of such research is published in proceedings of conferences and in Journals.

The third class of applications is perhaps most distant from the real practical use of numerical fracture models. In this "application", the models are used to design and interpret fracture experiments. In the end, the goal of such "applications" (or rather research) is to improve the accuracy of the numerical models. Of course such improvements have a direct impact on the quality of the class 1 and class 2 type of applications.

In proceedings of conferences organised by the International Association for Fracture Mechanics of Concrete and Concrete Structures (IA-FraMCoS), applications never go beyond class 2. Most reports concern the class 3 applications, where the numerical tools are used as tool for fundamental research. Of course this situation would have to change if fracture mechanics is to develop into a valuable practical tool in the future.

Materials engineering?

New applications of fracture mechanics emerge with the development of the new meso-level models (numerical concrete). Changes in the material structure can be analyzed with such models, and perhaps new composites with improved properties for structural applications might emerge. It is quite well known that by densifying the particle structure of the concrete, and by improving the bond properties of the aggregate to matrix material, the global (macroscopic) strength of the material improves. Densifying the concrete structure can be achieved by using superplasticizer, and by adding ultra-fine particles like micro-silica to close the finer gaps between the relatively large cement grains. In Figure 7a-c, the different steps in densifying the material structure are depicted.

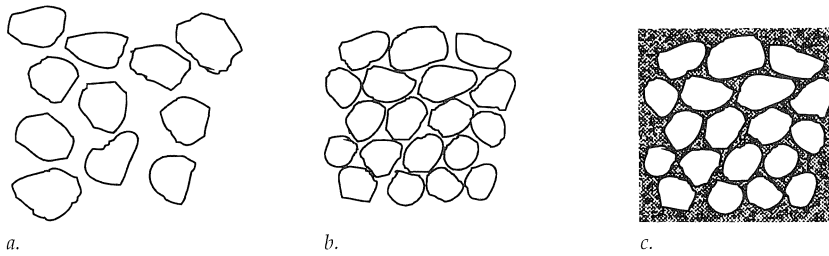


Fig. 7. Increasing the density of a cement composite (a), by using superplasticizer (b) and ultra-fine particles like micro-silica (c).

Unfortunately, increasing the strength, in particular the compressive strength of such particle composites, does not necessarily lead to an improved tensile strength and an improved ductility. The opposite is normally observed, namely the tensile strength increases only marginally, and the high strength concrete becomes more brittle. Brittleness can for example conveniently be expressed as the quotient of stored elastic energy and fracture energy following Elfgren (1989):

$$\frac{\text{elastic energy}}{\text{fracture energy}} = \frac{L^3 f_t^2 / E}{L^3 G_f} = \frac{L f_t^2}{E G_f} \quad (1)$$

where L is a characteristic size of the structure, f_t is the tensile strength of the material, G_f is the fracture energy and E is the Young's modulus. The dimension of fracture energy is J/m^2 or N/m . A structure behaves brittle if the stored elastic energy is larger than the fracture energy of the

material, whereas a structure behaves ductile in the reverse case, i.e. when the fracture energy becomes much larger than the stored elastic energy. Because the size of the structure enters in the equation, any structure can be made ductile if the size is decreased. Or for any structure that is sufficiently large, brittle behaviour can be found. Increasing the material toughness, or fracture energy, is however the most popular cure against brittleness. By adding a low volume percentage of fibres (Figure 8a), improved material ductility can be obtained, but generally still softening behaviour is measured as shown in Figure 8d. A further increase of the fibre content as in SIFCON (Figure 8b), improves the ductility substantially, but in addition also the strength. The largest increase in strength and ductility (or rather pseudo-strain hardening behaviour) can be obtained when aligned fibres are used (Figure 8c).

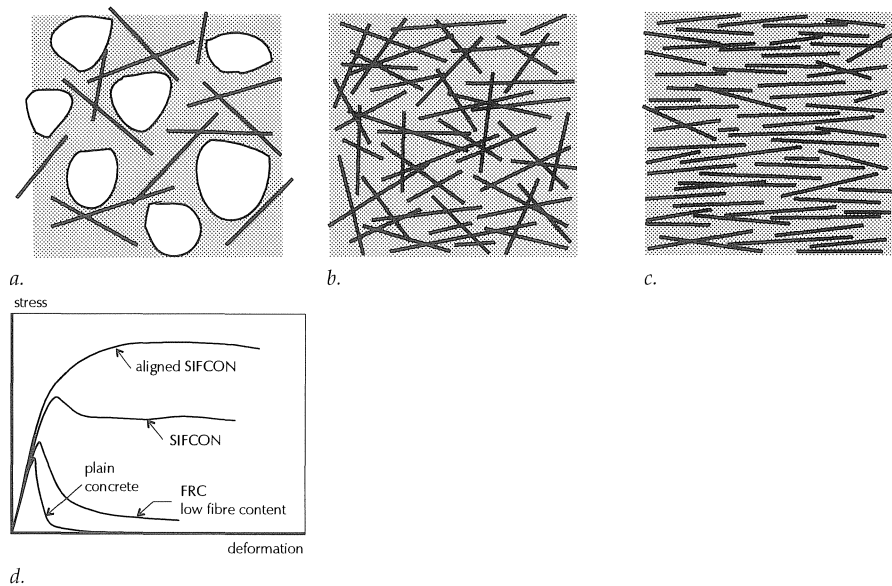


Fig. 8. Toughness increase by adding fibres to the concrete: randomly oriented low volume (a), randomly oriented high volume as in SIFCON (b), and uni-directional fibre composite (c). Figure (d) shows the difference in mechanical response of these three materials in tension.

In the Stevin Laboratory we have developed a fibre alignment method through which fibre volumes up to 21% by volume have been achieved. Needless to say that a material having such a quantity of aligned fibres requires an alternative manufacturing procedure. The uni-directional SIFCON is produced by first aligning the fibres in the mould, and subsequently impregnating a low viscosity cement slurry. The uni-directional SIFCON is a highly anisotropic material, and it should best be loaded in a direction parallel to the main fibre orientation. The optimum application would perhaps be to use the material in a truss-system as sketched in Figure 9. Because the truss elements are connected through hinges, only normal loads are carried by the SIFCON elements.

Note however that not only strength of the truss system should be considered, but also stiffness. Although for SIFCON a considerable increase of strength and ductility is obtained, especially for the material with aligned fibres, the Young's modulus will never increase by more than a factor of two. Since the deflection of a truss is proportional to the applied load and the size, and inverse proportional to the Young's modulus of the material and the cross-sectional area of the elements, the rather expensive uni-directional SIFCON would not be the best choice. Optimising the material composition in conjunction with the structural application in which the material is to be used might in the future be done using the new fracture mechanics tools. In the latter example, numerical tools might be employed successfully, but also more global analyses based on brittleness numbers (such as eq. (1)) might be quite suitable. In the end, experimentation is essential in order to validate the theoretical "predictions".

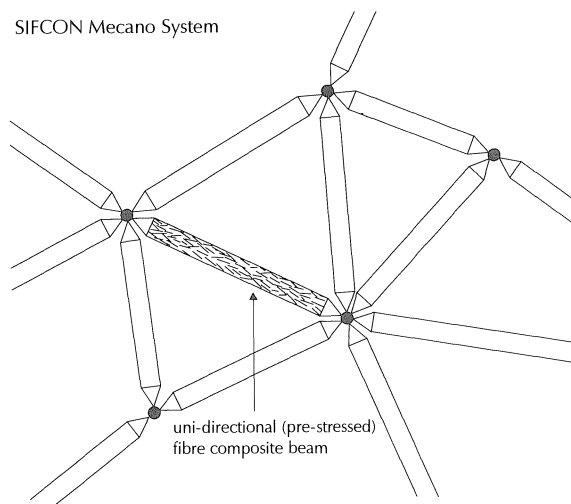


Fig. 9. Truss-system containing uni-directional SIFCON bar elements developed at the Stevin Laboratory.

Conclusion

In this paper the question from the title is addressed: "Will fracture mechanics applications of concrete start to emerge?" The question cannot be answered by a blunt yes or no because the definition of an application is not straightforward. Many different ideas circulate. Because fracture mechanics theories are most commonly applied in a numerical environment, it might suffice to discuss the application of the numerical tools. This does not mean that the role of experiment is degraded. Experiments are of extreme importance as they show us how the "real world" works, and moreover, they are essential to tune the numerical models. So the question could be rephrased as: Where and how are numerical fracture models applied? Three classes of applications were distinguished, namely the application of the models directly for solving practical problems (class 1 application),

the use of the models by research engineers for deriving guidelines for structural analysis (class 2 application), and thirdly, the use of the models as a research tool for designing and interpreting fracture experiments. These three classes of applications concern structural engineering.

Recent developments in numerical modelling allow to model the behaviour of materials at the level of their structure. For concrete this development has been started several years ago, and the term "numerical concrete" was first used by Roelfstra. The lattice technique provides an even simpler tool for analysing the mechanical and fracture behaviour of concrete (and other materials) starting from their composition. Although many of the problems in numerical analysis of structures are encountered in the numerical meso-level models as well, the new tools seem to point towards new applications where the effect of changing the composition of a material can be studied. In conjunction with experiments at the materials level such numerical tools seem to be a quite powerful research instrument for designing materials with specific properties for structural applications.

Finally, it can be concluded that applications of fracture mechanics to concrete structures and materials develop only in a very slow pace. Real structural applications are very limited. Perhaps the slow pace is caused by the fact that many practical engineers were not educated in fracture mechanics. Maybe, the knowledge should be disseminated much further before the new tools really become part of common engineering practice. Perhaps also the researchers are to blame because early promises were rather far reaching, and substantial parts of the early promise of a numerical tool "with predictive capabilities" will never be reached. The main cause for this is that the supposed fracture properties of concrete (softening diagram, tensile strength and fracture energy), are not really properties that can be determined independent of the experimental environment. The most positive part of fracture mechanics is that it leads to a much improved insight in the behaviour of materials and structures, and even when it is not used directly, the knowledge gathered during all research activities is an application in the true sense of the word, at least, as mentioned before if this knowledge is distributed in a sensible way to practitioners.

References

- ARSLAN, A., SCHLANGEN, E. and VAN MIER, J.G.M. (1995), Effect of model fracture law and porosity on tensile softening of concrete, in *Proceedings FraMCoS-2* (ed. F.H. Wittmann), AEDIFICATIO Publishers, Freiburg, pp. 45–54.
- BAŽANT, Z.P. (1984), Size effect in blunt fracture: concrete, rock, metal, *J. Eng. Mech. (ASCE)*, **110**, pp. 518–535.
- CARPINTERI, A. and FERRO, G. (1992), Apparent tensile strength and fictitious fracture energy of concrete: A fractal geometry approach to related size effects, in *Fracture and Damage of Concrete and Rock - FDCR-2* (ed. H.P. Rossmanith), E&FN Spon, London/New York, pp. 86–95.
- CARPINTERI, A., CHIAIA, B. and FERRO, G. (1995), Multifractal scaling law: An extensive application to nominal strength size effect of concrete structures, *Politecnico di Torino, Dipartimento di Ingegneria Strutturale, Research Report 51*, p.145.

- DE BORST, R. and MÜHLHAUS, H.-B., Continuum models for discontinuous media, in *Fracture Processes in Concrete, Rock and Ceramics*, Van Mier, J.G.M., Rots, J.G. and Bakker, A., Eds., Chapman & Hall/E&FN Spon, London/New York, pp. 601–618.
- ELFGREN, L., ed. (1989), *Fracture Mechanics of Concrete Structures*, Chapman & Hall/E&FN Spon, London/New York, p. 399.
- ELICES, M. and PLANAS, J. (1995), Numerical modelling and determination of fracture mechanics parameters: Hillerborg type models, in *Proceedings FraMCoS-2* (ed. F.H. Wittmann), AEDIFICATIO Publishers, Freiburg, Volume 3 (in press).
- ELICES, M., GUINEA, G.V. and PLANAS, J. (1992), Measurement of the fracture energy using three-point bend tests: Part 3 - Influence of cutting the P- tail, *Mater. Struct. (RILEM)*, **25**(150), pp. 327–334.
- HERRMANN, H.J. and ROUX, S. (1990), *Patterns and Scaling for the Fracture of Disordered Media*, Elsevier Applied Science Publishers B.V. (North Holland).
- HILLERBORG, A., MODÉER, M. and PETERSSON, P.-E. (1976), Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements, *Cem. & Conc. Res.*, **6**, pp. 773–782.
- HORDIJK, D.A. (1991), Local approach to fatigue of concrete, *Ph.D. thesis*, Delft University of Technology, The Netherlands.
- KAPLAN, F. (1961), Crack Propagation and the fracture of concrete, *J. Am. Conc. Inst.*, **58**, pp. 591–598.
- MODÉER, M. (1995), Offshore concrete platforms in Norway: Materials and static analysis, in *Fracture of Brittle Disordered Materials: Concrete, Rock and Ceramics* (eds. G. Baker and B.L. Karihaloo), E&FN Spon, London/New York, pp. 481–494.
- NOORU-MOHAMED, M.B., SCHLANGEN, E. and VAN MIER, J.G.M. (1993), Experimental and numerical study on the behavior of concrete subjected to biaxial tension and shear, *Adv. Cement Based Mater.*, **1**, pp. 22–37.
- OZBOLT, J. (1993), General microplane model for concrete, in *Numerical Models in Fracture Mechanics of Concrete* (ed. F.H. Wittmann), Balkema, Rotterdam, pp. 173–187.
- PAMIN, J. and DE BORST, R. (1995), Numerical simulation of localization phenomena using gradient plasticity and finite elements, *HERON*, **40**(1), pp. 71–92.
- REICH, R.W., PLIZZARRI, G., CERVENKA, J. and SAOUMA, V.E. (1993), Implementation and validation of a nonlinear fracture model in a 2D/3D finite element code, in *Numerical Models in Fracture Mechanics of Concrete*, (ed. F.H. Wittmann), Balkema, Rotterdam, 265–285.
- REINHARDT, H.W. (1984), Fracture mechanics of an elastic softening material like concrete, *HERON*, **29**(2).
- ROELFSTRA, P.E. (1989), Simulation of failure in computer generated structures, In *Fracture Toughness and Fracture Energy*, (eds. H. Mihashi et al.), Balkema, Rotterdam, pp. 313–324.
- ROTS, J.G., Computational modelling of concrete fracture, *Ph.D. thesis*, Delft University of Technology, The Netherlands, 1988.
- SCHLANGEN, E. (1995), Computational aspects of fracture simulations with lattice models, in *Proceedings FraMCoS-2* (ed. F.H. Wittmann), AEDIFICATIO Publishers, Freiburg, pp. 913–928.
- SCHLANGEN, E. and VAN MIER, J.G.M. (1992), Experimental and numerical analysis of micro-mechanisms of fracture of cement-based composites, *Cem. & Conc. Composites*, **14**, pp. 105–114.

- SCHLANGEN, E. and VAN MIER, J.G.M. (1993), Lattice model for simulating fracture of concrete, in *Numerical Models in Fracture Mechanics of Concrete* (ed. F.H. Wittmann), Balkema, Rotterdam, pp. 195-205.
- VAN MIER, J.G.M. (1986), Fracture of concrete under complex stress, *HERON*, **31**(3).
- Van Mier, J.G.M., Ed. (1987), Examples of non-linear analysis of reinforced concrete structures with DIANA, *HERON*, **32**(3).
- Van Mier, J.G.M. (1991), Mode I fracture of concrete: Discontinuous crack growth and crack interface grain bridging, *Cem. & Conc. Res.*, **21**, pp. 1-15.
- VAN MIER, J.G.M. (1996), *Fracture Processes in Concrete*, CRC Press, Boca Raton, FL (in preparation).
- VAN MIER, J.G.M. and NOORU-MOHAMED, M.B. (1990), Geometrical and structural aspects of concrete fracture, *Eng. Fract. Mech.*, **35**, pp. 617-628.
- VAN MIER, J.G.M., VERVUURT, A. and SCHLANGEN, E. (1994), Boundary and size effects in uniaxial tensile tests: A numerical and experimental study, in *Fracture and Damage in Quasibrittle Structures* (eds. Z.P. Bazant, Z. Bittnar, M. Jirásek and J. Mazars), E&FN Spon, London/New York, pp. 289-302.