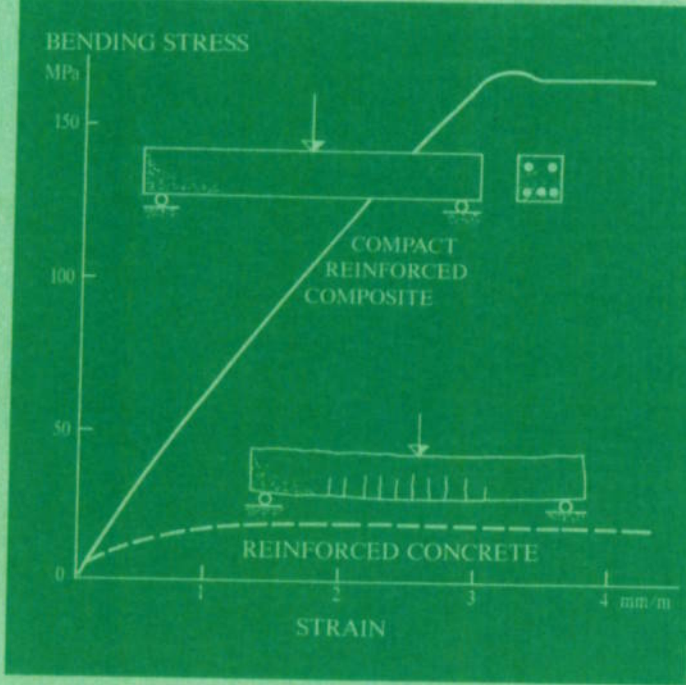
CBL RAPPORT NO. 41



COMPACT REINFORCED COMPOSITE BASIC PRINCIPLES

by

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Maj 1987

CRC is still in its infancy (the principles were demonstrated for the first time in May 1986). Aalborg Portland is interested in cooperation with regard to research and development of CRC technology.

CRC is the subject of a patent application notified by Aalborg Portland.

ABSTRACT

Compact Reinforced Composite - CRC - is the designation for a new type of high-performance composite material which is based on strong, brittle matrix materials given a high degree of ductility. The material is particularly suitable for large elements and structures, enabling them to resist very large forces in tension, compression and shear. CRC is reinforced with densely arranged bars and a high concentration of fine fibres.

An entirely new design strategy based on fracture mechanics has been used for the development of CRC. The main principles of this strategy have been:

1. to enable brittle matrix materials to strain harden by reinforcing them with a high concentration of fine, strong and stiff fibres; this increases the tensile stresses and tensile strains at which the matrix material cracks;

2. To increase still further the ultimate tensile strains of the matrix materials when these deform together with the reinforcing bars by effective fixation to the bars;

3. to achieve a high degree of global and local ductility by means that ensure a small "brittleness number".

Bending tests on CRC beams in which the binder consisted of densely packed Portland cement and microsilica in a steel-fibre-reinforced quartz-sand mortar and the main reinforcement was 8 mm diameter steel bars demonstrated the unique behaviour of the new materials. The load capacity in bending was 5-10 times that of traditional, good reinforced concrete and almost the same as for structural steel, the formalized ultimate bending stress (normalized bending moment: $M/\ 1/6\ bh^2$) being slightly more than 160 MPa. The matrix material remained uncracked under tensile loading right up to the yield limit of the reinforcing steel (tensile strains about 3 mm/m), whereas ordinary reinforced concrete cracks at tensile strains of only 3-5% of the yield limit of the reinforcing steel.

CONTENTS

1. INTRODUCTION

Compact Reinforced Composite - CRC - is a new type of very strong and stiff composite material showing exceptionally high ductility.

CRC is built up of strong, densely arranged main reinforcement in a strong, rigid, coherent matrix based on strong, brittle materials which are enabled to exhibit strain hardening through a high content of fine, strong, rigid fibres and further reinforced against cracking by firm fixation to the main reinforcement, see fig. 1.

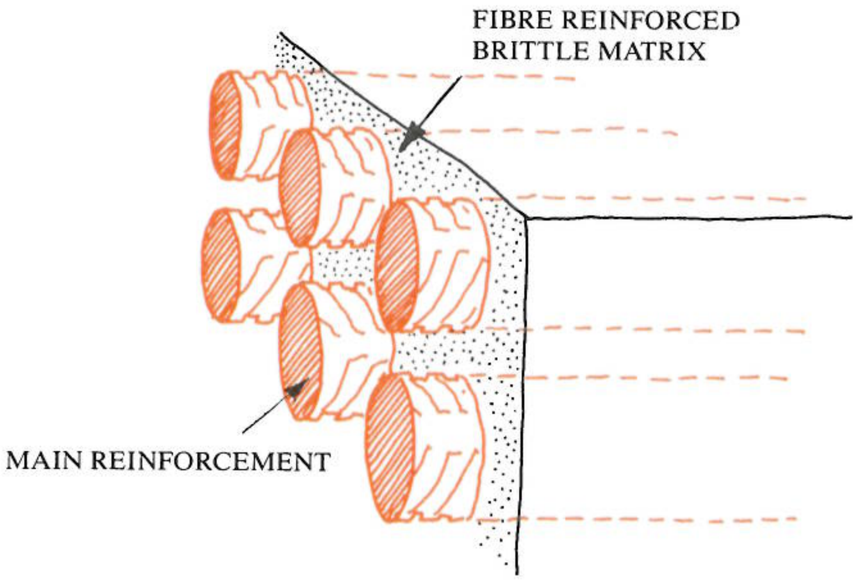


Fig. 1.1 CRC-structure.
The CRC-structure is built up of densely arranged main reinforcement (bars) firmly embedded in a strong, brittle matrix given high ductility by efficient fibre reinforcement.

The tensile load is carried primarily by the main reinforcement. This is secured by the specific matrix, which is able to transfer large forces between the reinforcing bodies. It is the special combination of rigidity, strength and internal coherence that enables the matrix to act in this way.

The matrix itself can transfer considerable stresses in compression but only about one fifth to one tenth in tension. The matrix is, however, able to follow the tensile deformations of the reinforcement as a coherent, crack-free, load-bearing body right up to yielding of the reinforcement.

CRC test beams have been fabricated using Portland cement, microsilica, quartz sand, steel fibres, and steel bars as the main reinforcement. The material is a kind of fibre-reinforced, reinforced concrete showing exceptional properties.

The new "reinforced concrete" is 5-10 times as strong and much stiffer than ordinary reinforced concrete and is largely free of cracks even at tensile loads right up to yielding of the main reinforcement. The tensile strains before cracking exceed 3 mm/m, whereas ordinary reinforced concrete typically cracks at strains of about 0.1-0.2 mm/m.

The structure is apparently like that of reinforced concrete, but deviates fundamentally from it in several ways, which is reflected in a load capacity more like that of structural steel than of reinforced concrete. The design principles, composition, and production, differ fundamentally from traditional reinforced concrete technology.

The production of CRC is not tied to any specific method, but in practice, the principles on which the fabrication of the test beams discussed here was based will probably play a dominant role.

Superficially, the production method may seem reminiscent of that used for traditional reinforced concrete and fibre-reinforced concrete - mixing, casting under vibration, etc. However, there are essential differences that have made it possible to produce the specific, very densely arranged, complex-shaped, internal structures: densely arranged, ultrafine, particle-based binder (water/-cement+silica ratio: 0.18 by weight) with a very high content of fine fibres (6% by volume of fibres 6x0.15 mm), arranged in the narrow space between the densely arranged main reinforcement in slender beams.

It has therefore been found requisite also to discuss the principles for the production of CRC.

CRC stands for COMPACT REINFORCED COMPOSITE. Seen as a composite structure, CRC is the (hitherto missing) counterpart of high-strength fibre composites, such as carbon-fibre-reinforced plastic, normally only used as small members that are specially suitable for transmitting large tensile stresses. CRC can transmit not only large tensile forces but also large compressive and shear forces and large flexural and torsional forces, exhibits great hardness and chemical resistance, and can work in a high temperature range. Furthermore, CRC is particularly suitable for very large members and structures.

CRC is not limited to Portland cement-based systems but also offers possibilities (as yet undocumented experimentally) within ceramics.

CRC is still in its infancy, and the tests performed so far have given us only a first glimpse of this new field.

Basic principles

The design of Compact Reinforced Composite is based on an entirely new strategy in which fracture mechanics play a central role.

The production of the very dense, complex CRC-structures is similarly based on a new strategy.

The basic principles for mechanical design and production are:

1. <u>to enable brittle matrix materials to strain harden under tensile loading</u>.

   This is achieved by making a matrix material with a high modulus of elasticity and a high fracture energy, and reinforcing said matrix with a high content of fine, strong and stiff fibres well fixed to the matrix. See fig. 1.2.

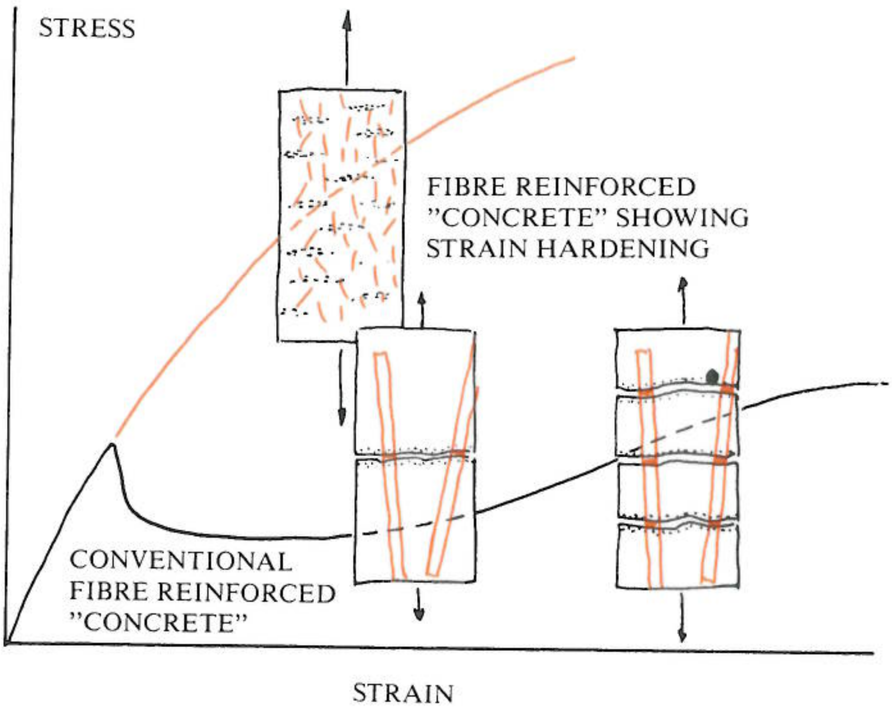


Fig. 1.2 STRAIN HARDENING OF BRITTLE MATERIALS WITH FIBRES.

In tensile fracture in brittle materials the material deforms largely elastically up to a state with maximum tension. Thereafter, fracture occurs by the opening of a single crack.

Before the crack develops, local deformations occur in a very narrow zone - "the crack zone". Conventional fibre reinforcement has little effect on the formation of the first matrix crack, but if the material is very effectively reinforced with extremely fine, strong, stiff fibres, the fibres can already be made to take over large loads before a crack zone develops into a real crack.

Increasing loads will thus not result in fracture but in the formation of new crack zones distributed over the entire body. In this way, an increase is achieved in the stresses and strains at which the first real matrix crack occurs. We get strain hardening.

2. <u>To increase still further the ultimate tensile strain of the matrix material when this deforms together with the main reinforcement (bars).</u>

   This is secured by effective fixation of the fibre-reinforced matrix material to the main reinforcement - which acts as a spatially stable, stiff frame. This ensures the formation of a multiple crack zone system having a very large tensile strain capacity - see fig. 1.3.

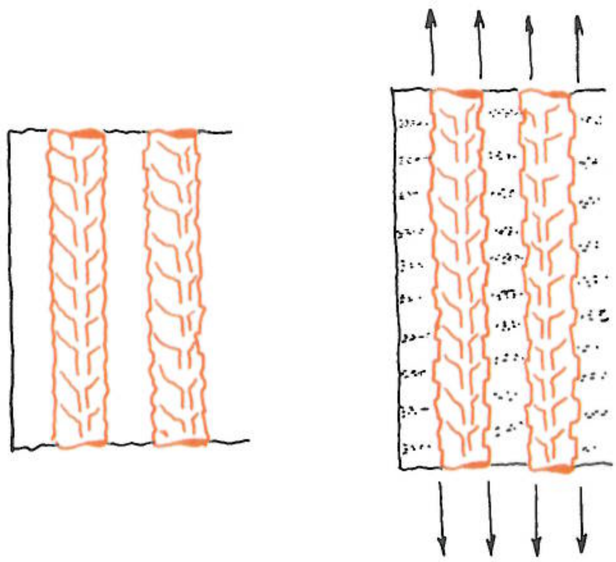


Fig. 1.3 STRAIN HARDENING OF BRITTLE MATERIALS BY FIXATION TO MAIN REINFORCEMENT.

By very effective fixation of the matrix material to the main reinforcement, the matrix material is made to following the deformations of the main reinforcement, whereby a multiple crack zone system with a large strain capacity forms before any real cracking occurs.

3. <u>To ensure a high degree of local and global ductility by means that ensure a small brittleness number:</u>

$$\frac{\sigma_o^2 D}{EG} \quad \text{or} \quad \frac{\sigma_o^2 L}{EG}$$

where, σ_o, E and G are the tensile strength, the modulus of elasticity and the fracture energy, respectively, and D and L are characteristic quantities (e.g. diameter of fibres or of main reinforcement and size of member, respectively).

CRC is based on new, strong binder materials (large σ_o) given very high ductility (by means of fibres, which greatly increase the fracture energy G). The ductility is increased considerably more than corresponding to the increased strength of the binder, see fig. 1.4.

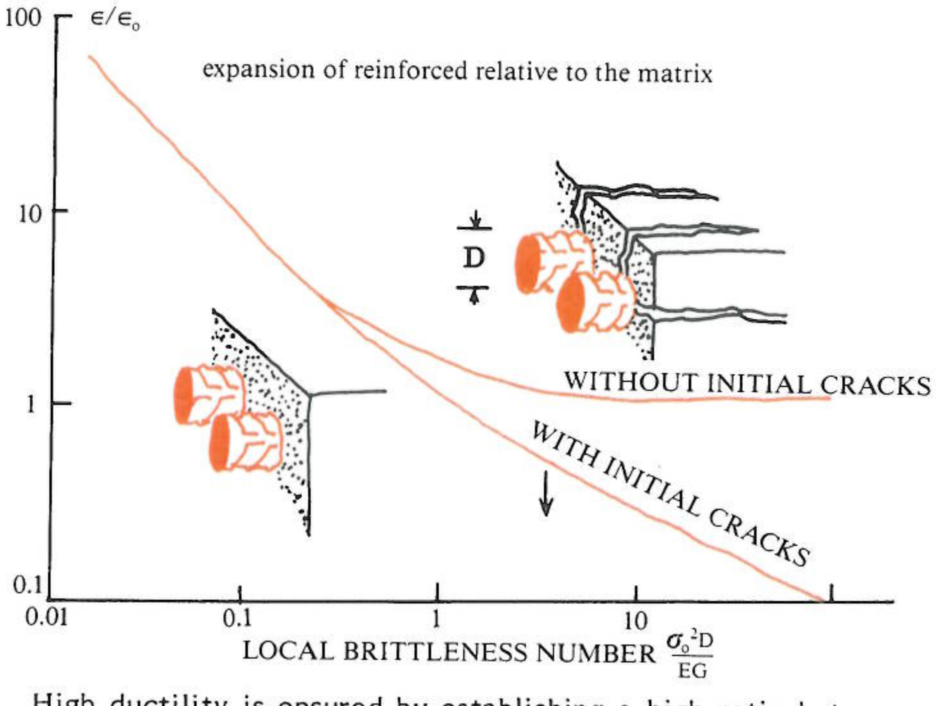


Fig. 1.4 High ductility is ensured by establishing a high ratio between the fracture energy (proportional to $G \times D^2$) and the elastic energy stored in the loaded system before fracture (proportional to $\sigma_o^2/E \times D^3$) - that is, a low brittleness number $\sigma_o^2 D/EG$.

In CRC, great ductility - low brittleness numbers - is ensured in connection with fixation of the main reinforcement by means of very effective fibre reinforcement, whereby the fracture energy of the matrix (G) is increased by a factor of 100 - 1000 compared with that of unreinforced matrix material.

4. To enable very dense and homogeneous particle-fibre packing - at both macro- and micro-level - during processing by effective use of geometrical and kinematic principles.
   This is ensured by overcoming interparticulate surface forces in the fine particle/ultra-fine particle-based binder and by ensuring substantially viscous behaviour during processing (mixing, casting and compaction) - assisted by well-designed mechanical vibration.

Construction of the report

The description of the structure and fundamental principles of CRC are given in the last third of the report (sections 8, 9, 10 and 11).

As CRC is an entirely new type of structure and as the description of its mechanical behaviour is based on fracture mechanical principles, which are not widely disseminated, it has been decided to present an actual example of a CRC body and to explain the general fracture mechanical relationships for brittle materials before describing the basic principles of CRC.

In section 2 the results of fracture tests etc. on small CRC-beams (50x50x500 mm) are presented. The fabrication of the beams is described in the section on production (section 11).

Sections 3 and 4 contains an account of the factors relating to reinforcement of brittle materials in general (section 3) and to "brittleness" and "ductility" (section 4), including definition of the concepts brittleness number and ductility number, which play a vital role in CRC-design.

In section 5, an explanation is given of the special crack zone deformation that takes places prior to cracking and of the related energy conversions - fracture energy.

In continuation of this, section 6 deals with fracture strain of brittle materials. Here, it is stressed that the deformations are not only the elastic deformations but also include a contribution from the crack zone deformations. This, too, plays a vital role for CRC, where we focus particularly on establishing large crack zone deformations and thus large tensile strain capacities.

Section 7 contains a survey of the modes of action of reinforcement of brittle materials, including traditional modes of action as we know them, for example, from ordinary fibre concrete and reinforced concrete.

The special methods of reinforcement, which are peculiar to CRC are discussed separately in sections 8 and 9 (crack propagation past reinforcement, strain hardening).

In section 10 (Fixation of Reinforcement) describes factors that are essential for CRC-behaviour, including - particularly - ensuring global and local ductility (low brittleness number) by means of effective fibre reinforcement.

The principles for production of CRC are described in section 11 (principles of dense packing, overcoming inter-particulate surface forces, viscous processing, and vibratory processing). The principles are exemplified by describing the composition and production of the CRC-beams described in section 2.

In the final section (section 12), CRC is considered in a broader perspective as a new, high-performance composite material. CRC is compared with known, high-performance composite materials based on ultra-strong fibres.

The notation and references are given at the end of the report, in sections 13 and 14, respectively. The report contains 45 figures numbered by section (first digit).

2. CRC TEST BEAMS

As a means of introducing CRC, this section gives the results of bending tests carried out on small test beams (50x50x500 mm) [1].

A major weakness of reinforced concrete lies in the fact that the ultimate tensile strain of the concrete is very small in relation to the yield point of the steel (typically 0.1 mm/m compared with an elastic deformation of the steel of about 3 mm/m - see figure 2.1).

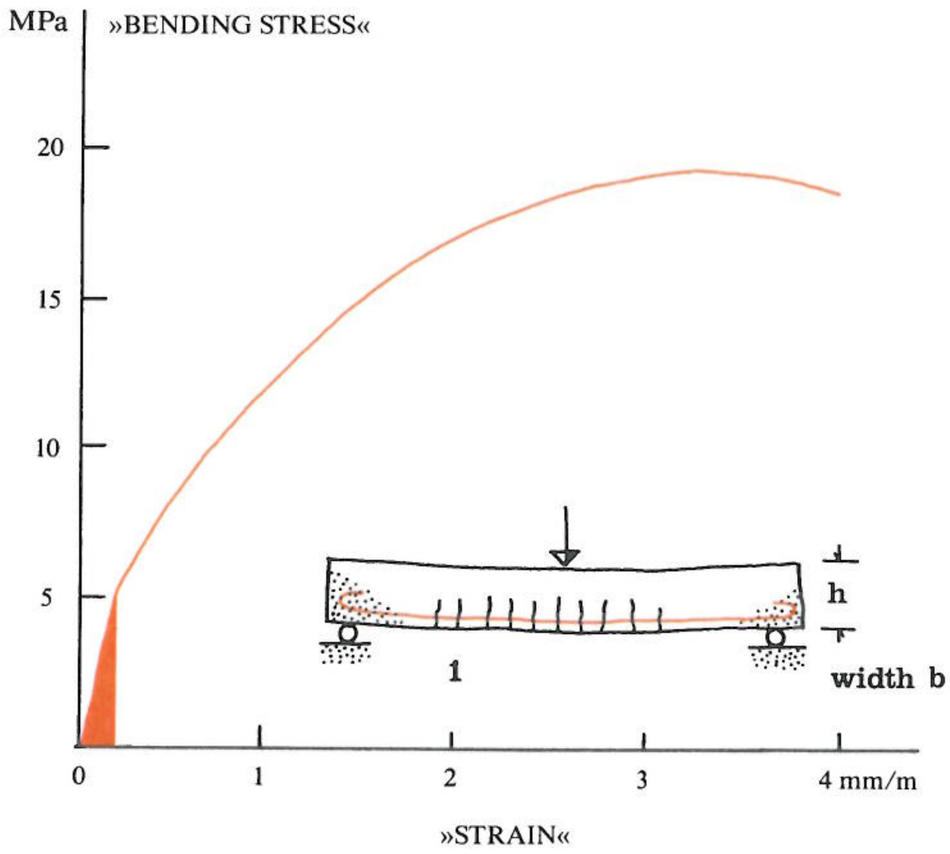


Fig. 2.1 Typical behaviour of an ordinary, strong, reinforced concrete beam in bending.

The bending stresses are normalized bending moments obtained by dividing the actual bending moment M by 1/6 bh^2, and the strains are normalized curvatures which correspond to the maximum strains in a similar, homogeneous beam with linear elastic behaviour.

At tensile strains of about 0.1-0.2 mm/m, the concrete cracks past the reinforcement, while the reinforcement deforms elastically up to 2-4 mm/m.

Engineers have therefore had to accept moderate cracking on the tensile side and have learnt to guard against more serious troubles by using moderate quantities of reinforcement and other means.

The behaviour is not changed by going over to high-strength concrete, since this also exhibits a very low ultimate tensile strain (approx. 0.2 mm/m). In fact, this sometimes even aggravates matters because high-strength concrete is often far more brittle than ordinary concrete.

In CRC these limitations are removed. For example, test beams loaded in bending deformed elastically without cracking at loads corresponding to "bending stresses" of more than 160 MPa (normalized bending moments calculated as $M/1/6xbh^2$) and tensile strains of more than 3 mm/m. Thereafter, plastic yielding occurred, with yielding of the main reinforcement and ductile opening of a single, central crack in the matrix.

The results of a bending test and the test arrangement are shown in figure 2.2. Results of supplementary investigations on the matrix material - with and without fibres are shown in figures 2.3, 2.4 and 2.5. The material composition and production are described in section 11.

As can be seen from figure 2.2, the load capacity was extremely high (formal flexural stresses over 160 MN/m^2, which is about 5-10 times that of normal reinforced concrete), and the test beams remained substantially free of cracks even at tensile strains above 3 mm/m. (Traditional reinforced concrete and fibre-concrete usually crack at tensile strains of about 0.1-0.2 mm/m).

The very high load capacities are primarily secured by the densely arranged main reinforcement, which transmits about 70-80% of the load at commencement of yielding.

The difference between CRC and ordinary reinforced concrete is that "the new concrete" has been enabled to ensure really effective utilization of a very high amount of reinforcement while remaining substantially free of cracks (figure 2.6).

The materials and composition used were by no means optimum for the achievement of great strength, stiffness and ductility.

For example, still using cement-silica-based materials but with stronger sand, e.g. burnt Bauxite, the compressive strength of the basic matrix could be increased from about 160 MPa to about 250 MPa [2]. If, at the same time, the volume concentration and quality of the main reinforcement were increased - for instance, corresponding to a 50-100% increase in the tensile strength - and the fibre reinforcement were optimized, it seems likely that the load capacity of cement-silica-based CRC beams could be increased from 160 MPa (formalized flexural stress) to 250-350 MPa.

The CRC-principles can also be applied with non-cement-based binders - ceramic binders, for example - combined with entirely different types, sizes and volumes of fibre reinforcement and main reinforcement.

The theories presented concerning CRC-bodies' behaviour and production processes provide a basis for evaluating the potentials - and for showing ways of realizing them.

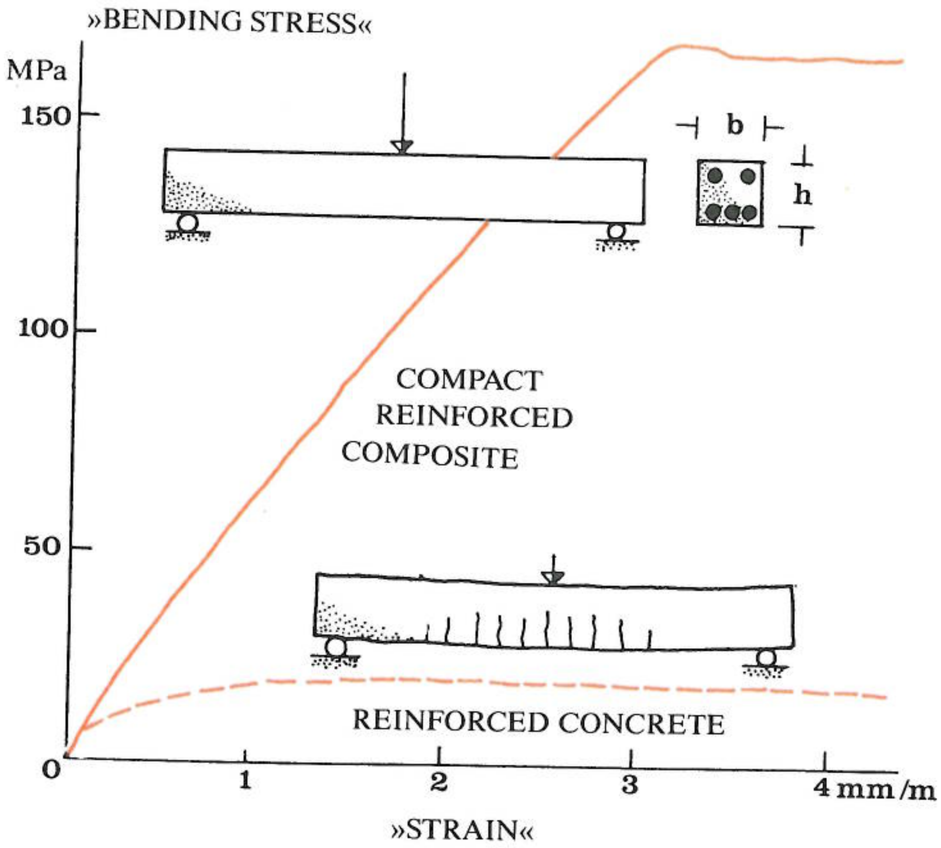


Fig. 2.2 Behaviour of an CRC-beam in bending.
Cross section 50x50 mm. Span 447 mm.

In the test, the relationship between force and deflection was recorded (maximum force 31 kN). For comparison, the results have been normalized (expressed by stresses and strains, respectively).

The bending stress is obtained by dividing the moment by the section modulus ($M / 1/6\ bh^2$). The strains correspond to the maximum strains in a similar, homogeneous beam with ideal, linear elastic behaviour.

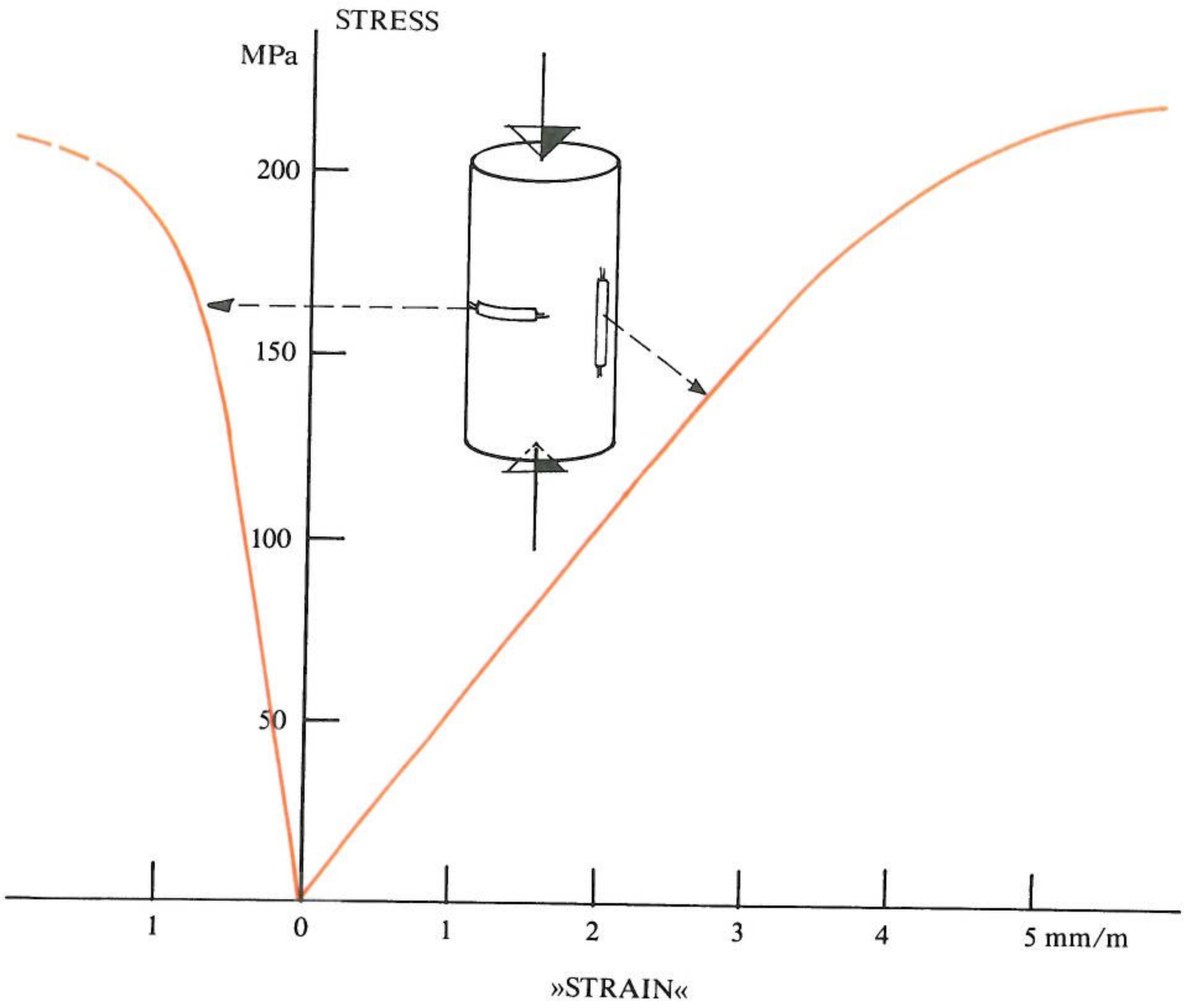


Fig. 2.3 Compression test on test cylinder (height 9 cm, dia. 4.5 cm) of fibre-reinforced matrix material, during which the compression in the pressure direction and the transverse expansion were recorded.

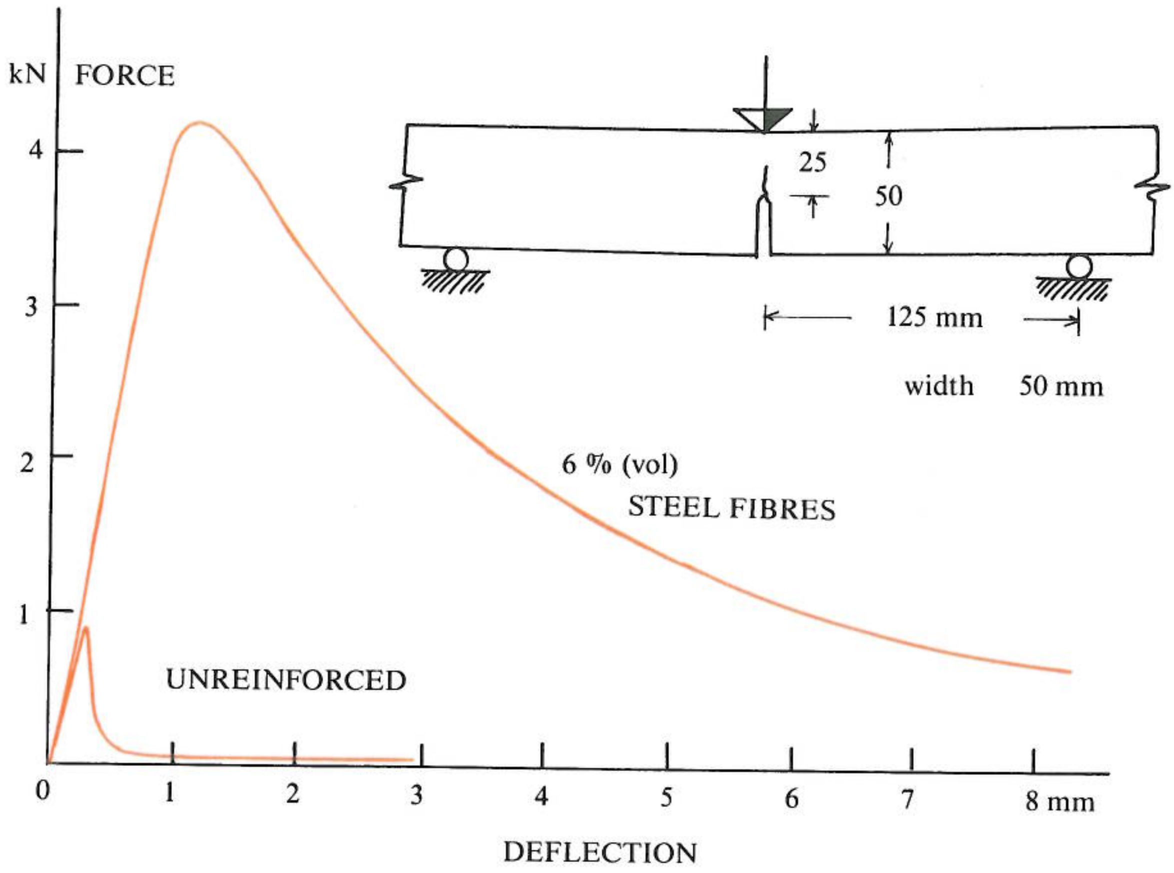


Fig. 2.4 Determination of fracture energy of the matrix material.

Bending test on notched beams to determine the fracture energy (G) in unreinforced matrix material and a fibre-reinforced matrix material identical to that used in the test on the reinforced beams (6-vol% steel fibres, length 6 mm, dia. 0.15 mm).

The fracture energy values - calculated as work performed (area below the force-load curve), divided by the respective crack areas, were 130 N/m and 13,000 N/m, respectively (average of 3 tests) [1].

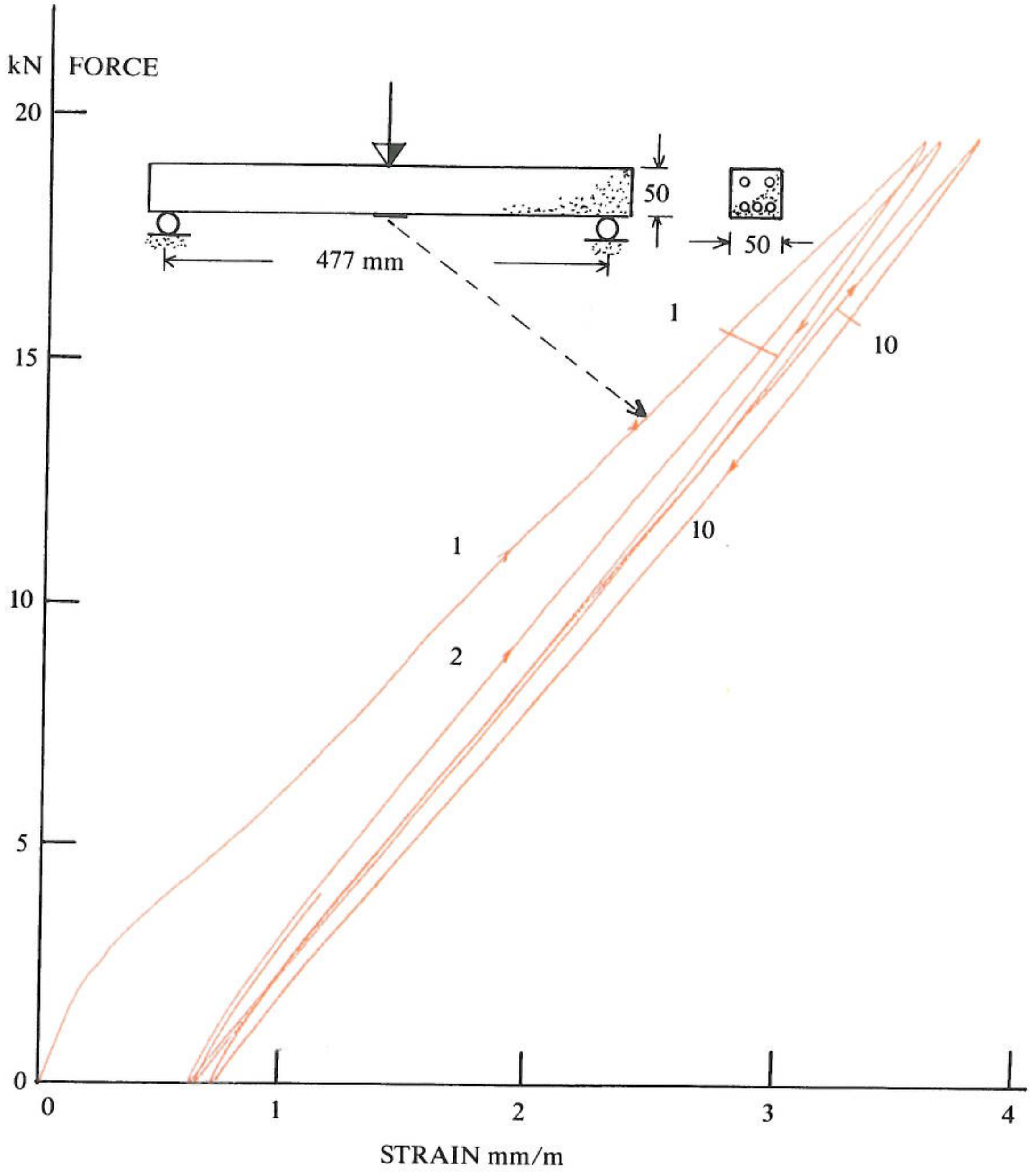
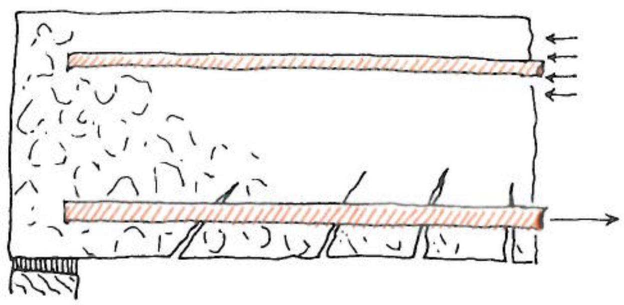


Fig. 2.5 Loading/deloading curve for CRC beam.

The beam was loaded and deloaded 10 times from 0 to 20 kN (corresponding to formal bending stresses from 0 to about 110 MPa). During the test, the force and strain at the middle of the tensile side of the beam were measured. After the test, the beam was examined microscopically. No cracks were observed [1].

1.



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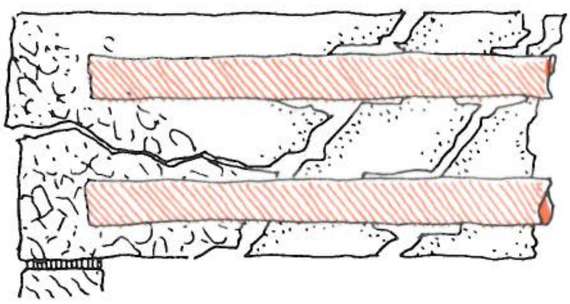

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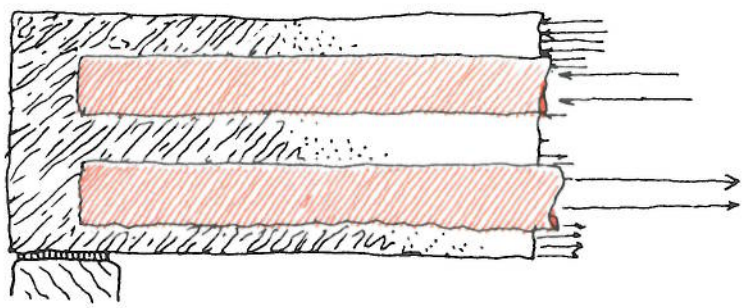


Fig. 2.6 Behaviour of reinforced concrete and CRC under loading.

In normal reinforced concrete (with moderate amount of reinforcement), the concrete cracks past the reinforcement, which resists the tensile stresses but retains acceptable inner coherence (1).

If we try to use more reinforcement, the "concrete" cracks and splits, and the inner coherence is lost (2).

With CRC we are now able to achieve an extremely large amount of reinforcement without losing inner coherence and without cracking for loads right up to the yield limit of the steel (3).

3. REINFORCED COMPOSITES WITH BRITTLE MATRICES

Brittle materials like ceramics, glass, and concrete, typically exhibit high chemical resistance, hardness, and thermal resistance, making them suitable for various structural purposes.

However, the materials also typically exhibit low tensile strength and brittle behaviour, which decisively restrict their usefulness.

Brittle materials can be improved by reinforcement. However, it is not possible to reinforce brittle materials effectively in the same way as we can with composite materials with ductile matrices, such as plastics (figure 3.1).

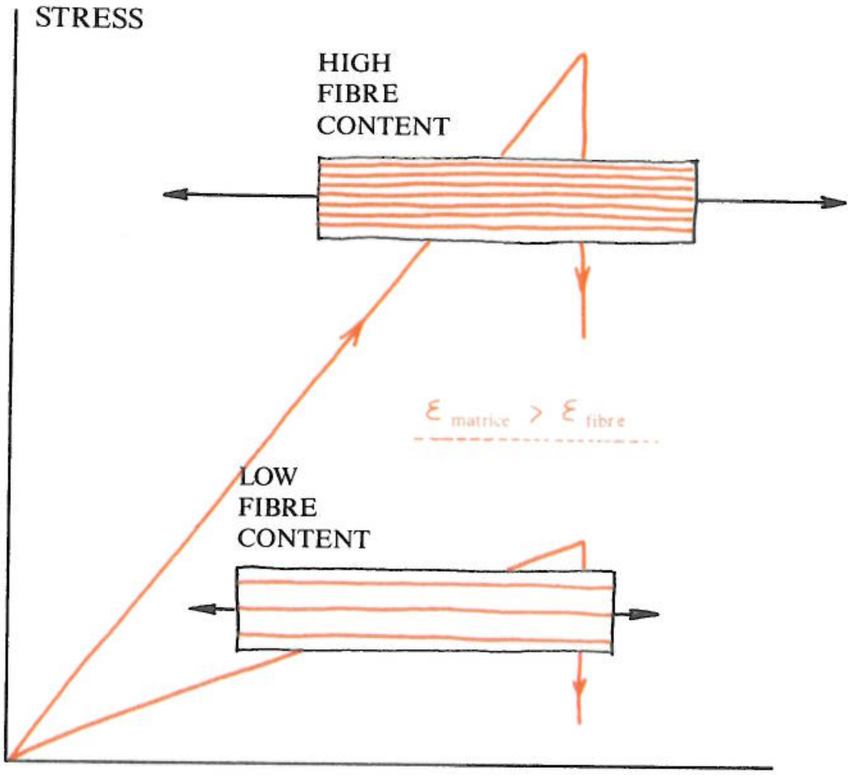


Fig. 3.1 Fibre composites with ductile matrix.

The ductile matrix ensures effective exploitation of the reinforcement, which can be loaded right up to failure before the matrix material fractures. (Sketch showing principle)..

Example: plastic reinforced with glass fibres or carbon fibres.

In materials with a brittle matrix such as reinforced concrete, the conditions are less favourable, the concrete cracking at tensile strains of only about 2-5% of the yield limit of the reinforcement.

With CRC, we have given cement-based materials ductility, so that the materials behave more like reinforced plastic than reinforced concrete.

The problems of making objects of reinforced brittle materials with good performance in tension arise from the fact that the ultimate tensile strains of the matrix materials are normally very low, and failure and cracking typically very brittle. Consequently, the matrix materials cannot follow major deformations of the reinforcement without cracking, which in turn means that the reinforcement cannot be utilized effectively in tension without the matrix materials cracking.

In reinforced concrete we can normally accept moderate tensile cracks. This is ensured by using moderate amounts of well-distributed reinforcement. When we attempt to utilize larger quantities of reinforcement the concrete fails (figure 2.6).

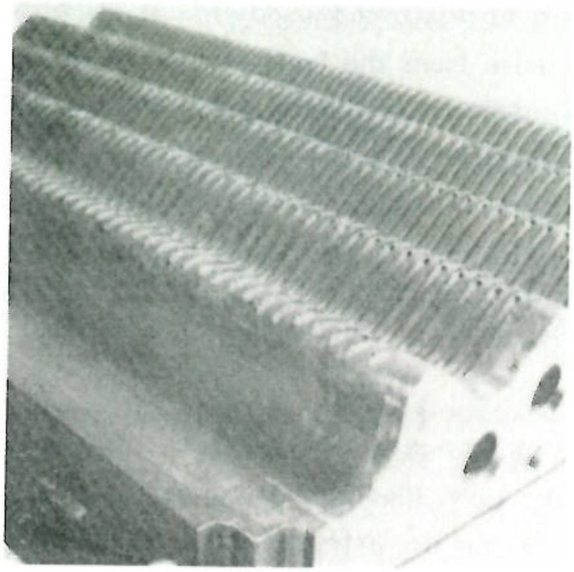
Reinforcement of brittle matrix materials requires fixation of reinforcement in the matrix in such a way that splitting and other destruction of the matrix do not occur.

In reinforced concrete, we strive to achieve good fixation of the reinforcement by observing a number of empirical rules about good distance between reinforcing bars, use of stabilizing secondary reinforcement, and so on.

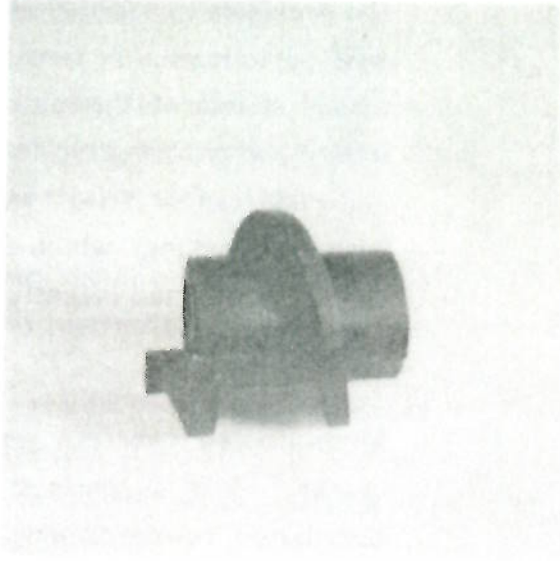
However, these design rules often prove entirely inadequate with high-strength concrete and are a serious obstacle to new development.

In the last ten years, work has been going on in various quarters to make use of fracture mechanics in the design of reinforced concrete. This is a logical move because failure and crack behaviour of reinforced brittle materials are naturally of a fracture-mechanical nature - and cannot be described purely on the basis of continuum mechanics.

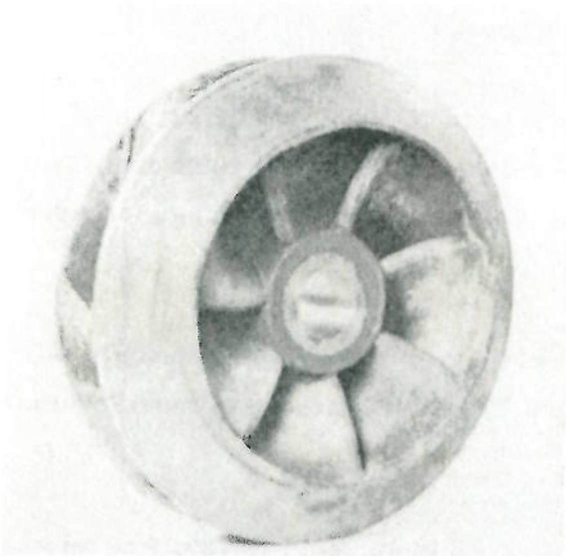
For example, design based on fracture mechanics has been used in connection with the development of new, high-strength, composite materials based on hard and strong, but also very brittle, matrix materials [2],[3]. The materials are often provided with ductility by means of fibre reinforcement (figure 3.2).



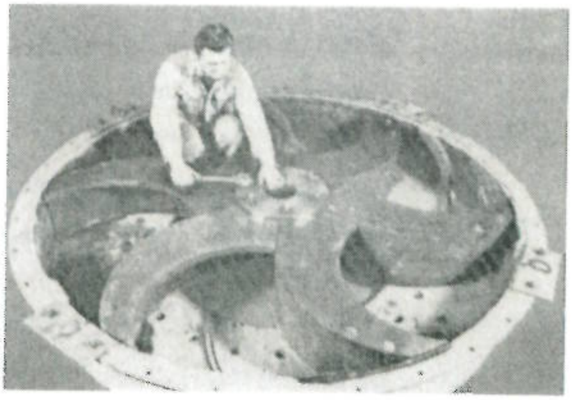
Bottom part of tool for pressing corrugated sheeting



Tip for screw-pump for fly ash



Impeller in a centrifugal pump



Scoop feeder for cement mill

Fig. 3.2 Machine components made of strong, dense concrete with a compressive strength of about 200-250 MPa and given considerable ductility by steel fibres.

The binder was made from well-dispersed mixtures of cement and microsilica with a water/cement + silica ratio of about 0.16 -0.20 by weight, and an Al_2-O_3-rich sand was used to secure high strength and high abrasion resistance. [3].

The purpose of basing design on fracture mechanics was to ensure that structures made of high-strength concrete did not get an undesirably high degree of brittleness but could be just as ductile as ordinary "reinforced concrete" despite the high strength.

In connection with the development of CRC, use is made of the specific possibilities offered by the new high-quality matrix materials for incorporating a very high degree of ductility by reason of their ability to fix high concentrations of very fine fibres in a very dense arrangement. This ensures a fascinating combination of extremely high strength and far greater ductility than in normal reinforced concrete and conventional fibre-reinforced cement-based materials (figure 3.3).

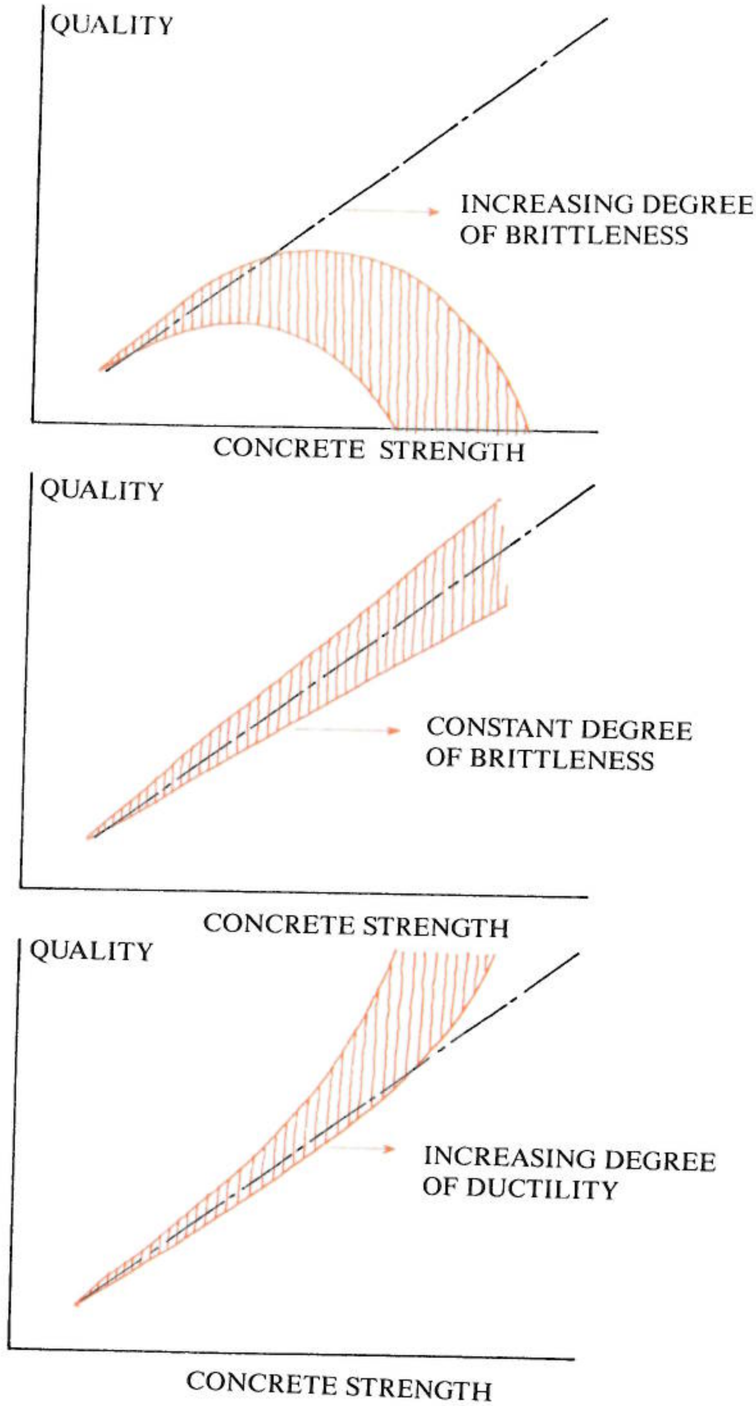


Fig. 3.3 Quality of reinforced concrete as function of concrete strength. Increased strength is accompanied by increased brittleness (top curve).

The increased brittleness is compensated for by adding fibres, whereby we exploit the strength of the concrete effectively (middle curve).

CRC is given far greater ductility - with heavy reinforcement with fine, strong fibres - than corresponding to the increased strength of the matrix material, which results in bodies with a combination of very high strength and exceptional ductility.

4. BRITTLENESS AND DUCTILITY

Brittleness and ductility are designations for behaviour occurring during fracture or yielding of solid bodies. They indicate relative behaviours, so it is more appropriate to indicate them by degree.

Brittleness and ductility are not material properties like strength, modulus of elasticity, and hardness, but designations describing the behaviour of "bodies", as the behaviour depends on the size and shape of the bodies.

It is thus imprecise and often misleading to talk of "brittle materials" and "ductile materials", as is usually done - (also in this article). For example, so-called brittle materials like concrete, ceramics, and glass, can exhibit ductile behaviour in bodies that are sufficiently small, whereas large bodies made of metal (where failure takes the form of plastic yielding) can exhibit distinctly brittle behaviour.

It is therefore more correct to speak of brittle and ductile behaviour and more precise to indicate a degree of brittleness or ductility.

The question is, what is understood by degree of brittleness or ductility and how these degrees can be quantified.

A generally valid quantification that would, for example, enable comparison of the degrees of brittleness of a china vase and a concrete pipe, is not possible.

It is possible, on the other hand, to quantify uniquely the degree of brittleness/ductility of geometrically similar bodies [4],[5].

The quantities quantifying brittleness and ductility are designated "brittleness number" and "ductility number" and are defined as follows:

$$B = \text{const.}\ \frac{\sigma_o^2 L}{E\,G} \quad \text{(brittleness number)}$$

and the reciprocal value:

$$D = \text{const.}\ \frac{E\,G}{\sigma_o^2 L} \quad \text{(ductility number),}$$

where σ_o, E and G are material parameters (tensile strength, modulus of elasticity and fracture energy, respectively), and L is a characteristic length of the body. B and D are dimensionless quantities. An example is shown in figure 4.1.

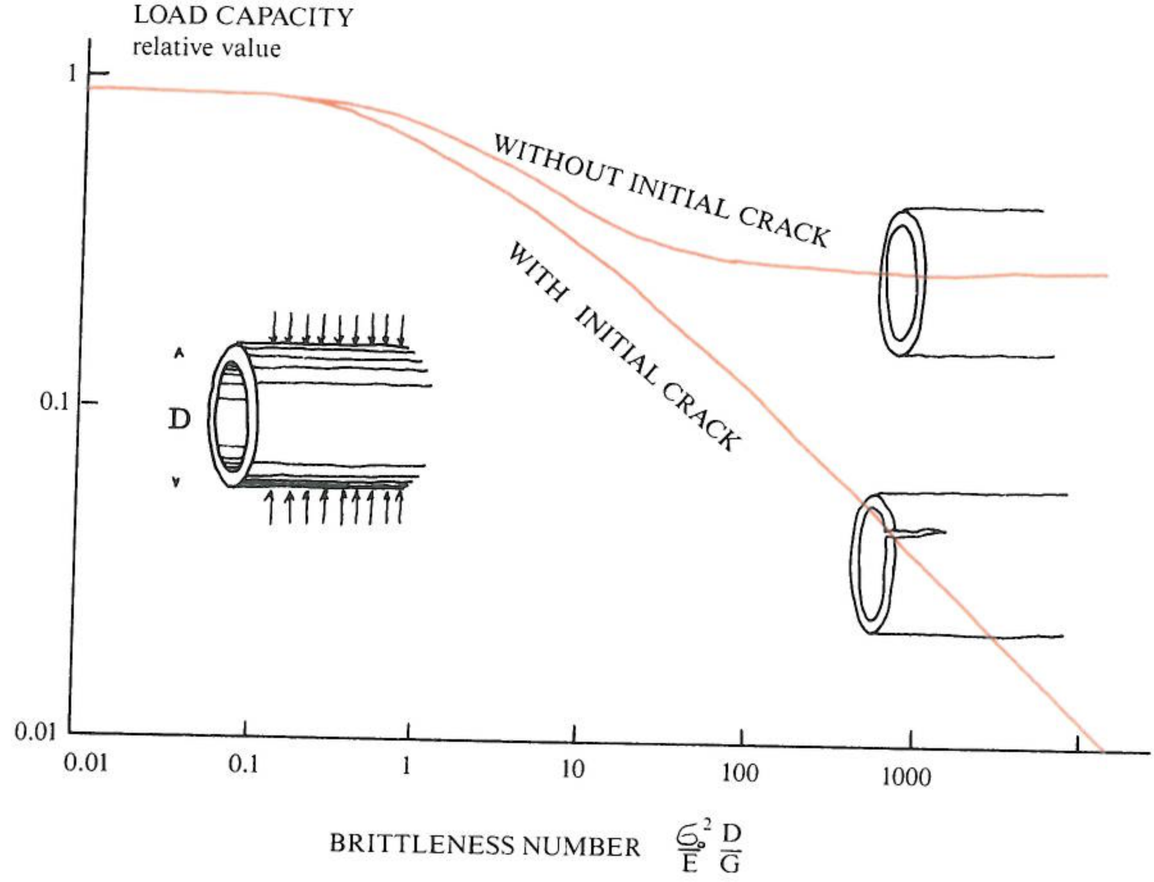


Fig. 4.1 Failure/yield behaviour as function of degree of brittleness for geometrically similar bodies -cylindrical pipes with and without initial crack. (the size of the crack is here assumed to be proportional to the size of the body). The ordinate is the load capacity divided by the corresponding value for bodies with ideal ductile behaviour, and the abscissa is the brittleness number, where the pipe diamter (D) is chosen as characteristic length. E is the modulus of elasticity, G the fracture energy, and σ_o the tensile strength.
Sketch showing principle.

In zones with low values of the brittleness number, the behaviour is distinctly ductile, characterized by:

1. simultaneous "yielding" in a substantial part of the failure zones,

   the behaviour at failure not being particularly sensitive to sharp notches and cracks and internal stresses,

   a high load capacity because large yield reserves are exploited.

In zones with high values of the brittleness number, the behaviour is brittle, characterized by:

1. local failure and cracking, where only a narrow zone at the tip of the crack is heavily loaded,
2. normally a smaller load capacity than in a body showing ductile behaviour - even for perfect crack-free bodies, because the yield reserves are not exploited,
3. the load capacity being extremely sensitive to sharp notches and cracks and internal stresses.

Degree of brittleness/ductility can be related to whole bodies (cf. figure 4.1) or to parts of bodies. An example of local fracture and/or yielding behaviour is shown in figure 4.2.

In CRC, we seek to establish distinctly ductile behaviour in connection with fibre pull-out and at sliding of main reinforcement during yielding. This is ensured by several means, including the use of fine reinforcement (D small) and a fibre-reinforced matrix with high fracture energy (G).

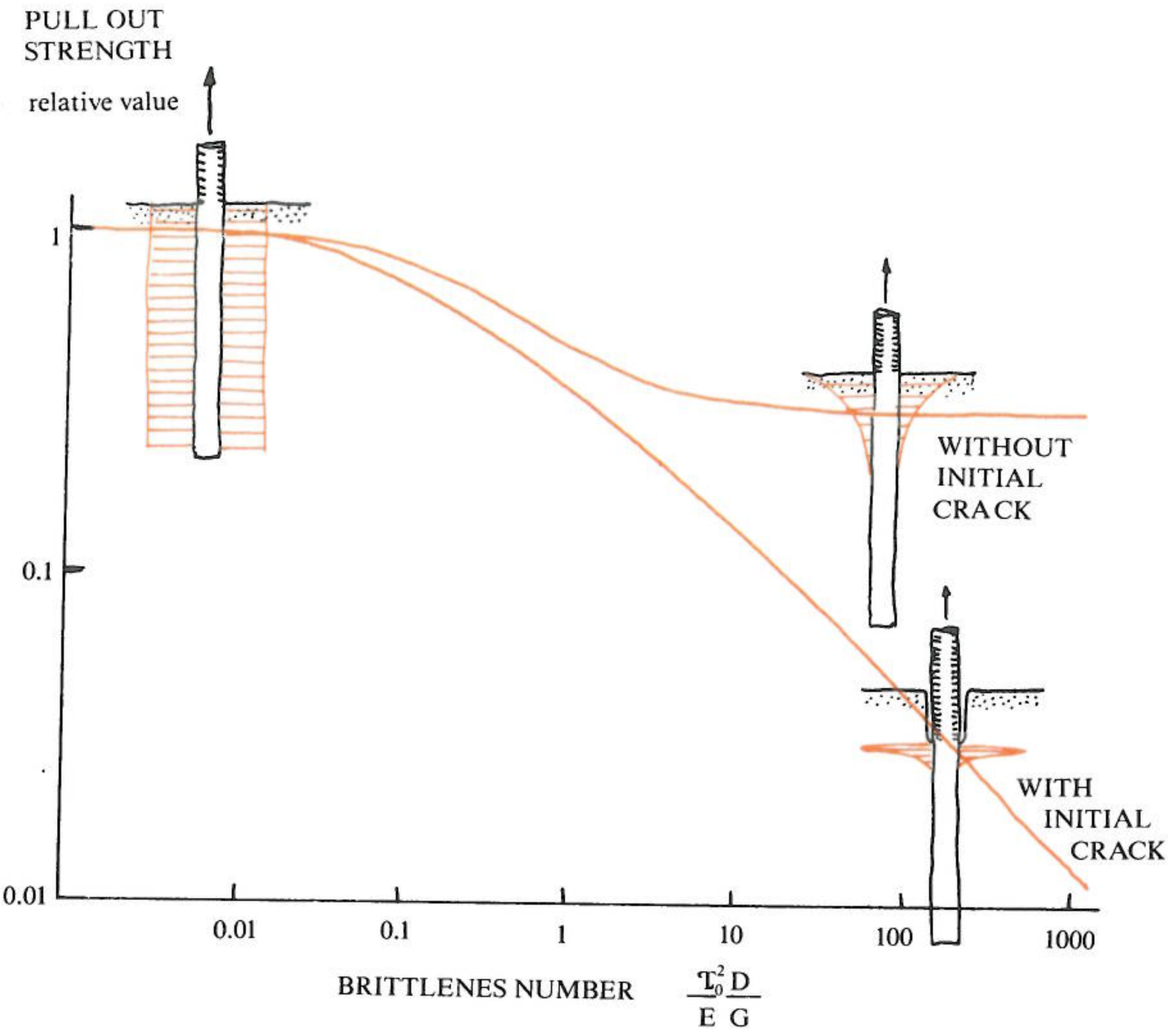


Fig. 4.2 Resistance to pulling-out of reinforcement as a function of the brittleness number. (Sketch showing principle).

τ_0 is the shear stress during sliding between reinforcement and matrix, G the fracture energy of the interface between reinforcement and matrix, E the modulus of elasticity of the reinforcement, and D the diameter of the reinforcement. The size of the initial cracks is here assumed to be proportional to the size of the reinforcement.

In CRC, ductile behaviour is aimed at, i.e. a small brittleness number.

5. FRACTURE ENERGY AND CRACK ZONE DEFORMATION

The degree of brittleness is closely related to what happens locally in the fracture zone. Before separating, brittle materials like glass, ceramics, and concrete, deform in narrow zones (crack zones), as illustrated in figure 5.1.

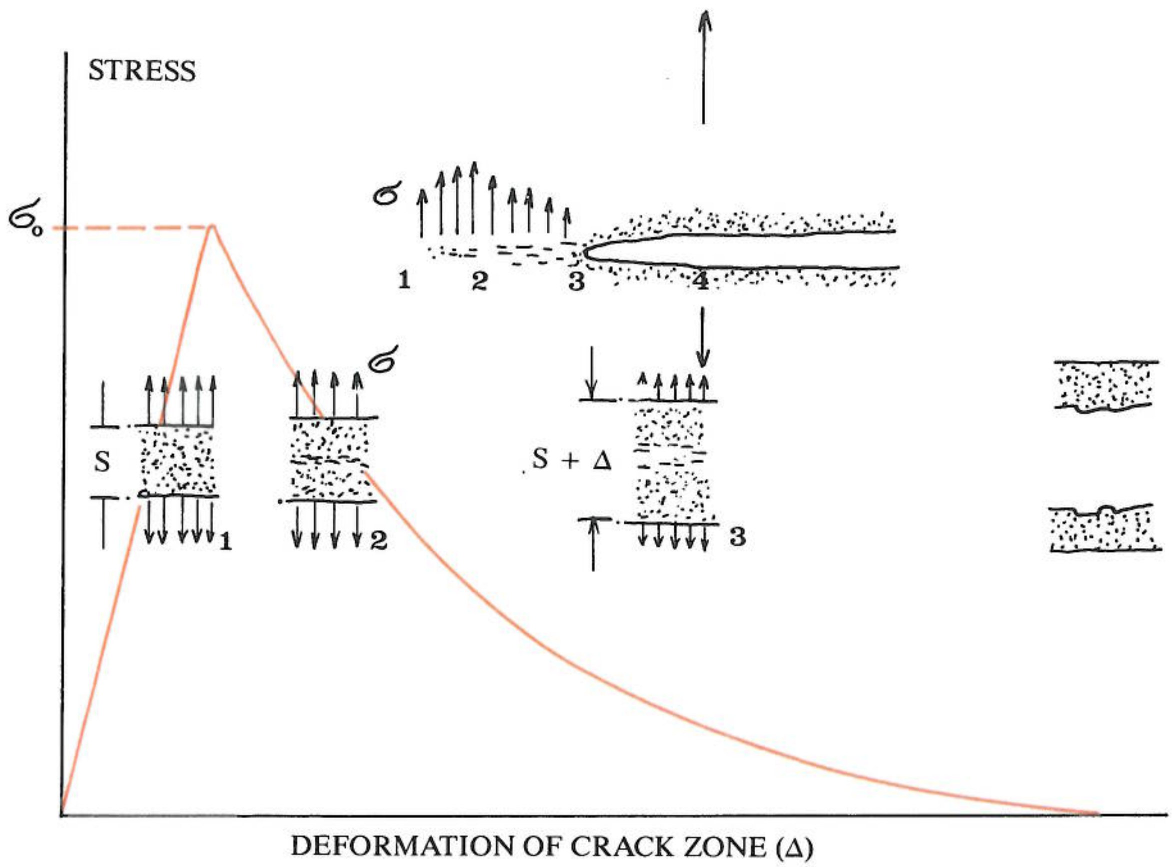


Fig. 5.1 Stress-deformation relationship in crack zone during tensile opening of crack in brittle material.

Up to maximum stress, the material deforms elastically. After maximum stress is reached, a small but important extra deformation - crack zone deformation - occurs.

For glass, the crack zone deformation is about 0.01-0.001 μm, while it is 2-10 μm for cement paste, 10-50 μm for concrete, and about 1 mm for the fibre-reinforced "concrete" used in CRC. The crack zone deformation Δ_o is of the order of magnitude G/σ_o, where G is the fracture energy (the area below the curve) and σ_o is the tensile strength.

In separation failure in ideal crystals through peeling open of sharp cracks along lattice planes, the crack zone deformations are small (of atomar size - about 10^{-10}m), and the separation work (fracture energy) is correspondingly small. The energy is largely equal to the theoretical value corresponding to the work of breaking the chemical bonds in the fracture face.

Bodies made of such perfect materials exhibit extreme brittleness and crack sensitivity. The cracks are very sharp, with a fictive radius of curvature of the size of one atom.

Many technical materials normally regarded as brittle have far greater crack zone deformations. Owing to the larger deformations, the fracture energy is normally also greater than for the "perfect materials", even though the tensile strength is lower. During tensile loading, pseudoplastic yielding takes place in a -measured on the atomic scale - much larger zone around the coming crack.

In tensile tests on concrete or mortar, only very moderate crack zone deformation, or none at all, was observed before the maximum load was reached. Thereafter, massive deformation occurred in the narrow crack zones, while the force transmission gradually diminished, indicating that local structural destruction had taken place before real cracking.

This behaviour is believed to be typical of materials held together by directionally oriented chemical bonds (covalent or ionic), which, unlike non-directionally oriented chemical bonds (metal bonds), are unable to re-establish atomic bonds and to get the material to exhibit yielding at the atomic level.

The fact that the stress over the crack zone diminishes with increasing crack zone deformation in brittle materials is perhaps the main reason why such materials are not as suitable for structural purposes as metals showing stress increase during yielding - "strain hardening" (figure 5.2).

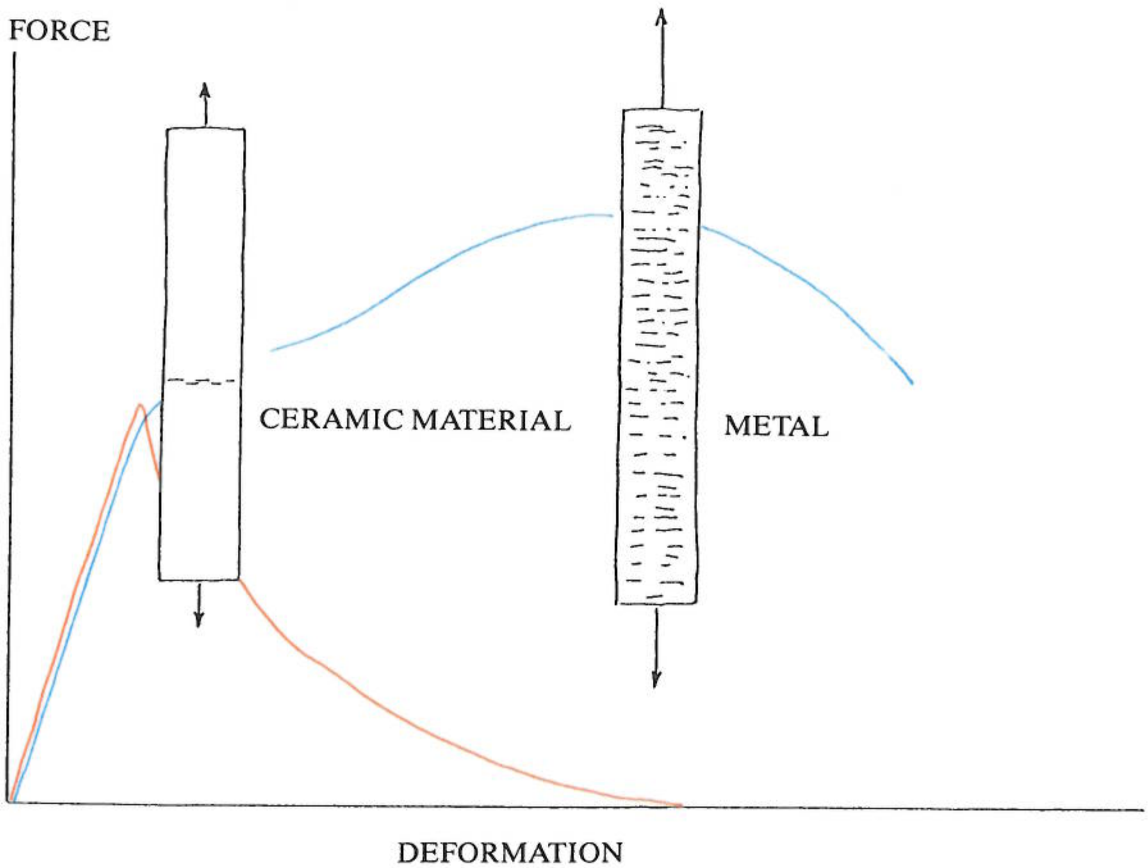


Fig. 5.2 Tensile behaviour of a bar of a "ceramic material" and a metal bar.

The ceramic bar fractures at the first "yield tendency" without yielding outside the narrow fracture zone.

The metal bar exhibits increased internal resistance during commencement of yielding, whereby the yielding spreads out over the volume - an effect that is termed strain hardening. (Sketch showing principle).

For most "brittle" materials, we know very little about the structural changes that take place in crack zones. Indirectly, we can state that a crack zone deformation of a given order of magnitude will take place. The crack zone deformation (Δ_o) is of the magnitude of the ratio between the material's fracture energy (G) and its tensile strength (σ_o), both of which are measurable quantities [4],[5]:

$$\Delta_o = G/\sigma_o$$

This statement is very important because it tells us about a behaviour that can be extremely difficult to observe directly. It tells us, for example, that crack zone deformations of the order of magnitude 0.1 to 1 μm occur during failure and cracking in strong, brittle ceramics - a fact that has rarely, if ever, been recognized. What happens to the microstructure during cracking is still largely unresearched.

6. FRACTURE STRAIN OF "BRITTLE" MATERIALS

The ultimate tensile strain of materials is normally defined as the ratio between the deformation of a test body just before failure and the length of the body in tensile tests. For brittle materials, the ultimate strain found in this way is regarded as a material constant that is independent of the size of the body (apart from a statistical effect with which we shall not concern ourselves here). This conception implies that crack zone deformations have no effect on the magnitude of the total deformation.

This is only true for bodies where the elastic deformation before fracture dominates complely. The criterion for such behaviour is expressed by the brittleness number being large (viz. figure 6.1).

For uncracked bodies, initiation of a crack will occur when the mean strain reaches the ultimate tensile strain of the material.

If the deformation is further increased, an extra deformation of the material will occur in a narrow zone - the crack zone -and, at the same time, the tensile stress will fall and a corresponding contraction of the material outside the crack zone will therefore take place [6],[7].

If the total deformation of material outside the crack zone is great in relation to the deformation within the crack zone, brittle and sudden failure will take place as soon as the ultimate strain is reached (figure 6.1).

If, on the other hand, the crack zone deformation is great in relation to the deformations outside the crack zone, the body will fail in a ductile manner (see figure 6.2). In this case, the total deformation will be almost identical to the crack zone deformation, and the mean strain will be almost equal to to the crack zone deformation divided by the size of the body.

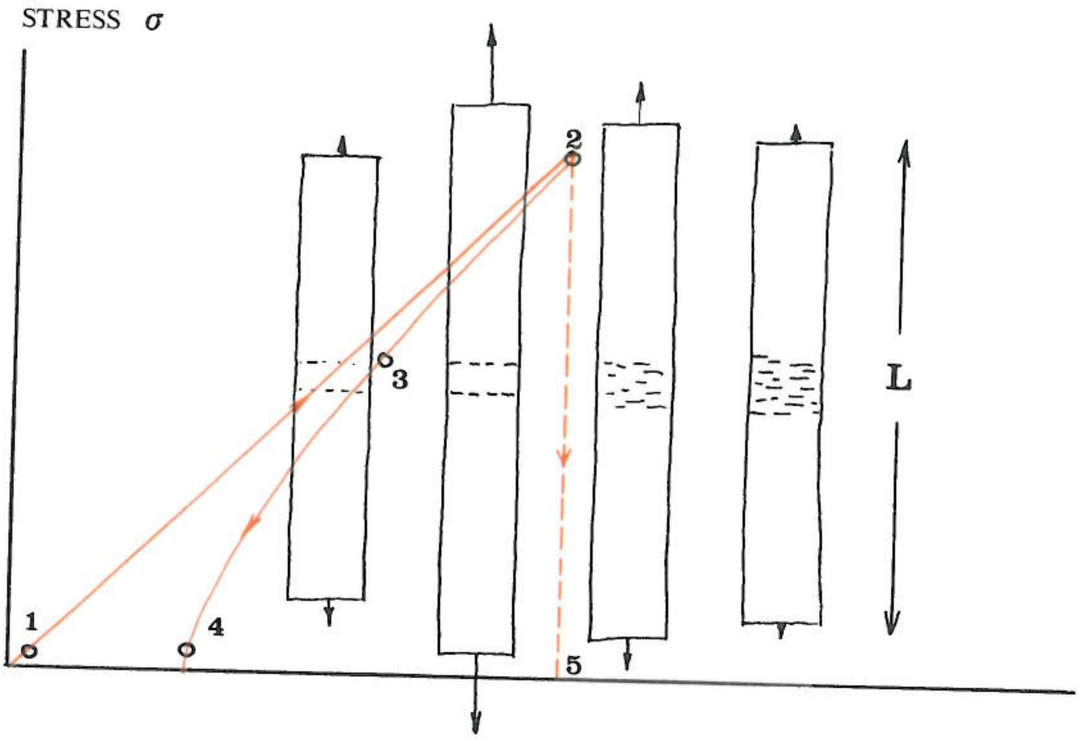


Fig. 6.1 Tensile behaviour of a body showing brittle behaviour.

The rod (length L) deforms elastically under increasing loading until crack initiation (2); the crack zone then deforms and, at the same time, the load diminishes and the material outside the crack zone is deloaded and contracts (curve 2-3-4).

In tests with steadily increasing deformation loading, the rod fractures suddenly (curve 2-5).

The ratio between the maximum elastic deformation δ_2 and the crack zone deformation $\Delta_0 \simeq \delta_4$ is a measure of the degree of brittleness:

$$\frac{\delta_2}{\delta_4} \simeq \frac{\varepsilon_0 L}{\Delta_0} \simeq \frac{\sigma_0^2 L}{E G} \qquad \text{(brittleness number)}$$

Here, the brittleness number is large.

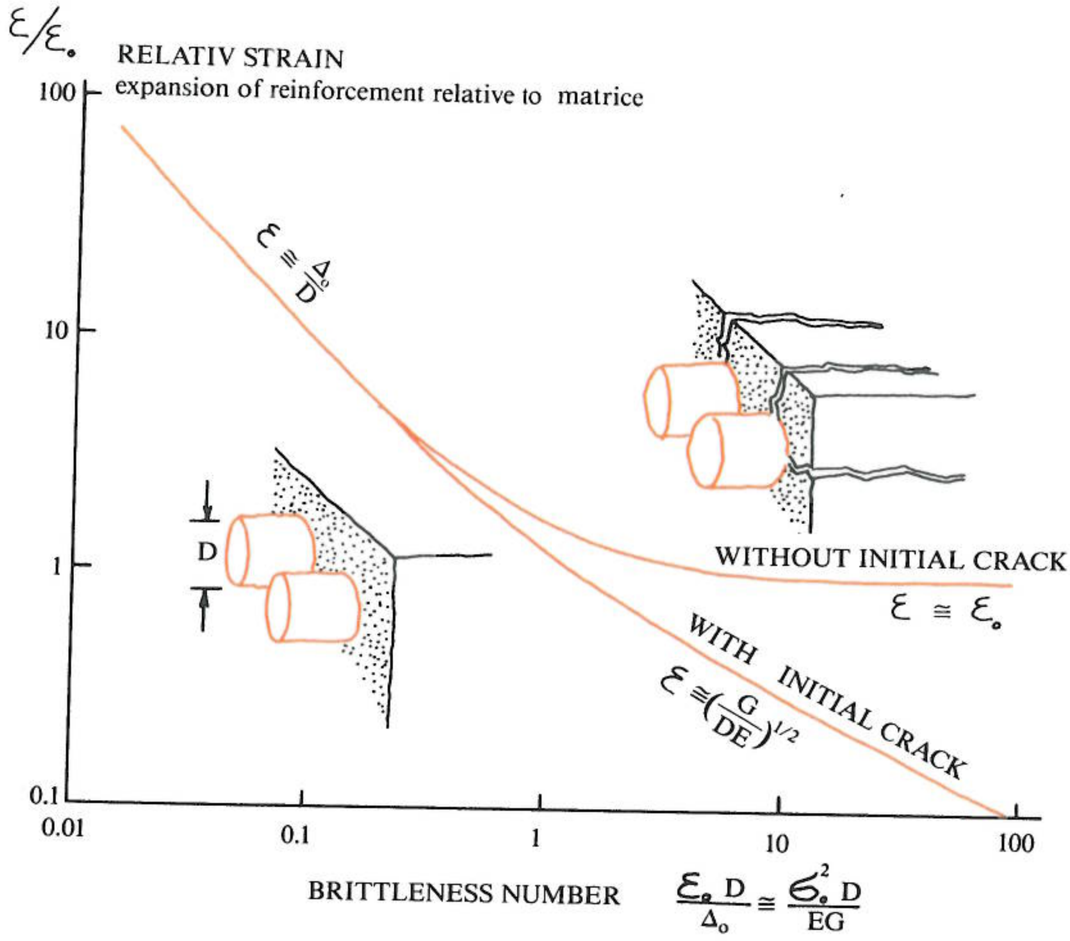


Fig. 6.3 Ultimate strain of the matrix when reinforcement expands relative to the matrix, as a function of brittleness number. (Sketch showing principle).

For bodies with brittle behaviour, the ultimate strain (ε) is equal to the material's ultimate tensile strain in bulk for perfect, uncracked bodies (ε_0).

For bodies with cracks, the ultimate strain decreases with increasing brittleness in accordance with a square root relationship (the crack length being assumed to be proportional to the size of the body).

For bodies with ductile behaviour, the ultimate strain increases with decreasing brittleness in accordance with a linear relationship.

Δ_0 is the crack zone deformation, E the modulus of elasticity, G the fracture energy, and σ_0 the tensile strength.

7. REINFORCEMENT FUNCTIONS

In systems with brittle matrices, reinforcement can be utilized in different ways and serve different purposes:

1. transmission of tensile forces,
2. control of the distribution of cracks and crack widths,
3. creation of a stabilizing compressive stress field in the matrix through prestressing,
4. giving the matrix material ductility,
5. control of the propagation of matrix cracks,
6. increasing the strain before matrix cracks start forming.

In the following, a short explanation is given of the mode of operation of reinforcement in normal reinforced concrete and fibre-reinforced concrete (cf. points 1, 2 and 4). An account is then given (in sections 8 and 9) of the special, less known aspects and potentials (points 5 and 6).

Figure 7.1 shows the behaviour of reinforced and unreinforced specimens loaded in tension up to failure.

When reinforced specimens are subjected to tension with steadily increasing deformation, the matrix will (normally) fracture at almost the same strain as the unreinforced matrix. Immediately after the matrix fractures, the load is carried past the cracks by the reinforcement.

Thus, the two systems do not differ from each other with respect to strain capacity as far as the matrix is concerned. The difference between them lies in the fact that the average stress at which the matrix fractures is slightly different (the stress is larger if the reinforcing material is stiffer than the matrix material, and vice versa) and that the reinforced material is capable of carrying loads also after the fracture occurs in the matrix, the load being carried past the cracks by the reinforcement.

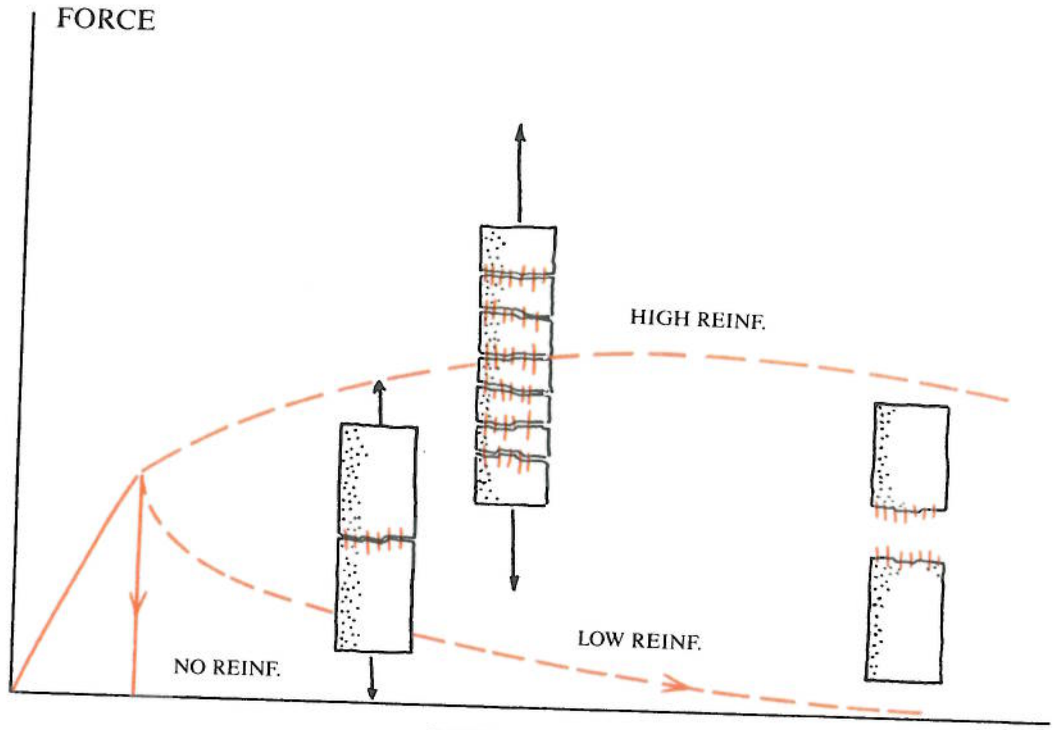


Fig. 7.1 Typical tensile behaviour of traditional, unreinforced and reinforced brittle materials. (Sketch showing principle).

At strains of the order of magnitude of the ultimate tensile strain of the matrix material, the matrix of the reinforced specimens cracks past the reinforcement, which takes over the load. With a low reinforcement effect, a single crack forms, while with a high reinforcement effect, multiple cracking occurs.

In CRC, the behaviour is fundamentally different, the crack strains being 1-2 orders of magnitude higher than for the unreinforced matrix material (see sections 8 and 9).

The behaviours discussed above, which represent "normal behaviour" for fibre-reinforced mortar and concrete, all have the common feature that the matrix starts to crack at largely the same strain as the unreinforced concrete. The crack bypasses both main reinforcement and fibres. This is the generally accepted behaviour of reinforced, brittle materials with matrix materials having a much smaller strain capacity than that of the reinforcement.

However, with special combinations of fibres and matrix, it is possible to break this "law" and obtain a genuine increase of the strain at which cracks start forming in the matrix.

This aspect, which is essential to CRC, is treated in the following two sections.

8. CRACK PROPAGATION PAST REINFORCEMENT

Structural destruction/cracks

Before we consider crack propagation past reinforcement, it is desirable to make it clear what is meant in this context by the concept crack and uncracked material with discrete - minor - structural destruction.

When CRC is subjected to large tensile loads, some structural destruction of the matrix material occurs - characterized by breaking of atomar bonds without re-establishment of corresponding bonds. The destruction that occurs is typically destruction in very small, discrete zones, for which reason the material is described as uncracked, despite some internal structural destruction. To avoid misunderstandings, it should be noted that the term cracks, in the context of this article, means narrow zones (formed by separation of material) which cannot transmit tensile forces acting at right angles to themselves, and whose extent in their own plane is large in relation to a reference length. Here, a crack is thus defined purely mechanically (lack of ability to transmit forces) and a size-criterion is attach to the definition.

Thus, when crack-free fibre-reinforced concrete is mentioned, it means fibre-reinforced concrete in which matrix destruction does not propagate past the fibre reinforcement and in which any structural destruction is smaller than the fibre spacing or the same size.

In the same way, crack-free reinforced concrete means that the reinforced concrete in question contains no cracks significantly larger than the distance between the main reinforcing components.

If, in another context, we consider a material with structural destruction limited to small, discrete zones on a smaller scale - for example, where the reference length corresponds to the size of the cement particles (5-10 μm), the destruction can be characterized as cracks even though, in a larger-scale description, the material is characterized as crack-free.

Here, it will often be convenient to use the term microcracks, where micro refers to the extent of the cracks in their own plane, not their width.

In connection with CRC, the concept crack-free, seen in contrast to cracks propagating past reinforcement, plays a fundamental role, because CRC, with reference to both main reinforcement and fibre reinforcement, typically exhibits crack-free behaviour up to the yield limit of the main reinforcement, whereas, in traditional materials, cracks propagate past the reinforcement. This is illustrated in fig. 8.1.

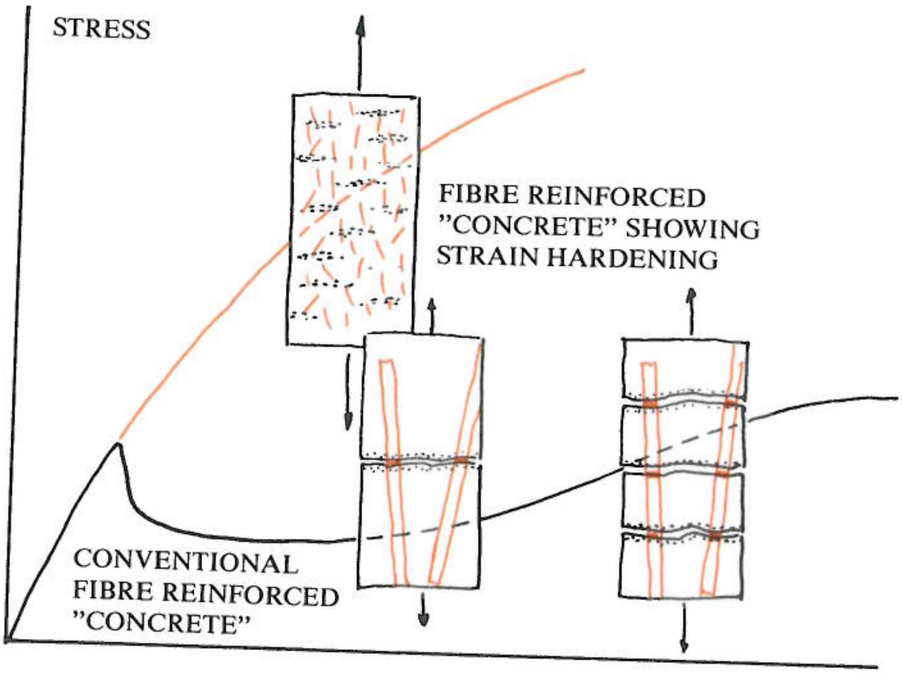


Fig. 8.1 Two heavily reinforced bodies loaded beyond the ultimate tensile strain of the matrix material, one exhibiting strain hardening with crack-free behaviour (A) and the other exhibiting multiple cracking (B).

In the material with crack-free behaviour, structural destruction occurs in the form of crack zones that are smaller than the reinforcement spacing, while in that with multiple cracking, the structural destruction of the matrix material takes the form of zones (cracks) that are large in relation to the reinforcement spacing.

Behaviour (A) is characteristic of the fibre-reinforced matrix materials used in CRC, while multiple cracking is typical of most of the conventional, heavily reinforced, cement-based materials.

The models for systems subjected to external tension are basically identical to models presented by Aveston, Cooper and Kelly 9 .

Fluid-loaded systems are included partly because crack behaviour and principles of analysis are more easily visualized here and partly because fluid loading in cracks often occurs in practice.

The models are derived for idealized systems - with parallel reinforcement, linear-elastic behaviour, sliding between reinforcement and matrix with constant shear stress etc.

The models cannot be used for precise, quantitative calculations but can be used for qualitative evaluations and considerations concerning order of magnitude.

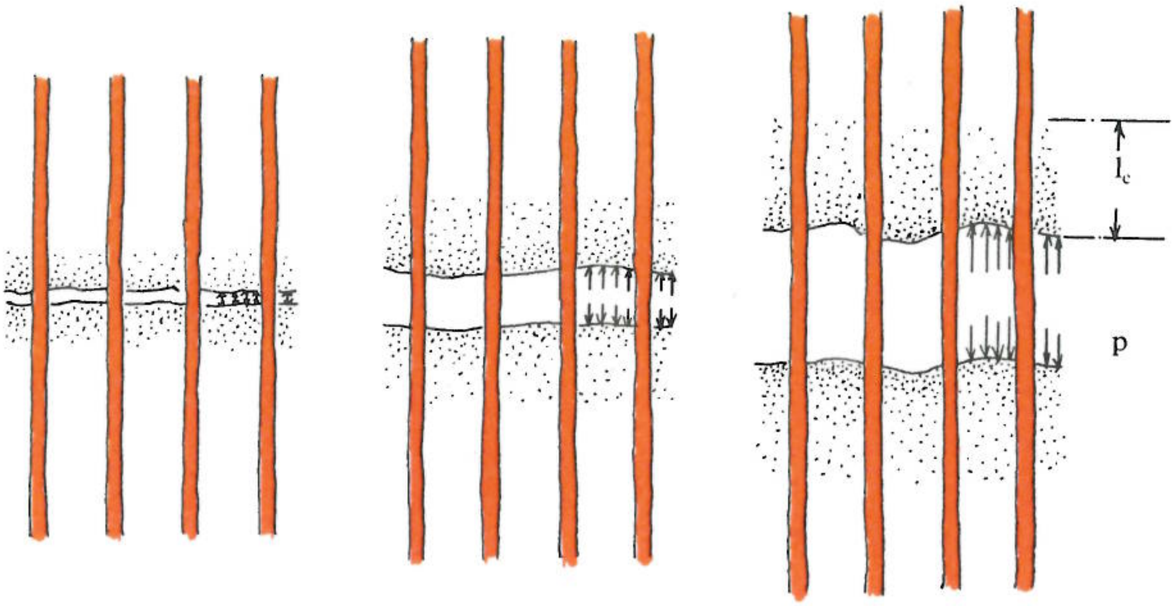
Fluid-loaded systems

Let us consider first a system with a crack all the way through the matrix, bypassing the reinforcement and assume that, before loading, the crack is infinitely thin (but incapable of transmitting forces).

Under fluid-loading in the crack, the crack adjusts itself in an equilibrium condition (equilibrium crack opening), where the reinforcement is stretched in a small anchorage zone on either side of the crack and the matrix is at the same time compressed (figure 8.3).

The material outside the anchorage zone is unstressed.

The thickness of the anchorage zone (l_c) grows proportionally with the fluid pressure (p), and the deformations (the crack opening (Δ)) increase proportionally with the product of the fluid pressure times the thickness of the anchorage zone - in other words, proportionally with the square of the fluid pressure. The work (w) required to open the crack increases proportionally with the product of the crack opening and the fluid pressure - in other words, proportionally with the cube of the pressure.



$p = p_0$ $\qquad$ $p = 2p_0$ $\qquad$ $p = 3p_0$

Fig. 8.3 Crack opening in a reinforced material loaded by internal fluid pressure acting in the crack..

l_c	Thickness of crack zone	$\frac{1}{2}\frac{1-\varphi}{\varphi}\frac{p}{\tau}r$
δ	Crack opening (thickness)	$\frac{1}{2}\left(\frac{1-\varphi}{\varphi}\right)^2\left(1+\frac{\varphi}{1-\varphi}\frac{E_f}{E_m}\right)\frac{p^2 r}{\tau E_f}$
	External work per area crack	$2p\delta(1-\varphi)$
	Internal work per area crack	$\frac{1}{3}\frac{(1-\varphi)^2}{\varphi}\frac{p^3 r}{E_m\tau}+\frac{1}{3}\frac{(1-\varphi)^3}{\varphi^2}\frac{p^3 r}{E_f\tau}$

where p is the fluid pressure, r the fibre radius, τ the shear stress during fibre sliding, E_m and E_f the modulus of elasticity of the matrix and the fibre, respectively, and φ the volume concentration of fibres [8].

Let us now consider a similar system, where, however, the crack has not propagated through the entire body. At low fluid pressure the material in front of the crack counteracts its propagation. When the crack propagates under internal fluid pressure, the matrix material in front of the crack peels open; this is accompanied by simultaneous elongation of the reinforcement and compression of the matrix, accompanied by shearing between fibres and matrix. The critical fluid pressure at which the crack just propagates is found as the pressure at which the work performed by the fluid pressure is equal to the internal deformation work (elastic deformation of reinforcement and matrix + sliding work and work to form a new matrix crack).

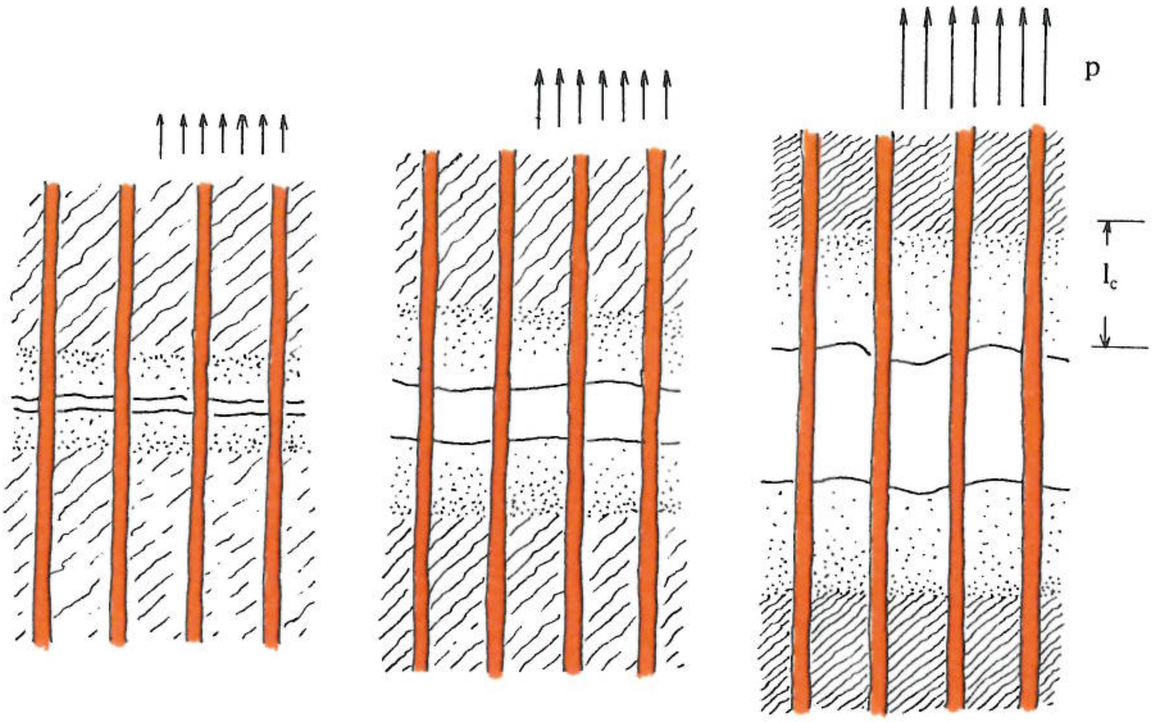
The resistance to crack propagation depends partly on how difficult it is to open an existing crack against the reinforcement and partly on the resistance to peeling opening of the matrix material in front of the crack.

The resistance to deformation (opening) of the crack against the fibre anchorage increases with increasing stiffness of the components (increases with increasing E_m, E_f) and decreasing thickness of the fixation zone l_c (diminishes with increasing E_m, E_c and and diminishing d), and the resistance to peeling opening of the matrix material in front of the crack increases with increasing critical stress intensity factor K_{IC} of the matrix material ($K_{IC} = \sqrt{E_m G_m}$). The theoretical expression of the critical fluid pressure is:

Systems loaded with external tensile stresses

For systems subjected to external tensile loading, the behaviour is almost identical, except that the material outside the crack zone is loaded and the matrix material in the crack zone is not subjected to compression but relief of the tensile stresses. The behaviour of the material in the crack zone is shown in figure 8.4.

The calculations are slightly more complicated than under fluid loading. The theoretical expression for the critical tensile load is shown in figure 8.4, and calculated crack propagation criteria for a number of reinforced materials are shown in figure 8.5.



$p = p_0$ $p = 2p_0$ $p = 3p_0$

Fig. 8.4 Crack opening in a reinforced material subjected to external tension.

l_c	Thickness of crack zone	$\frac{1}{2}\frac{1-\varphi}{\varphi}\left(1-\varphi+\varphi\frac{E_f}{E_m}\right)^{-1}\frac{pr}{\tau}$
δ	Crack opening (thickness)	$\frac{1}{2}\frac{1-\varphi}{\varphi}\left(1+\frac{1-\varphi}{\varphi}\frac{E_m}{E_f}\right)\left(1-\varphi+\varphi\frac{E_f}{E_m}\right)^{-2}\frac{p^2 r}{\tau E_m}$
	External work per area crack	$2p\delta$
	Internal work per area crack	$\left[\frac{1}{3}\frac{(1-\varphi)^3}{\varphi^2}\frac{p^3 r}{E_f \tau}+\frac{1}{3}\frac{1-\varphi^2}{\varphi}\frac{p^3 r}{E_m \tau}\right]\left(1-\varphi+\varphi\frac{E_f}{E_m}\right)^{-3}$

where p is the fluid pressure, r the fibre radius, τ the shear stress during fibre sliding, E_m and E_f the modulus of elasticity of the matrix and the fibre, respectively, and φ the volume concentration of fibres [8].

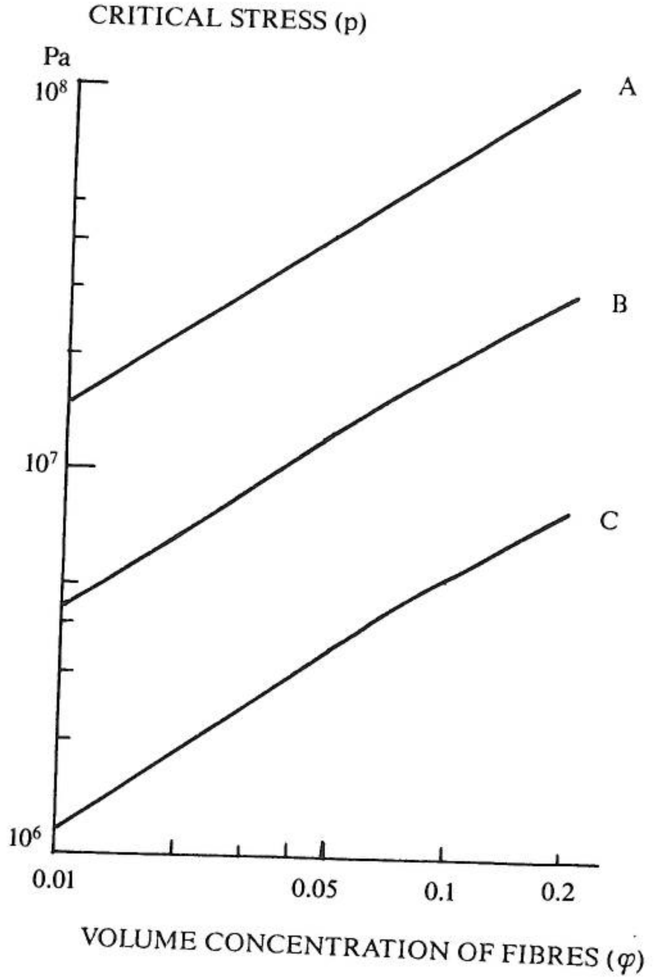


Fig. 8.5 Critical external tensile stress for propagation of crack past reinforcement.

Critical state where cracks just propagate past the reinforcement; as a function of the volume concentration of reinforcement - calculated for three different types of composite material from models described in [8].

Composite material	Type		A	B	C
E-modulus of reinforcement	(E_f)	MPa	200,000	20,000	2,000
E-modulus of matrix	(E_m)	MPa	50,000	50,000	10,000
Fracture energy of matrix	(G_m)	N/m	100	100	10
Shear stress	(τ)	MPa	20	5	1
Diameter of reinforcement	(d)	μm	150	150	150

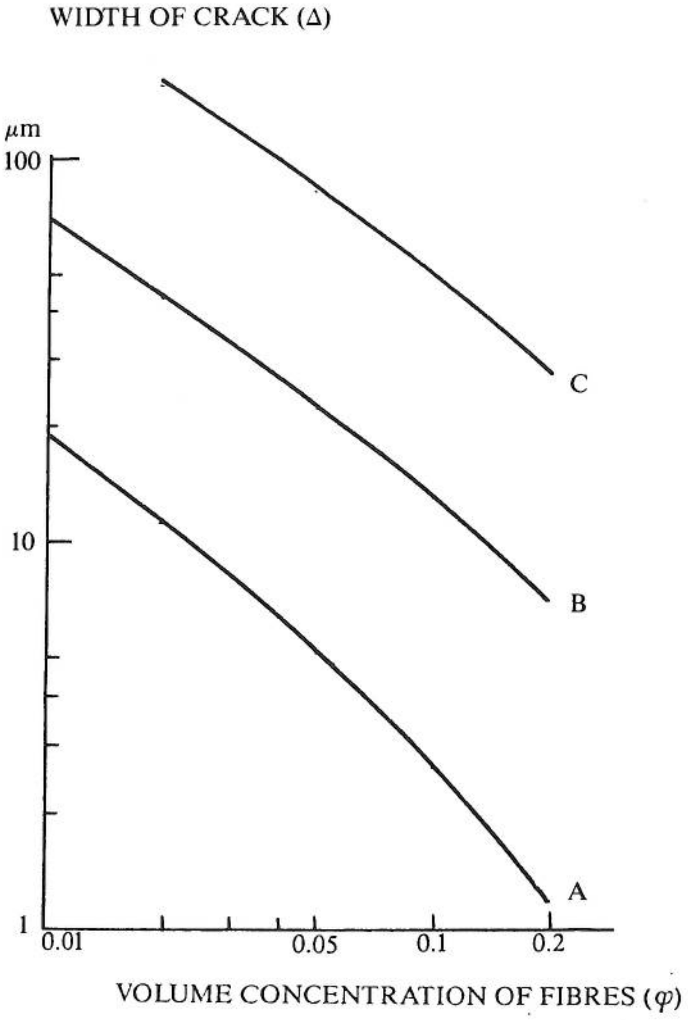


Fig. 8.6 Width of matrix crack in the critical state.
Under further loading the crack width grows proportionally with the square on the load - until the reinforcement function changes (or fails).

Critical state where cracks just propagate past the reinforcement; as a function of the volume concentration of reinforcement - calculated for three different types of composite material from models described in [8].

Composite material	Type		A	B	C
E-modulus of reinforcement	(E_f)	MPa	200,000	20,000	2,000
E-modulus of matrix	(E_m)	MPa	50,000	50,000	10,000
Fracture energy of matrix	(G_m)	N/m	100	100	10
Shear stress	(τ)	MPa	20	5	1
Diameter of reinforcement	(d)	μm	150	150	150

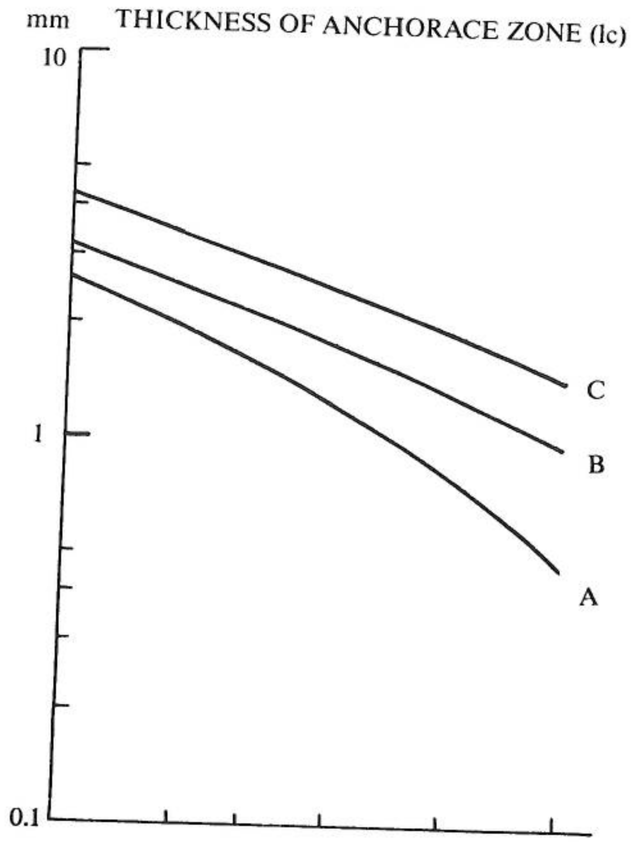


Fig. 8.7 Thickness of anchorage in the critical state.

Under further loading, the crack zone grows proportionally with the load.

Critical state where cracks just propagate past the reinforcement; as a function of the volume concentration of reinforcement - calculated for three different types of composite material from models described in [8].

Composite material	Type		A	B	C
E-modulus of reinforcement	(E_f)	MPa	200,000	20,000	2,000
E-modulus of matrix	(E_m)	MPa	50,000	50,000	10,000
Fracture energy of matrix	(G_m)	N/m	100	100	10
Shear stress	(τ)	MPa	20	5	1
Diameter of reinforcement	(d)	μm	150	150	150

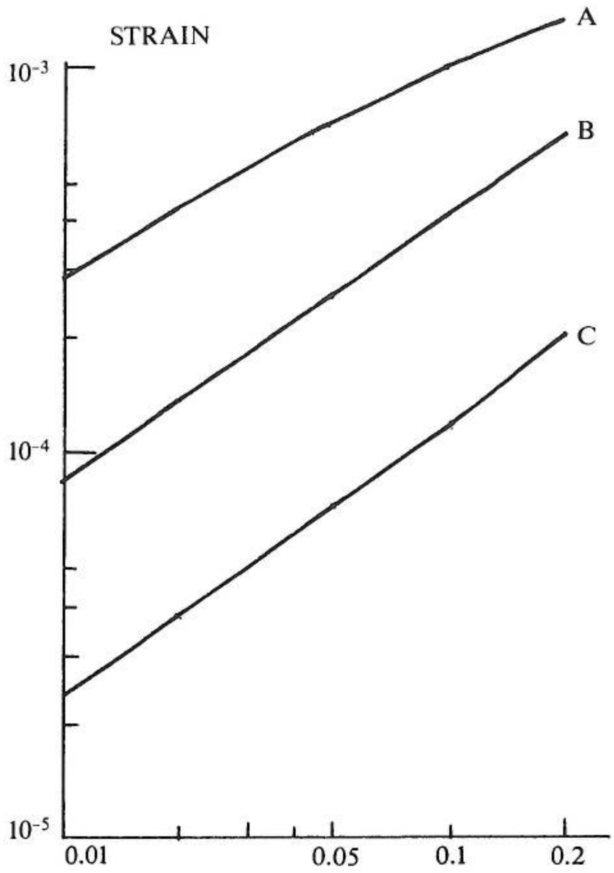


Fig. 8.8 Strain of material outside the anchorage zones in the critical state.

Under further loading the strain increases proportionally with the load - and at the same time, the number, width and total deformation of the anchorage zones increase.

Critical state where cracks just propagate past the reinforcement; as a function of the volume concentration of reinforcement - calculated for three different types of composite material from models described in [8].

Composite material	Type		A	B	C
E-modulus of reinforcement	(E_f)	MPa	200,000	20,000	2,000
E-modulus of matrix	(E_m)	MPa	50,000	50,000	10,000
Fracture energy of matrix	(G_m)	N/m	100	100	10
Shear stress	(τ)	MPa	20	5	1
Diameter of reinforcement	(d)	μm	150	150	150

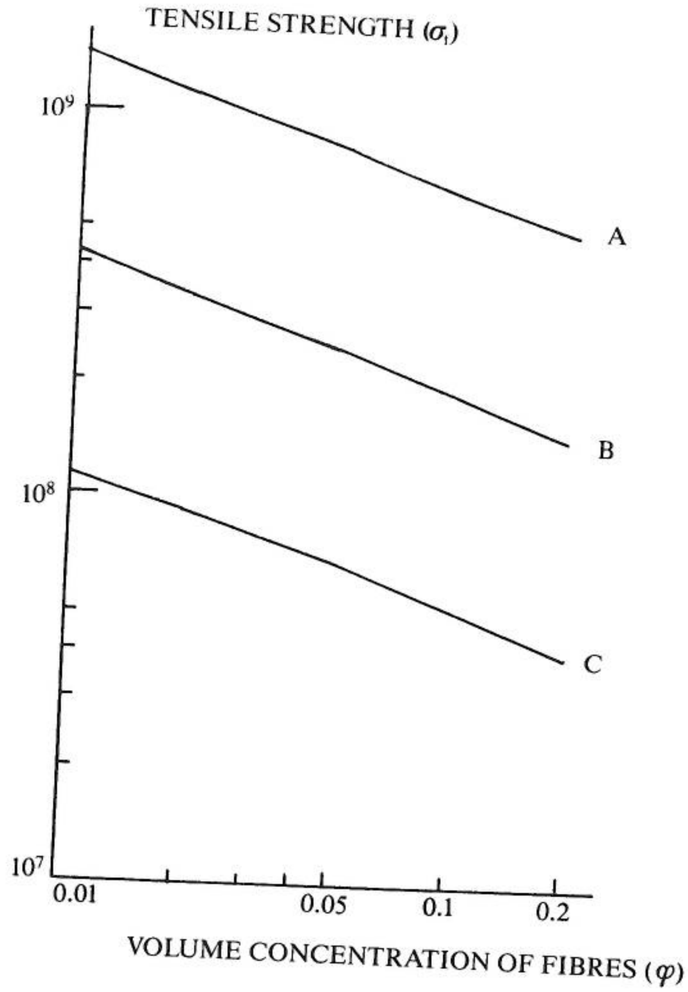


Fig. 8.9 Critical tensile strength of the reinforcement.

If the tensile strength is lower than the critical value, matrix cracking will be followed directly by total cracking with breaking of fibres.

With a reinforcement strength higher than the critical value, a matrix crack will propagate past the reinforcement.

Critical state where cracks just propagate past the reinforcement; as a function of the volume concentration of reinforcement - calculated for three different types of composite material from models described in [8].

Composite material	Type		A	B	C
E-modulus of reinforcement	(E_f)	MPa	200,000	20,000	2,000
E-modulus of matrix	(E_m)	MPa	50,000	50,000	10,000
Fracture energy of matrix	(G_m)	N/m	100	100	10
Shear stress	(τ)	MPa	20	5	1
Diameter of reinforcement	(d)	μm	150	150	150

The load required to cause a large crack to propagate past the reinforcement in normal concrete materials is substantially smaller than the tensile strength of the matrix materials.

That means that reinforcement does not normally have any appreciable effect on the load at which cracks are initiated but can have a big influence on the continued propagation of the cracks.

As will be seen from the models, however, the theory states that it should be possible with particularly effective reinforcement to increase the crack propagation load considerably beyond the tensile strength of the matrix material - and thereby at the same time increase the crack initiation loads, which must, of course, be at least as large as the propagation load.

Under such conditions the strain capacity increases by means of a mechanism very similar to strain hardening during yielding deformation of metals. This is dealt with in greater detail in sections 9 and 10.

Strain hardening of brittle materials is not just a theoretical possibility. As mentioned earlier, the theory for this behaviour has been described in 9 . It has also been clearly demonstrated on industrial products, for example, high-quality pressure pipes made of asbestos-reinforced cement paste (see figure 8.10).

As will be seen from the models, "strain hardening" requires a high content of extremely fine, very strong and stiff fibres. I used to think that strain hardening could only be achieved with sophisticated production processes and ultrafine fibres - not by soft casting concrete-like materials. However, as mentioned earlier, "reinforced concrete" with a very strong and dense, silica-based matrix provided with strain hardening capacity by incorporating 150 um dia. steel fibres (6 vol-%) was made by means of soft casting.

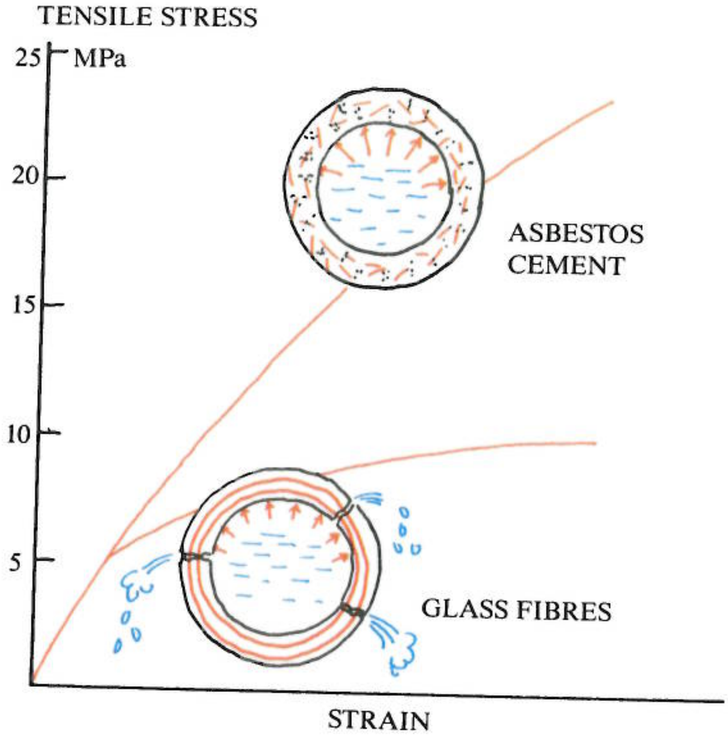


Fig. 8.10 STRESS VERSUS STRAIN DURING PRESSURE-TESTING OF PIPES.

Sketch based partly on information from testing of spun asbestos cement pipes [10].

Tests on high-strength pipes reinforced with spun glass thread gave disappointing results, showing multi-matrix cracking past the reinforcement and water leakage at low pressure corresponding roughly to the tensile strength of the unreinforced matrix material.

The asbestos-reinforced pipes resisted about 5 times higher water pressure without any leakage or cracking. The material showed pronounced strain hardening. This was due to a high concentration of very fine fibres with high strength and rigidity, firmly fixed to the matrix.

It is a condition for the development of cracks past the reinforcement that the reinforcement acting across the cracks is able to carry the load on its own. That means that the reinforcement must have sufficiently high strength not to be torn apart and that the reinforcing components (in the case of chopped fibres) are sufficiently well anchored in the matrix not to be pulled out:

If these criteria are not met, the material will crack as a homogeneous material, with simultaneous failure of matrix and reinforcement.

In this section we have considered crack propagation past reinforcement, together with the possibilities for increasing the strain capacity of the matrix by special arrangement of the fibre reinforcement. This last factor, which is essential to CRC, will be disussed from another angle in the following section.