APPLICATION OF FRACTURE MECHANICS TO HIGH STRENGTH AND OFFSHORE CONCRETE STRUCTURES

M. Modéer
Offshore Design AS, Stord, Norway

Abstract
Practice is where the theories come to life and become pulsating action. It is therefore argued for promotion of fracture mechanics in practice, by introducing the brittleness number as a simultaneous tool to the concrete grade. This is an efficient way to tie together the past, with its enormous empirical knowledge, with the future, with its physical understanding and computer modelling. The arguments are emphasised by two important milestone examples in the offshore industry. The first example describes the design of an ultra high strength concrete (C190), with a brittleness number 10 times the common one for high strength concrete (C70). The ultra high strength concrete has been used extensively in strengthening of steel jackets, decisively prolonging their life. The second example describes how fracture mechanics (i.e., softening considered) increased the design accuracy, and thereby eliminated the fear for a severe collapse of a concrete offshore platform. In this example fracture mechanics was the final key to success for one of the largest concrete structures ever built.

1 Introduction

According to Clifford Geertz : «If you want to understand what a science is, you should look in the first instance not at its theories or its findings, and certainly not at what its apologists say about it; you should look at what the practitioners of it do.». Clausewitz said : «It is not the theory of war that is fighting, it is the warrior. The task of the theory of war is to educate and to refine the mind of the warrior.». More peacefully, we have to ask ourselves what happens to knowledge when it is transformed from theory to practical action. In this lie the recognition that theoretical knowledge can not be used directly but only indirectly, as it as an action always is communicated through a mind.

As a predecessor to the philosophy of Socrates and Platon, and in the Cartesian spirit, the dominating heuristics of science are the context independent theories. This approach has dominated the scientific world so efficiently that other important ideas for understanding and action have been suppressed and made almost invisible. *Episteme* (scientific knowledge) and *techne* (technical knowledge) has been the guiding stars while *fronesis* (practical knowledge), as Aristoteles insisted on, has been almost forgotten. Even the word *fronesis* (phronesis) has disappeared from the modern man vocabulary, while word as «technology» is common for everybody and «epistemology» at least is common in the scientific world. Man would benefit a lot if the status of practical knowledge was the same as the status of scientific and technical knowledge. (The introduction is from Uhlin (1995).)

2 Fracture mechanics in practice

2.1 How to promote fracture mechanics among practitioners

One important synthesis of the introduction is that transfer of knowledge is not a matter only from scientist to practitioner, but equally a transfer from practitioner to scientist. The author is of the opinion that neither the fracture mechanics nor the practitioner society have considered this fully.

The potential gains of fracture mechanics in practice are tremendous, every fracture mechanics scientist will probably agree to that. More important, however, is that most practitioners still do not agree! Do we, as fracture mechanical scientists, think and act seriously about this matter?

The author strongly believes that a simple but efficient method to promote fracture mechanics in practice, is to introduce the brittleness number $B=L*f_t^2/E/G_F$ (or similar) as a simultaneous tool to the concrete grade (i.e., the compressive strength). If a certain level of the brittleness number always was demanded, and synchronised with all the empirical experience, the practice would use any concrete (e.g., also a C250) with the same degree of confidence! This is an efficient way to tie together the past and the future.

2.2 Fracture mechanics from the practitioners point of view

The author believes that the concept of fracture mechanics has to be demystified. Scientists have to use every possibility to point out that fracture mechanics is not a *new* science, but rather an extension of the classical approach (which is well known by the practitioners). The vital difference is that the classical condition of homogeneity and continuity of the materials is not a necessity anymore. In other words, the fracture mechanics theory *as a theory* is the well-known classical approach applied to more real-like material models. In that sense, fracture mechanics is more a material issue than an analytical issue!

By means of the stress function Φ of Airy and Maxwell in 1862 and 1863 respectively, it became possible to analyse the local stress condition around inhomogenities in elastic bodies. However, it was not until 1908 that Leon presented Φ for the simplest boundary problem, a circular hole (which is an ellipse with $a = b$) in a tensioned elastic plate. In 1913 Inglis presented Φ for the general inhomogenity, the ellipse, and as recently as 1938 Westergaard presented Φ for the mathematical crack, which is an ellipse with $b \rightarrow 0$.

The Inglis solution already shows that the stresses in front of ellipses with relatively small b-values become unnaturally high in linear elastic materials. Griffith's work in 1920 was the first serious attempt to solve this problem. A material will inevitable collapse when the stress becomes high enough, with the work of Griffith the collapse begun to be predictable. He postulated,

- The driving force for crack extension is the difference between the strain energy that is released if the crack is extended and that needed to create new fracture surfaces, or, elastic strain energy is transformed to surface energy during cracking.

First in the late 1940's the fracture mechanics got a *genuine* meaning. Orowan and Irwin pointed out that the surface energy of most building materials is only a negligible quantity of the strain energy transformed. *Most of the energy is expended in producing plastic strains during stress redistribution's.*

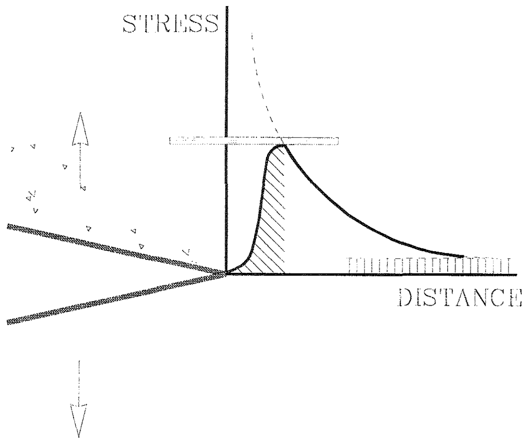

Fig. 1. The Barenblatt recognition

This is relatively simple for metals. For a composite as concrete, which is a material without an obvious plastic flow, the picture is somewhat more complicated. With the Barenblatt recognition, however, that all opening cracks (contra dictionary to parallel separated cracks) have a crack *tip*, and this crack tip *has to* have plastic redistribution's (a hinge), the concrete solution is just around the corner.

Ahead of a crack tip in concrete there are many and very small local regions with mainly plastic-like redistributions. The *sum* of the expended energy of these local regions, together they establish the *softened zone,* is in the same order as the one recognised in the laboratory when measuring the fracture energy G_F. How this can be handled in numerical analyses was shown by Andersson (1973), see figure 2.

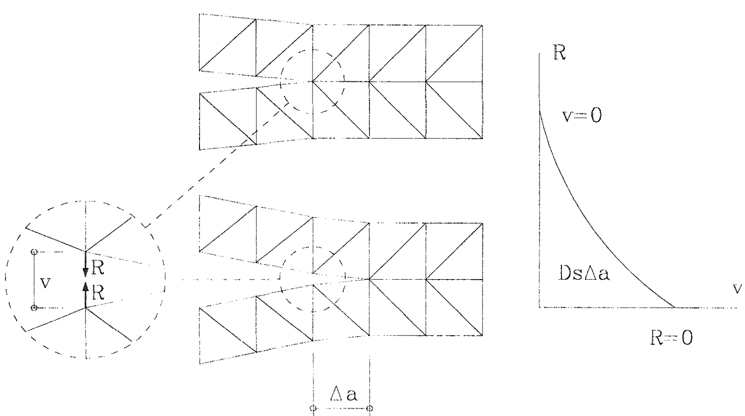

Fig. 2. The Barenblatt crack tip in analyses, Andersson (1973)

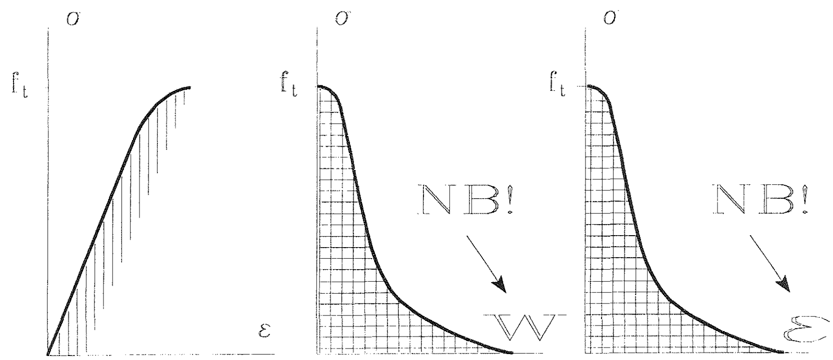

Fig. 3. The Andersson method, in the discrete and smeared approaches

The Andersson approach to Barenblatts recognition, surprisingly not acknowledged as his among concrete scientists, is today called the «discrete approach» with the variant the «smeared approach».

3 Applications

3.1 Elimination of the brittleness anxiety - material design

Several steel tubular frame structures (jackets) on the EKOFISK field (in the Norwegian sector of the northern Atlantic) are strengthened. The reason for this is the increasing subsidence, at present larger than 6 m (within more than 1 km^2!). The strengthening is done by injecting mortar (grout) into highly utilised structural members. By allowing a compressive strength of 190 MPa of the grout injected into jacket steel tubes, the lifetime of the jackets is dramatically increased (saving tremendous amounts of money). The grout was designed by means of fracture mechanics. The point is that fracture mechanics, as a material issue, can eliminate the brittleness anxiety of practitioners.

The grout compressive/tensile strengths are 190/8 MPa, the Young's modulus is 70 GPa, and the specific fracture energy G_F is 12,000 Nm/m^2 (normal concrete $G_F \sim$ 100-200 Nm/m^2). FEM-analyses have been performed to quantify the increased capacity of joints with grouted members, as Eurocode 4 analyses have been performed for single members.

The ultimate capacity analyses of one joint, where the chord is grouted, are presented briefly: The steel and the grout are modelled with 3D FEM elements, see figure 4. The bond and friction between the inside of the steel tube and the outside of the grout was not accounted for (the capacity would be *much* higher if they were).

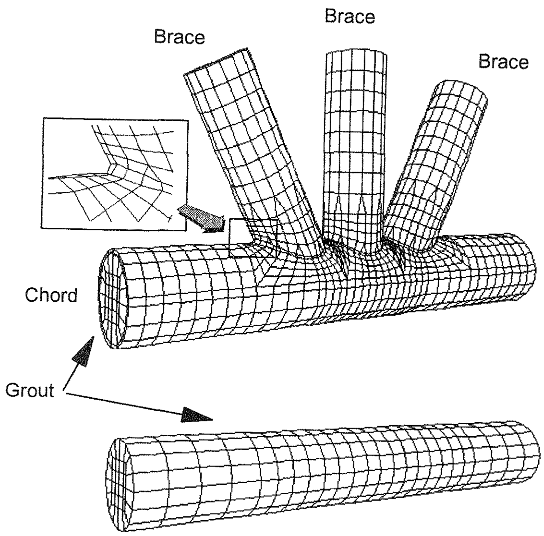

Fig. 4. FEM mesh of the joint including grout in the chord

The ultimate capacity is calculated for two load cases:

1. One diagonal brace in axial compression and one in axial tension.
2. Out-of-plane bending moment at the brace ends.

In the figures 5-7 the improvement achieved when the actual chord is grouted are visualised (the figures are all similar to the *structural* σ-ε response). The structural improvement is 50-85%, in spite of the conservative bond approach (without bond, the grout is not active until ovalisation starts).

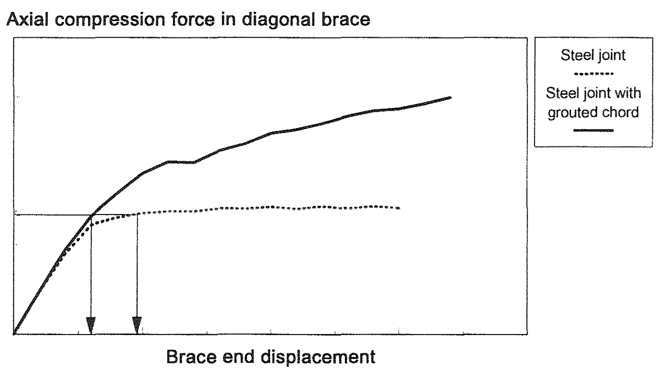

Fig. 5. Brace end displacement versus a given force for the diagonal brace in compression, load case #1

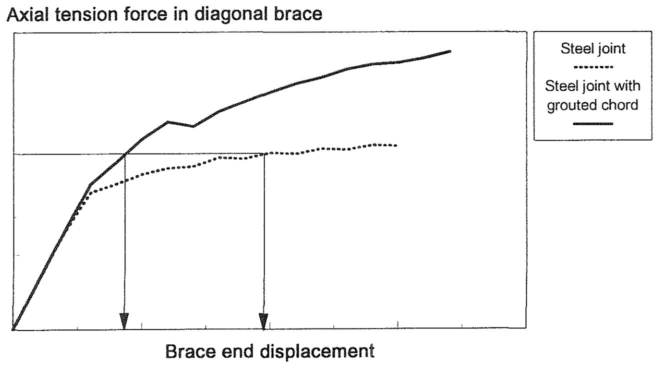

Fig. 6. Brace end displacement versus a given force for the diagonal brace in tension, load case #1

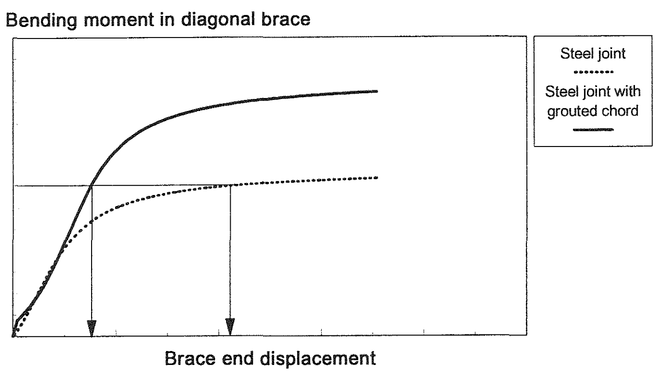

Fig. 7. Brace end displacements versus a given bending moment at the brace ends, load case #2

3.2 The concrete between reinforcement bars is plain

Along the mid circumference of the DRAUGEN GBS (in the Norwegian sector of the Atlantic) shaft there are vertical steel ducts for the pre-stressed reinforcement. Analysed with a classical approach, the shaft was predicted to split in the hoop direction, due to the presence of the ducts. A reassessment using fracture mechanics was performed to evaluate the split. The reassessment rejected the split prediction, and the presumed problem was neutralised. The point is that the practitioners accepted moderate softening (some called it speculative basic research!) and its almost amazing effect when it comes to transferring unacceptable local tensile deformations to acceptable sub-local tensile deformations.

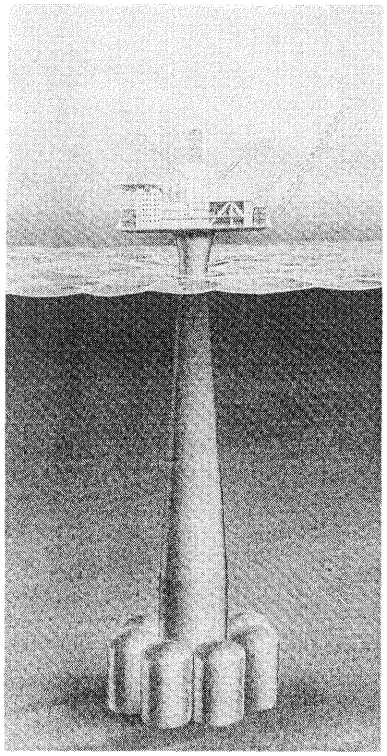

Fig. 8. The Draugen production platform

The Draugen Gravity Base Structure (GBS) is a mono-tower (with one shaft only) production platform, see figure 8. Draugen is the first mono-tower condeep ever. It has a concrete volume of 85,300 m^3, incorporating 22,400 tons of ordinary and 2,600 tons of pre-stressed reinforcement. The total height of the concrete structure is 285 m. Draugen is breaking several engineering frontiers, one being the decisive use of fracture mechanics.

Earlier concrete platforms have been designed by means of a classical approach only, to manage the Draugen concept it was necessary to use a fracture mechanics approach *as well.* Draugen is probably one of the milestones for the fracture mechanics approach, the total economics and trade conservatism considered.

Draugen was first submerged to a water depth of 125 m. There the ducts (steel tubes with the prestressed steel inside) were injected with mortar. Then the GBS was submerged to a water depth of 280 m (mating).

Already during the first phase the outer water pressure raised a concrete stress field of -11.8 MPa in the hoop direction, resulting in deformations corresponding to a radial tension of more than 9 MPa at the edge of the ducts (12 m up the 238 m high mono shaft).

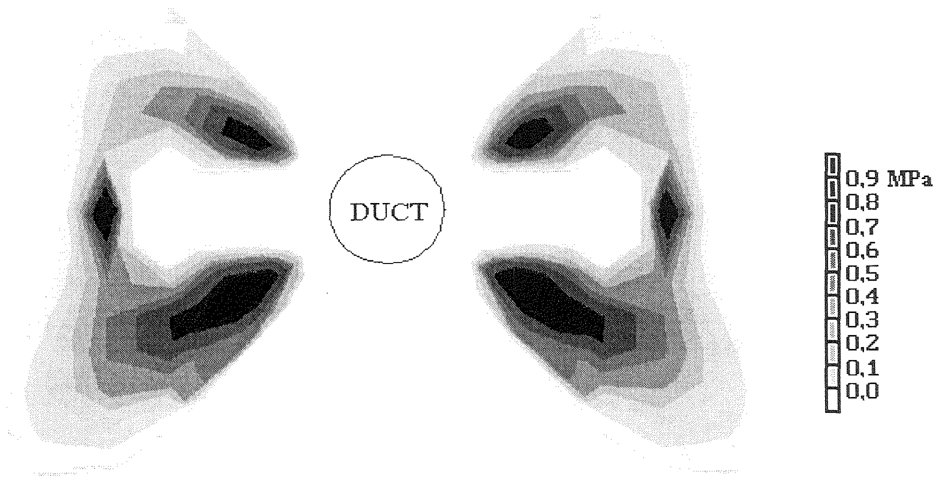

Fig. 9. Final 2D principal stresses around a duct in the shaft of the mono-tower platform DRAUGEN GBS, Modéer (1995)

During all phases softened zones developed in the hoop direction on both sides of the ducts. The maximum length of the softened (areas with microcracks, still globally continuos) and cracked zones was 123 mm, of which 25 mm was the crack. The final principal tension fields around the ducts are shown in figure 9. As seen, the maximum tension is less than 10 % of even the first phase corresponding classical value.

4 Concluding remarks

The author strongly believes that a simple but efficient method to promote fracture mechanics in practice, is to introduce the brittleness number as a simultaneous tool to the concrete grade. If a certain level of the brittleness number always was demanded, *and synchronised with all the empirical experience*, the practice could use any concrete with the same degree of confidence! This is an efficient way to tie together the past, with its enormous empirical knowledge, with the future, with its improved physical understanding and computer modelling.

Fracture mechanics in practice is one of the most important issues for both structural scientists and structural practitioners. The concrete world has to better realise what the steel world realised 30-40 years ago: Practice is where the theories are alive and become pulsating action. Phronesis ought to be the ultimate goal for the theoretical science!

5 References

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