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APPLICATIONS OF THE COHESIVE CRACK MODELS TO CONCRETE, CERAMICS AND POLYMERS

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Abstract. It has been well over thirty years since Hillerborg and Bažant presented their landmark papers (cohesive crack and size effect models respectively), and since the author submitted his Ph.D. dissertation on the application of fracture mechanics to concrete. Yet, the practical applications of fracture mechanics have been few and far in between. In this paper, the author will share his experience in trying to apply fracture mechanics not only to concrete structures, but also to other "neighboring" materials such as polymers and ceramics.

1 INTRODUCTION

It has been over thirty years since Hillerborg et al. (1976) and Bažant, Z.P. (1976) (simultaneously) published their landmark papers on the cohesive crack model and the size effect respectively, and also since the author submitted his Ph.D. dissertation on the application of fracture mechanics to concrete, (Saouma, 1980). Since then, there has been countless publications, as well as seven FraMCoS conferences focusing on the fracture of concrete.

Discarding case studies where one performs a numerical simulation of a laboratory test, it is blatantly clear that there has been, few, very few, discouragingly few reported cases of practical applications of fracture mechanics[1].

This is indeed a matter of concern, as our infrastructure is aging, and most failure result in micro, or macro cracks. Whether cracks are the primary cause of failure or are the consequence of (another) failure (mechanism), is another fundamental issues often neglected. Hence, one has to remain hopeful that ultimately fracture mechanics will play a more prominent role in the safety assessment of existing structures, or in forensic studies (which often require a non-linear analysis) than for the design of new ones.

Usually papers tend to emphasize theoretical/experimental aspects and terminate with "some sort" of an application, this one will focus exclusively on applications and conclude with personal remarks.

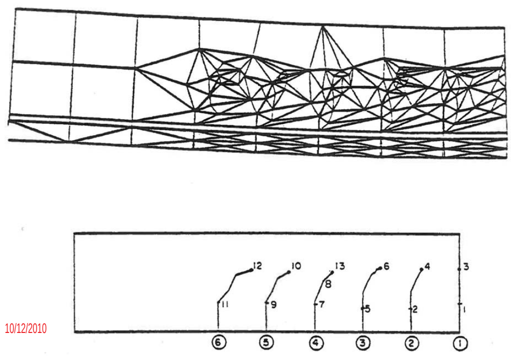
2 APPLICATIONS

Trying to put things into perspective, the author's PhD thesis (Saouma, 1980) was probably one of the first doctoral dissertations focusing on the fracture mechanics of concrete structures. Largely inspired by the earlier work of his mentor, (Ingraffea, 1977), it developed a computer program (Finite Element Fracture Analysis Program) with adaptive remeshing for discrete crack propagation. Fig. 1 is an illustrative example of the analysis of the "mythical" reinforced concrete beam OA-1 tested by Bresler and Scordelis (1961) who were investigating the shear strength of reinforced concrete beams (and we still do).

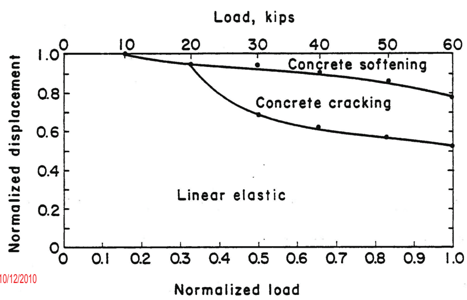
[1] From a computational side, this issue was addressed by Emery et al. (2007).

Fig. 1(a) is a snap-shot of the mesh after 13 crack propagation increments. The (crude) automatic remeshing is evident, yet such an early analysis yielded a reasonable nonlinear load-displacement curve, Fig. 1(b). Finally, a realistic crack profile, consistent with ACI-318 prediction was obtained, Fig. 1(b).

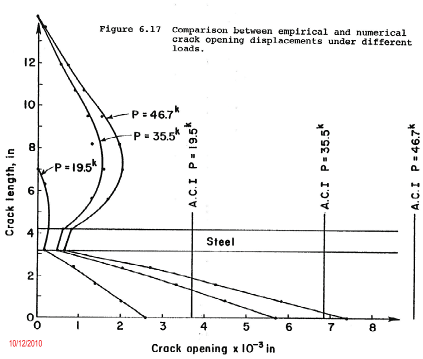
Though this program was used for a couple of subsequent years, when the opportunity came, an entirely new program (Merlin) was developed, (Saouma et al., 2010), and all results presented in this paper are based on it.



(a) R/C beam OA-1



(b) Non-Linear load displacement curve



(c) Crack profile

Figure 1: Origial figures from the author's PhD thesis in 1982

In the following pages, practical examples of fracture mechanics applications will be shown. The author has been involved in all those analysis, and for obvious reasons structure names, locations, and specific details will be omitted.

2.1 Civil Engineering

Fracture mechanics may be implicitly or explicitly used in concrete structures. Implicitly through code equations which account for the size effect law (such as in the shear strength equation). Unfortunately the most widely referenced design code (ACI-318) has not yet recognized the need for such a consideration. This abberation can only be attributed to the inability of the research community and the practicing world in this country to properly communicate and understand each other.

What is more pertinent to the topic of this paper are the explicit applications of fracture mechanics in real structures. Such applications have recently been made possible through the consideration of the cohesive crack model in commercial codes such as Atena, or Diana with various degrees of sophistication. Description of these applications is better left to others.

A daunting question (which we may have tried to avoid) is how relevant is fracture mechanics (i.e. to which extent a 10% change in the fracture energy G_F would alter final results) to reinforced concrete structures when cracks are by definition anticipated to occur (in order to mobilize the load carrying capacity of the reinforcement) and cohesive stresses are negligibly small compared to those in the reinforcement. On the other hand, fracture mechanics could address some of the finer points (such as crack width, critical in nuclear) or massive unreinforced concrete structures (dams) or zones of limited shear reinforcement.

2.1.1 Dams

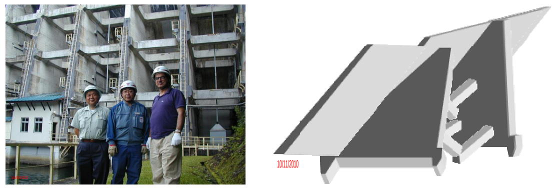
Dams have historically been catalysts for structural analysis innovations. If many of us are aware that the first reported application of the finite element in civil engineering was precisely the fracture analysis of a concrete dam by Sims et al. (1964), few know that one of the first applications of the finite differences was also masonry dams (Richardson, 1911) not to mention the numerous examples of dams in the first edition of Zienkiewicz (1967).

In the US, the identification of so-called “Potential Failure Modes” (which often means some form of cacking/sliding) is engrained in recent regulations (Federal Energy Regulatory Commission, 2006). Conceptually, this is analogous to the well accepted “Performance Based Design” (FEMA-349, 2000). Both paradigms would allow engineers to consider spending more resources to achieve quantifiable higher performance thereby reducing risk. Hence, the structural performance of critical structures such as dams, nuclear containment vessels, and offshore structures, could be improved through appropriate non-linear analysis provided that an appropriate model can be used. Indeed the author has recently examined a merger of those two approaches, Saouma et al. (2012).

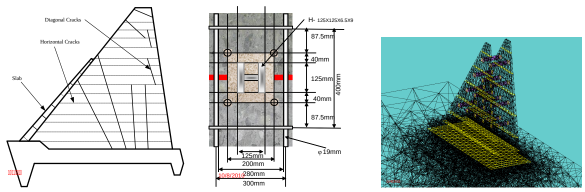
The analysis of a massive lock and dam (Reich et al., 1994) did lead to a US Army Corps of Engineers Technical Letter (Army Corps of Engineers, 1993), which stipulated that *[one]need(s) to perform a fracture mechanics based investigation prior to major rehabilitation*. Regretfully, it appears that this directive has been escinded (lack of sufficient “expert”?).

Finally, putting things in perspective, it is important to realize that with dams one is dealing with very large concrete structures, that no major distinction is made between cracks and joints (horizontal or vertical), and that “Achile’s heel” is the joint between rock and concrete. Hence, whereas we assume (in design) that those joints are perfectly closed, they constitute potential cracks once they open.

Seismic Safety Assessment of a Buttress Dam This first example, is an old buttress dam in Japan, Fig. 2(a). Though a relatively small one, there was some concern about its vulnerability to lateral seismic excitation, Fig. 2(b), specially that cracks where already present, Fig. 2(c). To mitigate possible damage, a strengthening plan was put together, Fig. 2(d). However, the safety assessment of the dam did not account for the presence of mild steel reinforcement in the buttresses which could have provided shear strength through dowel effect. At this point, the author got involved in this project.



(a) Buttress dam (b) Possible failure mode



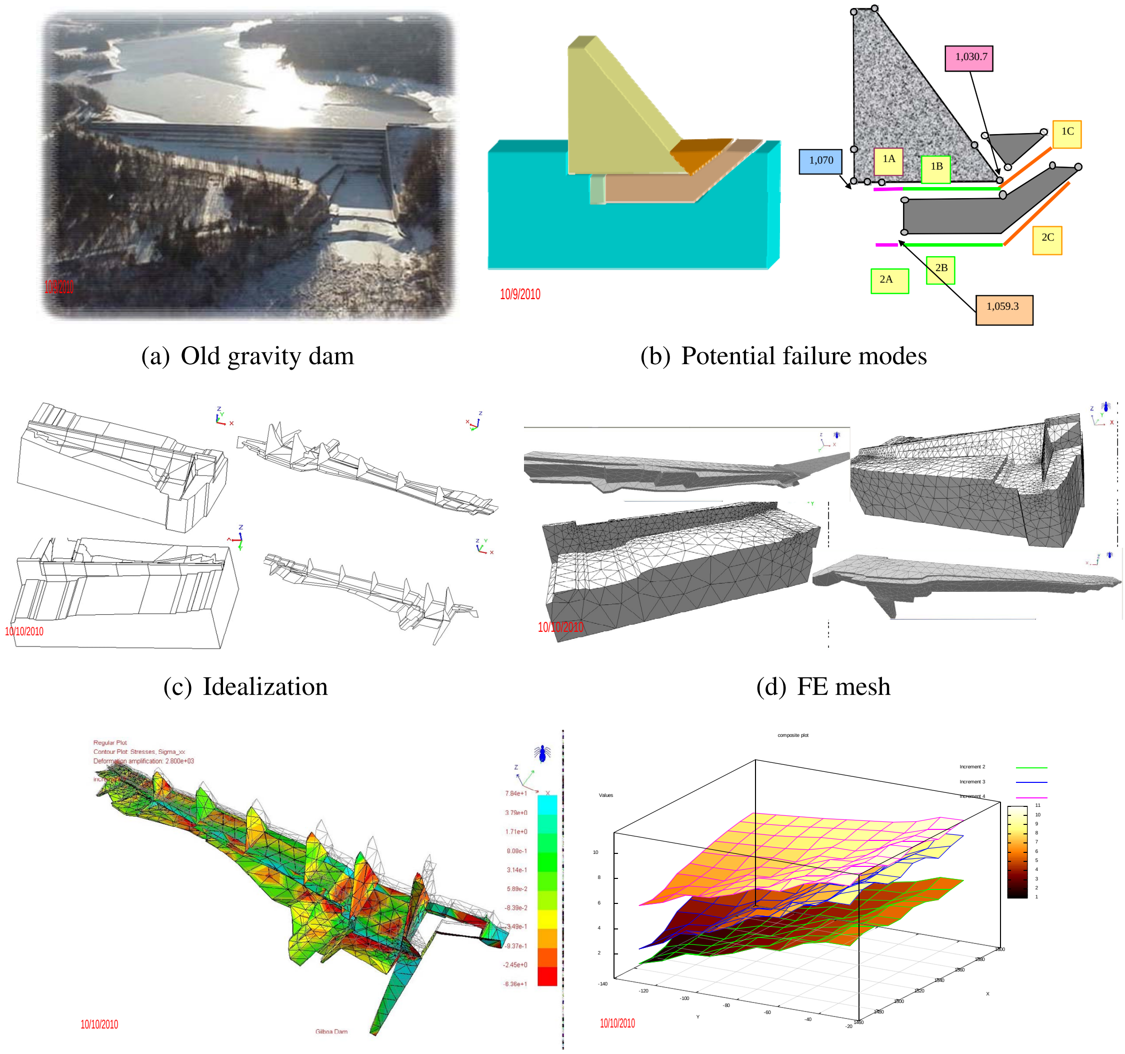
(c) Mapped cracks (d) Planned rehabilitation (e) 3D FE mesh; Joints highlighted in yellow

Figure 2: Buttress Dam

Modeling reinforcement across the multiple joints was problematic, however joint modeling through interface elements was simple. As such, an experimental program, Fig. 13,was put together to determine a set of (fracture mechanics based) interface element properties equivalent to the one of a joint with reinforcement. Once determined, those properties were assigned to all the joints and thus circumvented the need to model dowel effects.

Finally, a 3D transient nonlinear fracture mechanics based analysis was undertaken, Fig. 2(e) and the dam was found to be sufficiently strong to withheld the earthquake, and rehabilitation plans shelved. This was one of the best example in which a reasonable investment in laboratory tests and advanced analysis, yielded substantially larger savings in unnecessary rehabilitation costs.

Safety Assessment of a Complex Gravity Dam This old gravity dam, Fig. 3(a), raised much concern to the surrounding population in light of its apparent deterioration. Much silt had accumulated, it was overtopped numerous times, and simple 2D rigid body analysis failed to yield a sufficiently high factor of safety against sliding. At that point, the author was approached by a consulting firm to perform a 3D fracture mechanics based analysis.



(a) Old gravity dam

(b) Potential failure modes

(c) Idealization

(d) FE mesh

(e) Vertical joints and potential failure joints

(f) Uplift pressures

Figure 3: Old gravity dam

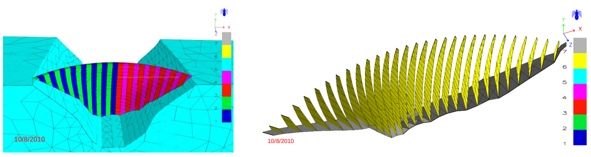
A particularly challenging aspect was the complex geometry: the dam had a shear key, is partially built under existing rock, and has complex geometry which includes a stiff wall at one end.

Hence, the first task was to identify potential failure modes. Fig. 3(b) is an idealization of the two most likely ones. The first cuts across the shear key, goes along the rock/concrete interface and then daylights at approximately 45 degrees. The second assumes a strong shear key, and failure initiates below it, propagates horizontally, and then again daylights at about 45 degrees. To further complicate matters, this was a 3D analysis with not only varying longitudinal geometry , but also spatially varying rock properties (cohesion, angle of friction). Idealization is shown in Fig. 3(c), while the actual mesh is shown in Fig. 3(d), and the joints (deformed shapes) are in Fig. 3(e).

Given the complex geometry, it was critical to ensure that the mesh was indeed well put together. This was critical as if two nodes across a potential failure modes are not connected by an interface element (i.e. tightly coupled), then no failure would occur (albeit close examination of the deformed shape and stress contour would reveal an irregularity).

Another complexity is the ability to adjust uplift pressures automatically as the crack develop, and most importantly translate the results of a finite element analysis into a safety factor against sliding. The first was addressed by the computer program, and Fig. 3(f) is a graphical representation of the 3D uplift distribution between two parallel vertical joints in terms of the hydrostatic pressure. The second is to compute the safety factor. In 2D hand calculations, the safety factor can be easily determined from SF=$cL_{uncr} + \Sigma F_v \tan\phi / \Sigma F_h$. In the 3D analysis, this requires special attention.

Seismic Safety of an Arch Dam Dams are interesting structures. In the simplest cases, hand calculations are often enough to assess the safety of a gravity dam. At the other end of the spectrum the seismic analysis of an arch dam may very well be amongst the most complex structural analysis one can undertaken.

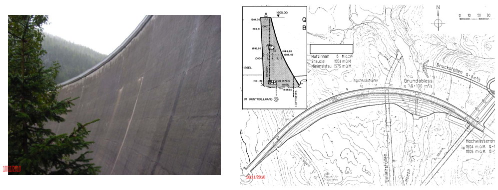


(a) Dam (b) Interface Elements

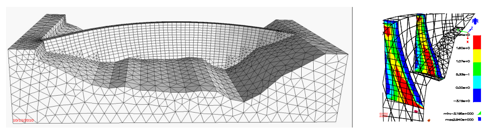
Figure 4: Ach Dam

What is most striking in the following analysis, Fig. 4(a) is the extensive use of fracture mechanics based interface elements to model vertical joints, and the rock-concrete interface, Fig. 4(b). At first those joints are "zipped" together, and they open or slide when certain failure criteria are met. It should be noted that there is no need for adaptive remeshing in these analysis as (most often) it is unlikely that new crack will develop in the concrete, since the joints constitute "fuses" which would open first and redistribute the stresses.

Dam with AAR Many old concrete structures suffer from alkali aggregate reactions (AAR) which result in volumetric expansion. Whereas this may be merely a nuisance for small structures, it is of major concern in massive concrete ones as the constrained expansion is likely to result in structural cracking, inability to operate spillway gates, or worst yet misalignment of the turbines.



(a) Arch dam suffering from AAR



(b) Finite element mesh (c) Internal Stress contour plots

(d) Observed cracks along internal the gallery and inside a borehole (e) COD, CSD, uplift, σ_n and σ_t

Figure 5: Arch gravity dam suffering from AAR

AAR is a very slow thermodynamically driven reaction, and many years (over 20) may pass before the dam instrumentation can with certainty indicate that we are in presence of an irreversible deformation (typically upstream, and a crest elevation).Though nothing can stop this reaction, it is of paramount importance for dam owner to assess the evolution (kinetics) of the swelling with appropriate models, (Saouma and Perotti, 2006).

Fig. 5(a) is an arch dam suspected of suffering from AAR (it turned out not to be AAR but another chemically induced reaction in the concrete which results in a volumetric expansion too). Fig. 5(b) is the finite element mesh used. It should be noted that vertical joints were not modeled, however it was deemed indispensable to model the rock concrete interfaces with fracture mechanics based interface elements. Fig. 5(c) shows the internal stresses, and we note the zone of high tensile stresses in the center which may result in some hidden cracks. Indeed a crack was observed along the gallery, and a borehole drilled to determine its extent, Fig. 5(d), as it had not “daylighted” on the downstream face (yet). More details can be found in (Saouma et al., 2007).

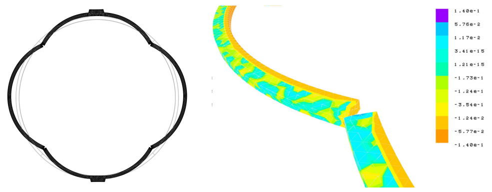
2.1.2 Nuclear Reactor Containment Vessels

Another major civil infrastructure of which cracking we should be concerned for obvious reasons are nuclear reactor containers. Indeed, the major design constraint is not strength but serviceability, i.e. no leakage should occur, and thus “no cracks allowed” This is ensured through occasional Internal Pressurization Tests where the inside of the container is pressurized up to around 60 psi, and possible leaks identified.

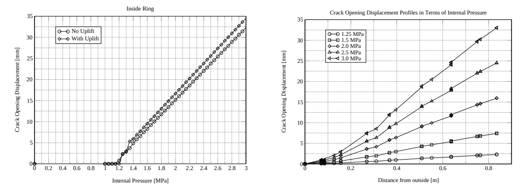
Another major concern with nuclear reactor is the (often unanticipated) cost of decommissioning. As such, many utility companies find it more cost effective to seek NRC’s approval for life extension from the usual 25-30 years life span to well over 50 years, (Graves et al., 2011). A major cost associated with this life extension is the replacement of massive steam generator (SGR) as those become so embrittled through radiation exposure, that repair is no longer an option, and full replacement is a must.

Crack in a ring There is a class of French reactors without inner liners. The analysis of the pressurization of these containers has never accounted for the crack pressurization, and the question which begs for an answer is “how bad is it if we neglect this effect”. Such an analysis, was facilitated by the fact that Merlin supports various uplift models for dams, uplift which can be defined as a function of crack opening. Henceforth, the following analysis addresses precisely this problem, (Hansen and Saouma, 2003).

The deformed shape of the ring cross section is shown in Fig. 6(a).



(a) Deformed Shape of the Ring (b) Close-Up on the Deformed Shape of the Ring



(c) Crack Opening Displacement in terms of Pressure, with and without “uplift” (d) Crack Opening Profiles

Figure 6: Analysis of a nuclear reactor container ring

A closer look at Fig. 6(b) highlights the kinematics of the ring under internal pressurization, crack opening from the inside, and closed crack on the outside.

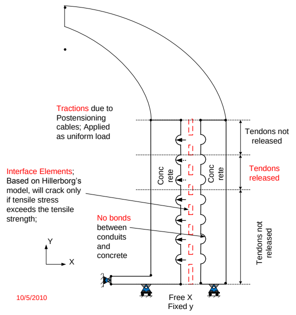
Crack opening versus internal pressure is plotted in Fig. 6(c)for both analysis cases, whereas the crack profile is shown in Fig. 6(d). Finally Fig. 6(d) illustrates the deformed shape of the interface element by itself. The small overlap on the exterior of the ring is caused by the finite (yet large) stiffness given to the interface element.

From this analysis, it was determined that accounting for crack pressurization did not substantially increase the crack openings. On the other hand, the discrete nature of the crack model, did provide with a more realistic estimate for the crack opening displacement than a smeared crack model. As mentioned earlier, this estimate of the COD is critical as it provide required information to assess the container permeability to gas leak.

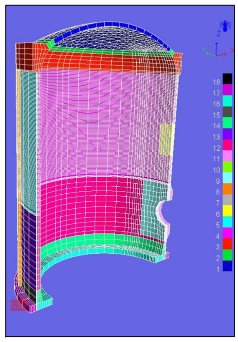
Delamination of a Container Wall As mentioned earlier, the life extension of nuclear reactor may require the replacement of the steam generator. When this is needed, and the circular hatch opening (present in most container) can not be used, then the only alternative is to cut the container wall. Such an operation entails multiple steps which must be carefully planned for:1) Detensioning of the horizontal and vertical prestressing tendons (which are usually not bonded); 2) Removal of the outer layer of steel reinforcement; 3) Mechanical cut of the concrete walls through the entire wall thickness and liner; 4) Plugging the concrete hole; and 5) Retensioning of the cables. A critical issue is the order in which tendons are detensioned/retensioned, whether tendons in the immediate vicinity of the cut are also to be released, and commensurate nonlinear finite element analysis to assess the safety of such an operation. Analysis which should account for creep, aging, and potential cracking of the wall.

Whereas many such operations were safely performed, it is a matter of public record that in one particular case a major delamination crack was observed on the plane defined by the horizontal postentioning sleeves, Fig. ??. This incident has resulted in multi-million dollars costs, (Danielson, 2010).

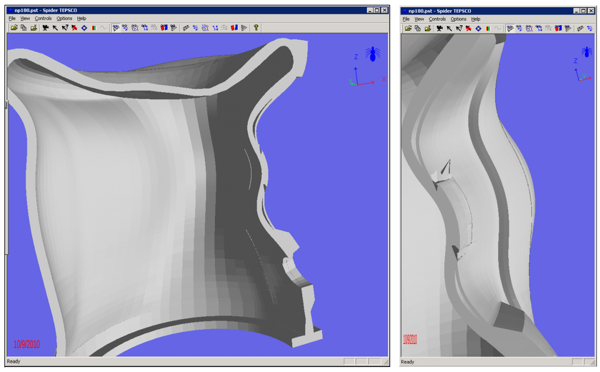
If such an analysis was to be undertaken using a nonlinear fracture mechanics approach, the key question is how to model the container. Since in this particular case the crack/delamination plane is known, a discrete crack is the most natural candidate. Hence, one would model the concrete as a linear (visco)elastic continuum, however interface elements would be placed along the plane of the delamination crack, Fig. 7(a). To account for the presence of the tendons, discontinuities will be introduced, and those in turn will be subjected to the tendon hoop stresses. Hence, interface elements will interlace discontinuities along which postentsioning force could be applied.



(a) Idealization of the crack



(b) Finite element model



(c) Deformed Shape

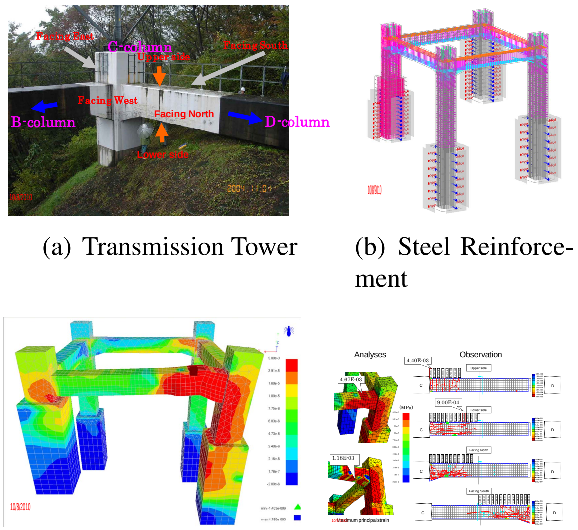
Figure 7: Analysis of a cracked nuclear reactor wall container

One would have to model the all too important creep occurring in the concrete, the proper sequence of cable detensioning, and the removal of the concrete. All of this while accounting for the complex geometry which would require different set of material properties in accordance with the internal reinforcement (not explicitly modeled but resulting in modified effective Young modulus).

Indeed, such an analysis did capture what may be the failure mode, Fig. 7(c) where at some stage delamination initiates in the upper/lower part of the cut as shear cracks "coerced" to realign themselves vertically by the closely spaced discontinuities due to the posttensioning sleeves.

2.1.3 Massive R/C Support

Another example of a critical structure subjected to AAR is a massive reinforced concrete support of an electric transmission tower, (Saouma et al., 2007). It was discovered that a segment (painted in white in Fig. 8(a)) was undergoing such a reaction as evidenced by extensive cracking. Since AAR results also in a degradation of the elastic modulus and the tensile strength, the main concern was whether such a structure could resist a strong earthquake following years of deterioration.



(a) Transmission Tower (b) Steel Reinforcement

(c) Finite Element Mesh (d) Combined

Figure 8: Transmission Tower

This was addressed by first putting together a finite element mesh which accounted for the heavy reinforcement shown in Fig. 8(b) and winkler springs to account for the soil structure interaction. Various models were considered, and it was determined that modeling the full structure with localized AAR, Fig. 8(d) yielded the best (and excellent) strain correlation with those measured *in-situ*. In this analysis, the smeared crack model of Merlin was used, it is based on the fracture plastic model developed by Červenka and Červenka (1999). *in-situ* cracks have been monitored for many years and thoroughly mapped. Average strain was determined by averaging the ratio of crack width over multiple length scale.

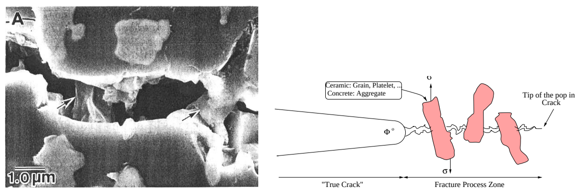
Finally, the code was modified to allow a dynamic restart following the 20 years AAR simulation to perform a seismic evaluation. The restart was essential, as it was critical for the dynamic simulation to begin with the existing static stress field, and corresponding damaged elastic modulus and tensile strength.

2.2 Others

In this section, completed or initiated applications outside concrete will be presented.

2.2.1 Ceramic-Composites

Ceramics are being increasingly used in a number of industrial components. Yet they suffer from a major drawback: they are inherently brittle, or quasi-brittle. An important similarity with concrete is the presence of grains which will confer the ability to transfer cohesive stresses, and potentially exhibit a size effect, Fig. 9. Yet, most research in ceramics has limited itself to LEFM, and occasionally at simple plasticity based models around Dugdale's postulate.



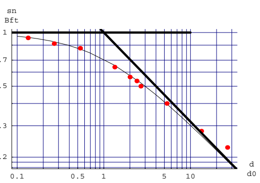
(a) Stretched Mo ligaments bridging crack faces, (Sbaizero et al., 1998) (b) Analogy with concrete

Figure 9: Ceramics FPZ

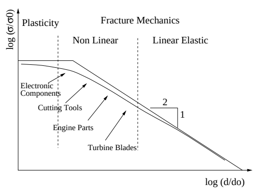
As such, the "concrete community" had much opportunity to develop ever increasingly complex models as there appeared to be few applications. On the other hand, the "ceramic community" is confronted with both manufacturing challenges and multiple applications, and as such may not have developed models of the same sophistication as the one developed for the more mundane concrete material.

Though not specifically addressing a practical application, this section was inserted to highlight the potential cross-fertilization potential between those two “communities”.

Hence, the objective was to explore the possibility of applying concrete models to ceramics, (Saouma et al., 2002). This was accomplished in performing a nonlinear fracture mechanics analysis (based on Hillerborg’s model) of the experimental tests of Sbaizero et al. (1998) who tested Rectangular bars 3mm x4mm x20mm (B x W x L)with an a/W of 0.5. Cohesive crack parameters were first adjusted to yield comparable load deformation curves, and then those were frozen ana analysis of different specimen sizes performed. This resulted in a crisply defined size effect, Fig. 10(a). This is important as ceramics are used in many different applications of varying sizes, Fig. 10(b) and as such size effect adjusted properties should be used.



(a) Size Effect in $Al_2O_3/20\%Mo$



(b) Size effect of ceramics

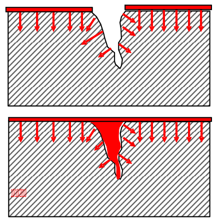
Figure 10: Nonlinear fracture mechanics simulation of ceramics

More recent studies, (Saouma et al., 2006) looked at the presence of residual stresses in ceramics, and the effect of physical transformation on increased fracture toughness, (Saouma et al., 2005).

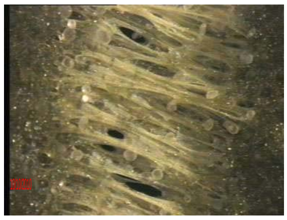
2.2.2 Polymers

The last application focuses on polymers used for solid rocket propellants. A composite solid rocket propellant is generally made of a saline oxidizer, such as ammonium perchlorate, and a rubbery binder, such as Polybutadiene, which acts as a fuel. Most rockets today use AP and Hydroxyl-Terminated PolyButadiene, mixed with other minor but fundamental constituents. The salt is milled in one, two or three different grain sizes, and mixed with the liquid HTPB. Hardener, Bonding Agent and Catalyser are then added, and the propellant is cast in the rocket case, generally made of some high-performance steel alloy or of composite material. A mandrel shapes the propellant surface. The motor is cured at high temperature in an oven, and the propellant solidifies, becoming a rubber-like, filled elastomer. However, a critical step is the extraction of the mandrel, Fig. **??** as it may results in microcracks at the bore, Fig. 11(a).

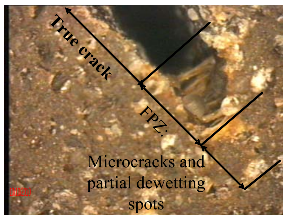
(a) Internal crack



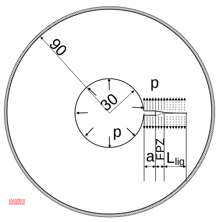
(b) Uneven combustion



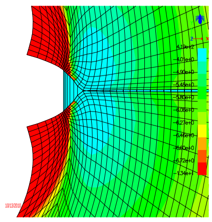
(c) Crack bridging



(d) Fracture process zone



(e) Simplified 2D model



(f) Finite element mesh; Deformed shape

Figure 11: Fracture of polymers

In the presence of a crack, binder filaments bridge the crack partially connecting the two sides, the bonding agent anchors the oxidizer particles to the binder with strong bonds, Fig. **??** and confers higher toughness to the material, generating crack bridging through binder anchoring at two opposite oxidizer grains, Fig. 11(c). Hence, along a portion of the crack, there is a transfer of stress through the stretched binder, giving rise to a fracture process zone, Fig. 11(d). Another great analogy with concrete, and a prime candidate for nonlinear fracture mechanics.

Should there be a crack, the mechanical/thermal stress may cause crack growth resulting in additional surface area. The risk is that there would be combustion inside the crack, Fig. 11(b) producing pressures much higher than the designed maximum pressure resulting in the rocket explosion.

This is not an academic exercise, as indeed there has been a motor explosion of a Titan IV PQM, (Chang et al., 1995). Since then, fracture mechanics to predict the service life of a motor and the determination of the critical crack size as an acceptance criterion for high-valued SRM (such as the Titan IV boosters), has been partially published, (Liu, 2003).

Whereas most of the early fracture mechanics applications were driven by LEFM, there were only timid attempts to use the more appropriate cohesive crack model. In light of the above, an experimental program was first set up to determine the fracture energy of solid propellants, Sect. 3.3, (Tussiwand et al., 2006), and then numerical simulation using the fictitious crack model were undertaken, Fig. 11(f).

This work is currently being extended to couple the nonlinear fracture mechanics code with the one which simulates the combustion. Hence at each time step, the updated pressure and crack profile are passed to the stress analysis code from the combustion one.

3 UNDEPINNINGS; EXPERIMENTAL WORK

The previously presented applications could not have been achieved by merely using a computer program as a "black box", and without a good grasp of both the physics of the problem and first principles. Furthermore, in many cases, models had to be based on proper testing, and finally computer models must be validated.

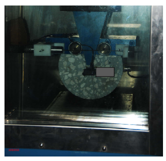
Henceforth, this last section will briefly present the underpinnings of the applications presented. Any complex nonlinear, fracture mechanics based, analysis must rely on proper models (as described above), and those in turn must rely on proper experimental tests. This section will detail two such set of experiments.

3.1 Concrete

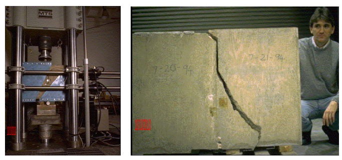
First, large scale tests with specimens as large as 5' and 3" maximum size aggregates were tested, Fig. 12(a),

(a) Large Scale testing

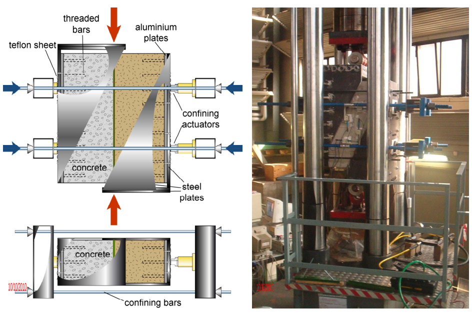
(b) Fluid fracture interaction



(c) Accelerated core test



(d) Shear crack under confinement fracture



(e) Reverse cycle loading

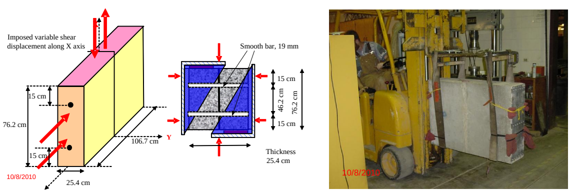
Figure 12: Laboratory testing for concrete

to determine the fracture energy of "dam concrete", (Saouma et al., 1991). Direct tension tests on 36x6 inch cross section specimens were also conducted, (Slowik et al., 1996).

Since we have at the base of a dam a large shear stress, the potential shear crack propagation was also investigated, Fig. 12(d), (Slowik and V.E., 1996). Then the interaction of fluid and fracture was investigated, Fig. 12(b), to determine the variation of uplift pressures in terms of crack opening, (Brühwiler and Saouma, 1995a) and (Brühwiler and Saouma, 1995b). Much later, the effect of reverse cyclic loading on the degradation of concrete roughness, Fig. 12(e), was experimentally derived, (Puntel and Saouma, 2008). Finally, as fracture mechanics is likely to be more widely used in the context of structural assessment, one must test concrete cores recovered from site. Fig. 12(c) is such a test on an 8" core inside an environmental chamber at 80^{o}C to accelerate creep fracture.

3.2 Project Specific Testing

Whereas laboratory tests are most often performed to determine generic models, at times, they can be project specific. In support of the analysis reported in Sect. 2.1.1, laboratory tests were performed on large jointed concrete blocks crossed by 19 mm smooth rebars. The objective being to determine the global response (which would account for the dowel effect), and then determine a set of interface joint properties which could provide a similar response prior to a full dam analysis. Fig. 13(a) describes the test, the actual specimen is shown in Fig. 13(b).

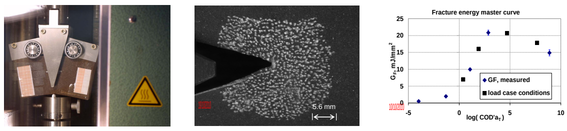


(a) Test scehmatic (b) Test Specimen

Figure 13: Project specific testing

3.3 Polymers

This last test is an illustration of the cross-fertilization between concrete and other material. Fig. 14(a) is a (enclosed) wedge splitting test of a polymer used as a rocket propellant, and the fracture process zone is shown in Fig. 14(a) where image analysis is used to determine (and control) crack openings. Finally Fig. 14(c) is the resulting master curve for the fracture energy (which accounts for rate and temperature of this visco-elastic material).



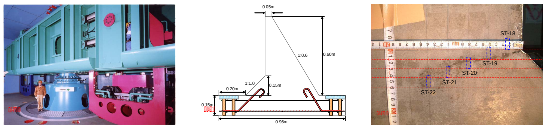
(a) Wedge splitting test of polymer (b) Fracture process zone (c) Master curve

Figure 14: Fracture of polymers

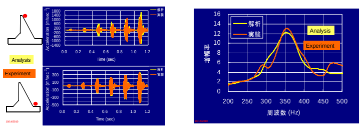
3.4 Centrifuge Based Validations

Finally, any finite element program must be validated. Though it is customary to validate a program by reanalyzing the very same tests from which the constitutive model was (implicitly or explicitly)derived, this is barely acceptable. In our case, some aspects of Merlin capabilities were assessed through centrifuge tests of a dam model subjected to varying hydrostatic load, (Gillan et al., 2004). Then a more ambitious test was performed by dynamically exciting a dam model inside a centrifuge, (Uchita et al., 2005).

Fig. 15(a) is the large centrifuge of Obayashi Corporation in Tokyo where the test was performed. Fig. 15(b), shows the dam model (1/30th scale). Pre-test calculations were made by Merlin, and Fig. 15(c) is an illustration of the crack and location of some of the instruments. Accelerometers were mounted at the base and the crest. The dam was subjected to a series of 6 increasing harmonics. Measured and predicted crest accelerations are shown in Fig. 15(d), and the transfer functions in Fig. 15(e). From the last two figures, it was evident that merlin captured well the nonlinear dynamic response of the dam, and thus provided additional confidence in its use for nonlinear transient fracture mechanics analysis.



(a) Obayashi centrifuge (b) Dam model (c) Instrumentation and crack



(d) Dynamic responses (e) Transfer functions

Figure 15: Centrifuge/shake table tests for Merlin validation

4 Final Remarks

Based on the experience gained through this reported work, the following needs are identified:

1. The engineering professions must trust the academic world in helping them address complex problems as is often the case in Europe and Japan.
2. ACI-318 should seriously consider impact of size effect laws on some of its provisions (shear equation in particular).
3. University professors should broaden their research goals to address complex interdisciplinary, multi-scale practical problems. Fundamental research will always be essential, and should be recognized as such. It is presumptuous to think that one single narrow engineering discipline (such as fracture mechanics) by itself can help us solve societal problems.
4. Fracture mechanics is much more relevant to assess the integrity of existing structures than the design of new ones. Henceforth, core based laboratory specimens should be favored over prismatic ones for G_f testing.
5. One critical research need is creep fracture. The only major such tests was performed about 20 years ago by Zhou (1992).
6. A certification program to "validate" computer codes with nonlinear fracture mechanics capabilities should be put in place. Such an effort could be spearheaded by NRC, FEMA or EPRI.
7. Reliable (fracture mechanics based or not) non-linear analysis of reinforced concrete remains a challenge. As evidenced by numerous benchmarks, even the simple analysis of a R/C beam can yields widely different results.
8. Though numerical modeling was not addressed in this paper, the author feels "vindicated" that the discrete crack model pioneered by Ingraffea and Saouma over thirty years ago, is back in favor, albeit under different form.

5 CONCLUSIONS

Thirty years after his dissertation on the application of fracture mechanics to concrete, this paper was an attempt to summarize some of the practical applications undertaken by the author. Within "traditional" civil engineering, they covered concrete dams, nuclear reactor containment vessels, massively reinforced concrete structures. Other application to ceramics and polymers were also presented. Also presented are some of the innovative testings which made those analysis possible.

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