Bažant, Z.P. (1996). "Mechanics of failure of materials and structures: An apercu of problems and progress" (keynote lecture), Proc., Int. Conf. on *Design and Assessment of Building Structures* held at Czech Technical University, Prague, to commemorate 75th Anniversary of Klokner Institute. Ed. by M. Holick'y, Vol. II, pp. 1-17.

This issue is devoted to the 75 anniversary of the Klokner Institute,
Czech Technical University
and contains contributions to the International Conference

Design and Assessment of Building Structures

VOLUME II

held in Prague on 12 and 13 September 1996

KEY- NOTE LECTURES

MECHANICS OF FAILURE OF MATERIALS AND STRUCTURES: An Aperçu of Problems and Progress

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Summary

At a major anniversary such as this, it is proper to reflect broadly on the progress achieved in our field. The major field of activity of Klokner institute has been the prediction of failure of materials and structures and the design to prevent failure. This paper, summarizing the opening keynote lecture, presents a nonexhaustive overview—an aperçu—of some the major advances that have been made in the mechanics of failure, and of the directions in which the research is moving. Some of the transparencies projected during the lecture are presented below.

1. Economic Perspective: First the difficulties in funding of research in materials and structures are discussed from the viewpoint of the national economy, particularly in the light of fifty years of nearly uninterrupted growth of governmental outlays for social programs as a percentage of the total governmental spending. This growth (which is documented in Fig. 1 for the U.S. but is similar for most developed countries) has been made possible largely by technological progress and increasing productivity, in which advances in mechanics play a significant role.[2] Although the growth of this percentage cannot continue for a long time, any further increases would be, at least partly if not fully, predicate on further technological advances in various fields, including mechanics[3]

2. Lessons from Catastrophes and Their Classification: A historical and pictorial discussion of some noteworthy catastrophes of structures is presented. The catastrophes are classified into three kinds:

First Kind: These are catastrophes, in which both the code and the theory are not followed. They lead to search for the guilty and punishment. They offer to engineers little or nothing to learn from.

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[2]To appreciate the broad importance of the subject, note, for example, that if a computer fails, it is usually by nothing else than fracture (of a chip, a solder, a disk, a connection,...).

[3]The 'growth theory' model by Paul Romer at Stanford University has confirmed that the long term growth of the world economy can be achieved by technological progress only. Changes of other factors such a labor and capital inputs can lead only to short-term growth and terminate with a stable state. Schumpeter was right! (Economist, Vol. 340, No. 7985, 1996)

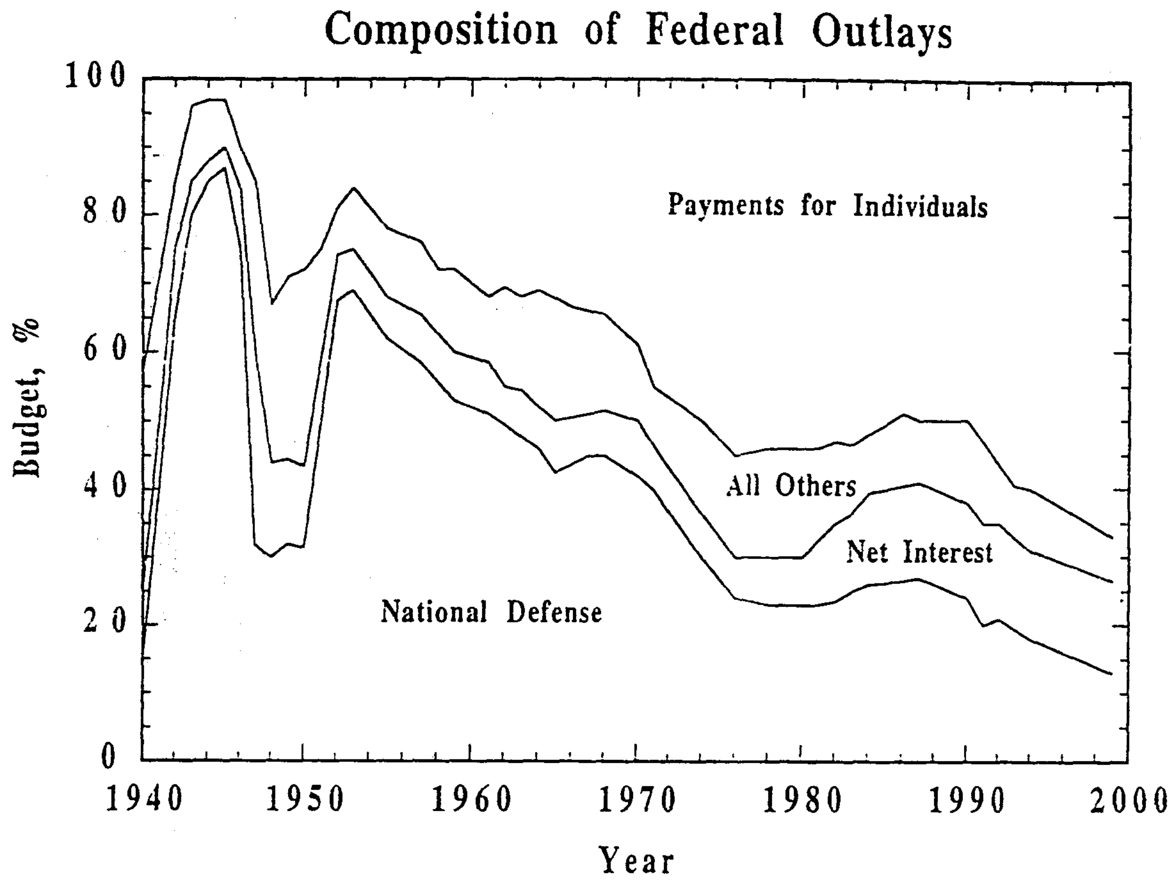

Figure 1: Advances in the mechanics of failure are an essential component in the technological progress and improvements of productivity. One way their importance can be made clear is this diagram of the composition of federal financial outlays of the U.S. Government, in which the payments for individuals represent for the most part the "social budget". The research funding is hidden in the category "all others". Despite the drastic decrease of outlays for national defense, the enormous increase of the social expenditures could have taken place simultaneously with the general increase in the living standard only because of improvements of productivity and great technological progress. Advances in the mechanics of failure have contributed to this progress.

Second Kind: In such catastrophes the theory explaining the disaster is available but ignored (e.g., because the solution has been considered "too theoretical". while the wrong design is protected by the code. This results in embarrassment.

Third Kind: In this case, the theory is unavailable. The catastrophe, as deplorable as it may be, results in further research. Obviously, only this third kind of catastrophe leads to further significant progress.

The occurrence of catastrophes of the first and second kind can be minimized by caution and education. The third only by timidity in design, reluctance to innovate. But this hinders progress and is not a desirable remedy. Inevitably, the range of application of any type of structure will be getting extended (in size, economy, loading, environmental conditions, etc.) until a disaster occurs. In this sense, the third kind of catastrophe is inevitable, although its probability can, and must be, minimized. Hence, progress is inevitable![4]

As examples, the following catastrophes are discussed:

1. Break of a large and expensive stone column stored horizontally in a yard in Venice during the 1630's. This was clearly a catastrophe of the third kind (Fig. 2). Its explanation was attempted by Galileo in his *Mecanica i Movimenti Locali* (1638) and induced him to start investigations of the strength of beams.

2. Collapse of the suspended walkways of the Hyatt Regency Hotel in Kansas City (1981)—a catastrophe of the first kind.

3. Collapse of Quebec Bridge over the Saint Lawrence River at the beginning of this century—a catastrophe mainly of the first kind, caused by ignorance of a much earlier paper by Engesser on the buckling of built-up latticed columns with low shear stiffness.

4. Explosion of space shuttle Challenger, caused mainly by embrittlement of a sealing O-ring at unexpectedly cold temperature (essentially the first kind[5].

5. Collapse of a viaduct in Kobe during the 1995 earthquake, caused by a brittle compression failure of support columns that had insufficient confining reinforcement—a catastrophe of mixed second and third kinds (the reinforcement adhered to the code at the time of construction; the inadequacy of the code was already partly understood before the earthquake but the degree of risk was not).

6. Fractures of the Liberty ships after the second World War, caused by fatigue embrittlement of steel (third kind).

7. Collapse of Schoharie Bridge in the state of New York about a decade ago, caused by failure of an unreinforced foundation plinth whose subsoil was washed out during a flood. The size effect was a major factor and the catastrophe must be judged essentially of the second kind.

[4]Some recent innovations, such as cable-stayed bridges, high strength concrete, have not yet led to a major catastrophe, which means that an increased caution is called for.

[5]A distinction from the second kind is impossible because the U.S. aerospace industry operates without any design codes, having only performance requirements

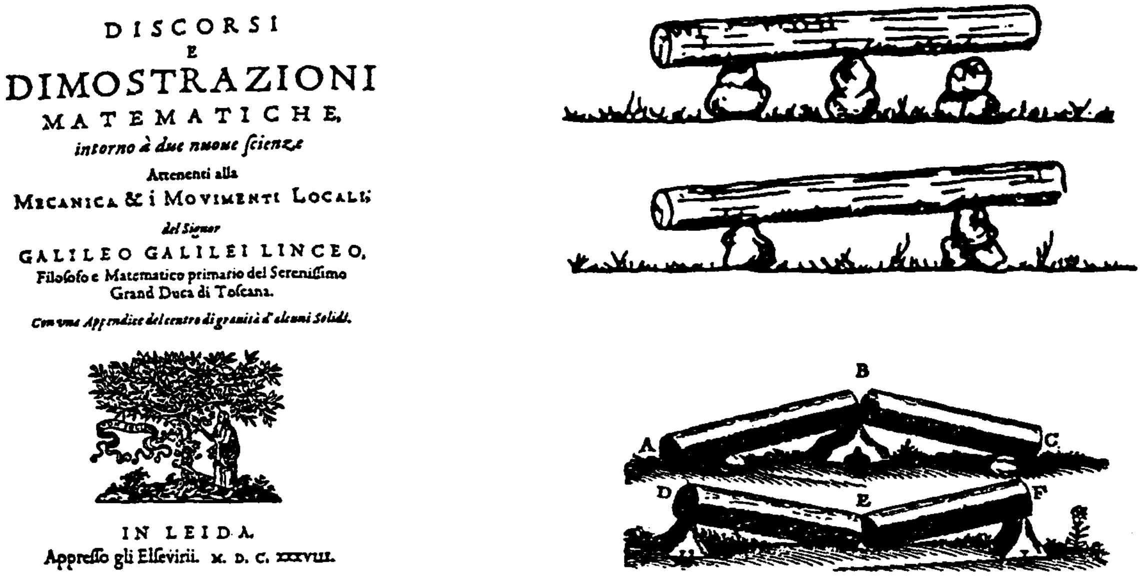

Figure 2: One of the earliest catastrophes of the third kind. A large and expensive stone column was stored in a yard in Venice in the 1630's on two supports. The builder, concerned that this precious column might break, proposed that a third support be added in the middle, and all experts agreed. However, some time later the column was found broken. This was one event that made Galileo interested in the mechanics of bending of beams. He concluded (left) that a settlement of the outside support must have been the cause of this catastrophe (as shown on top right), and compared the modes of failure due to positive and negative bending moments (bottom left).

8. Explosive brittle collapse of Sleipner oil platform in Norway, which occurred several years ago during the submergence test of the platform. It was caused by shear failure near the connection of two thick cylindrical shells, and the three main factors were an improper design of reinforcement at the connection, a gross inaccuracy of linear finite element analysis at the critical cross section, and an increase of brittleness due to the size effect, which was ignored. This costly catastrophe was essentially of mixed first and second kinds (the size effect was known before the construction but its importance was not quite appreciated by the profession and its consideration was not required by the codes).

9. Collapse of Tacoma Bridge in 1940, caused by aerodynamic instability—a catastrophe of the third kind and a problem that required a quarter century of intensive research to become well understood.

3. Stability: The fascinating history and the main features of four major advances in this century are briefly described: (1) Imperfection sensitivity (von Kármán and Tsien, 1941; Koiter, 1945; Hutchinson, Roorda, Tennyson)(Fig. 3). (2) Inelastic bifurcation (Shanley, 1947, von Kármán) (Fig. 4); (3) General catastrophe theory (Thom, 1975, Zeeman, 1977, Arnold, 1972). (4) Nonconservative loads, nonlinear oscillations, chaos, aeroelasticity (von Kármán, Fung, Miloš Novák). The localization instabilities of damage and fracture are pointed out as a major current problem.

4. Plasticity: The importance of the theory of dislocations, predicted theoretically by G.I. Taylor in 1938 and verified by electron microscope after the world war) is commented on. Some noteworthy recent results in elastic and plastic composites are pointed out (G.J. Dvorak, Hashin, Christensen). It is emphasized that plasticity per se causes only the inception of failure. Complete failure is caused by instability such as plastic buckling or necking (Hutchinson, Tvergaard, Rice). As persisting problems, the nonassociated yield and loading surfaces, the vertex effects and their generation through simultaneous action of many yield surfaces, are mentioned. As a new experimental result at Northwestern University, the large strain tests of concrete showing its high ductility under enormous pressures, are highlighted (Fig. 5).

5. Fracture: Fracture mechanics is characterized in general as a theory that considers propagation of failure, and uses energy release criteria. The importance of the pioneering work of Griffith (1921), Orowan, Irwin (1958), Eshelby, Rice and others is discussed, along with the application to concrete initiated by Kaplan (1961) and Walsh (1972). A major post-war result has been the cohesive crack model for quasibrittle materials (concrete, rock, ice, tough ceramics, composites, etc.), originated by Dugdale (1960) and Barenblatt (1959, 1962), with an extension to concrete by Hillerborg (1976) and to polymers by Knauss. Simultaneously, the equivalent crack band model was developed. The widespread traditional assumption that the so-called 'no-tension' analysis is always safe and makes it possible to avoid fracture mechanics is shown to be fallacious, and an example that an increase of the strength of a quasibrittle material can lead to a decrease of load capacity is given.

6. Damage mechanics: Mechanics of progressive damage due to distributed cracking or void growth is probably the most difficult problem of solid mechanics today, as difficult as is turbulence in fluid mechanics. The initial idea of continuum damage mechanics due to Kachanov (1958), later expanded by Hult and Lemaitre, is reviewed. Its value has been proven for creep, fatigue and hardening damage. But it is now understood that, in the case of strain-softening, continuum damage mechanics leads to spurious localization, change of type of the

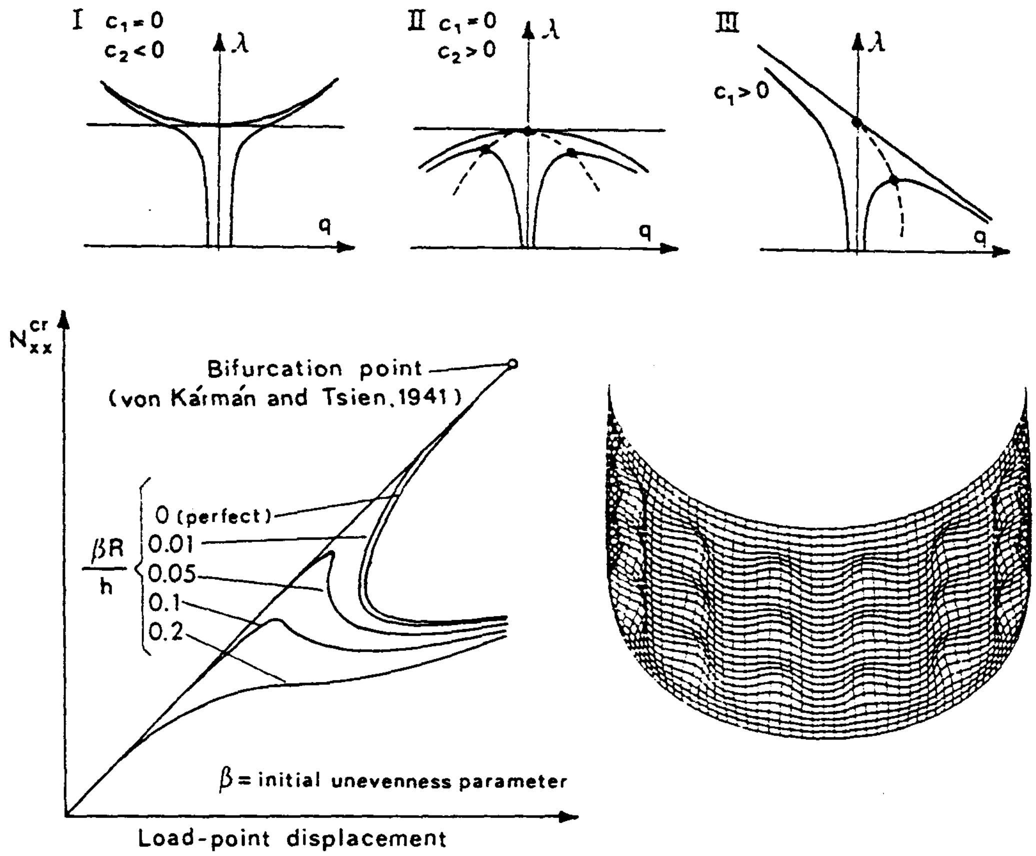

Figure 3: Top: Imperfection sensitivity of the failure load in various types of elastic buckling described by Koiter's power laws (left—stable symmetric bifurcation, no imperfection sensitivity, middle—symmetric unstable bifurcation, mild imperfection sensitivity, right—asymmetric bifurcation, strong imperfection sensitivity); bottom: Imperfection sensitivity seen in load-deflection diagrams of axially compressed cylindrical shell, with the buckle pattern calculated by finite elements at Northwestern University (after S.C. Liu et al., 1988).

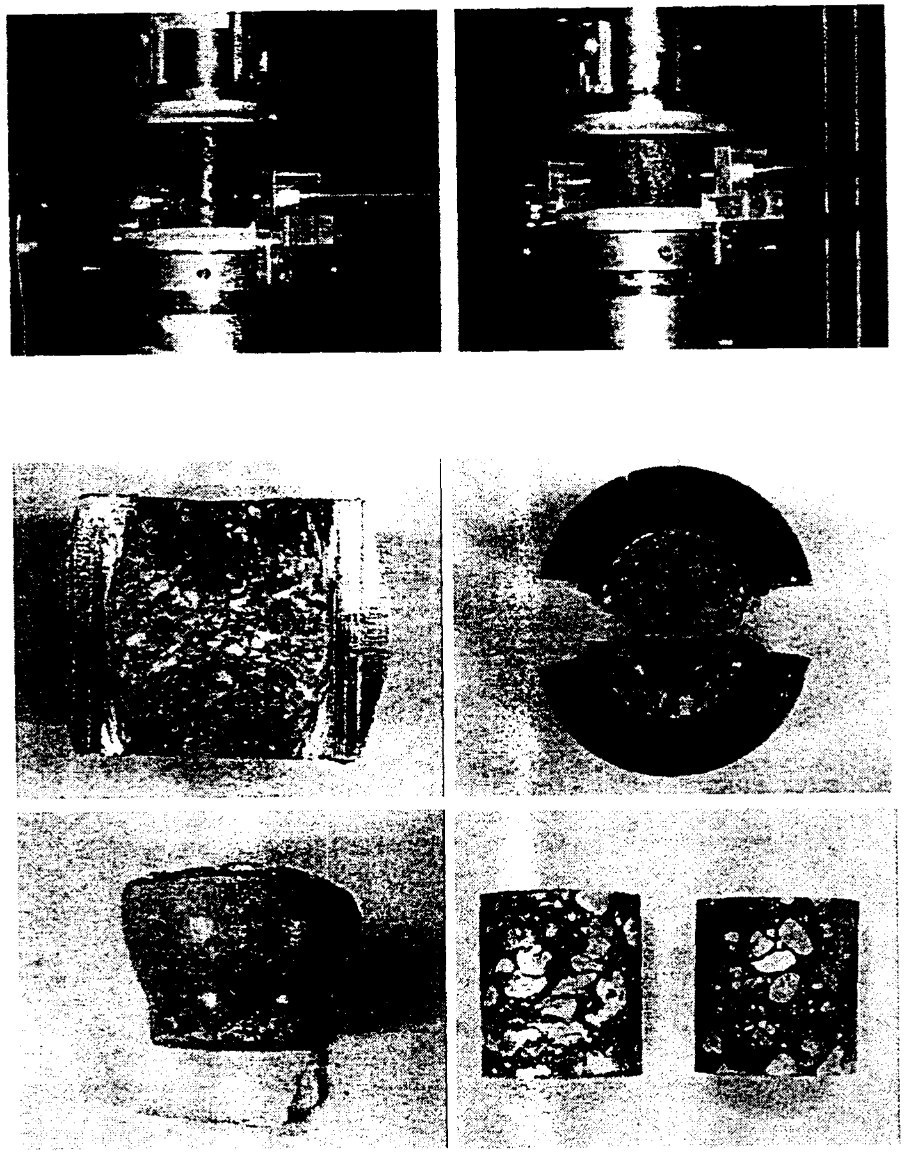

Figure 5: Experiments in which concrete cylinders confined in a very thick and highly ductile steel tube were compressed to 65% of their original length (top), and the appearance of cuts and breaks through the specimens after the test and of the cores taken from the highly strained concrete (bottom) (after Bažant and Kim, tests at Northwestern University in progress). (The cores taken from these enormously compressed specimens had compression strength about 30% of the virgin compression strength.)

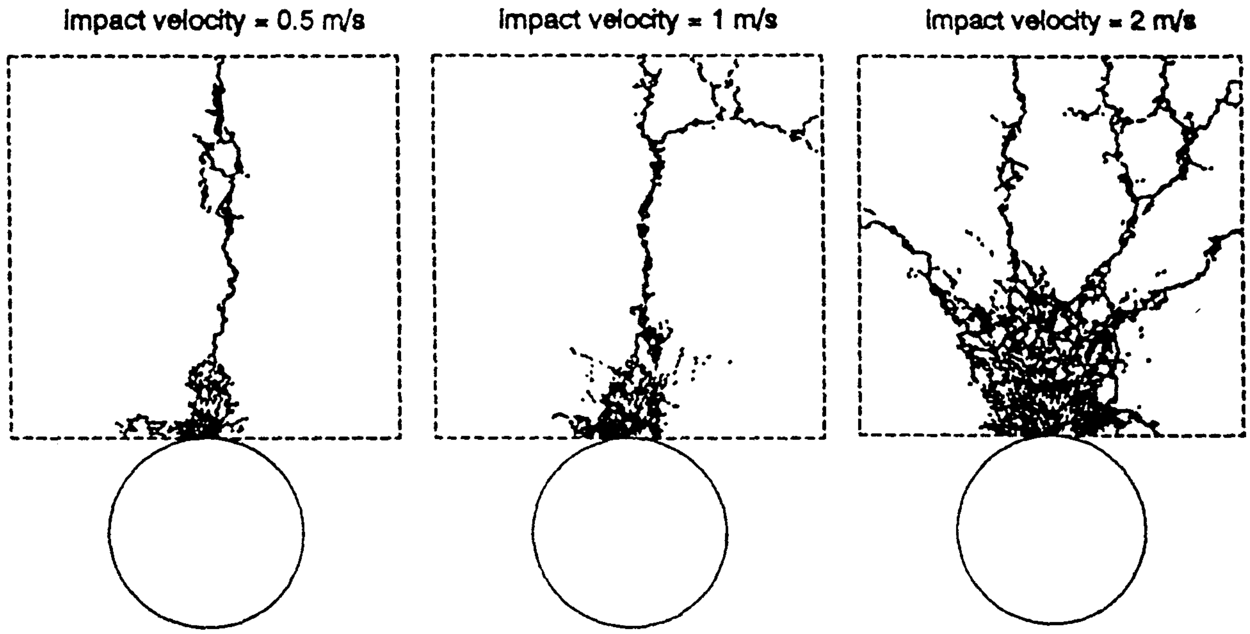

Figure 6: Discrete element simulation of compression fracture in a sea-ice floe impacting a rigid obstacle at various velocities. This calculation, based on quasibrittle fracture characteristics (and involving the solution of a system with over 120,000 degrees of freedom by an explicit algorithm), yields the force exerted on the rigid object (after Jirásek and Bažant, 1994).

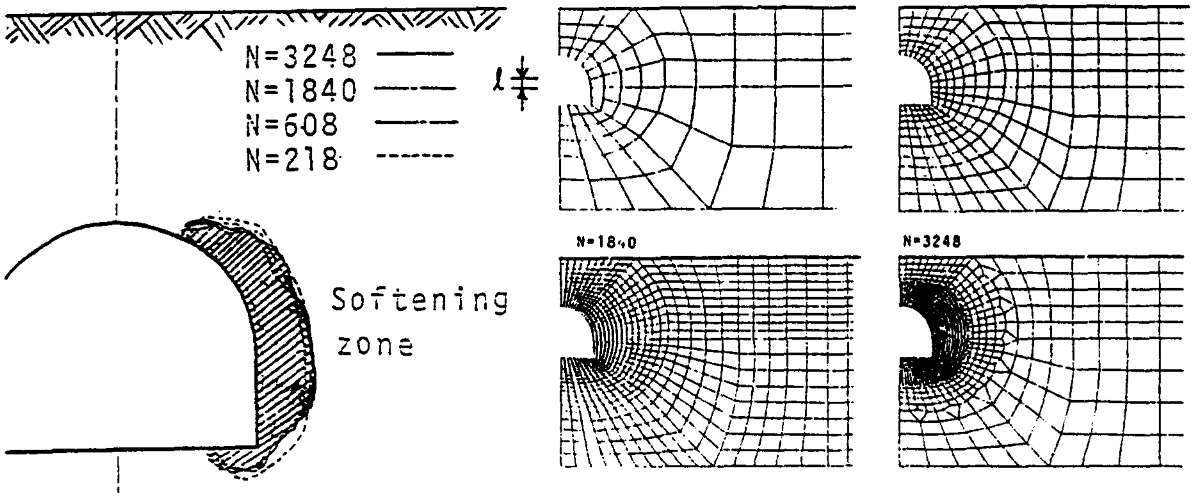

Figure 7: Nonlocal finite element analysis of the softening damage zone caused by excavation of a tunnel in a stiff soil, analyzed (in connection with Milano subway) by meshes of various refinements, with the number of the degrees of freedom ranging from 218 to 3,248. The approximate agreement between the results for different mesh refinements confirms the validity of this analysis, which decides whether or not the excavation can be done by a full-profile boring machine and left temporarily unsupported until a lining is installed. (after Bažant and Lin, 1988).

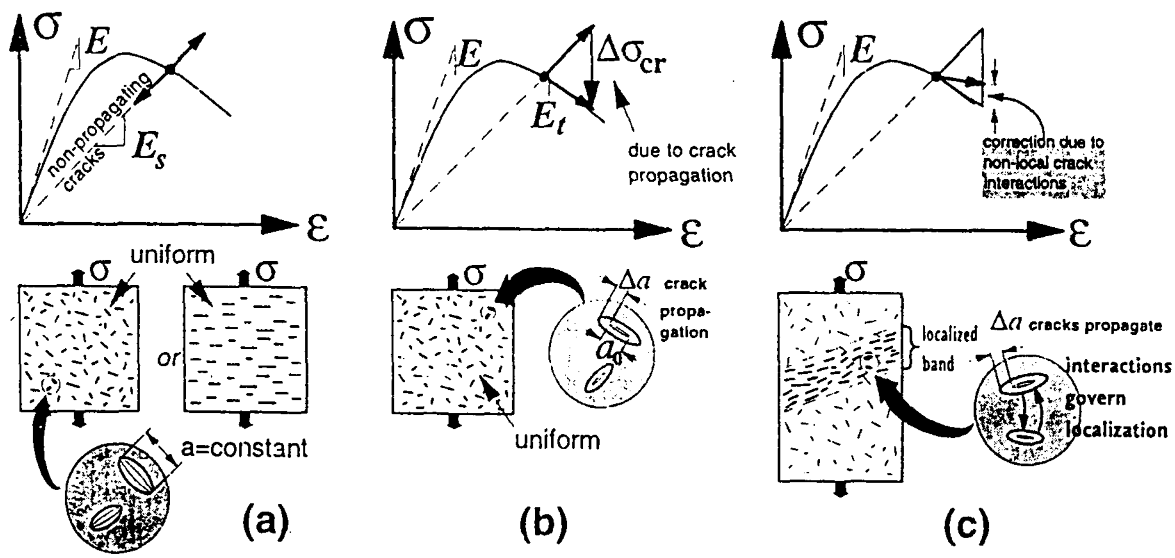

Figure 8: Three types of problems in the modeling of cracking damage. Left: Secant stiffness of a body with many cracks, Middle: Tangential stiffness of a body with growing cracks, Right: Tangential stiffness of a body in which the growing cracks localize. Only the first case has become well understood. Studies of the second and third case have been initiated at Northwestern University, but much remains to be done.

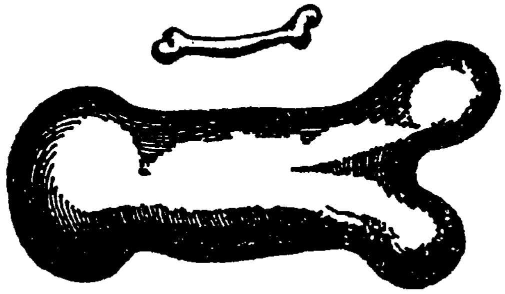

Figure 9: Probably the earliest observation of size effect, as manifested in the shape of the bones of small and large animals (according to Galileo's Two New Sciences, 1638).

etc.; the boundary layer theory is particularly noted). In solid mechanics, the scaling problem is old (Fig. 9) but has not received proper attention until recently. It is nevertheless extremely important for quasibrittle materials.

The experimental studies of *Klokner* and his Institute concerning the size effect in the bending failure of unreinforced concrete beams of different spans and compression failure of concrete cubes of different sizes, published at a 1933 congress in Amsterdam (Fig. 10), are described. The results showed that the nominal strength of plain concrete specimens decreases with increasing size. Along with similar studies at EMPA, Switzerland, an institute with which Klokner had rich contacts, these were indeed pioneering researches for those times.

The classical mathematical explanation of the size effect was the randomness of material strength (Weibull, 1939). This explanation is true for metal fatigue, but not for quasibrittle materials, which have a large fracture process zone and fail only after a large crack growth that causes significant energy release form the structure as a whole. The proper explanation, consisting of the size effect law, formulated in 1983, is briefly described (Fig. 11). Several different derivations and justifications of this simple but rather broadly applicable law are mentioned, including: (1) The energetic derivation based on large-size and small-size asymptotic expansions, and their asymptotic matching; (2) for simple geometries, the energy release explanation based on "stress diffusion" lines; (3) derivation as the deterministic limit of a nonlocal generalization of Weibull theory; (4) numerical solutions by the cohesive (fictitious) crack model; (5) nonlocal finite element solutions (Fig. 12); and (6) numerical simulations by discrete elements (random particle model). As applications, the size effect corrections to code-type ultimate load formulae (e.g., for the diagonal shear failure), and the determination of nonlinear material fracture characteristics from test data, are mentioned.

9. **Disorder:** (a) *Random Strength*—Weibull's (1939) theory has been an important development, useful mainly for fatigue embrittled metal structures. It is emphasized, though, that it applies only to chain-like (series) systems, which are an acceptable approximation only when the structure fails at the initiation of macroscopic crack growth from a microscopic flaw, which is not true for quasibrittle materials. Extension to quasibrittle materials requires a nonlocal generalization of Weibull theory, whose deterministic limit is the aforementioned size effect law. (b) *Fractal Cracks.*—Within a certain range, the fracture surfaces are fractal (Mandelbrot, 1983; Mecholsky, Cahn, Brown, Xie, Saouma, Molosov and Borodich, Lange). Does it cause the size

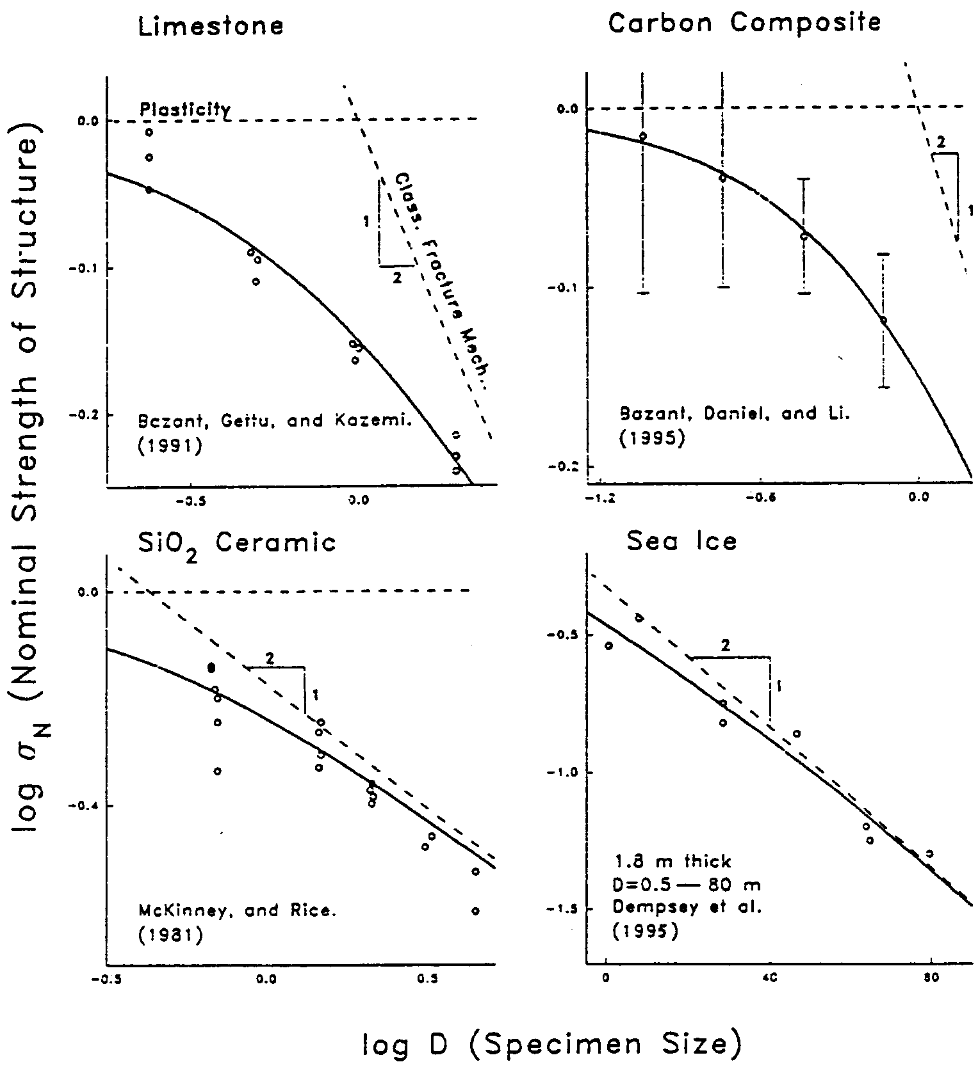

Figure 11: The size effect law for the nominal strengths of quasibrittle structures failing after a large stable crack growth, and its comparisons to some typical test data.

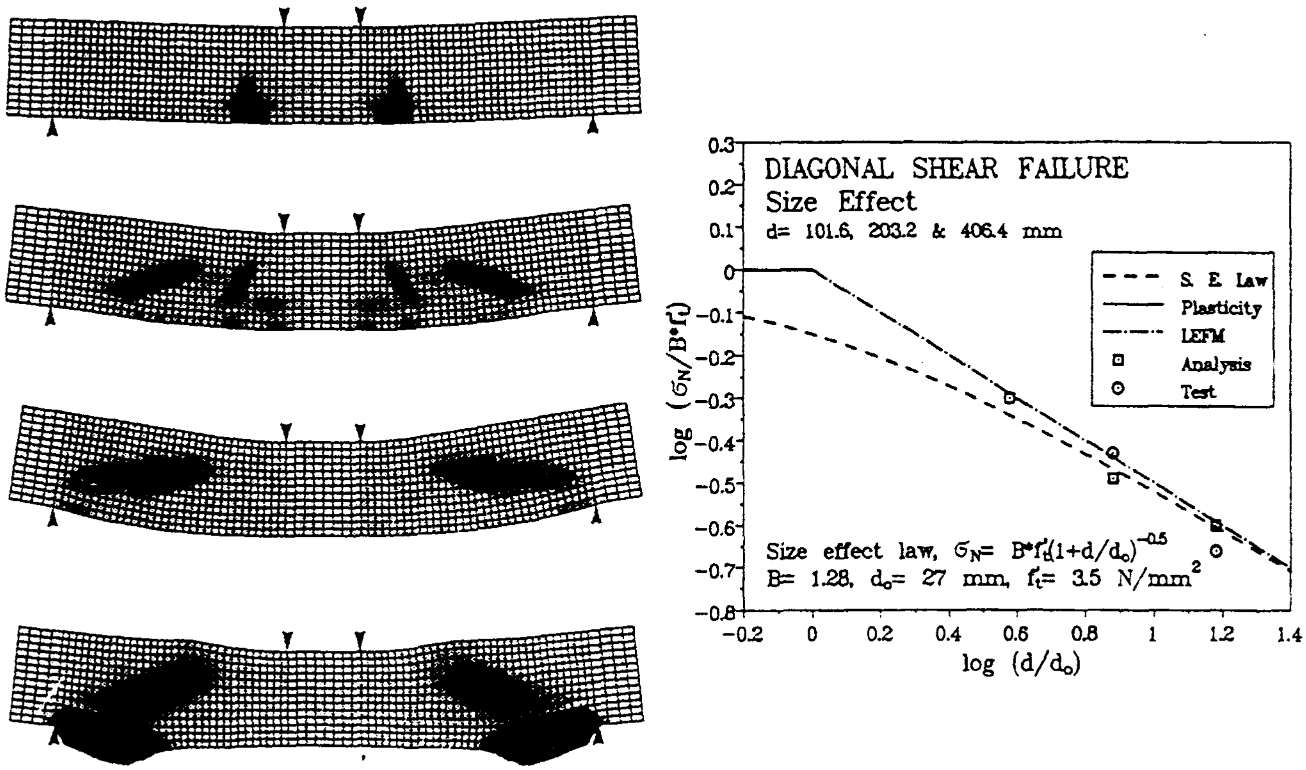

Figure 12: Results of nonlocal finite element simulations of the size effect in the diagonal shear failure of longitudinal reinforced concrete beams, base on a model with crack interactions, and evolution of cracking damage zone (after Ožbolt and Bažant, 1996).

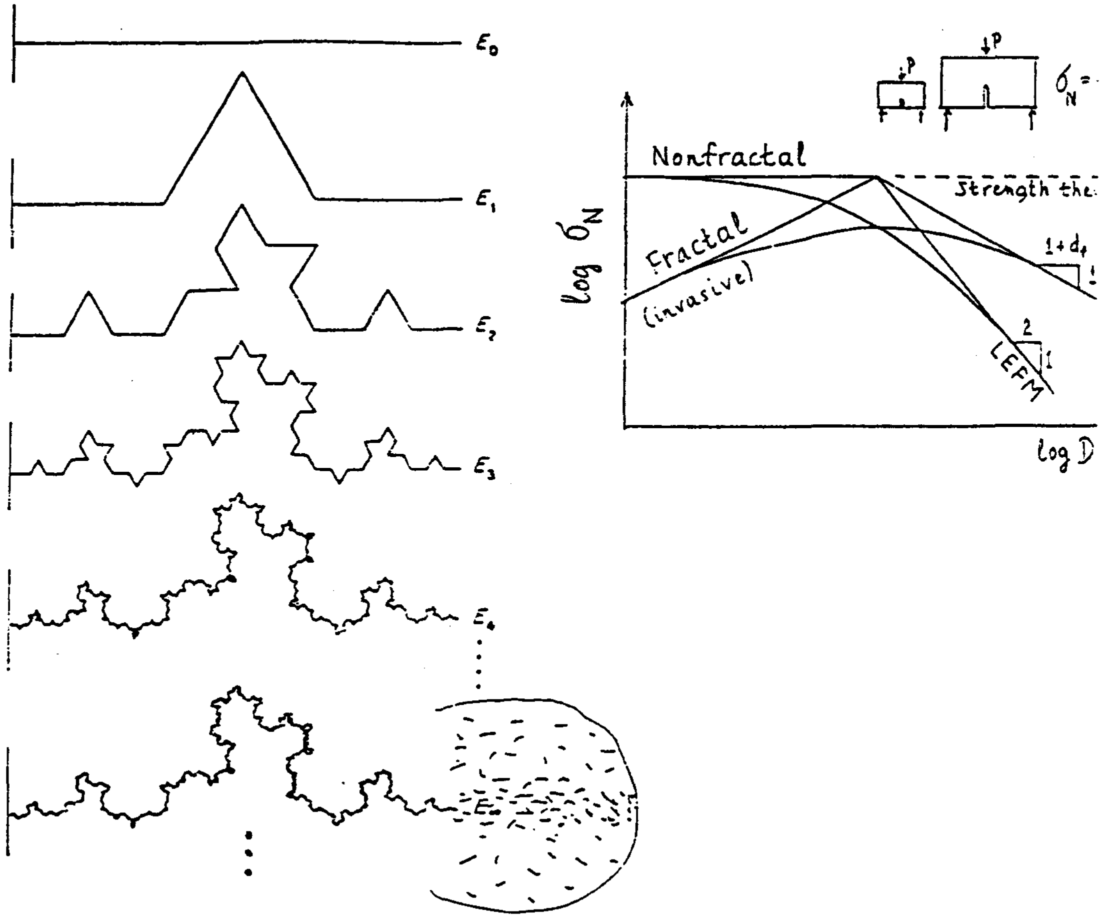

Figure 13: The concept of a fractal crack curve, and the consequences obtained by a mechanical analysis of the size effect. The fractal crack curve is illustrated by the von Koch curve obtained by progressive self-similar refinements of straight segments with triangular bumps. Obviously, in the infinite refinement, the curve is infinitely long, which requires a non-standard definition of fracture energy. Yet, despite various confirmations of fractal characteristics of crack roughness, this concept does not appear to explain the size effect on nominal strength of structures.

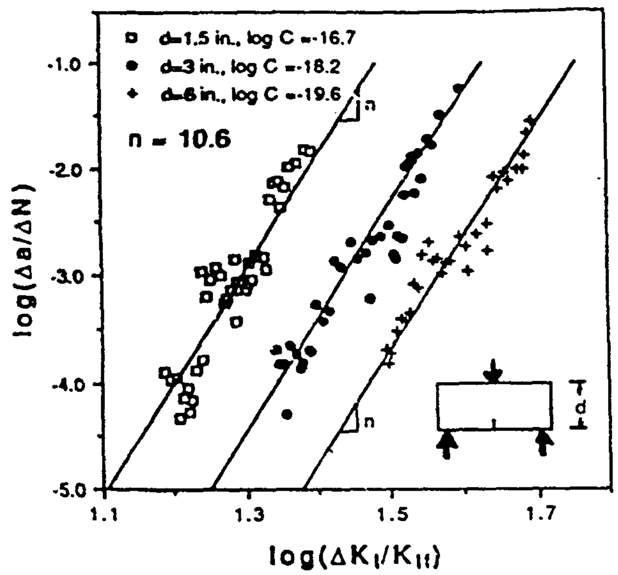

Figure 14: Demonstration that the well-known Paris law relating the rate of fatigue crack length growth per cycle to the amplitude of the stress intensity factor requires a correction for the size effect. In the plot shown, the Paris law represents a single straight line, for different sizes different lines are obtained the testing of concrete. (After Bazănt and Schell, 1991 ?).

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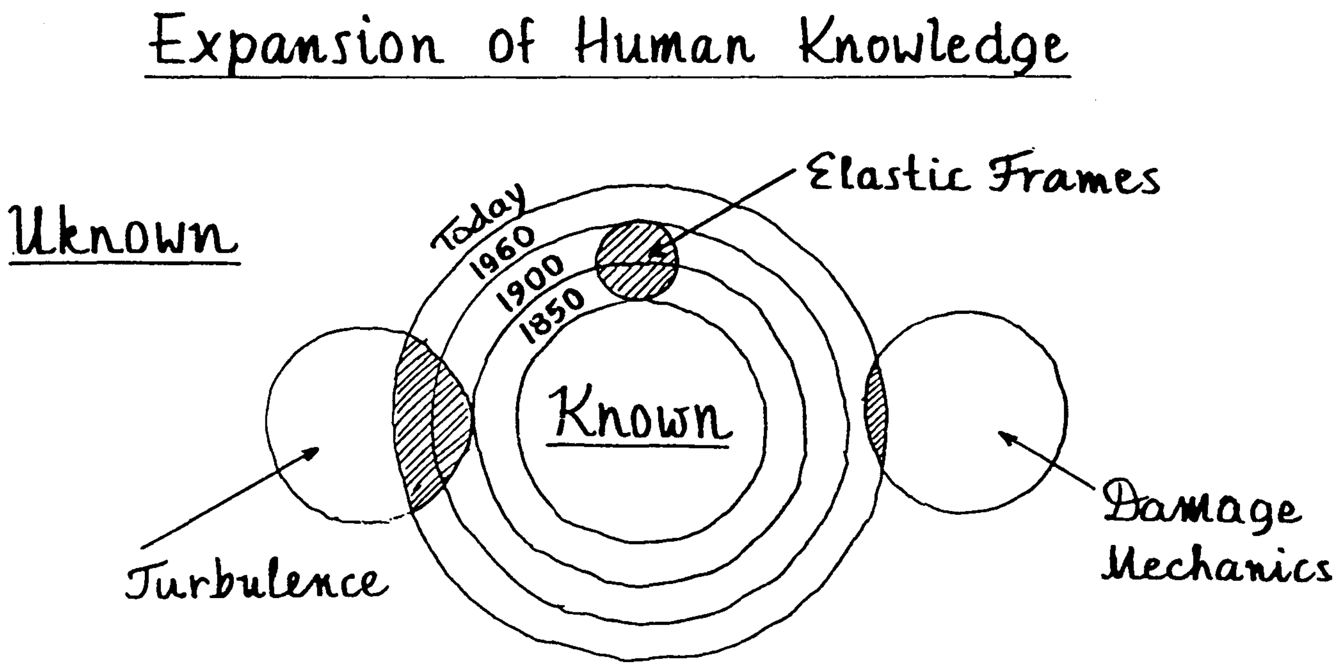

Figure 15: Perception of the current stage of evolution of the mechanics of damage and failure in comparison to the expansion of human knowledge. The interior of each circle represents what is known and the exterior what is unknown. At any given time, only the problems in the exterior that are in contact with the current circle are accessible to study. With time, the diameter of the circle is growing. This explains that the amount of what is unknown and accessible to study is increasing with time despite the previous expansion of knowledge. Damage mechanics appears to be a formidable problem, of a similar level of difficulty as turbulence in fluid mechanics, and probably will take a century to become fully understood. However, many problems of solid mechanics that have once loomed large, such as the elastic frames, have already reached the stage of complete understanding.