SP 118-1

Technological Implications of Concrete Fracture Research— An Overview of Tensile Failure in Cementitious Materials and Structures

by V.C. Li

Synopsis: This paper reviews the tensile failure of concrete structures subjected to a variety of practical loading. Attention is focused on the propensity of fracture failure of concrete structures and the fracture properties of cementitious materials. The relevance of fracture mechanics to a modern concrete design code is highlighted.

Keywords: building codes; concretes; cracking (fracturing); failure; fiber reinforced concretes; fracture properties; research; reviews; tensile stress; structural design

Victor C. Li has done research in non-linear fracture analysis, fracture testing method and micro/meso-mechanics of concrete. He is pursuing the advancement of high strength/high ductility concrete as a construction material of the future. Victor Li is an Associate Professor of Civil Engineering at the Massachusetts Institute of Technology, Cambridge, MA 02139, USA.

INTRODUCTION

Extensive experiments have revealed the dependence of concrete structural component strength on its size. This size dependence cannot be explained by the Weibull distribution of flaw size alone. Instead, it has been shown that the quasi-brittle nature leading to a fracture mode of failure in concrete is responsible for this phenomenon. Current reinforced concrete design codes (e.g. ACI 318 Building Code Requirements for Reinforced Concrete) are based on strength or similar concepts. Is the code over-conservative and economically wasteful? Is the code under-conservative and represents potential hazards? Does the code reflect modern design concerns such as structural durability and the introduction of concrete with higher strength but perhaps more brittle behavior? In addition, increasing observational evidence of macroscopic fracture failure in concrete structures suggests a need for new tools beyond the traditional means of concrete structural analysis under certain circumstances.

WHAT CAUSES TENSILE FAILURE IN CONCRETE STRUCTURES?

What causes tensile stress in the concrete if the structure is reinforced or even prestressed? The origin of tensile stresses may come from several sources -- applied loading such as in the flexing of a beam and that due to punching on a slab, material shrinkage during curing of the concrete, stress concentration related to structural geometry as in shear keys (such as those in precast concrete bridge segments [1]), and ironically, even from the reinforcing bar itself. This last source has been documented as spalls developed on concrete covers caused by the propagation of cracks in the concrete as the steel bar corrodes and expands (NCHRP Synthesis No. 57, 1979). In addition, when a reinforced concrete beam or slab is loaded in excessive bending, the reinforcing bar may slip. The ribs of a re-bar can cause local tensile stresses in adjacent concrete when the re-bar deforms in tension [2]. Given the wide variety of situations when tensile loads are directly or indirectly induced in concrete, and that concrete is a brittle material (concrete has 0.1 to 1 % of the tensile strength of structural steel, and

only 0.2 to 4 % of its fracture toughness), it is no wonder why cracks develop in concrete structures. It should be noted that even predominantly compressive loading, such as caused by post-tensioning in certain concrete structures, can generate tensile cracks in the transverse direction which leads to surface spalling. This is, after all, the failure mechanism of an unconfined concrete cylinder under compressive loading.

WHY SHOULD TENSILE CRACKS BE OF CONCERN?

Are cracks benign in reinforced concrete structures? It depends on many factors. It is rather rare, at least from past experience, that reinforced concrete structures collapse from a brittle fracture failure in concrete. In some metal structures, a small crack may grow rapidly and rather suddenly lead to a catastrophic structural collapse. In reinforced concrete structures, failure associated with cracks may occur in different manners. For example, cracks increase the permeability of concrete and allow greater penetration of chloride ions and other agents which cause the corrosion of the reinforcing steel. Concrete bridge deck delamination and spalling have been traced to tensile cracking near corroding re-bars which expand with time (Figure 1). Thus certain poor durability of reinforced concrete structures may be associated with the lack of tensile load bearing capacity of concrete. Thermal loading has been known to be responsible for tensile crack development leading to failure of concrete dams [3]. Failure of the Kolnbrein dam has also been traced to excessive loading and its acute geometry, in combination with low fracture resistance of the material, resulting in large fractures at the base of this arch dam [4].

For certain structures, especially thin wall structures such as concrete pipes and shells, the reinforcement ratio could be very low or none at all due to difficulty in placing the reinforcing bars. In this case, the potential of fracture failure and structural collapse becomes more likely [5] . Even in reinforced structures, there are locations where reinforcement may be difficult to place due to the structural geometry. This is the case near the shear keys of concrete segments in segmental bridge construction [1]. It is often in such locations where tensile stress and concrete cracking occurs. Cracks growing from such a region may extend into an initially compressive zone where there is little or no reinforcement in the structural member. Such cracking development could compromise the structural integrity of the joint. In addition, it has been shown [6] that the post-tensioning of steel tendons in precast concrete segmental bridges could cause high tensile stresses in the direction transverse to the steel tendons which may lead to surface spalling. The loss of anchorage and bond of a re-bar has been associated with the development of tensile cracks in the concrete [2]. Moreover, it is known that reinforced concrete structures often develop dangerous surface spalls under impact loads.

The above observations represent a spectrum of problems in concrete structures related to the lack of tensile bearing capacity of concrete. These problems can be avoided if we understand how the tensile stresses arise, how the material responds to these tensile stresses, and how the material may be engineered to perform adequately under tensile loading.

STATE OF THE ART IN RESEARCH IN CONCRETE FRACTURE

It is the recognition of the importance of cracking in concrete structures that research of concrete and concrete structures in the tensile field has intensified in recent years (e.g. NATO Advanced Research Workshop on Application of Fracture Mechanics to Cementitious Composites, Evanston, 1984; International Conference on Fracture of Concrete and Rock sponsored by RILEM & SEM, Houston, U.S.A., 1987; American Concrete Institute Symposium on Applications of Fracture Mechanics to Concrete Structures, Seattle, U.S.A., 1987; MRS International Meeting on Advanced Materials: Symposium on Fracture of Rock and Concrete, Tokyo, Japan, 1988; International Conference on Fracture and Damage of Concrete and Rock, Vienna, Austria, 1988; International Workshop on Fracture Toughness and Fracture Energy -- Test Methods for Concrete and Rock, Sendai, Japan, 1988). Since concrete is a brittle material, it has become common place to study concrete failure in tension by means of fracture mechanics. Here several issues arise: Does 'fracture mechanics' accurately describe concrete failure in tension? How does one accurately characterize and measure the 'fracture resistance' of the material? How does one apply the appropriate fracture mechanics theory and the measured 'fracture resistance' of the material to predict the performance of a reinforced or unreinforced concrete structure? How can one improve the structural performance by improving the mechanical behavior of the material? In spite of extensive research in recent years, these questions have only been partially answered. There is, however, growing convergence of opinion. For example, it is now generally agreed that linear elastic fracture mechanics may not be directly applicable to concrete, unless the structure or laboratory specimen size is very large [7], and that a non-linear 'fracture mechanics' theory accounting for the growth of a fracture process zone and subsequently a structural size effect could be used instead [7,8,9,10,11,12]. However, the issue of fracture resistance

characterization and measurement is still much debated and a standard test method has yet to be established. Apart from theories, there are also recent advances in numerical methodology, especially in finite element method, and to a lesser extent, boundary element method, in incorporating these theories in the analyses of increasingly more complex structures. Successful modelling of concrete structural behavior using fracture based finite element codes have been achieved by various researchers [e.g. 4,5,13,14,15,16]. Additional work in fracture resistance characterization and measurement, and in numerical simulation of simultaneous tension-softening and slip-weakening mixed mode concrete fracture appears to be necessary to deal with structures subjected to mixed mode loading. Introduction of new construction materials such as high strength concrete and polymer concrete having different fracture characteristics from normal concrete, demands further investigations into how such materials influence structural performance, especially when they are subjected to tensile stresses.

With the recognition of fracture resistance as an important material parameter for concrete, there is increasing research in improving this property through materials engineering. At present the most successful technique of achieving fracture resistance improvement is by means of fiber reinforcement. It has been demonstrated experimentally [17] that the corresponding flexural strength of a concrete beam also increases with the material fracture resistance through fiber reinforcement. This interesting phenomenon has been explained in terms of fracture mechanics [17,18] and applies also to other types of reinforced concrete structures and loading such as shear in an axially reinforced beam, in which the material eventually fails by developing tensile cracks. In addition, fiber reinforced concrete has been shown to improve the durability of concrete structures by shrinkage crack size and in resisting crack growth under freeze-thaw cycling [19,20,21]. It has also been shown that fiber reinforcement can significantly improve the fatigue strength and impact strength of concrete [22]. And of course, they reduce the possibility of fracture failure by significantly improving the fracture toughness [22,23]. Other relatively young but promising research areas include the study of the relation between micro/meso-structures and internal deformations of concrete and concrete mechanical properties. It is reasonable to expect that such research may lead to the development of cementitious materials with improved performance. Such advanced construction materials may reduce the amount of steel bar reinforcements (with the greatest potential in reducing the amount of shear reinforcement) which form one of the most expensive components in a number of important reinforced concrete structures. They may also reduce the self-weight of the structure.

IMPLICATIONS OF CONCRETE FRACTURE RESEARCH ON THE CONCRETE STRUCTURE CODE

Ultimately research results of concrete and concrete structure in the tensile field must contribute to the engineering performance of concrete structures, whether in the form of safety or economic efficiency. These research results may find their way into the concrete codes if they are perceived to be important by concrete and concrete structure professionals.

Two modern trends in construction may accelerate the transition of academic research into engineering practice. Concrete structural members are increasing in size due to advances in materials and improvements in design and construction techniques [24]. It is well known that larger size structures lead to failure modes which are more 'fracture' like. Such reduction in load bearing capacity, generally known as the "size effect" has been demonstrated experimentally by [24,25,26]. (See also the article by Shioya et al and by Hillerborg, this volume). Presently the ACI code does not recognize this phenomenon, thus leading to an unconservative estimate of shear beam strength. The European CEB code is based on empirical fit to limited experimental data, and appears to be overconservative at small beam depth and unconservative at large beam depths. Hillerborg (Figure 5 of [18]) and Bazant and Sun [27] showed that this size effect can be predicted based on non-linear fracture mechanics theory. In addition, concrete structures subjected to excessive torsional load have been shown experimentally [28] and analytically [29] to fail in accordance with a fracture type size effect. Furthermore, other concrete structural capacity such as the pull-out capacity of a short anchor bolt in concrete (Figure 2) has been demonstrated to be controlled by the fracture resistance [30] instead of the strength of the concrete material.

These works suggest that the fracture energy is a fundamental material property as important as the compressive strength in controlling the flexural and shear strength of concrete structural members. This may be considered a solid step in bringing about the use of fracture mechanics in structural design. From a structural safety viewpoint, such studies provide strong motivation for concrete code revision [31]. To this end, fracture mechanics provides a rational means. Although it is possible to conduct large scale structural tests, they can only be done with limited number of specimens, limited number of reinforcement ratios, limited geometries, and limited loading configurations, and with great expense. Prediction of structural performance based on fracture mechanics overcomes all of these limitations.

Another trend in the construction industry is the gradual adoption of high strength concrete as a construction material. While these materials provide higher compressive strength (sometimes up to 3 or 4 fold that of normal concrete), there are indications that they are more brittle [32,33]. (The word 'brittle' here is best interpreted as having a small material characteristic length, l_{ch}, as defined by Hillerborg [7]. In contrast, most fiber reinforced concrete with low fiber volume fraction has a large l_{ch} through improvement of the fracture energy, while maintaining the Young's modulus and the tensile strength more or less unchanged.) This implies that high strength concrete structures are more prone to catastrophic failure once a crack is initiated. (ACI Committee 363 also recognizes the likely relative decrease in shear strength with high fc' and presently requires nominal stirrups if fc' > 12,000 psi.) Because of the finer microstructure, high strength concrete also tends to be more notch sensitive and may result in compromise of reliability. Current use of high strength concrete often requires additional steel reinforcement which increases cost and weight and defeats the purpose of using high strength concrete in the first place. Jacketing of high strength concrete to increase confinement also leads to difficulty in quality control on the construction site. In addition, shrinkage cracking may be more severe than ordinary concrete because of the higher modulus of the material. These problems associated with high strength concrete could be resolved with the use of fiber reinforcement (leading to high strength/high ductility concrete) and better understanding of structural behavior through fracture mechanics concepts.

The construction trends of using larger structural members and higher strength concrete place additional urgency to incorporate research results of concrete and concrete structures in the tensile field into a modern concrete design code.

A DISASTER RELATED TO THE FRACTURE FAILURE OF A CONCRETE STRUCTURE

Apart from the Kolnbrein Dam mentioned earlier, there is at least one more documented case where the destruction of a structure is associated with the fracture failure of concrete. This is the sudden collapse of the New York Thruway Bridge at Schoharie Creek (Figure 3a) where two spans fell into the creek leading to the loss of ten lives. The direct cause of the disaster is traced to the rapid flow in the flood-swollen creek leading to undermining beneath the footing of the piers [34]. A finite element analysis revealed that the tensile stress in the top part of the plinth which broke into halves (Figure 3b) at the time of the accident was much below the tensile strength as determined from laboratory test of cored samples. Instead the tensile stress at failure for the large size plinth was in accordance to that predicted by non-linear elastic fracture mechanics (Figure 4). The report prepared for the New York Thruway Authority further pointed out that "because of the very large size of the unreinforced plinth in Pier 3, average stress at failure will not correspond to the estimated modulus of rupture of 750 psi, or even the commonly accepted value of $7.5 \sqrt{f'_c}$ or 550 psi that is given in the ACI code. Rupture would be expected at a much lower value, on the order of 200 psi."

Based on this case experience, the following observations can be made: 1). Fracture mechanics may be used to predict the size effect on structural strength of concrete members (including those that are reinforced). 2). The structural strength of concrete members may depend on the fracture energy in addition to conventional material properties (E, f'_c, etc). 3). As an important material property in fracture control, research efforts should be directed towards engineering of improved fracture energy of ordinary and particularly high strength concrete. 4). Fracture failure in the form of fast running cracks in concrete structures may lead to loss of structural integrity and human life. 5). A modern concrete structural design code should be extended beyond strength concepts. It should include energy concepts embodied in fracture mechanics.

CONCLUSION

The study of tensile behavior of concrete and concrete structures provides the technological basis leading to the safe and economic design of concrete structures. Fracture mechanics, when used appropriately, can be a powerful tool for predicting concrete structure behavior when the material is subjected to tensile stresses in various practical situations, even when the structure is reinforced. Fracture mechanics also contributes to a framework for the characterization, measurement and material engineering of fracture resistance of concrete and cementitious composites. Among other advantages, improved fracture resistance in fiber concrete composites will prevent small cracks from growing into major fractures, will reduce crack widths (and subsequently concrete permeability), will prevent delamination in reinforced concrete structures, will provide greater structural integrity (e.g. by improved resistance to losing anchorage of the re-bar in concrete), and will provide greater ductility to the structure when subjected to extreme loads such as that associated with earthquakes or impact loads associated

with flying projectiles. Developments in concrete fracture mechanics technology are particularly important when viewed in the context of the construction trend of using higher strength concrete and in building larger concrete structures, and when the durability of concrete structures is of concern. A concrete structural design code which accounts for the tensile behavior of concrete and which incorporates fracture concepts will promote the safety, the service life, and the structural performance of concrete structures. Development of cementitious materials with improved tensile performance may lead to structural design innovations.

ACKNOWLEDGEMENT

The author would like to thank A. Argon, Z. Bazant, and S. Swartz for their review of the manuscript. Their helpful suggestions resulted in several improvements in this paper.

This work was partially supported by grants from the National Science Foundation and the Shimizu Corporation.

REFERENCES

1. Kashima, S. and Breen, J.E., "Construction and Load Tests of a Segmentally Precast Box Girder Bridge Model", Research Report 121-5, Center for Highway Research, U. of Texas at Austin, 1975.

2. Ingraffea, A., Gerstle, W.H., Gergely, P., and Saouma, V., "Fracture Mechanics of Bond in Reinforced Concrete", ASCE Structures, April 1984, p.871-890.

3. Saouma, V., Ayari M, and Boggs, H., "Fracture Mechanics of Concrete Gravity Dams", in *Fracture of Concrete and Rock*, ed. Shah and Swartz, 1987, pp 496-519.

4. Ingraffea, A., Linsbauer, H, and Rossmanith, H.,"Computer Simulation of Cracking in a Large Arch Dam-Downstream Side Cracking", in *Fracture of Concrete and Rock*, ed. Shah and Swartz, 1987, pp 547-557.

5. Gustafsson, P.J. and Hillerborg, A., "Improvements in Concrete Design Achieved Through the Application of Fracture Mechanics", in *Application of Fracture Mechanics to Cementitious Composites*, ed. Shah, 1985, pp 667-680.

6. Wium, D.J.W., and Buyukosturk, O., "Behavior of Precast Segmental Concrete Bridges", MIT Dept. of Civil Engineering Research Report R84-06, 1984.

7. Hillerborg, A., "Analysis of One Single Crack", in *Fracture Mechanics of Concrete*, ed. F.H. Wittmann, Elsevier, 1983, pp. 223-250.

8. Ingraffea, A.R. and Gerstle, W.H., "Nonlinear Fracture Models for Discrete Crack Propagation", in *Application of Fracture Mechanics to Cementitious Composites*, ed. Shah, 1985, pp 247-286.

9. Ballarini, R., Shah, S.P. and Keer, L.M. "Nonlinear Analysis for Mixed Mode Fracture", in *Application of Fracture Mechanics to Cementitious Composites*, ed. Shah, 1985, pp 51-86.

10. Li, V.C. and Liang, E., "Fracture Processes in Concrete and Fiber Reinforced Cementitious Composites", *ASCE J. of Engineering Mechanics*, 112, pp. 566-585, 1986.

11. Bazant, Z.P., "Fracture Energy of Heterogeneous Materials and Similitude", in *Fracture of Concrete and Rock*, ed. Shah and Swartz, 1987, pp 390-402.

12. Reinhardt, H.W., "Fracture Mechanics of an Elastic Softening Material Like Concrete" *Heron*, Vol. 29, No. 2, 1984.

13. Leibengood L, Darwin, D. and Dodds, R., "Finite Element Analysis of Concrete Fracture Specimens", Structural Engineering and Engineering Materials SM Report No. 11, The University of Kansas Center for Research, Inc., 1984.

14. Wium, D.J.W., Buyukozturk, O. and Li,V.C., "Hybrid Model for Discrete Cracks in Concrete", *ASCE J. of Engineering Mechanics*, 1211-1229, 1984.

15. Bazant, Z. P., Kim, J.K. and Pfeiffer, P., "Continuum Model for Progressive Cracking and Identification of Nonlinear Fracture Parameters", in *Application of Fracture Mechanics to Cementitious Composites*, ed. Shah, 1985, pp197-246.

16. Carpinteri, A., Di Tomaso, A. and Fanelli, M., "Influence of Material Parameters and Geometry on Cohesive Crack Propagation", in *Fracture Toughness and Fracture Energy of Concrete*, ed. Wittman, Elsevier Science Publishers, Netherlands, 1986, pp 117-135.

17. Ward, R., Yamanobe, K., Li , V. C. and Backer, S.,"Effect of Fiber Volume Fraction on the Mechanical Properties of Fiber Reinforced Concrete and Concrete Structures", this volume, 1988.

18. Hillerborg, A., "Fracture Mechanics and the Concrete Code", this volume,1988.

19. Ohama,Y., "Durability and Long-Term Performance of FRC", in *Proceedings of the International Symposium on Fiber Reinforced Concrete*, Madras, India, December 1987, Oxford & IBH Publishing Co., 1987, pp. 5.3-5.16.

20. Hasegawa, T., Koh, Y., Akihama, S. and Suenaga, T.,"Frost Resistance of Glass, Aramid, Vinylon Fiber Reinforced Cement Composites", Annual Meeting of the Architectural Institute of Japan, Sapporo, August 1986, A, pp. 89-90.

21. Komlos, K. and Brull, L., "Early Shrinkage of Fiber Reinforced Cements and Mortars", in *Proceedings of the International Symposium on Fiber Reinforced Concrete*, Madras, India, December 1987, Oxford & IBH Publishing Co., 1987, pp. 4.41-4.50.

22. Ramakrishnan, V., "Materials and Properties of Fiber Reinforced Concrete", in *Proceedings of the International Symposium on Fiber Reinforced Concrete*, Madras, India, December 1987, Oxford & IBH Publishing Co.,1987, pp. 2.3-2.23.

23. Li, V.C., Backer, S., Wang, Y., Leung, C. and Yamanobe, K. "Tensile Failure Mechanisms and Mechanical Properties of Fiber Reinforced Concrete", in *Proceedings of the International Symposium on Fiber Reinforced Concrete*, Madras, India, December 1987, Oxford & IBH Publishing Co.,1987, pp. 1.163-1.172.

24. Iguro, M., Shioya T., Nojiri, Y. and Akiyama, H. "Experimental Studies on Shear Strength of Large Reinforced Concrete Beams under Uniformly Distributed Load," Japanese Society of Concrete Engineering, Concrete Library International, No. 5, 1985, pp 137-154.

25. Leonhardt, F., "Shear in Concrete Structures," Bulletin d'information No. 126, Shear and Torsion, CEB, Paris, 1978, 66-124.

26. Taylor, H.P.J., "Basic Behavior in Shear and the Model Code," Bulletin d'information No. 126, CEB, Paris, 1978, 125-140.

27. Bazant, Z.P. and Sun, H.H. "Size Effect in Diagonal Shear Failure: Influence of Aggregate Size and Stirrups", *ACI Materials Journal,* July-August, 1987, pp 259-272.

28. Hsu, T.T.C., "Torsion of Reinforced Concrete", Van Nostrand Reinhold Company, New York, 1984, 516 pp.

29. Bazant, Z.P., Sener, S. and Prat, P.C. "Fracture Mechanics Size Effect and Ultimate Load of Beams under Torsion," this volume, 1088.

30. Ballarini, R, Shah, S.P., and Keer, L.M., "Failure Characteristics of Short Anchor Bolts Embedded in a Brittle Material," *Proceedings R. Soc. London* A 404, 1986, pp. 35-54.

31. Hawkins, N., "The Role for Fracture Mechanics in Conventional Reinforced Concrete Design", in *Application of Fracture Mechanics to Cementitious Composites*, ed. Shah, 1985, pp639-666.

32. Shah, S., "Fracture Toughness of Cement Based Materials", *Materials and Structures*, 21, 1988, pp.145-150.

33. Wecharatana, M. and Chimamphant, S. "Bond Strength of Deformed Bars and Steel Fibers in High Strength Concrete", in *Bonding in Cementitious Composites*, MRS Symposium Volume 114, Ed. S. Mindess and S.P. Shah, 1988.

34. "Collapse of the Thruway Bridge at Schoharie Creek", Wiss, Janney, Elstner Associates, Inc., and Mueser Rutledge Consulting Engineers, a report prepared for New York State Thruway Authority, 1987.

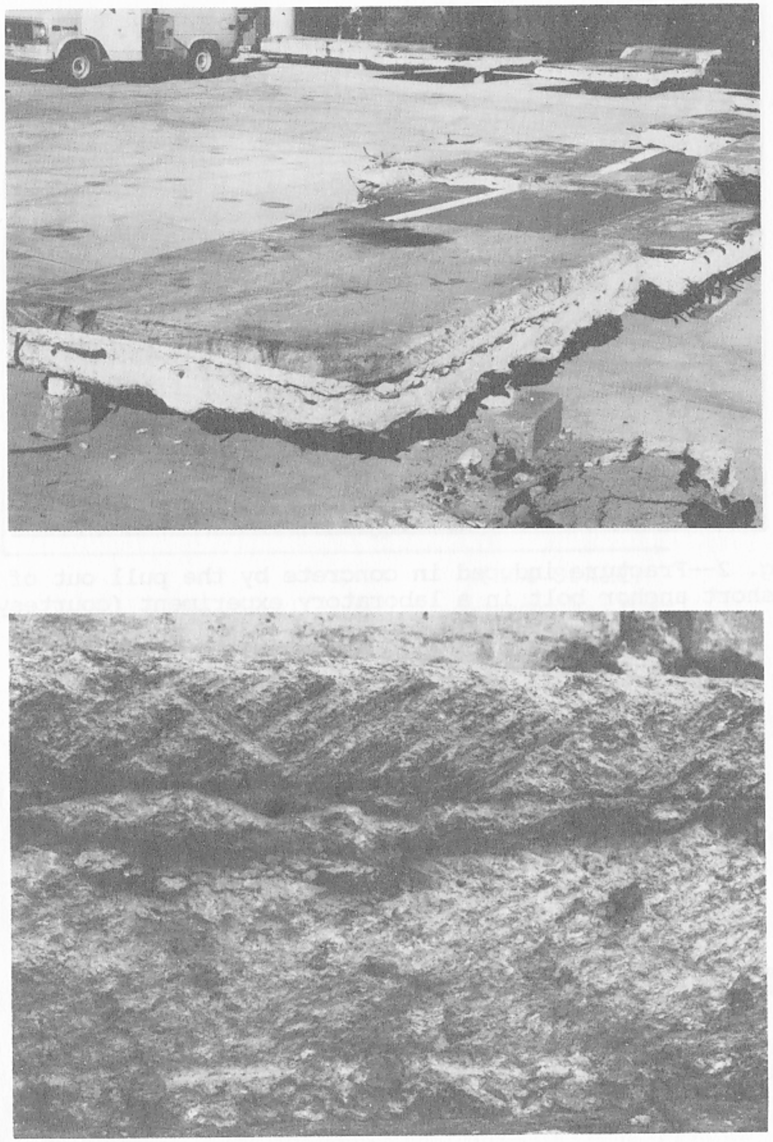


Fig. 1--Fracture delamination in a concrete bridge deck due to expansion of corroded reinforcement bars (courtesy of K. Maser, 1988) -- (a) cutout showing extent of the delaminated region, (b) closeup view of the delaminated concrete above the corroded reinforcement bars -- a layer of asphalt is on top of the delaminated concrete

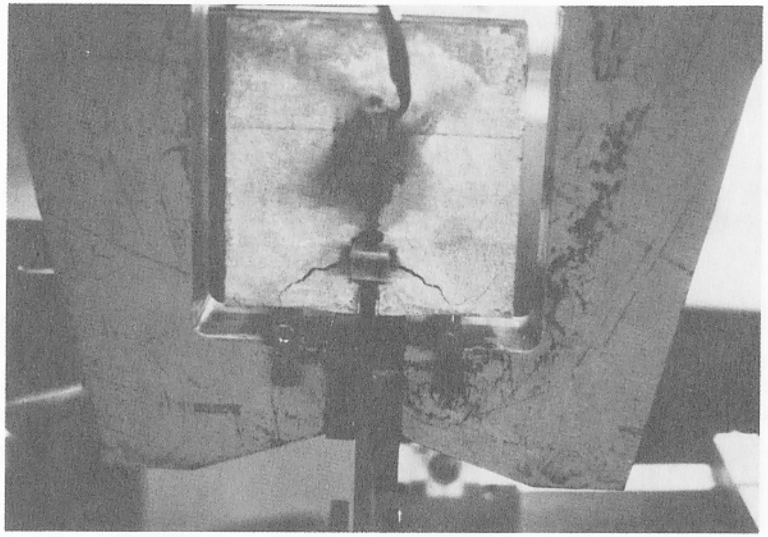
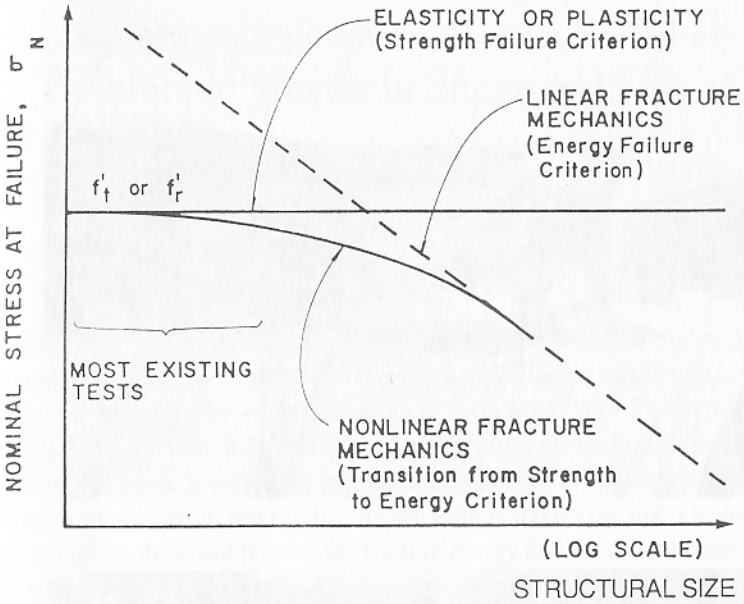


Fig. 2--Fracture induced in concrete by the pull out of a short anchor bolt in a laboratory experiment (courtesy of R. Ballarini, 1988)



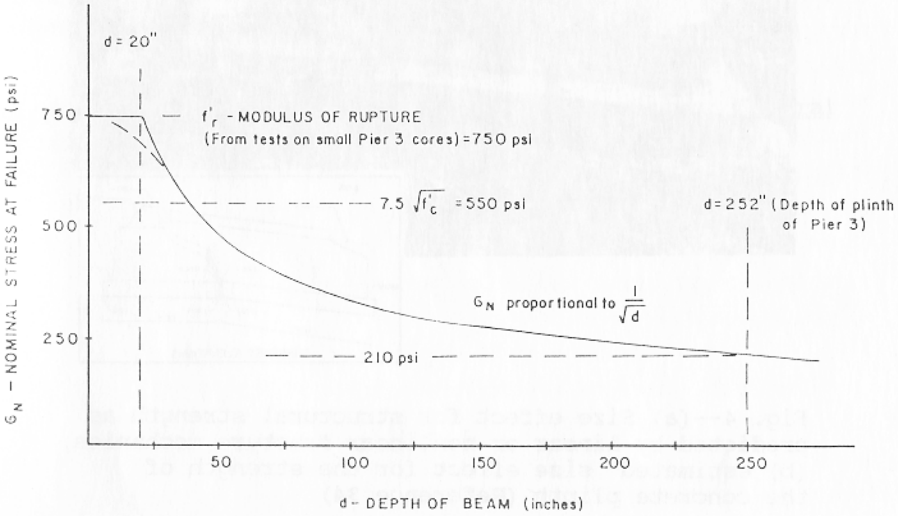


Fig. 3--(a) Continued collapse sequence of Span 2 subsequent to the falling of the adjacent two spans (3 and 4 to the left of span 2) of the New York Thruway Bridge at Schoharie Creek, (b) fractured failure of the plinth supporting the pier of spans 3 and 4 (Reference 34)

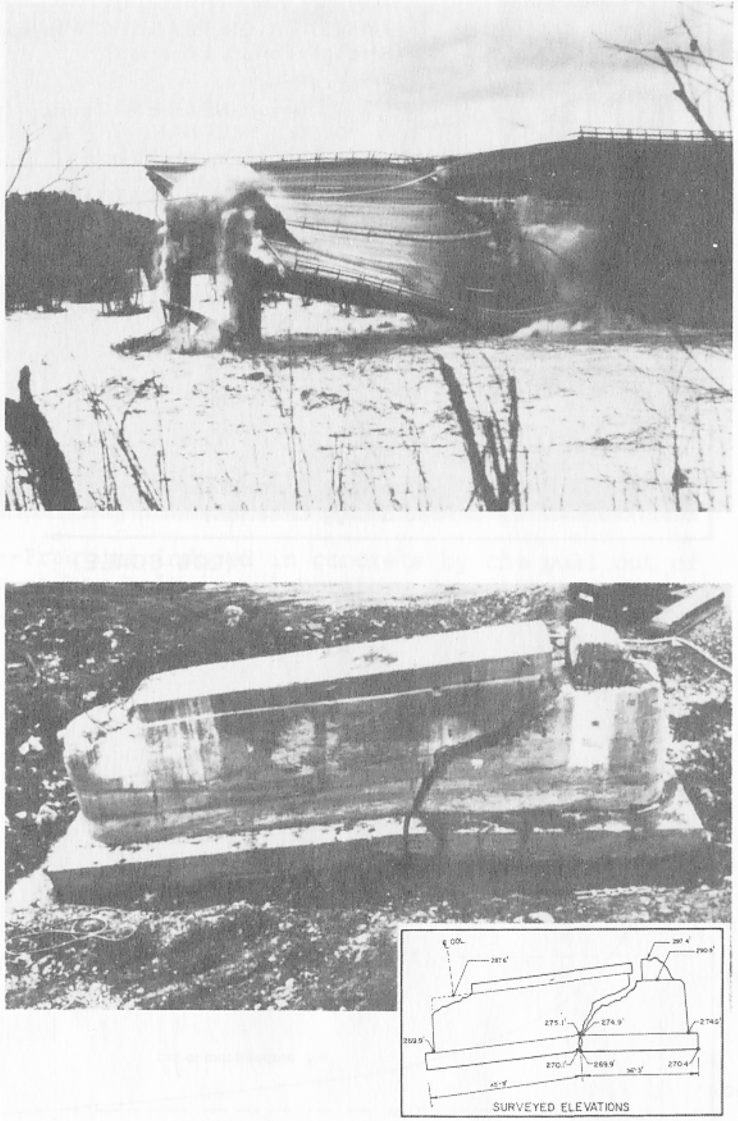


Fig. 4--(a) Size effect for structural strength as predicted by linear or nonlinear fracture mechanics, (b) estimated size effect for the strength of the concrete plinth (Reference 34)

Fracture Resistance of Acrylic Fiber Reinforced Mortar in Shear and Flexure

by R.J. Ward, K. Yamanobe, V.C. Li, and S. Backer

Synopsis: The results of notched beam, direct tension, splitting tension, compression, shear beam and flexural tests on plain mortar and on mortar reinforced with different volume fractions of short acrylic fibers are reported. An indirect J-integral technique is employed to determine the tension-softening curve and thus the tensile strength, the fracture energy and the critical crack opening from the notched beam test results. As the volume fraction of fibers is increased the strength in shear and flexure, the fracture energy and the critical crack opening all increase, the tensile strength remains essentially constant and the compressive strength shows some reduction. The characteristic length l_{ch} is used as a material property to characterize the post peak tensile behavior. The shear and flexural strengths are related to the normalized dimension d/l_{ch} and good agreement between the experimental results and theoretical predictions of decreasing strength with increasing d/l_{ch} is found.

Keywords: acrylic resins; fiber reinforced concretes; flexural strength; fracture properties; mortars (material); shear strength; synthetic fibers; tensile strength