Report on Dynamic Fracture of Concrete

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Vellore S. Gopalaratnam, Chair | Walter H. Gerstle*, Secretary

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Anthony R. Ingraffea	Barzin Mobasher	Yunping Xi
Jeremy Isenberg†	Charles D. Norman	

*Members of subcommittee who prepared this document.
†Co-chair of subcommittee who prepared this document.

This report summarizes information regarding the analysis of concrete systems subjected to rapid loading. Engineers will obtain an overview of the subject matter along with recommended approaches for analysis and selection of material properties. Researchers will obtain a concise source of information from leading authorities in the field conducting research and applying these concepts in practice. This report describes how, as strain rates increase above 10^{-4} to 10^{-3} s^{-1}, concrete in tension and compression becomes stronger and stiffer, with less prepeak crack growth and less ductile behavior in the postpeak region. The rate dependence of bond is shown to be due to local crushing around deformations of the bar and to have the same relationship to rate as compressive strength. The practical effect of this local crushing is to concentrate strains in a small number of cracks, thus lowering the overall ductility of reinforced members. Finally, it is concluded that computational models of postpeak behavior under either dynamic or static load should use a localization limiter so that strain softening into arbitrarily small regions is prevented. The models should also properly pose the equations of motion; one appropriate way to do this is to represent softening through rate dependence, such as viscoplasticity.

Keywords: computational modeling; concrete-reinforcement bond; cracking; fracture energy; fracture mechanics; fracture toughness; size effect; strain rate; stress-intensity factor; stress rate.

CONTENTS

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CHAPTER 1—INTRODUCTION

1.1 General

Impact, explosions, and earthquakes impose dynamic effects on concrete structures. Impact loading on a parapet can occur if it is struck accidentally by a crane. Seismic loading produces significant strain rates in concrete shear-walls and other lateral force-resisting elements. Explosive loading, due to accidental detonation of industrial vapor clouds or terrorist bombing, produces high strain rates in floor slabs and columns. These possibilities have prompted experiments on plain concrete specimens to investigate basic properties of concrete under various states and rates of loading. Under dynamic loading (rapidly applied loads of short duration), both structural and material responses depend on the applied loading rate. Although both the geometry of the structure and the material properties control the rate of cracking, this report is concerned primarily with the material effects.

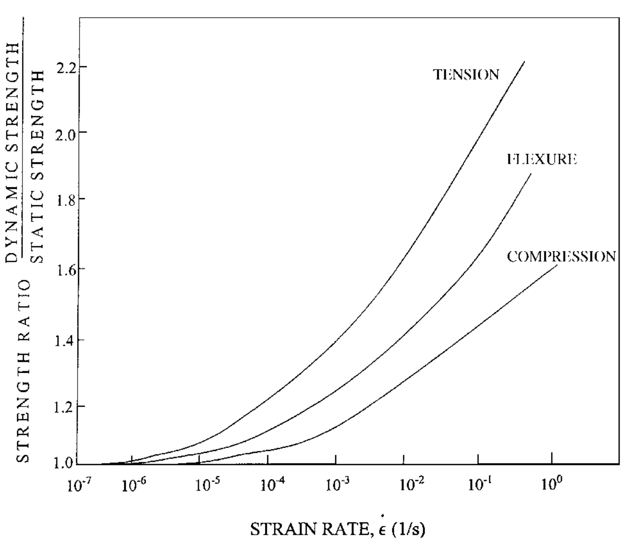

Fig. 1.1—Strain rate behaviors of plain concrete in different simple response modes (Suaris and Shah 1983).

Common practice for evaluating the resistance of concrete structures to dynamic loading is to:

a) Estimate the transient state of stress in the structure using an elastodynamic analysis; and

b) Evaluate the resistance of the structure using strength properties for the concrete and steel that are enhanced by strain-rate-dependent factors. For the failure modes of a concrete structure controlled by yielding of the reinforcement or crushing of the concrete, common practice usually provides reliable design information. For those failure modes controlled by crack propagation, however, such as diagonal tension or splitting failures, and where resistance to fracture is of fundamental importance for computations of energy absorption and energy dissipation, common practice does not usually yield reliable information. This inadequacy is due primarily to the fact that dynamic fracture of concrete structures does not involve instantaneous fracture, but continuous dynamic crack propagation under dynamic loading. Reliable dynamic failure analyses of concrete structures requires knowledge of the dynamic fracture properties of the concrete as well as its strain-rate-dependent properties. Therefore, this report concerns not only strain rate effects but also consideration of the dynamic fracture properties of concrete in general.

As shown in Fig. 1.1, the strength of concrete in tension, flexure, and compression increases with an increase in the loading rate. The strain corresponding to the maximum strength also increases with an increase in the loading rate. The increase in strain is due to the development of multiple cracks in the failure zone, and the value of the maximum strain is strongly dependent on the width assumed for the failure zone.

The differing rates of increase in tensile, flexural, and compressive strengths with increasing loading rates, and the crack propagation effects that cause failure, can result in the mode of failure of a concrete member changing from flexure to shear with an increase in the loading rate. Consequently, a dynamically loaded beam may require more shear reinforcement to ensure ductile behavior than the same beam loaded statically. Characterization of the rate effects for the materials of the beam, its inertial effects, and how those effects combine to control crack propagation, are essential to successful designs to resist high strain-rate loadings.

Inertial effects are involved in any impact loading of a structure or in any impact testing in a laboratory. In the latter case, many efforts have been devoted to reducing this effect so that dynamic test data can be used to evaluate the dynamic strength of concrete by static analysis. Inertial effects, however, are inherent in any dynamic event of material deformation or fracture. The inertial effect of a large mass of material, such as concrete, considerably increases the impact resistance of the structure. This effect occurs because the input energy should be transformed into kinetic energy, which is directly proportional to the mass, for moving the material necessary for crack formation and propagation. Therefore, any dynamic loading analysis should incorporate inertial effects rather than avoid them. Fortunately, current dynamic finite-element computer programs can readily handle this problem.

Because of inertial and crack propagation considerations, it is not possible to directly link strain rates and loading rates. The test method used in the laboratory to investigate dynamic effects for a given type of loading is usually related to a given strain rate range. As indicated in Fig. 1.1, the lowest strain rate at which testing is performed is approximately 10^{-7} s^{-1}. That rate, which corresponds to static loading, also has creep associated with it. The next higher strain rate region, up to 10^{-6} s^{-1}, is a quasistatic loading regime and is the rate commonly involved in laboratory testing to investigate seismic effects using servo–controlled hydraulic jacks. In the third region, up to 10^{-3} or 10^{-2} s^{-1}, mechanical resonance in the specimen and testing apparatus may need to be considered to properly interpret the response of the concrete within the complex specimen-machine interaction that occurs. Such higher rates can occur in shaketable experiments and in structures dynamically loaded by earthquakes. Rates up to 1 s^{-1} can be achieved in the laboratory using special hydraulic testing machines equipped with high-capacity servo-valves. Loading rates between 10^{-2} and 1 s^{-1} correspond to those imposed by impact loadings such as vehicles hitting bridge piers or aircraft landing on airport runways. Finally, rates above 10^{-2} s^{-1} cannot be readily achieved with a hydraulic testing machine. Impact or drop weight machines should be used or wave propagation utilized (Split-Hopkinson pressure bar device) to induce rate effects in small volumes of material. Loadings in this region correspond to those that can occur in bombing adjacent to or within the building, and service system and other explosions that occur within the building.

Rate dependence is thought to have a microstructural origin in the viscoelastic character of the hardened cement paste. Rate dependence probably originates from the ability of the bonds in calcium silicate hydrates to break and reform in a process governed by their thermal activation energy. A second origin of rate dependence is thought to be the time-dependent nature of crack growth, which originates in the successive ruptures of interparticle bonds in the hardened cement paste or concrete. Those ruptures cause growth of the fracture crack, an effect that is also a thermally activated process (Bazant, Gu, and Faber 1995; Bazant and Prat 1988).

This report examines the factors that cause strain-rate effects on concrete properties such as elastic modulus and tensile strength, and on fracture properties such as crack initiation, crack propagation, critical stress-intensity factor, and fracture energy. The effects of strain rates between 10^{-6} to 10^{4} s^{-1} are considered. The primary focus is on unreinforced specimens because the vast majority of the data reported in the literature deal with such specimens. Relatively little unclassified work has been reported on the dynamic fracture of reinforced concrete structures. Therefore, some interpretation is needed to apply the work summarized herein directly to reinforced structures.

1.2—Conceptual models

Any conceptual model that takes into account static and quasistatic as well as strain-rate effects in concrete depends on the scale of observation. The use of Wittmann's (1983) approach of studying concrete on three levels (macro, meso, and micro) helps to clarify the origins of rate effects.

1.2.1 *Macrolevel*—At the macrolevel, concrete is idealized as homogeneous and isotropic. For very large structures with dimensions measured in meters, linear elastic fracture mechanics (LEFM) may be used; a single crack can be assumed, and a critical combination of crack length and applied boundary conditions can then lead to crack growth. Growth can be locally stable (slow) or unstable (fast), depending on the stress gradients that the growing crack encounters. A critical value of K_1 (the stress intensity factor) should be reached as a necessary condition for crack growth to occur. This critical value of stress intensity, also referred to as the fracture toughness, has been measured and found to be much larger under dynamic loading than under static loading, (Mindess, Banthia, and Yan 1987; John and Shah 1986). Macrolevel models regard the cause of strain-rate effects as a transfer of strain energy at finite velocity from the structure surrounding the crack to the newly formed cracked surfaces. If the velocity of the advancing crack is low, strain-energy transport from the remainder of the stressed body along the crack surfaces to the crack tip is communicated via Rayleigh waves that travel at the Rayleigh wave velocity C_r. In tests carried out by Mindess, Banthia, and Yan (1987), John and Shah (1986), and Ross, Tedesco, and Kuennen (1995), crack velocities at strain rates in the range of 0.1 to 1 s^{-1} were of the order of 100 ms^{-1}, or less than 10% of the Rayleigh wave velocity. Yon, Hawkins, and Kobayshi (1991a) measured somewhat higher crack velocities of 132 and 250 ms^{-1} but again, their values are considerably less than the Rayleigh wave velocity. On the other hand, Ross, Tedesco, and Kuennen (1995) have suggested that the crack velocity increases linearly with an increasing strain rate on a log-log plot. They report experimentally measured crack velocities well in excess of 100 ms^{-1} at strain rates greater than 1 s^{-1}. Curbach and Eibl (1989) have measured crack-tip velocities in the range of 120 to 540 ms^{-1}, and Takeda (1986) has reported crack-tip velocities as high as 1000 ms^{-1} using an extremely high loading rate. In theory, however, as the crack velocity V approaches the Rayleigh wave velocity C_r, crack faces do not move apart fast enough to provide the localized strains necessary for a high crack tip stress-intensity factor K_1. It follows that the localized stress intensity at the crack tip is less able to break bonds as the crack-tip speed increases. Thus, the strength (which might theoretically be calculated from a knowledge of the interparticle bond strengths and the crack size distribution) of a linear, isotropic material depends on V/C_r and is therefore rate-dependent.

Although this conceptual model correctly predicts the tendency for increasing strength with increasing crack velocity, it does not correctly predict the magnitude of that increase. Shah (1983) has found experimentally that crack velocities in impact tests are less than 15% of the Rayleigh wave velocity. According to the theoretical results of Freund