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DYNAMIC INCREASE FACTORS FOR CONCRETE

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ABSTRACT

For reinforced concrete structures subjected to blast effects, response at very high strain rates (up to 1000 s^{-1}) is often sought. At these high strain rates, the apparent strength of concrete can increase significantly. The dynamic increase factor (DIF), i.e. the ratio of the dynamic to static strength, is normally reported as function of strain rate. For concrete, the DIF can be more than 2 in compression, and more than 6 in tension. Knowledge of the DIF is of significant importance in the design and analysis of structures for explosives safety. DIF curves for concrete have been published in manuals by the Tri-Services, the Defense Special Weapons Agency, the Air Force, and the Department of Energy. However, these curves are typically based on limited data.

A literature review was conducted to determine the extant data to characterize the effects of strain rate on the compressive and tensile strengths of concrete. This data support the dynamic increase factor (DIF) being a bilinear function of the strain rate in a log-log plot. The DIF formulation recommended by the European CEB was described, together with its origins. For tension, it was found that the data differed somewhat from the CEB recommendations, mostly for strain rates beyond 1 s^{-1}, and an alternate formulation was proposed based on the experimental data.

INTRODUCTION

Several reviews of the properties of concrete in both tension and compression under dynamic loading have been completed recently [1-5]. More emphasis is typically placed on the compressive behavior, for which more data is available, and less on the tensile response. The effect of strain rate on the concrete compressive and tensile strengths is typically reported as a dynamic increase factor (DIF) – i.e. the ratio of dynamic to static strength – versus strain rate, on

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a semi-log or log-log scale. This is a convenient format for implementation into numerical models. In particular the CEB Model Code [6] reports DIFs for compressive and tensile strengths under high rates of loading, based both on test results and analytical models. Recent data by Ross et al. [7-15] provides additional insight in the tensile range that was not previously available. All the previous data are hereby analyzed and used in providing an updated DIF versus strain rate relationship for concrete in tension.

RESEARCH SIGNIFICANCE

In the analysis of reinforced concrete structures subjected to blast loading, both concrete and steel are subjected to very high strain rates, in the order of 10 s^{-1} to 1000 s^{-1}. At these high strain rates, the apparent strength of these materials can increase significantly, by more than 50% for the reinforcing steel [16-20], by more than 2 for concrete in compression [2], and by more than 6 for concrete in tension [1,21-24].

The Defense Special Weapons Agency (DSWA), under the Conventional Weapons Effects (CWE) program, has sponsored the numerical study of the response of reinforced concrete structures subjected to internal explosions. In these structures, reinforced concrete walls often fail in tension beyond the tensile membrane range. The response of these structural elements is very dependent on the tensile behavior of concrete. The relatively large strain rate enhancement of the tensile strength emphasizes the importance of an accurate assessment of the dynamic behavior of concrete in tension.

A DIF versus strain rate relationship for concrete in tension is of direct use in numerical models. As part of the DSWA study an assessment of material properties at high strain rates was completed [25] and is enhanced in the current paper for concrete in tension. In the numerical analyses, DIF versus strain rate relationships for concrete in both tension and compression were used for input in explicit Lagrangian finite element codes such as DYNA3D [26-29] and in a modified version of the nonlinear concrete material model in the finite element code ADINA [30].

CEB FORMULATION

Perhaps the most comprehensive model for strain rate enhancement of concrete both in tension and compression is presented by the CEB Model Code [6].

Compression

In compression, the CEB model appears to properly fit the available data [2]. The dynamic increase factor (DIF) for the compressive strength, is given by:

$$f_c / f_{cs} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_S}\right)^{1.026\alpha_s} \qquad \text{for } \dot{\varepsilon} \le 30 \text{ s}^{-1}$$

$$= \gamma_s \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3} \qquad \text{for } \dot{\varepsilon} > 30 \text{ s}^{-1}$$

where f_c = dynamic compressive strength at $\dot{\varepsilon}$
f_{cs} = static compressive strength at $\dot{\varepsilon}_s$
f_c / f_{cs} = compressive strength dynamic increase factor (DIF)
$\dot{\varepsilon}$ = strain rate in the range of 30×10^{-6} to 300 s^{-1}
$\dot{\varepsilon}_s$ = 30×10^{-6} s^{-1} (static strain rate)
$\log \gamma$ = $6.156\,\alpha - 2.$
α_s = $1/(5+9 f_{cs} / f_{co})$
f_{co} = 10 MPa = 1450 psi.

This formulation captures specific material behaviors that are reflected in the following properties:

- in a log(DIF) versus log($\dot{\varepsilon}$) the relationship is bilinear with a change in slope around 30 s^{-1}
- the DIF is higher for concretes with lower strengths
- all DIFs are related to a strength measured at a specific “quasi-static” strain rate
- the strength enhancement is different for tension and compression.

This DIF formulation for concrete in compression has typically been accepted by most researchers as an accurate representation of actual behavior, and is of direct application in numerical analyses [1-5].

Tension

The dynamic increase factor (DIF) for the tensile strength, is given by:

$$f_t / f_{ts} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_S}\right)^{1.016\delta} \qquad \text{for } \dot{\varepsilon} \le 30 \text{ s}^{-1}$$

$$= \beta \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_S}\right)^{1/3} \qquad \text{for } \dot{\varepsilon} > 30 \text{ s}^{-1}$$

where f_t = dynamic tensile strength at $\dot{\varepsilon}$
f_{ts} = static tensile strength at $\dot{\varepsilon}_s$
f_t / f_{ts} = tensile strength dynamic increase factor
$\dot{\varepsilon}$ = strain rate in the range of 3 x 10^{-6} to 300 s^{-1}
$\dot{\varepsilon}_s$ = 3 x 10^{-6} s^{-1} (static strain rate)
$\log \beta$ = $7.11\delta - 2.33$

$\delta \quad = 1/(10+6 f_{cs} / f_{co})$
$f_{co} \quad = 10$ MPa = 1450 psi

This tensile DIF is plotted in Figure 1 versus strain rate for two concrete compressive strengths, 30 and 70 MPa (4350 and 10150 psi). In a log-log plot, the curves obtained are bilinear. As in the compression case, these curves have a discontinuity in their slope which, according to the CEB formulation, occurs at a strain rate of 30 s^{-1}. The CEB expression is reported to be valid up to 300 s^{-1}, where the factor is 3.9 for the 30 MPa (4350 psi) concrete. Although this is significantly higher than the compression DIF at that same strain rate, several researchers have reported even higher enhancement factors in tension.

DATA AT HIGH STRAIN RATES

Several sets of data are available for strain rates in the range of 1 s^{-1} to 200 s^{-1} in tension, as follows.

Mellinger and Birkimer's data

Mellinger and Birkimer [21] completed two sets of 3 tests on plain concrete cylinders. The cylinders were 10.25 inches long and 2 inches in diameter, and loaded under end impact. The compression wave from the impact would travel along the specimen and get reflected at the end of the specimen as a tension wave. If the total stress due to the reflected tension wave minus the incident compression wave exceeded the concrete tensile strength the specimen would rupture. For the first set of 3 tests, the dynamic tensile strength was somewhere between 2500 and 3210 psi (17.2 to 22.1 MPa), compared to a static tensile strength of 491 psi (3.4 MPa), obtained at a quasi-static strain rate of about 0.57×10^{-6} s^{-1}. This represents a DIF between 5.1 and 6.5 (average 5.8) at a strain rate of about 20 s^{-1}. For the second set of 3 tests, the dynamic tensile strength was somewhere between 2240 and 4000 psi (15.4 and 27.6 MPa), i.e. a DIF between 4.5 and 8.1 (average 6.3) at a strain rate of about 23 s^{-1}. These two points are shown in Figure 2.

Birkimer's thesis data

For his thesis work, Birkimer conducted 46 impact tests on plain concrete cylinders at strain rates between 2 and 23 s^{-1} [23]. The cylinders were 2 inches in diameter, and 35 inches in length. Static strength was 491 psi (as in Mellinger and Birkimer's tests). The corresponding DIF varied from about 2.5 to 6. For this range of strain rates the DIF was expected to be proportional to $\dot{\varepsilon}^{1/3}$ (a straight line of slope 1/3 in a log-log plot). Out of the 46 tests, 33 yielded results, and are shown in Figure 2.

McVay's data

McVay reports results from close-in explosions on concrete walls [24]. Concrete failure was obtained in the form of back face spalling. Two rate enhancement factors in tension of 7.1 and 6.7 were reported, at strain rates of about 38 and 157 s^{-1}, respectively.

Ross' data

Ross et al. tested several cylindrical concrete specimens in a Split-Hopkinson Pressure Bar (SHPB) in direct tension, splitting tension (Brazilian test), and direct compression [7-15]. The specimens diameter varied from 0.75 to 2 inches (19 to 51 mm) in diameter, and were 1.75 to 2 inches (45 to 51 mm) long. The SHPB diameter was either 2 or 3 inches (51 or 76 mm).

In tension, most tests were conducted in the strain rate range from about 10^{-7} to 20 s^{-1}. Ross reported dynamic increase factors of up to 6.47 at 17.8 s^{-1}. These DIF values match well with the previous DIF data at high strain rates, i.e. beyond 1 s^{-1}. Ross' data points are shown in Figure 2 as well.

John, Antoun and Rajendran's data

John et al. [31,32] tested six sets of specimens in splitting tension in a Split Hopkinson Pressure Bar. Specimens with thickness of 0.25 and 0.50 in (6.4 and 12.7 mm) and diameters of 0.5, 1 and 2 inches (12.7, 25.4 and 50.8 mm) were tested. The strain rates ranged from about 5×10^{-7} to 70 s^{-1}, and measured DIF values reached up to 4.8 (Figure 2).

Antoun [32] also conducted plate impact tests to determine the spall strength, or uniaxial strain tensile strength, which, for concrete, is assumed to be similar to the uniaxial unconfined tensile strength. Data from these tests fell within the scatter of the previous tensile splitting tests, with DIF values in excess of 3.

Discussion

One important point to be made here is that all the data above the strain rate of 1 s^{-1}, obtained from the various test devices and procedures, show the same trend. The data from Birkimer et al. [21-23] were obtained by measurement of strain pulses on long concrete rods impacted by metallic projectiles. McVay [24] and Antoun [32] obtained their data by back calculating stress and strain from spall tests. Data collected by Ross et al. [7-15] were obtained using two different size split Hopkinson pressure bars, three different specimen sizes, six different concrete mixtures and two different type tensile specimens, direct tension and splitting tensile (Brazilian test). Finally, data by John et al. [31] was obtained from independent SHPB tests. In all cases, very high dynamic tensile strengths were observed, when compared to the quasi-static strength of concrete, for strain rates above 1 s^{-1}.

COMPARISON BETWEEN ANALYTICAL MODELS

Quasi-static strain rate

To develop DIF versus strain rate curves, a quasi-static value of the strain rate has to be adopted, where the DIF is taken as 1. Since concrete properties are usually obtained following ASTM standards, these were deemed appropriate for determining the quasi-static value of the strain rate where the DIF curve starts.

For concrete cylinders in uniaxial unconfined compression, ASTM C39-94 recommends a quasi-static loading rate of 20 to 50 psi/second (0.14 to 0.34 MPa/second). For typical concretes the modulus of elasticity is between 3 and 6 Msi (20 and 41 GPa), hence for the linear part of the stress-strain curve, this translates into a test strain rate between $3\text{x}10^{-6}$ and $17\text{x}10^{-6}$ s^{-1}. If a constant strain rate to failure at 0.002 strain is used, this corresponds to a test strain rate between $4\text{x}10^{-6}$ and $33\text{x}10^{-6}$ s^{-1} for concrete strengths between 3000 and 10000 psi (20 and 69 MPa). This is in agreement with the CEB quasi-static strain rate of $30\text{x}10^{-6}$ s^{-1} for compression [6].

For concrete cylinders in a tensile splitting test, ASTM C496 recommends a tensile rate of loading of 100 to 200 psi/min (0.7 to 1.4 MPa/min). For tensile strengths between 300 and 700 psi (2 and 5 MPa) this translates into times to failure of about 90 to 420 seconds. If the tensile strain at peak is (using ACI 318 formulas R11.2.1.1 and 8.5.1 and assuming linear behavior) :

$$\varepsilon_p = \frac{f_t}{E} = \frac{6.7\sqrt{f_c'}}{57000\sqrt{f_c'}} = 0.000118$$

then the average strain rate to peak is between $0.28\text{x}10^{-6}$ and $1.3\text{x}10^{-6}$ s^{-1}. The CEB Model Code recommends an actual strain at peak of 0.000150, yielding a range for the average strain rate from $0.36\text{x}10^{-6}$ to $1.7\text{x}10^{-6}$ s^{-1}. Both ranges are slightly lower than the $3\text{x}10^{-6}$ s^{-1} used by CEB. A quasi-static strain rate of $1\text{x}10^{-6}$ s^{-1} seems more appropriate as the origin.

Scaling of Ross' curve in tension

Figure 1 shows a comparison between an early DIF curve by Ross and the CEB formulation for concrete in tension [11]. At first these curves appear as two seemingly very different alternatives, but this is actually due to the different choice for quasi-static strain rate. The CEB curves start at $3\text{x}10^{-6}$ s^{-1} whereas the Ross curve starts at $1\text{x}10^{-8}$ s^{-1}. These are simply two different definitions of static strength. The recommended strain rate for a standard tensile splitting tensile test (ASTM C496) is closer to the CEB quasi static loading rate. It is known that even slower loadings will result in measured compressive strengths lower than $f\bullet_c$. Hence the Ross curve which starts $1\text{x}10^{-8}$ s^{-1} will already show a significant DIF at $3\text{x}10^{-6}$ s^{-1}.

It was decided to scale the Ross curve so that its DIF would be 1 at 3.E-6 s^{-1}, to match the CEB curves. Figure 1 shows that the first branch of the scaled Ross data now falls between the 30 and the 70 MPa CEB curves. Hence, up to the change in slope, both models are in agreement. More recent data by Ross uses a quasi-static strain rate of about 10^{-6} [7].

ORIGIN OF THE CEB FORMULATION

The CEB Model Code formulas are based on the 1988 CEB Bulletin 187 [33]. The CEB Bulletin 187 itself is based on work by Reinhardt in 1985 [34]. In the bilinear CEB formulation, the change in slope DIF versus strain rate curves is located at 30 s^{-1}. This is consistent with a some theoretical models such as Weerheijm's [34-37]. This is shown in Figure 3 (adapted from Figure 9 of [34]) where the CEB formulation can closely follow the theoretical models of Kipp and Grady, Mihashi and Whittmann, and Weerheijm. However, that same figure shows that the experimental data at high strain rates falls to the left of the theories and point to a change in slope in the bilinear relationship closer to 1 s^{-1}. In fact Figure 9 of [34], Figure 4 of [35], Figure 16 of [36], and Figure 1 of [37] (assuming E = 33 GPa = 4.8 Msi as done in CEB Bulletin 187), all show that the available data indicated a change of slope closer to 1 s^{-1}.

In addition to the above data, John and Shah's work also seems to point to a change of slope around 1 s^{-1} [38]. Ross' data, as shown in Figure 2, also supports this.

MODIFIED CEB FORMULATION

Data at Low Strain Rates

For concrete in tension, the number of researchers that have provided data in the range up to 1 s^{-1} is also limited. In particular the work of Cowell [39], Takeda and Tachikawa [40], Hatano (as reported by Kvirikadze in reference [41]), Kormeling at al. [42], and Toutlemonde et al. [43,44] should be mentioned.

Cowell reported strain rate enhancements for various concrete strengths (Figure 2) [39]. Cowell indicated that concretes with the lowest compressive strengths exhibited the highest DIF in tension. His static tests were conducted at stress rates of 3 psi/sec (0.02 MPa/sec) (similarly to ASTM C-496). Assuming a peak strain of 0.00015 and given the tensile strengths between 515 and 805 psi, the corresponding quasi-static strain rates should have been between $5.6x10^{-7}$ and $8.7x10^{-7}$ s^{-1}, close to the suggested origin at $1x10^{-6}$ s^{-1} , but somewhat different from the reported $1.7x10^{-6}$ to $9x10^{-6}$ s^{-1}.

Takeda and Tachikawa [40] reported some DIF values of up to 1.74 for strain rates between $3x10^{-7}$ and $4x10^{-2}$. These values are in agreement with results from the other studies (Figure 2).

Kvirikadze [41] reports work by Hatano for 4 strain rates of concrete in tension. The quasi-static strain rate was chosen as 10^{-6}. The concrete static tensile strength was 384 psi (2.65 MPa).

Kormeling et al. [42] report 26 series of large Hopkinson bar tests for strain rates of up to 1.5 s^{-1}. This data also shows an effect of concrete strength on the DIF (larger DIF for lower concrete strengths), but it is lesser than the effect shown by Cowell's data.

Toutlemonde [43] reports tensile tests at 5 stress rates equivalent to strain rates between 10^{-6} and 1.7 s^{-1}. Tests on a dry concrete showed DIFs of up to 1.39 while tests on the same , but wet, concrete resulted in DIFs of up to 2.1. This supports the theory that part of the strain rate enhancement is due to the presence of water [43,45]. DIF also seemed to increase for higher water/cement ratios (i.e. decreasing compressive strength) [43].

Proposed Formulation

The available data at high strain rates seems to support that the change in slope occurs close to 1 s^{-1} instead of at 30 s^{-1} as assumed by CEB (Figure 2). In addition it seems appropriate to assume the quasi-static strain rate at 1×10^{-6} s^{-1}. Hence a formulation similar to that of the CEB was fitted against the available data for strain rates below 1 s^{-1}, and for higher strain rates a slope of 1/3 on a log (strain rate) versus log (DIF) plot was used, also following the CEB formulation. The proposed formulation then becomes:

$$f_t / f_{ts} = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{\delta} \qquad \text{for } \dot{\varepsilon} \le 1 \text{ s}^{-1}$$

$$= \beta\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right)^{1/3} \qquad \text{for } \dot{\varepsilon} > 1 \text{ s}^{-1}$$

where f_t = dynamic tensile strength at $\dot{\varepsilon}$

f_{ts} = static tensile strength at $\dot{\varepsilon}_s$

f_t / f_{ts} = tensile strength dynamic increase factor DIF

$\dot{\varepsilon}$ = strain rate in the range of 10^{-6} to 160 s^{-1}

$\dot{\varepsilon}_s$ = 10^{-6} s^{-1} (static strain rate)

$\log \beta = 6\delta - 2$

$\delta = 1/(1+8 f_{cs} / f_{co})$

f_{co} = 10 MPa = 1450 psi

This new formulation is shown in Figure 4 for 30 and 70 MPa (4350 and 10150 psi), together with the available data.

EFFECT OF STRAIN RATE ON BOND

A limited amount of research on the effects of strain rate on bond strength is available in the literature [46-55]. Hansen and Liepins [46] concluded that “for all practical lengths of embedment of bonded bars, the increase in load capacity of a bonded bar under dynamic loading over static loading is due only to the increase of steel strength under dynamic loading.” Reinhardt [48] concluded that, if the bond strength is linearly related to the concrete tensile strength, under dynamic loading the bond strength would be linearly related to the dynamic concrete tensile strength. Takeda [55] indicated that, under dynamic loading, the concrete strain field around the bar is much narrower and could result in brittle steel fracture. This could be numerically verified, since the dynamic increase factors for concrete in tension are significantly larger than those for reinforcing bars [16].

In summary, it appear that the original bond-slip equations, updated with the enhanced concrete and reinforcing steel strengths at the current strain rate, would still be applicable.

CONCLUSIONS

A literature review was conducted to determine the available data to characterize the effects of strain rate on the tensile strength of concrete. In particular additional new data by Ross et al. were considered. The data support the dynamic increase factor being a bilinear function of the strain rate (in a log-log plot), with no increases for strain rates below 10^{-6} , and with a slope change at a strain rate of 1 s^{-1}. A DIF of about 7 was obtained at the highest measured strain rate of 157 s^{-1}. The DIF formulation recommended by the European CEB was described, together with its origins. It was found that the data differed somewhat from the CEB recommendations, and a similar formulation was proposed based on the experimental results.

The effects of strain rate on bond of reinforcement were also briefly addressed. It is expected that those effects will be accounted for if both the concrete and rebar strengths are enhanced to reflect the strain rate.

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REFERENCES

1. Malvar, L.J., Ross, C.A., “Review of Static and Dynamic Properties of Concrete in Tension,” Accepted for publication, ACI Materials Journal, December 1997
2. Bischoff, P.H., Perry, S.H., “Compressive Behavior of Concrete at High Strain Rates,” Materials and Structures, Vol. 24, 1991, pp. 425-450.
3. Williams, M.S., “Modeling of Local Impact Effects on Plain and Reinforced Concrete,” ACI Structural Journal, Vol. 91, No. 2, March-April 1994, pp. 178-187.

4. Fu, H.C., Erki, M.A., Seckin, M., "Review of Effects of Loading Rate on Concrete in Compression," Journal of Structural Engineering, Vol. 117, No. 12, December 1991, pp. 3645-3659.
5. Fu, H.C., Erki, M.A., Seckin, M., "Review of Effects of Loading Rate on Reinforced Concrete," Journal of Structural Engineering, Vol. 117, No. 12, December 1991, pp. 3660-3679.
6. Comité Euro-International du Béton, *CEB-FIP Model Code 1990,* Redwood Books, Trowbridge, Wiltshire, UK, 1993.
7. Ross, C.A., Jerome, D.M., Tedesco, J.W., Hughes, M.L., "Moisture and Strain Rate Effects on Concrete Strength," ACI Materials Journal, Vol. 93, No. 3, May-June 1996, pp. 293-300.
8. Ross, C.A., Tedesco, J.W., Kuennen, S.T., "Effects of Strain Rate on Concrete Strength," ACI Materials Journal, Vol. 92, No. 1, January-February 1995, pp. 37-47.
9. Tedesco, J.W., Ross, C.A., Kuennen, S.T., "Experimental and Numerical Analysis of High Strain Rate Splitting Tensile Tests," ACI Materials Journal, Vol. 90, No. 2, March-April 1993, pp. 162-169.
10. Hughes, M.L., Tedesco, J.W., Ross, C.A., "Numerical Analysis of High Strain Rate Splitting-Tensile Tests," Computers and Structures, Vol. 47, No. 4/5, 1993, pp. 653-671.
11. Ross, C.A., Kuennen, S.T., Tedesco, J.W., "Effects of Strain Rate on Concrete Strength," ACI Spring Convention, Session on Concrete Research in the Federal Government, Washington, D.C., March 1992.
12. Tedesco, J.W., Ross, C.A., McGill, P.B., O'Neil, B.P., "Numerical Analysis of High Strain Rate Concrete Direct Tension Tests," Computers and Structures, Vol. 40, No. 2, 1991, pp. 313-327.
13. Ross, C.A., "Fracture of Concrete at High Strain Rate," Proceedings, NATO Advanced Research Workshop: Toughening Mechanism in Quasi-Brittle Materials, Northwestern University, Evanston, Illinois, July 1990 (Kluwer Academic Publishers, The Netherlands, 1991, pp. 577-591).
14. Ross, C.A., Thompson, P.Y., Tedesco, J.W., "Split-Hopkinson Pressure-Bar Tests on Concrete and Mortar in Tension and Compression," ACI Materials Journal, Vol. 86, No. 5, September-October 1989, pp. 475-481.
15. Tedesco, J.W., Ross, C.A., Brunair, R.M., "Numerical Analysis of Dynamic Split Cylinder Tests," Computers and Structures, Vol. 32, No. 3/4, 1989, pp. 609-624.
16. Malvar, L.J., "Review of Static and Dynamic Properties of Steel Reinforcing Bars," Accepted for publication, ACI Materials Journal, October 1997
17. U.S. Navy Naval Facilities Engineering Command, "Structures to Resist the Effects of Accidental Explosions," NAVFAC P-397 Design Manual, Alexandria, VA, 1991 (also Army TM5-1300 and Air Force AFM 88-22).
18. Defense Special Weapons Agency, *DAHS CWE Manual*, Manual for the Design and Analysis of Hardened Structures under Conventional Weapons Effects, Draft, 1997.

19. Drake, J.L. et al., *Protective Construction Design Manual: Resistance of Structural Elements (Section IX)*, Report ESL-TR-87-57, Air Force Engineering and Services Center, Tyndall Air Force Base, FL, November 1989.

20. Department of Energy, A Manual for the Prediction of Blast and Fragment Loading on Structures, Albuquerque Operations Office, July 1992.

21. Mellinger, F.M., Birkimer, D.L., “Measurement of Stress and Strain on Cylindrical Test Specimens of Rock and Concrete under Impact Loading,” Technical Report 4-46, U.S. Army Corps of Engineers, Ohio River Division Laboratories, Cincinnati, Ohio, April 1966, 71 pp.

22. Birkimer, D.L., Lindemann, R., “Dynamic Tensile Strength of Concrete Materials,” ACI Journal, Proceedings, Jan. 1971, pp. 47-49.

23. Birkimer, D.L., “Critical Normal Fracture Strain of Portland Cement Concrete,” Ph.D. thesis, University of Cincinnati, 1968, 122 pp.

24. McVay, M.K., “Spall Damage of Concrete Structures,” Technical Report SL-88-22, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, June 1988.

25. Defense Special Weapons Agency, “DSWA Material Properties Meeting,” Volumes I and II, Proceedings of the meeting held at Logicon RDA, Los Angeles, 5-6 November 1996 (Limited Distribution).

26. Whirley, R. G. and B. E. Engelmann, “DYNA3D: A Nonlinear Explicit Three-Dimensional Finite Element Code for Solid and Structural Mechanics,” User Manual, Report UCRL-MA-107254 Rev. 1, Lawrence Livermore National Laboratory, Livermore, CA, November 1993.

27. Malvar, L.J., Crawford, J.E., Wesevich, J.W., Simons, D., "A Plasticity Concrete Material Model for DYNA3D," International Journal of Impact Engineering, vol. 19, no. 9/10, Dec. 1997, pp. 847-873.

28. Malvar, L.J., Crawford, J.E., Wesevich, J.W., Simons, D., "A New Concrete Material Model for DYNA3D - Release II: Shear Dilation and Directional Rate Enhancements," TM-96-2.1, Report to the Defense Nuclear Agency, Karagozian and Case Structural Engineers, Glendale, CA, January 1996.

29. Malvar, L.J., Simons, D., “Concrete Material Modeling in Explicit Computations,” Proceedings, Workshop on Recent Advances in Computational Structural Dynamics and High Performance Computing, USAE Waterways Experiment Station, Vicksburg, MS, April 1996, pp. 165-194.

30. Tedesco, J.W., Powell J.C., Ross, C.A., and Hughes, M.L., “A Strain Rate Dependent Concrete Material Model for ADINA,” Computers and Structures, Vol. 64, No.4/5, 1997.

31. John, R., Antoun, T., Rajendran, A.M., “Effect of Strain Rate and Size on Tensile Strength of Concrete,” Proceedings, 1991 APS Topical Conference on Shock Compression of Condensed Matter, Williamsburg, VA (Schmidt, S.C., Dick, R.D., Forbes, J.W., Tasker, D.G., editors), Elsevier Science Publishers, 1992, pp. 501-504.

32. Antoun, T.H., “Constitutive/Failure Model for the Static and Dynamic Behaviors of Concrete Incorporating Effects of Damage and Anisotropy,” Ph.D. Thesis, The University of Dayton, Dayton, Ohio, 1991, 230 pp.

33. Comité Euro-International du Béton, "Concrete Structures under Impact and Impulsive Loading", CEB Bulletin 187, Lausanne, Switzerland, August 1988.

34. Reinhardt, H.W., "Strain Rate Effects on the tensile Strength of Concrete as Predicted by Thermodynamics and Fracture Mechanics Models," Cement Based Composites: Strain Rate Effects on Fracture, S. Mindess and S.P. Shah, editors, December 1985, pp. 1-13.

35. Weerheijm, J., Reinhardt, H.W., "Modelling of Concrete Fracture under Dynamic Tensile Loading", Fracture of Concrete and Rock - Recent Developments (S.P. Shah, S.E. Swartz and B. Barr, editors), 1989, pp. 721-728.

36. Reinhardt, H.W., "Tensile Fracture of Concrete at High Rates of Loading", Application of Fracture Mechanics to Cementitious Composites, NATO-ARW, S.P. Shah editor, 1984, pp. 559-590.

37. Reinhardt, H.W., "Concrete under Impact Loading - Tensile Strength and Bond," HERON, Vol. 27, No. 3, 1982.

38. John, R., Shah, S.P., "Effect of High Strength and Rate of Loading on Fracture Parameters of Concrete", SEM /RILEM Conference on Fracture of Concrete and Rock (S.P. Shah and S.E. Swartz, editors), Houston, Texas, June 1987, pp. 35-52.

39. Cowell, W.L., ""Dynamic Properties of Plain Portland Cement Concrete," Technical Report R447, Naval Civil Engineering Laboratory, Port Hueneme, CA, June 1966, 46 pp.

40. Takeda, J., Tachikawa, H., "Deformation and Fracture of Concrete Subjected to Dynamic Load," Mechanical Behavior of Materials, Proceedings of the International Conference, Kyoto, 1971, Vol. IV.

41. Kvirikadze, O.P., "Determination of the Ultimate Strength and Modulus of Deformation of Concrete at Different Rates of Loading," International Symposium, Testing In-Situ of Concrete Structures, Budapest, 1977, pp. 109-117.

42. Kormeling, H.A., Zielinski, A.J., Reinhardt, H.W., "Experiments on Concrete under Single and Repeated Uniaxial Impact Tensile Loading," Stevin Report 5-80-3, Delft University of Technology, May 1980.

43. Toutlemonde, F., "Résistance au Choc des Structures en Béton – Du Comportement du Matériau au Calcul des Ouvrages," Ph.D. Thesis, Laboratoire Central des Ponts et Chaussées, Section des Publications, Paris, France, July 1995 (in French).

44. Toutlemonde, F., Rossi, P., "Are High Performance Concretes (HPC) Suitable in Case of High Rate Dynamic Loading," 4th International Symposium on Utilization of High Strength/ High Performance Concrete, Paris, 1996.

45. Rossi, P., Toutlemonde, F., "Effect of Loading Rate on the Tensile Behavior of Concrete: Description of the Physical Mechanisms," Materials and Structures, Vol. 29, March 1996, pp. 116-118.

46. Hansen, R. J. and A. A. Liepins, "Behavior of Bond under Dynamic Loading," Journal of the American Concrete Institute, Vol. 59, No. 4, 1962, pp. 563-582.

47. Vos, E. and H. W. Reinhardt, “Influence of Loading Rate on Bond Behavior of Reinforcing Steel and Prestressing Strands,” Materiaux et Constructions (Materials and Structures), Vol. 15, 1982, pp. 3-10.

48. Reinhardt, H. W., “Concrete under Impact Loading: Tensile Strength and Bond,” HERON, Vol. 27, No. 3, 1982.

49. Shima, H. and Y. Ishimoto, “Effect of Loading Rate on Stretching Out of Anchored Reinforcing Bars,” Transactions of the Japan Concrete Institute, Vol. 15, 1994, pp. 459-466.

50. Bentur, A. S., S. Mindess and N. P. Banthia, “The Fracture of Reinforced Concrete under Impact Loading,” Cement-based Composites: Strain Rate Effects on Fracture, Materials Research Society Symposia Proceedings Vol. 64 (S. Mindess and S. P. Shah, eds.), Pittsburgh, 1986, pp. 225-234.

51. Banthia, N. P., “Impact Resistance of Concrete,” Ph.D. Thesis, University of British Columbia, Vancouver, B.C., Canada, 1987.

52. Mindess, S. and C. Yan, “Bond of Reinforcement in FRC under Impact Loading,” High Performance Fiber Reinforced Cement Composites, Proceedings (H. W. Reinhardt and A. E. Naaman, eds., ISBN 0 419 17630 6), 1992, pp. 479-491.

53. Yan, C., “Bond Between Reinforcing Bars and Concrete Under Impact Loading,” Ph.D. Thesis, The University of British Columbia, 1992, 417 pp.

54. ACI Committee 446, State-of-the-Art Report on Dynamic Fracture, Section 2.4, Bond Failure, Draft, American Concrete Institute, February 1996.

55. Takeda, J. J., “Strain Rate Effects on Concrete and Reinforcements and their Contributions to Structures,” Cement-based Composites: Strain Rate Effects on Fracture, Materials Research Society Symposia Proceedings Vol. 64 (S. Mindess and S. P. Shah, eds.), Pittsburgh, 1986, pp. 15-20.

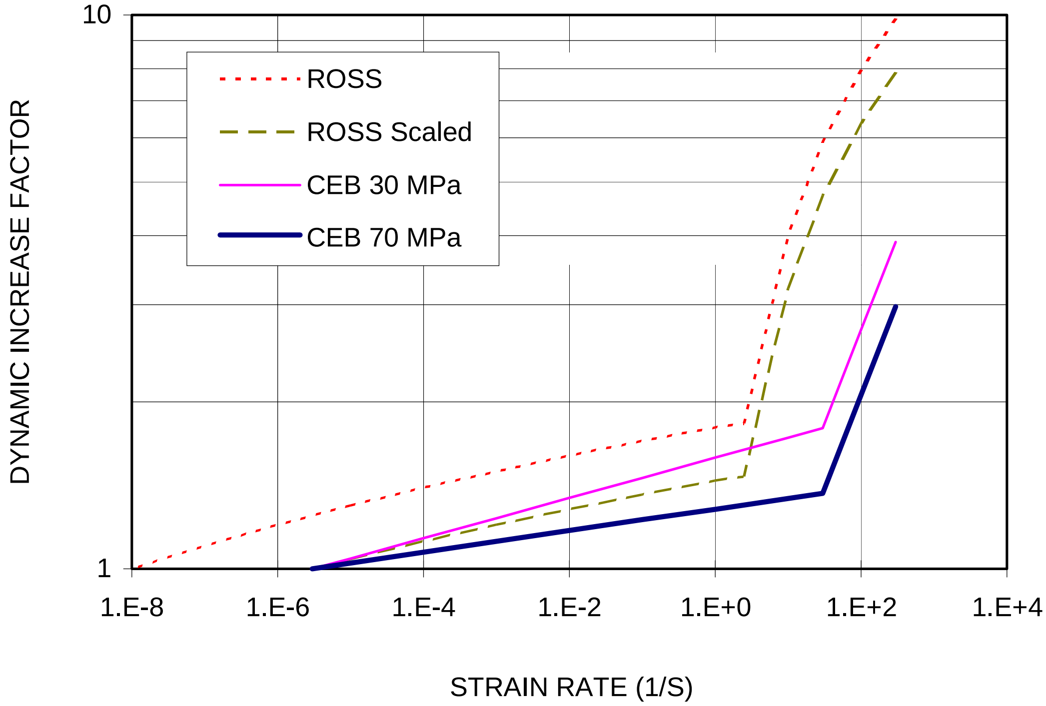

Figure 1. Ross scaled versus CEB for concrete in tension.

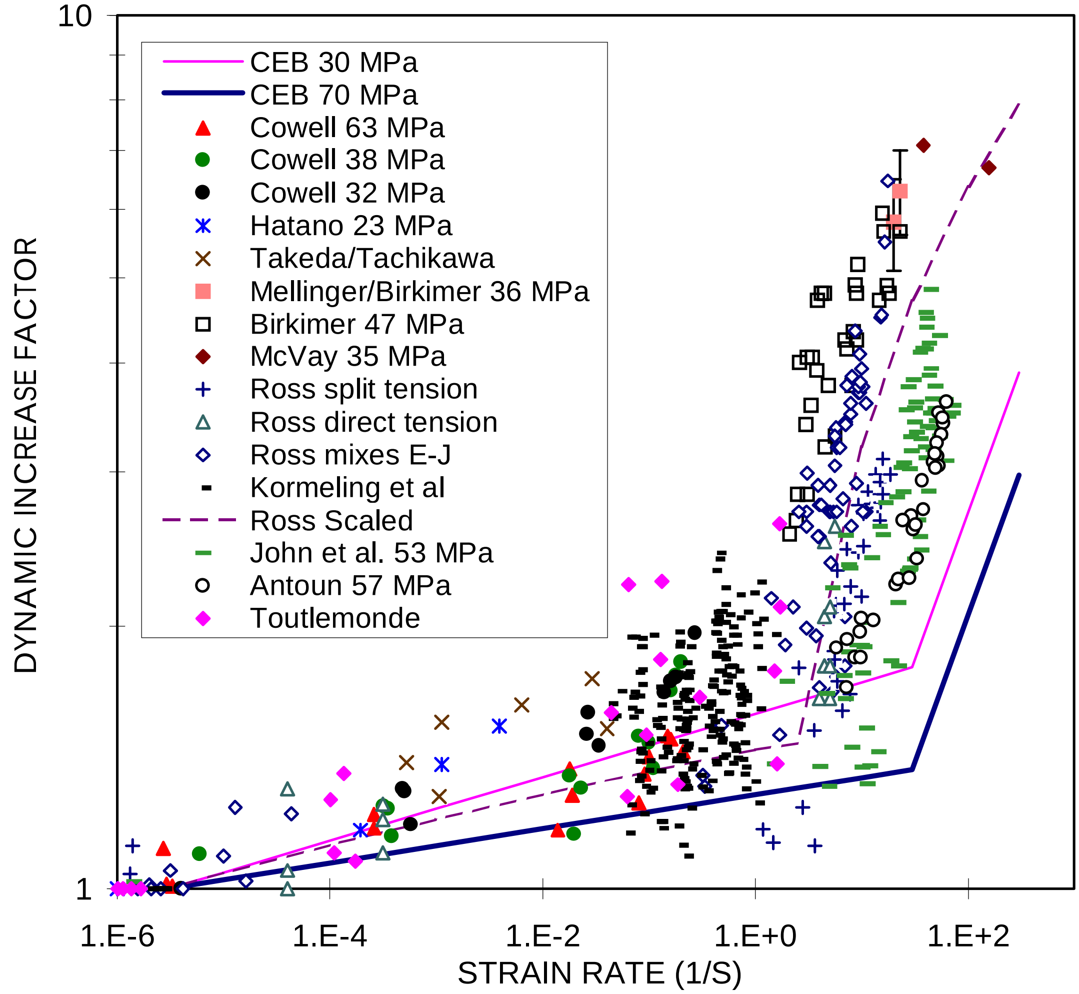

Figure 2. Ross scaled and CEB versus test data.

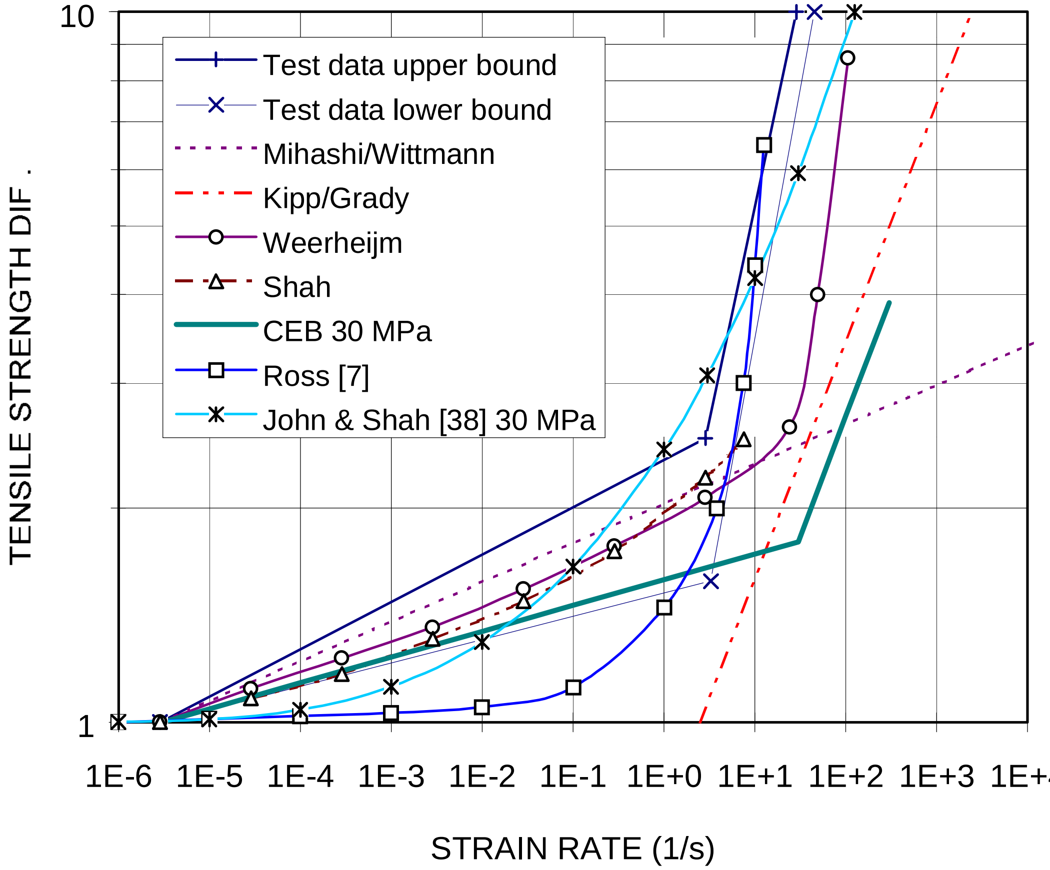

Figure 3. Comparison of various theories and experimental data, adapted from [34].

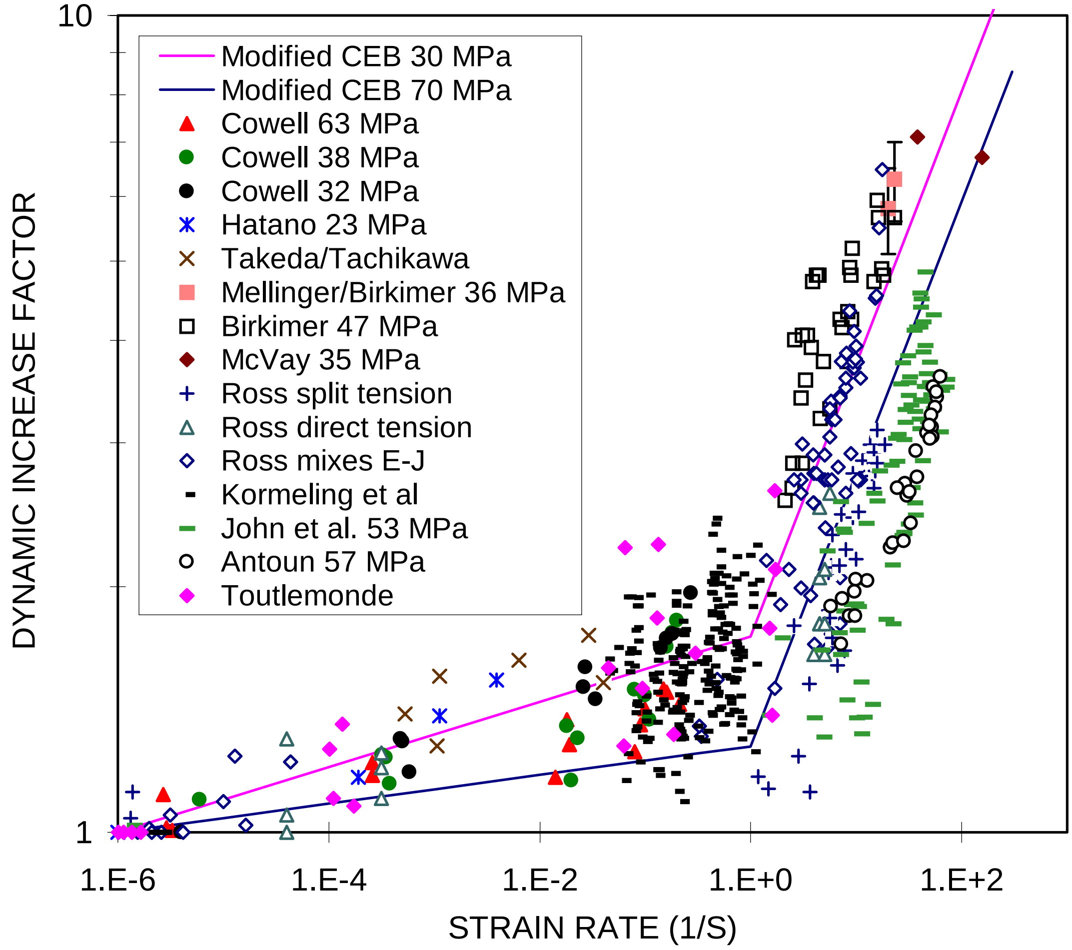

Figure 4. Proposed modified CEB curves in tension.