Chapter 3
Material Properties of RCC

3-1. Similarities of RCC and Conventional Concrete

The strength and elastic properties of RCC vary depending on the mix components and mix proportions in much the same manner as that for conventional mass concrete. Aggregate quality and water-cement ratio are the principal factors affecting strength and elastic properties. Properties important to the seismic analysis of RCC dams include compressive strength, tensile strength, shear strength, modulus of elasticity, Poisson's ratio, and unit weight. Except for unit weight, all these properties are strain rate sensitive, and the strain rates that occur during major earthquakes are in the order of 1,000 times greater than those used in standard laboratory testing. Guidance concerning the determination of RCC material properties is given in EM 1110-2-2006 and ETL 1110-2-343.

3-2. Compressive Strength

The relationship between water-cement ratio and compressive strength is the same for RCC as for conventional mass concrete. Normally, for durability reasons, the RCC mix will be designed to provide a minimum strength of 2,000 psi; however, for seismic reasons higher compressive strengths are often required to achieve the desired tensile and shear strength. The compressive strength at seismic strain rates will be 15 to 20 percent greater than that at the quasi-static rates used during laboratory testing (ACI Committee-439 1969); however, compressive strength is never the governing factor in seismic design.

3-3. Tensile Strength

The tensile strength of RCC shall be based on the direct tensile strength tests of core samples. For the final design of new dams, cores shall be taken from test-fill placements made with the proposed design mixes, and placed with the proposed consolidation and joint treatment methods. When an existing dam is evaluated for compliance with the requirements of this EP, cores shall be taken directly from the structure. Cores should be taken vertically so that tests can be made which reflect weaknesses inherent at lift joint surfaces in addition to the tests to determine the tensile strength of the parent concrete.

a. Location of critical tensile stress. Critical tensile stresses are located at the upstream and downstream faces of the dam. The tensile stress distribution within the dam mass is of interest to help establish zone boundaries for superior, higher strength RCC mixes that may be required to control cracking near the faces.

(1) Usually the tensile stress in the lift joints in the direction normal to the joint surface is critical near the upstream face of the dam. This is because the direction of the principal tensile stress near the upstream face is very nearly normal to the joint surface, thus there is little difference between the joint stress and the maximum principal stress in the parent concrete. Since tensile strength of the lift joint is notably less than the parent RCC, it will control the design near the upstream face.

(2) Near the downstream face, the direction of the principal tensile stress is nearly parallel to the face which results in significantly higher principal tensile stresses in the parent concrete compared to the tensile stresses in the lift joints normal to the joint surface. The ratio of the tensile strength of parent concrete to the tensile strength of the lift joints varies according to several parameters including workability of the mix, joint preparation, and maximum size aggregate. Thus, it usually becomes necessary to investigate both the principal tensile stress and the component tensile stress normal to the lift joints to determine which is critical near the downstream face.

b. Preliminary design. For preliminary design, the tensile strength of the RCC may be obtained from Figures 3-1 through 3-6 for the proposed concrete compressive strength (f'_c). These figures show both the tensile strength of the parent material and the tensile strength of the lift joint based on the proposed consolidation and joint treatment method. These figures were developed from Tables E2 and E3, Appendix E.

c. Tensile strength tests. Splitting tensile tests are easier to perform and provide more consistent results than direct tensile tests. However, splitting tensile test results tends to overpredict actual tensile strengths, and should be adjusted by a strength reduction factor to reflect results that would be obtained from direct tensile tests. When splitting tensile tests

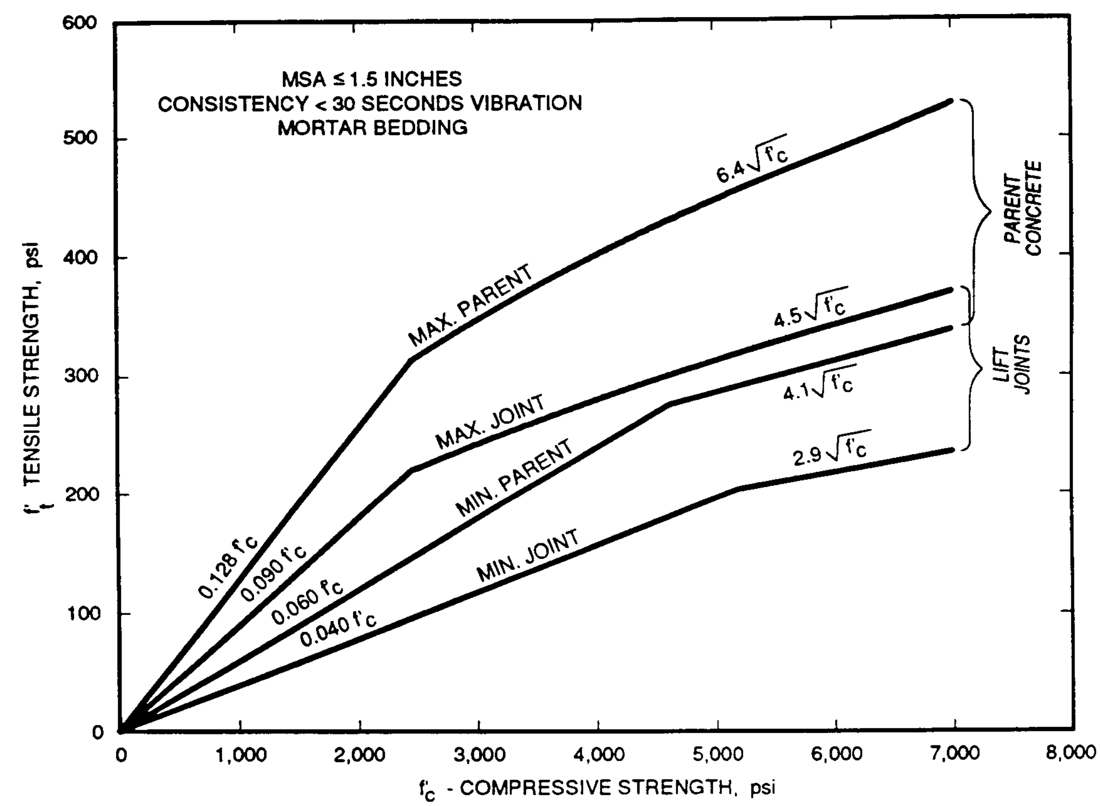

Figure 3-1. Tensile strength range, RCC, MSA ≤ 1.5 inches, consistency < 30 seconds vibration, mortar bedding

are used as the basis for determining the tensile strength of RCC, the test results shall be reduced by a strength reduction factor of 75 percent as recommended in Appendix E.

d. Factors affecting tensile strength. The tensile strength of RCC, as well as of conventionally placed mass concrete, is dependent on many variables including paste and aggregate strength, aggregate size, loading history, and load deformation rates. See paragraph 3-9 concerning strain rate sensitivity and dynamic tensile strength.

(1) RCC differs from conventionally placed mass concrete due to the many horizontal planes of weakness (construction joints) created during placement. RCC is placed and compacted in layers ranging from 6 to 24 inches with each layer creating a joint with tensile strength less than that of the parent concrete. The joint strength can be improved by placing a layer of high slump bedding mortar on each lift; however, the resulting joint strength is always somewhat less than the parent concrete. The consistency of RCC can also affect tensile strength with lower strength values for harsh mixes with low paste contents. Refer to Chapter 2 for additional discussion of these factors.

(2) Inherent in some RCC mixes are certain anisotropic material properties. In the RCC compaction process, the flatter coarse aggregate particles in these mixes have a tendency to align themselves in the horizontal direction. When this occurs, the strength of vertical cores will be less, and the strength of horizontal cores greater than the average tensile strength. The variance from average could be as high as 20 percent, although in general these effects will

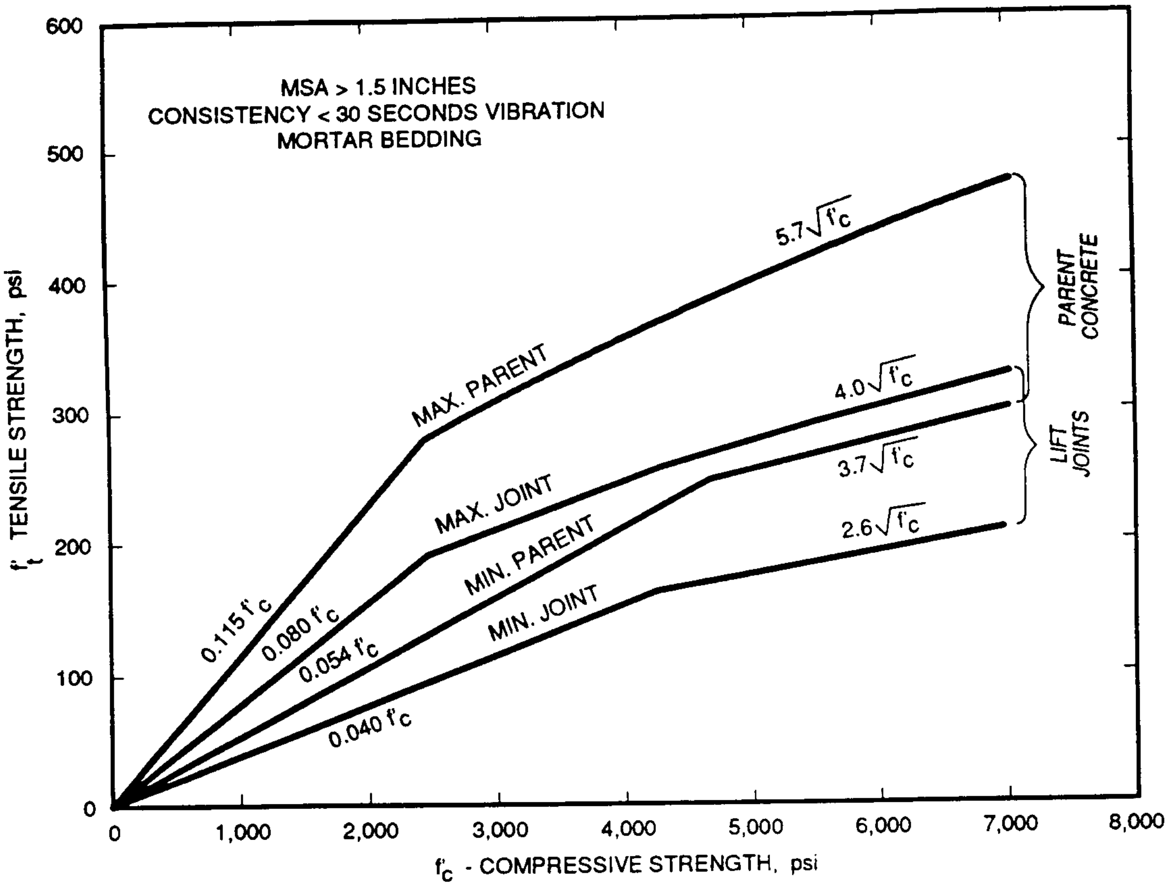

Figure 3-2. Tensile strength range, RCC, MSA > 1.5 inches, consistency < 30 seconds vibration, mortar bedding

be small. If the coarse aggregate particle shape indicates the possibility of significant anisotropy, both vertical and horizontal cores obtained from the laboratory test placement should be tested.

3-4. Shear Strength

The shear strength along lift joint surfaces is always less than the parent concrete; therefore, final shear strength determination should be based on tests of representative samples from the dam or test fill. Both the bond strength and the tangent of the angle of internal friction can be increased by 10 percent to account for the apparent higher strengths associated with seismic strain rates.

3-5. Modulus of Elasticity

RCC will usually provide a modulus of elasticity equal to, or greater than, that of conventional mass concrete of equal compressive strength. The modulus of RCC in tension is equal to that in compression. The static modulus of elasticity, in the absence of testing, can be assumed equal to (ACI Committee-207 1973):

$$E = 57{,}000\sqrt{f_c^{\prime}}$$

where E = static modulus of elasticity

$f_c^{\prime}$ = static compressive strength of RCC

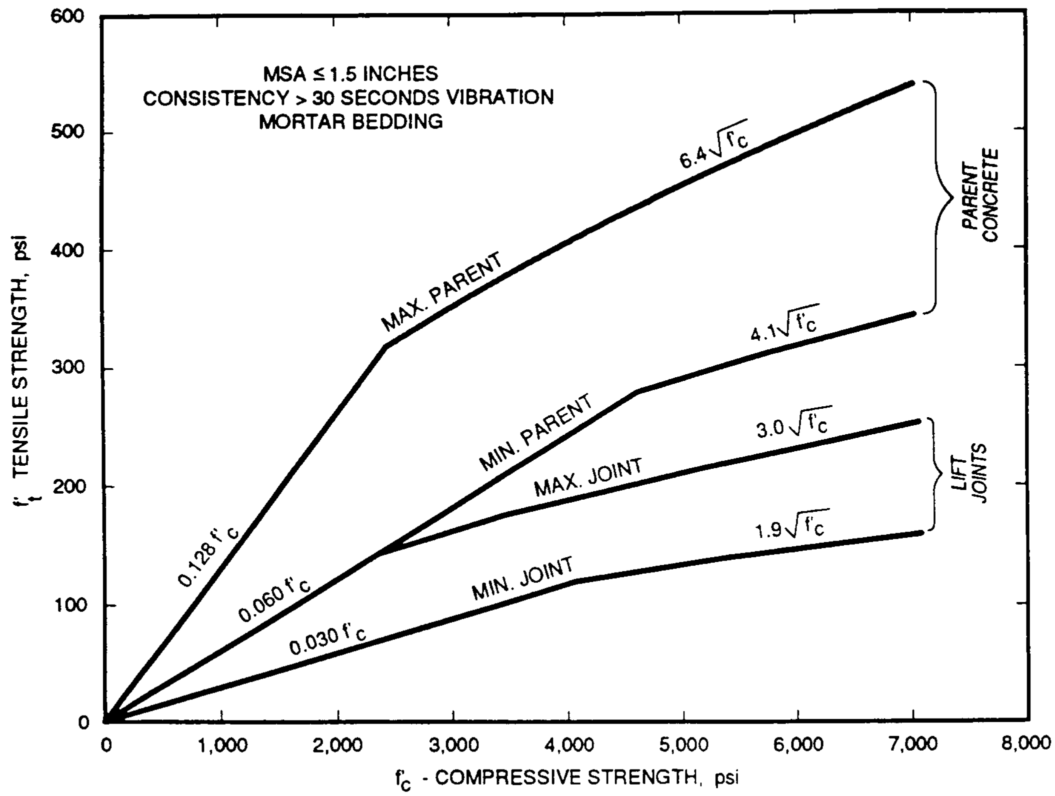

Figure 3-3. Tensile strength range, RCC, MSA ≤ 1.5 inches, consistency > 30 seconds vibration, mortar bedding

The relationship between strain rate and modulus of elasticity is as follows (Bruhwieler 1990):

$$E' = E(E_r)^{0.020}$$

where E = static modulus of elasticity

E' = seismic modulus of elasticity at the quasi-static rate

$$E_r = \frac{\text{high seismic strain rate}}{\text{quasi-static rate}}$$

For a seismic strain rate equal to 1,000 times the quasi-static rate the seismic modulus of elasticity is 1.15 times the static modulus. For long-term loadings where creep effects are important, the effective modulus of elasticity may be only 2/3 the static modulus of elasticity calculated by the above formula (Dunstan 1978). The modulus of elasticity may exhibit some anisotropic behavior due to the coarse aggregate particle alignment as discussed in paragraph 3-3*d*(2); however, the effects on the modulus will be small and can be disregarded when performing a dynamic stress analysis.

3-6. Poisson's Ratio

Poisson's ratio for RCC is the same as for conventional mass concrete. For static loads, values range between 0.17 and 0.22, with 0.20 recommended when testing has not been performed. Poisson's ratio is also strain rate sensitive, and the static value should be reduced by 30 percent when evaluating stresses due to seismic loads (Bruhwieler 1990).

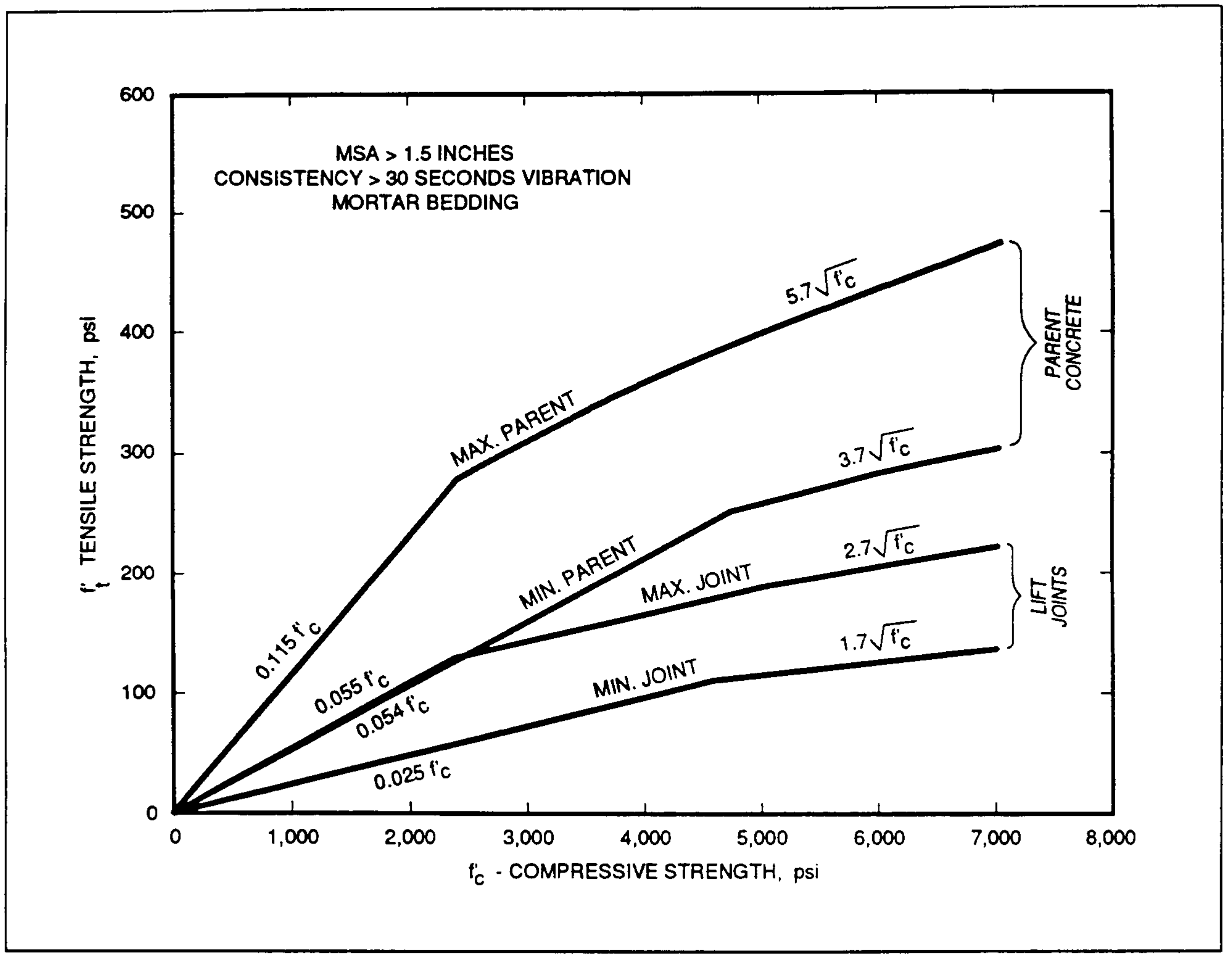

Figure 3-4. Tensile strength range, RCC, MSA > 1.5 inches, consistency > 30 seconds vibration, mortar bedding

3-7. Tensile Stress/Strain Relationship

As mentioned in paragraph 2-2*b*, concrete cracking, crack propagation, and the energy dissipated in the process are complex and nonlinear in nature. For a simplified linear-elastic analysis, a constant modulus of elasticity is required. Thus, a linear stress/strain relationship is used for the analysis with a tensile modulus equal to the modulus of elasticity for concrete in compression.

a. Compression and tension differences. Although a linear relationship is assumed for the analysis, in actuality the stress/strain relationship becomes nonlinear after concrete stresses reach approximately 60 percent of the peak stress (Raphael 1984). In compression this does not cause a problem because, in general, concrete compressive stresses even during a major earthquake are quite low with respect to the peak stress or ultimate capacity. In tension, it is a different matter since tensile stress can approach and exceed the peak tensile stress capacity of the concrete and in some cases cracking will occur.

b. Tensile stress/strain curve. The actual nonlinear stress/strain relationship for RCC concrete is shown in Figure 3-7. The assumed linear relationship used for finite element analysis was developed from the work done by Raphael (1984). The actual nonlinear performance of concrete in tension consists of a linear region from zero stress up to 60 percent of the peak stress, a nonlinear ascending region from 60 percent of peak stress to peak stress (this point on the curve corresponds to the direct tensile strength test value described in paragraph 3-3*c*), and a nonlinear descending region from peak stress back to zero

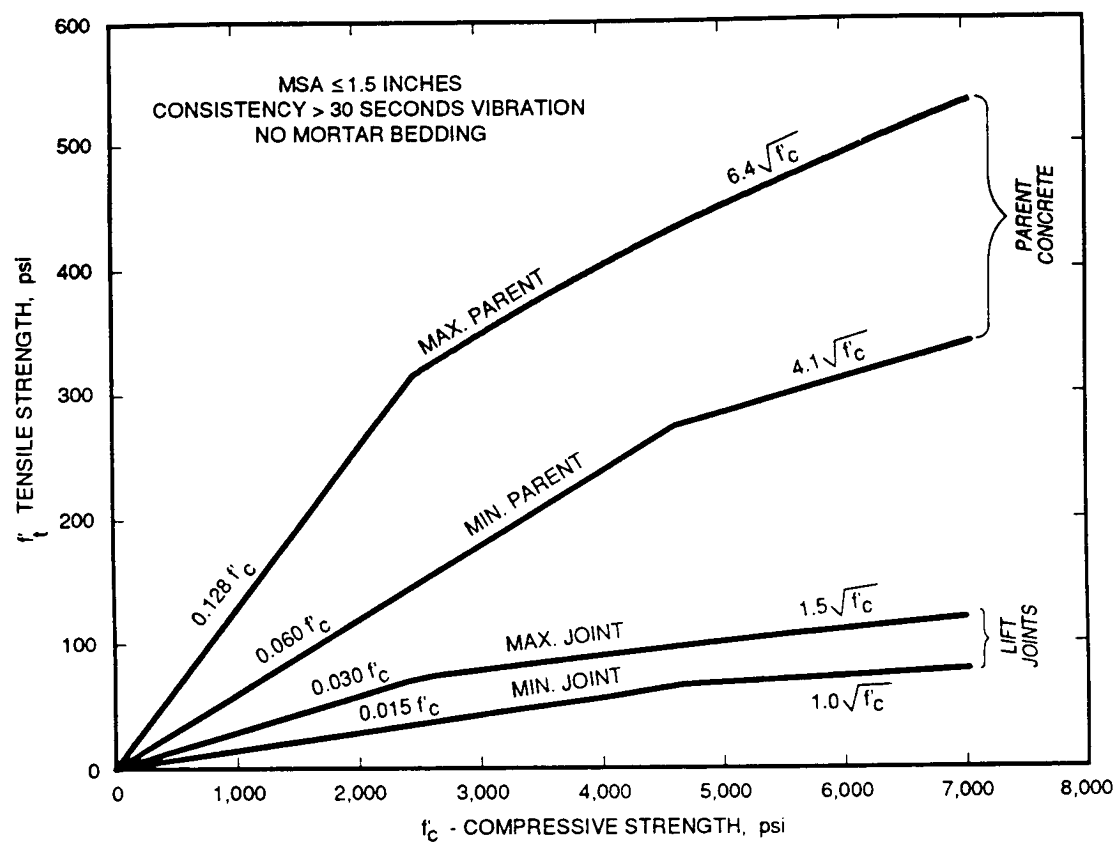

Figure 3-5. Tensile strength range, RCC, MSA ≤ 1.5 inches, consistency > 30 seconds vibration, no mortar bedding

stress. The last region is termed the "tensile softening zone." In this region, where deformation increases with decreasing stress, deformation controlled stable test procedures are required to capture the stress/strain behavior (Bruhwieler 1990), where conventional test procedures will cause the strain to fall off abruptly to zero strain at a point on the curve just beyond the peak stress point. The area under the tensile softening region of the stress/strain curve represents additional energy absorbed by the RCC structure during the crack formation process. As such, this region is quite instrumental in dissipating the energy imparted to the dam through seismic ground motion. The transition from linear to nonlinear in the ascending region of the stress/strain curve represents the development of microcracking within the concrete. These microcracks eventually coalesce into macrocracks as the tensile softening zone is reached.

3-8. Dynamic Tensile Strength (DTS)

The tensile strength of concrete is strain rate sensitive. During seismic events strain rates are related to the fundamental period of vibration of the dam with the peak stress reached during a quarter cycle of vibration. The high strain rates associated with dam response to ground motion produce tensile strengths 50 to 80 percent higher than those produced during direct tensile strength testing where the strain rate is very slow. For this reason, the dynamic tensile strength (DTS) of RCC shall be equivalent to the direct tensile strength multiplied by a factor of 1.50 (Cannon 1991, Raphael 1984). This adjustment factor applies to both the tensile strength of the parent material and to the tensile strength at the lift joints.

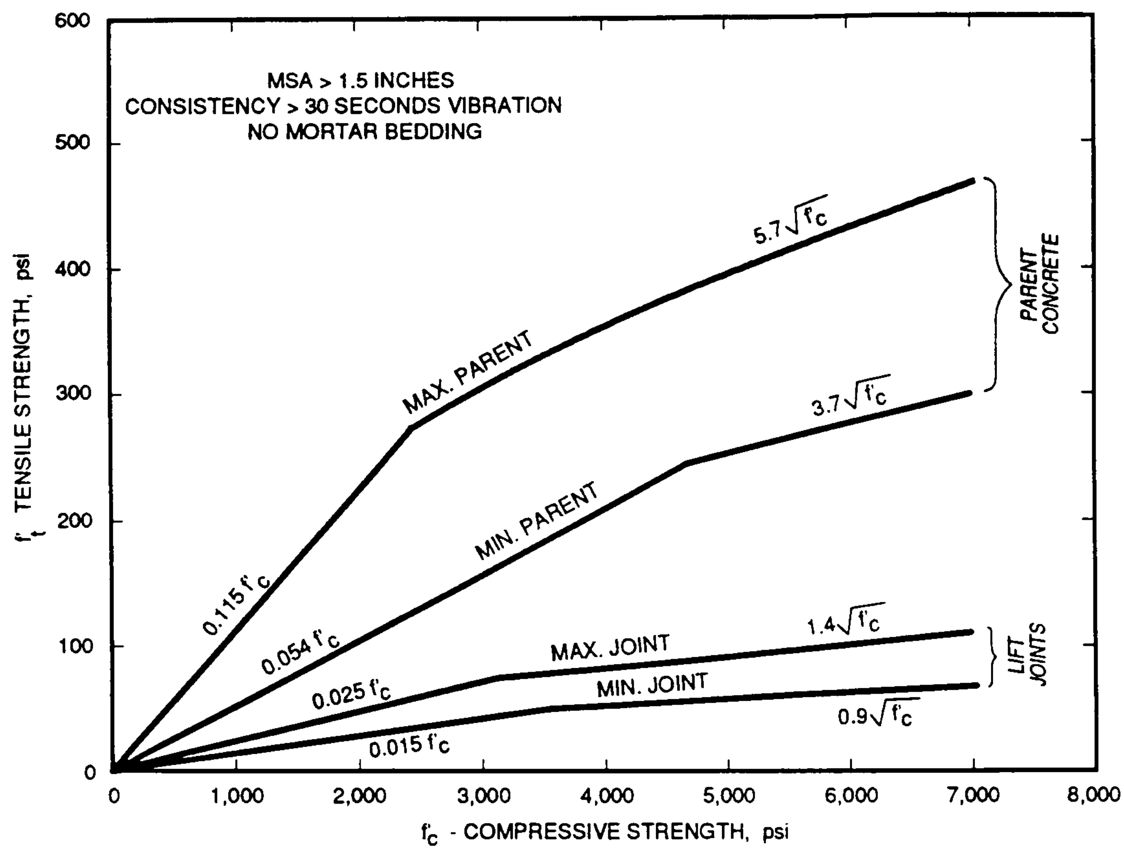

Figure 3-6. Tensile strength range, RCC, MSA > 1.5 inches, consistency > 30 seconds vibration, no mortar bedding

3-9. Allowable Tensile Stresses

When the response to ground motion increases beyond the elastic limit, energy is dissipated through crack development and crack propagation in accordance with the stress/strain relationship shown in Figure 3-7. To account for all nonlinear response including that in the tensile softening zone of the stress/strain curve requires a complex nonlinear analysis. The simpler linear-elastic analysis may be utilized in a manner which accounts for response in the linear region, and the nonlinear pre-peak region.

a. Comparing linear and nonlinear curves. Since a linear-elastic analysis converts strains to stress using a constant modulus of elasticity, the stresses from the analysis will be higher than actual stresses when in the nonlinear pre-peak and post-peak strain regions. This may be compensated for by establishing an allowable tensile stress which is greater than the actual peak tensile stress as shown in Figure 3-7. In this figure, the dashed line represents the tensile stress/strain relationship assuming linear-elastic behavior as opposed to the actual nonlinear stress/strain relationship which is shown as a heavy solid line. The amount the peak tensile stress is increased in establishing the allowable stress depends on the extent of tensile cracking that can be tolerated, which in turn is based on the performance requirements for the design earthquake under consideration. The economics of the design also becomes a factor in the higher seismic zones. In these zones, a somewhat greater amount of cracking can be justified economically because there is a point where the cost of producing RCC mixes with high tensile strengths to resist cracking will exceed the cost of repairing the cracks as long as the cracking is not too extensive.

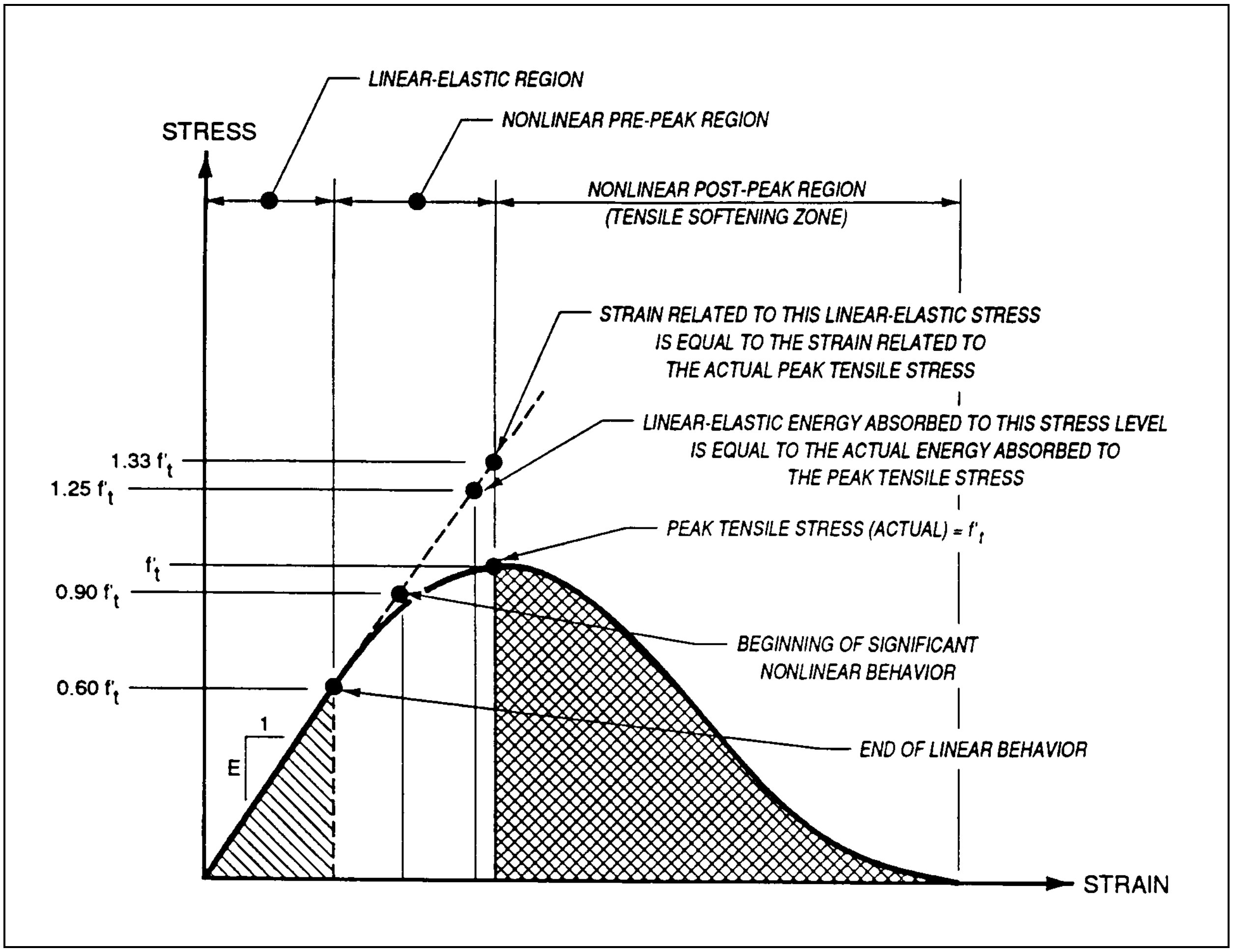

Figure 3-7. Tensile stress/strain diagram for RCC

b. Key points on stress/strain curve. Several points on the stress/strain curve are of interest when establishing the allowable tensile stresses that are used in linear-elastic analyses (refer to paragraphs 4-2*c* and 4-3*c*). Based on f'_t = actual peak tensile stress (tensile stress that corresponds to that which would be attained by a direct tensile strength test), and f_t = the stress level based on linear-elastic behavior (refer to the dashed line in Figure 3-7), the following key values of f_t are of interest:

(1) $f_t = 0.60\ f'_t$ -- the end of the elastic range and the beginning of microcracking.

(2) $f_t = 0.90\ f'_t$ -- this point was selected because the stress/strain dashed line for linear-elastic behavior is just beginning to significantly separate from the actual stress/strain curve. If the tensile stresses for a linear-elastic analysis stay within the stress level for this point, the response can still be judged as primarily linear.

(3) $f_t = 1.25\ f'_t$ -- the area under the dashed line for linear-elastic behavior up to this stress level is approximately equal to the area under the solid line for the actual stress/strain curve up to the peak tensile stress point (this point is the end of microcracking and the beginning of macrocracking). Thus, the energy absorbed in a linear-elastic analysis to this point of stress is equal to the actual energy absorbed through the microcracking pre-peak region.

(4) $f_t = 1.33\ f'_t$ -- the strain corresponding to this point of stress based on linear-elastic behavior is equal to the strain corresponding to the actual peak tensile stress. This strain point signifies the end of microcracking and the beginning of macrocracking. This point also represents a practical limit for the

linear-elastic response spectrum analysis described in paragraph 2-2*c*. Beyond this point in the tensile softening zone, the stress/strain relationship based on linear-elastic behavior diverges so rapidly from the actual stress/strain curve that a linear-elastic analysis will no longer provide an acceptable approximation of either the energy absorbed by the dam-foundation system, or the strain deformation of the system. Cracking could be extensive enough to change the dynamic properties of the dam structure.