

# Seismic Design of High-Strength-Concrete Bridge Piers and Columns

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The structural design applications and mechanical properties of high-strength concrete (HSC) are briefly reviewed. Analytical design studies of reinforced HSC bridge piers and columns subjected to static and seismic loadings are presented. Flexible and rigid foundation systems are incorporated into the analysis. The results of this study show that the use of HSC will reduce column size and stiffness. As the columns become more flexible, seismic shears and moments are reduced. Cost estimates show that the use of HSC with minimum reinforcing steel provides the most economical solution for bridge piers and columns. Economy is also achieved because smaller foundations can be used.

The production and placement of high-strength concrete (HSC) in either precast or cast-in-place (CIP) construction using conventional materials and methods with close cooperation among the engineer, contractor, concrete producer, and testing agency are technically and economically feasible (1-16).

HSC with a 28-day uniaxial compressive strength,  $f'_c$ , of 6,000 to 14,000 psi (41.4 to 96.6 MPa) is rapidly gaining acceptance in building design in the United States. When used in buildings, the number of columns and their sizes can be reduced, resulting in two economic advantages to the building owner: (a) more space to lease and (b) lower construction costs (1-3). If HSC can be produced and placed by the building construction industry, the bridge construction industry should be able to do the same.

With some exceptions, bridge designers in the United States have been slow to accept HSC and are still specifying strengths of 3,000 and 4,000 psi (20.7 and 27.6 MPa) for concrete. Normal-strength concrete (NSC) has a 28-day compressive strength ranging from 3,000 to 6,000 psi.

Nearly 20 years ago, HSC with a strength of 6,000 psi was used in the on-site fabrication of the precast posttensioned concrete T-beams used for the Willows Bridge in Toronto, Ontario, Canada (4).

In today's precast prestressed concrete industry, bridge girders can be produced utilizing HSC under manufacturing plant conditions. In the Pacific Northwest, precast prestressed concrete bridge girders with strengths as high as 7,000 and 9,000 psi (48.3 and 62.1 MPa) have been used (5, 6). The majority of precast prestressed girder bridges designed by the Washington State Department of Transportation (WSDOT) have concrete with a 28-day strength of 6,000 psi, with 5,000 psi (34.5 MPa) permitted at the strand release. On the Pasco-

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Kennewick cable-stayed bridge over the Columbia River in eastern Washington, the precast prestressed girder segments had an average 28-day strength of 7,500 psi (51.7 MPa) based on a specified 6,000-psi design mix (7).

The current upper limit for CIP concrete in U.S. bridge construction appears to be 6,000 psi. Concrete with this strength has been used successfully on several major bridge projects to reduce the size and weight of structural elements. On the Houston Ship Channel bridge, the subcontractor substituted 5,500-psi (37.9-MPa) concrete for the pier construction and 6,000-psi concrete for the CIP posttensioned box girders. Originally, concrete with a strength of 3,600 psi (24.8 MPa) had been specified for the substructure and concrete with a strength of 5,000 psi for the superstructure (8). On the East Huntington cable-stayed bridge over the Ohio River, concrete with a 28-day strength of 8,000 psi (55.2 MPa) was specified for the precast hybrid concrete-and-steel deck segments and 6,000 psi for the CIP "wishbone" tower (9, 10).

In 1979, FHWA, through the U.S. Department of Transportation, authorized a study, Applications of High Strength Concrete for Highway Bridges (11, 12). This study explored the potential for using HSC in precast prestressed girder beams, bulb-tees, posttensioned box girders, segmentally posttensioned box girders, compression members, and thin-walled precast plate elements. In addition, a square hollow pier was tested. The study concluded that HSC permitted the use of longer spans, reduced dead loads, and provided higher load capacities.

Society expects aesthetically pleasing and durable structures that combine strength with simplicity for the least cost. Furthermore, these structures should be relatively maintenance free. HSC will satisfy these needs. Would the use of HSC in bridge construction result in more economical bridge structures? This paper examines one aspect of that question, the design of bridge piers and columns subject to static and seismic loadings.

## MECHANICAL PROPERTIES OF HSC

Some of the mechanical properties of HSC are different from those of NSC. A brief summary follows.

### Stress-Strain Behavior

As shown in Figure 1, the slope of the ascending part of the stress-strain curve is more linear and steeper up to a higher stress/strength ratio, the strain at maximum stress level is

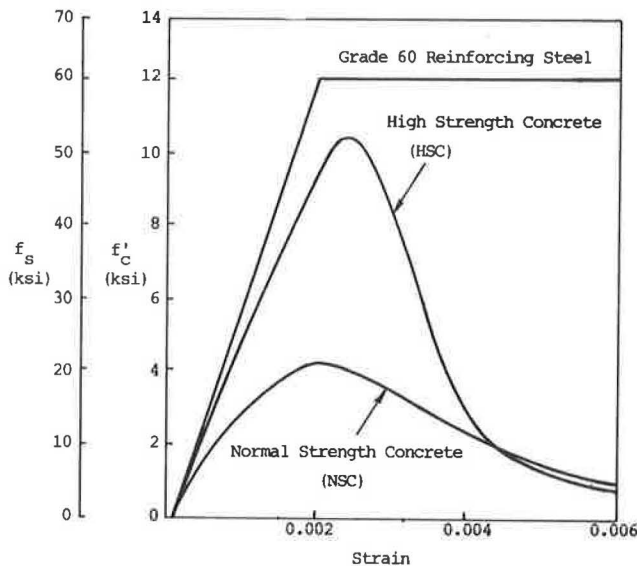


FIGURE 1 Stress-strain curves for steel reinforcement and concrete.

higher, and the slope of the descending portion of the curve is steeper when compared with the curve for NSC (13, 16–18).

#### Poisson's Ratio

The value of Poisson's ratio is in the range of 0.20 to 0.28 for normal-weight HSC; it is independent of compressive strength, coarse aggregate size, and age of specimen (13, 16, 19).

#### Static Modulus of Elasticity

For concrete with a dry unit weight of 145 lb/ft<sup>3</sup> (2320 kg/m<sup>3</sup>), the 1983 ACI Building Code (ACI 318-83) recommends the following equation for predicting the static modulus of elasticity of concrete (20):

$$E_c = 33w^{1.5}(f'_c)^{0.5} \text{ or } 57,000(f'_c)^{0.5} \text{ (psi)} \quad (1)$$

For other dry unit weights, Equation 1 can be used in the following form:

$$E_c = 57,000(f'_c)^{0.5}(w/145)^{1.5} \quad (2)$$

For concrete with compressive strengths over 6,000 psi, this equation overestimates the value of  $E_c$  by as much as 15 percent.

For concrete with a dry unit weight of 145 lb/ft<sup>3</sup> and a compressive strength over 3,000 psi and less than 12,000 psi (82.8 MPa), a better correlation can be obtained from the following expression (13):

$$E_c = [40,000(f'_c)^{0.5} + 1.0 \times 10^6](w/145)^{1.5} \quad (3)$$

Equation 3 is valid for lightweight concrete, 90 to 145 lb/ft<sup>3</sup> (1440 to 2320 kg/m<sup>3</sup>), when the compressive strength is between 3,000 and 9,000 psi.

Other empirical equations for predicting the modulus of elasticity are (21)

$$E_c = w^{2.5}(f'_c)^{0.325} \text{ (psi)} \quad (4)$$

$$E_c = 27.55w^{1.5}(f'_c)^{0.5} \text{ (psi)} \quad (5)$$

#### Tensile Strength

For concrete with a compressive strength between 3,000 and 12,000 psi, ACI Committee 363 recommends the following empirical equations to predict the average modulus of rupture ( $f'_r$ ) and tensile splitting strength ( $f'_{sp}$ ) (17):

$$f'_r = 11.7(f'_c)^{0.5} \text{ (psi)} \quad (6)$$

$$f'_{sp} = 7.4(f'_c)^{0.5} \text{ (psi)} \quad (7)$$

Other empirical expressions that give lower tensile strengths than those proposed by ACI Committee 363 are (18, 21)

$$f'_r = 2.30(f'_c)^{2/3} \text{ (psi)} \quad (8)$$

$$f'_{sp} = 4.34(f'_c)^{0.55} \text{ (psi)} \quad (9)$$

#### Effects of Confinement Reinforcement

Transverse reinforcing steel places lateral confining pressure on the concrete core, which is in a state of triaxial stress. This increases the axial strength and strain capacity of the concrete, causing the column to exhibit a ductile, post-peak-strength behavior. Therefore, HSC columns, together with adequate reinforcing steel, can withstand seismic forces.

For normal-weight HSC, the axial strength of a confined column can be determined from the following expression (17):

$$f''_c = f'_c + 8.0A_{sp} \times f_{sp}(1 - S/D)/SD \quad (10)$$

where

- $f''_c$  = compressive strength of confined column,
- $f'_c$  = compressive strength of unconfined column,
- $A_{sp}$  = area of confinement reinforcement,
- $f_{sp}$  = actual stress in confinement reinforcement at maximum load,
- $S$  = spacing of confinement reinforcement, and
- $D$  = core diameter of column.

#### ANALYTICAL DESIGN STUDY

##### Slenderness Effects

A state-of-the-art survey conducted by Poston et al. (22) indicated that multiple-pier bents accounted for 83 percent of the bridge piers used and single-pier bents accounted for 17 percent. The use of solid cross sections was much more prevalent than hollow cross sections. However, the study found that the use of hollow cross sections increased dramatically with height (22). The use of HSC in lieu of NSC will reduce the column cross section and stiffness. The magnification of moment due to this increase in slenderness for compression members not braced against sidesway must be considered in the design. When the slenderness ratio,  $l/r$ , exceeds 100, both the AASHTO Specifications (23) and the ACI Building Code 318-83 (20, 24) recommend a second-order frame analysis that considers sidesway, nonlinear effects due to cross-section cracking, creep, and stress-strain behavior of the concrete.

Note that the significantly lower creep coefficient and increased modulus of elasticity of HSC will affect the value of the effective flexural rigidity,  $EI$ .

### HSC Column Design

#### Static Analysis

As shown in Table 1, the axial load capacity for a column with a constant cross section can be increased twofold or more when the concrete compressive strength is increased from 4,000 to 12,000 psi, depending on the slenderness ratio.

For the column subjected to axial load and biaxial bending, increases in the bending moments are possible with HSC. As the interaction diagram in Figure 2 shows for an axial load of 1,620 kips (7,205 kN) on a 5- by 7-ft (1.5- by 2.1-m) cross section, the nominal transverse moment capacity increases 20 percent and the nominal longitudinal moment capacity increases 10 percent. These increases occur when the concrete compressive strength is increased from 4,000 to 12,000 psi.

When slenderness effects are considered, the use of HSC is beneficial. Figure 3 shows the interaction diagram for a 6- by 6-ft (1.8- by 1.8-m) column using NSC with  $f'_c = 4,000$  psi and HSC with  $f'_c = 12,000$  psi for various slenderness ratios. This illustrates that compression members are an excellent application for HSC. Smaller cross sections can be used for a given member, or fewer members can be used. In addition to weight, material costs are reduced.

#### Seismic Analysis

The bridge shown in Figure 4 was subjected to seismic motion to study the effects of using HSC in the columns. Concrete compressive strengths ranged from 4,000 to 12,000 psi, with data obtained at every 2,000-psi (18.3-MPa) interval. The column cross sections corresponding to the appropriate value of concrete compressive strength are shown in the lower part of Figure 4 and in Figure 5.

A three-dimensional response spectrum analysis using the computer program SEISAB (Seismic Analysis of Bridges) was performed for each column cross section and compressive strength to obtain the overall response of the structure. SEISAB contains both single-mode and multimodal response spectrum techniques and includes a linear transient analysis capability (25). To understand the influence that the foundation type has on the overall response of the structure, flexible (vertical-pile) and rigid (battered-pile or drilled-shaft) foundation systems were modeled by introducing low and high foundation spring constants into the analysis. The unreduced ground response spectrum used in the analysis is shown in Figure 6.

#### Vibration Characteristics

A comparison of the vibration characteristics of the bridge structure for the different column concrete strengths is shown

TABLE 1 AXIAL LOAD CAPACITY FOR 5 × 7-FT RECTANGULAR PIER

Slenderness Ratio, $l/r$	Concrete Strength (ksi)	$e=0$ $P/P_4$	$e=0.1D^*$ $P/P_4$	$e=0.2D^*$ $P/P_4$
0	4	1.00	1.00	1.00
	8	1.88	1.85	1.80
	12	2.76	2.65	2.60
50	4	1.00	1.00	1.00
	8	1.85	1.81	1.72
	12	2.68	2.65	2.50
100	4	1.00	1.00	1.00
	8	1.75	1.60	1.40
	12	2.43	2.25	2.05

Note:  $P_4$  = Axial load capacity of pier with 4,000 psi concrete compressive strength and 32-#11 reinforcing bars

$$\phi \text{ factor} = 0.90 - 0.2 \frac{P_u}{0.1Agf'_c}$$

\* = eccentricity in the weak direction

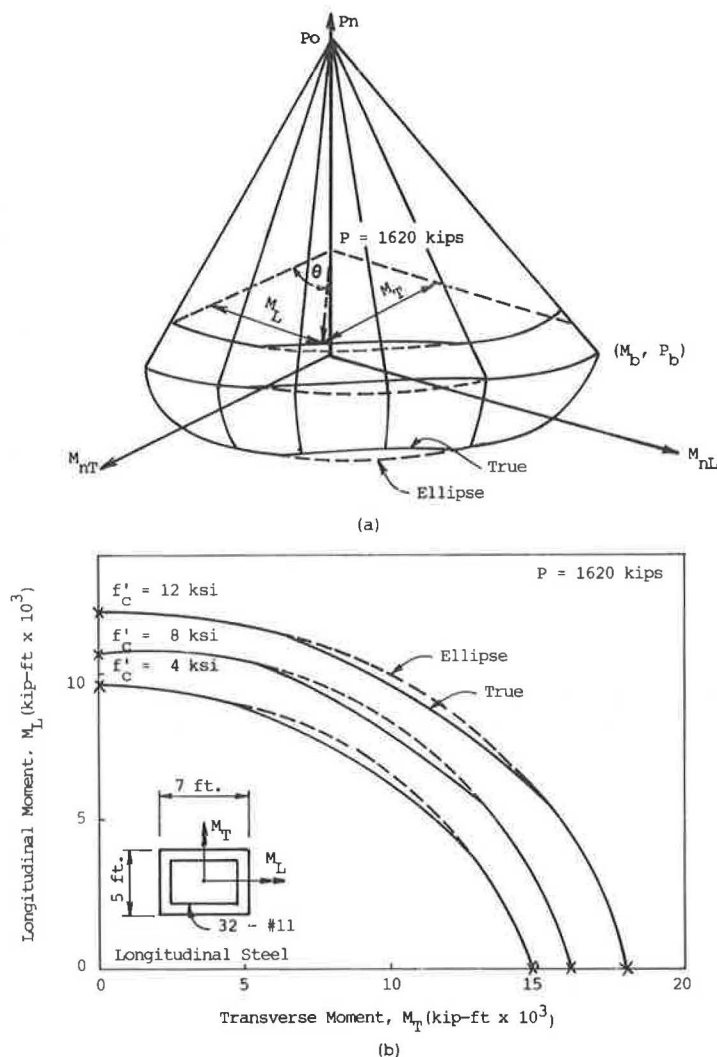


FIGURE 2 Biaxial bending on pier: (a) interaction diagram; (b) moment contour at axial load of 1,620 kips.

in Figure 7. As the column strength increases, the natural period of the structure increases and the Elastic Seismic Response Coefficient (ESRC) decreases. ESRC is commonly thought of as the ratio of transverse inertia force to static dead load and is used as a comparison with other bridges with similar characteristics that have been previously analyzed.

The ESRC is lower for the bridge with a flexible foundation than for the one supported by a rigid foundation. The flexible foundation system effectively lengthens the columns of bridges supported by such a foundation system.

### Displacement

A comparison of the Complete Quadratic Combination (CQC) displacements at the top of Pier 4 for the different concrete strengths is shown in Figure 8. The data presented show that higher displacements result when the concrete strength of the columns is increased. As expected, the displacement at the top of the column supported by the flexible foundation exceeds the displacement when a rigid foundation is used. The higher values of the displacement for slender columns with a flexible

foundation imply that the moment magnifier for these columns will be increased.

### Forces and Moments for Columns and Foundations

Figure 9 shows how the shears and moments at the top of Pier 4 vary as the concrete strength is increased. The reduction is much higher for the rigid foundation system than for the flexible foundation system. When a comparison is made between the flexible and the rigid foundation systems, the shears and moments of the flexible foundation system are much less than those of the rigid foundation system. This is because the flexible foundation provides less stiffness to the columns and overall system than the rigid foundation; consequently, less inertial force is attracted to these flexible columns. However, as the concrete strength approaches 12,000 psi, it appears that the foundation stiffness makes less difference in the top of column shears and moments.

Bending deformations in rigid foundation systems will generate high reaction force. Figure 10 shows that the reduction in

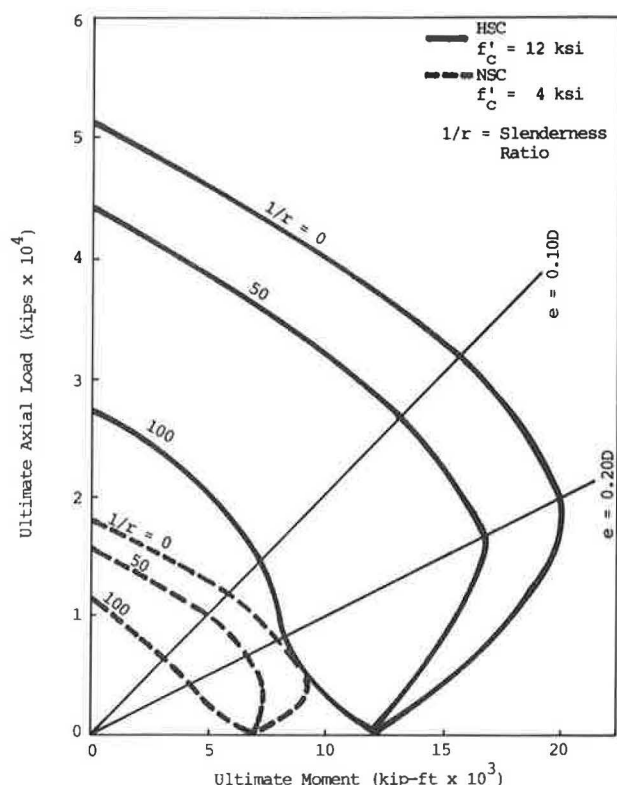


FIGURE 3 Interaction diagram for 6- by 6-ft (1.8- by 1.8-m) column.

the seismically induced axial force at the top of the pile is much greater for the rigid foundation system when compared with that for the more flexible foundation system. This is due to the transmission of lower foundation forces and bending moments from the flexible columns. On the other hand, the

large relative lateral displacements of the flexible foundation system induce high bending moments at the top of the piles.

### Economic Considerations

The current economic situation places increasing pressure on designers to use stronger materials. In most concrete structures, the cost of materials amounts to a small percentage of the total cost. To examine the savings of using HSC over NSC, cost estimates for the columns of the bridge shown in Figure 4 were computed and are shown in Figure 11. The column dimensions and concrete strengths used are those shown in the lower part of Figure 4. Longitudinal steel varied from 1 to 4 percent. Typical material costs for comparison purposes are as follows (1):

Description	Unit Price
Reinforcing steel (\$/lb)	0.40 (or \$800/ton)
Concrete (\$/yd <sup>3</sup> )	
4,000 psi	45
6,000 psi	59
8,000 psi (I)	82
10,000 psi	102
12,000 psi	124
14,000 psi (I)	145
Formwork (\$/ft <sup>2</sup> )	3

For the rigid foundation system and using Figure 11, the cost per foot for the 5-ft by 7-ft 4,000-psi cross section with 48 No. 11 reinforcing bars (1.5 percent) is \$285/ft and for the 3- by 4-ft (0.9- by 1.2-m) column cross section using 12,000-psi concrete with 28 No. 11 reinforcing bars (2.5 percent) is \$190/ft. The difference is \$95/ft, for a 33 percent savings in material cost. As shown, the use of HSC is more cost-effective in piers and columns with the smallest cross-sectional area and minimum reinforcing steel.

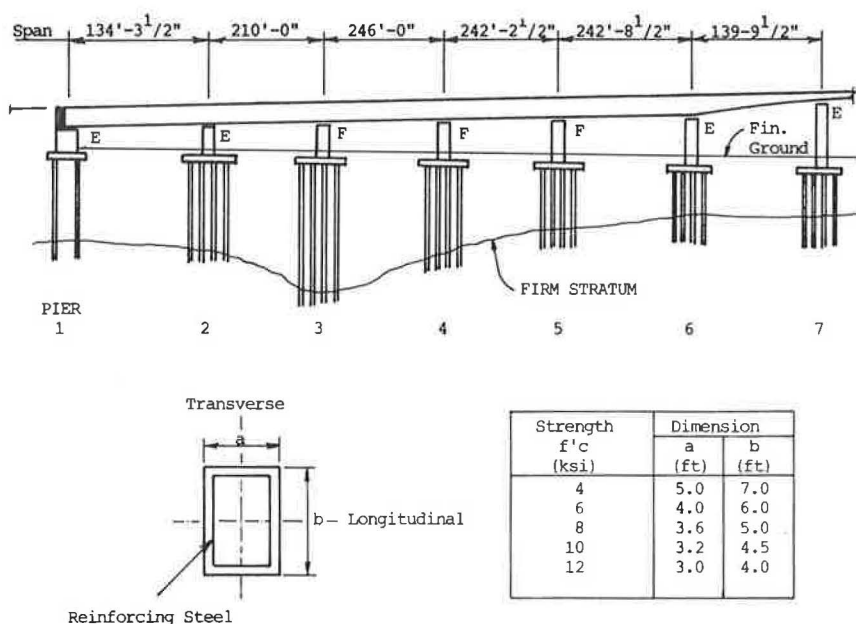


FIGURE 4 Top: Elevation of bridge used in seismic analysis. Bottom: Pier cross-section dimensions and concrete compressive strength used in seismic analysis.

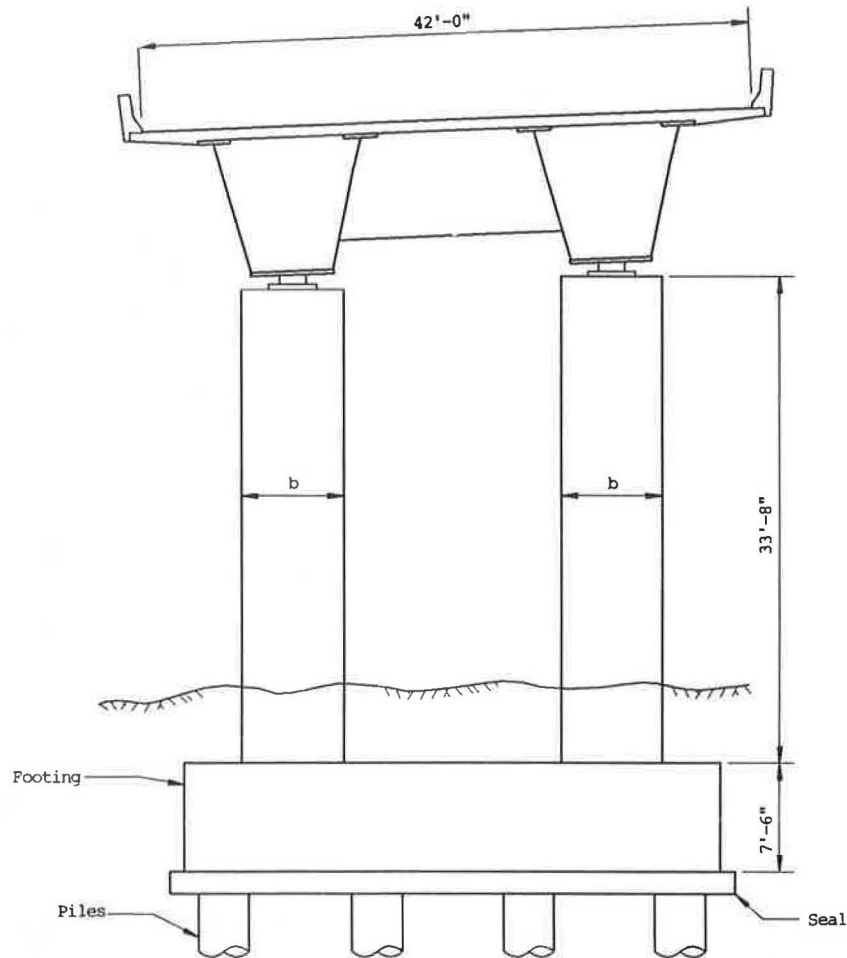


FIGURE 5 Section at Pier 4.

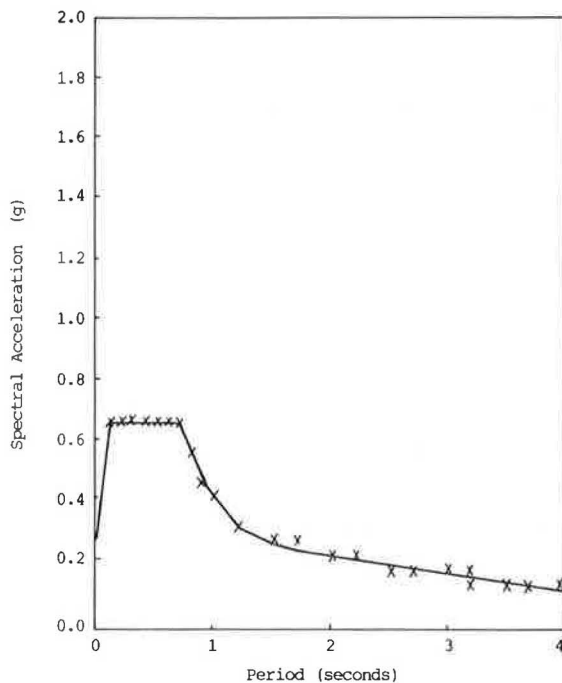


FIGURE 6 Response spectrum.

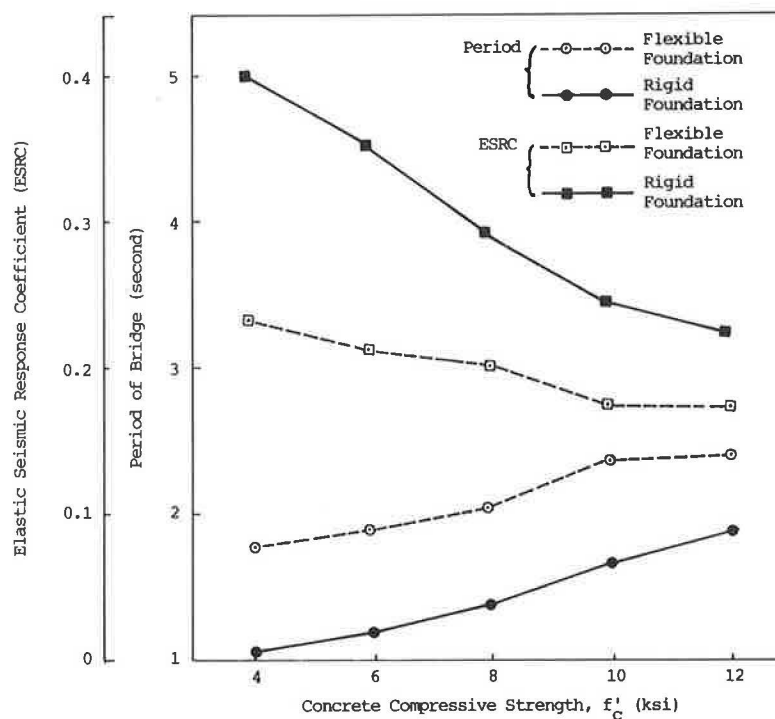
## CONCLUSIONS AND RECOMMENDATIONS

The use of HSC in bridge piers and columns supported by rigid foundation systems can potentially reduce column shears and moments due to seismic loading. Savings of up to 33 percent in the material cost of the piers may be possible when HSC is used in lieu of NSC. Additional economy is achieved because smaller bearings and foundations can be used.

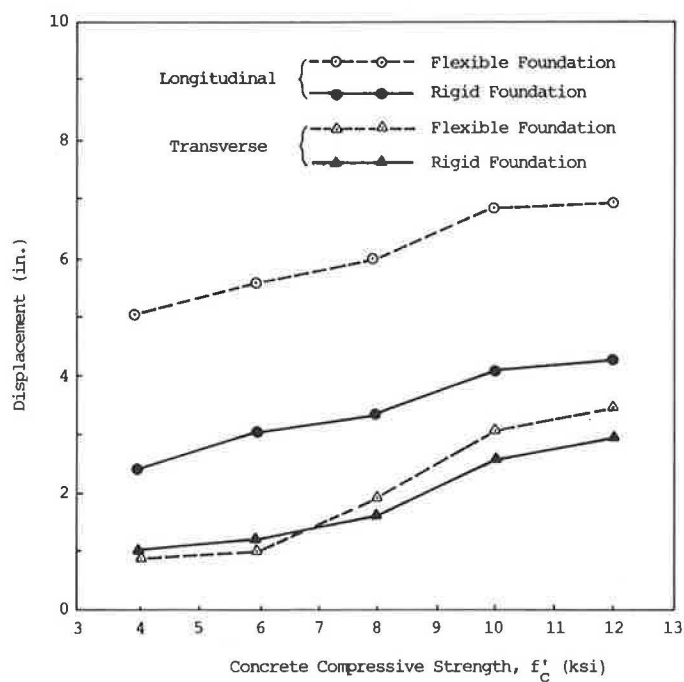
For piers and columns that are supported by flexible foundation systems, HSC will not reduce column shears and moments due to seismic loading as much as rigid foundation systems. However, cost savings will still be possible because less material is required in the columns.

Because foundations represent a significant portion of the cost of a bridge, greater savings can be realized by using HSC in the piers and columns of bridges supported by rigid foundations instead of in those supported by flexible foundations.

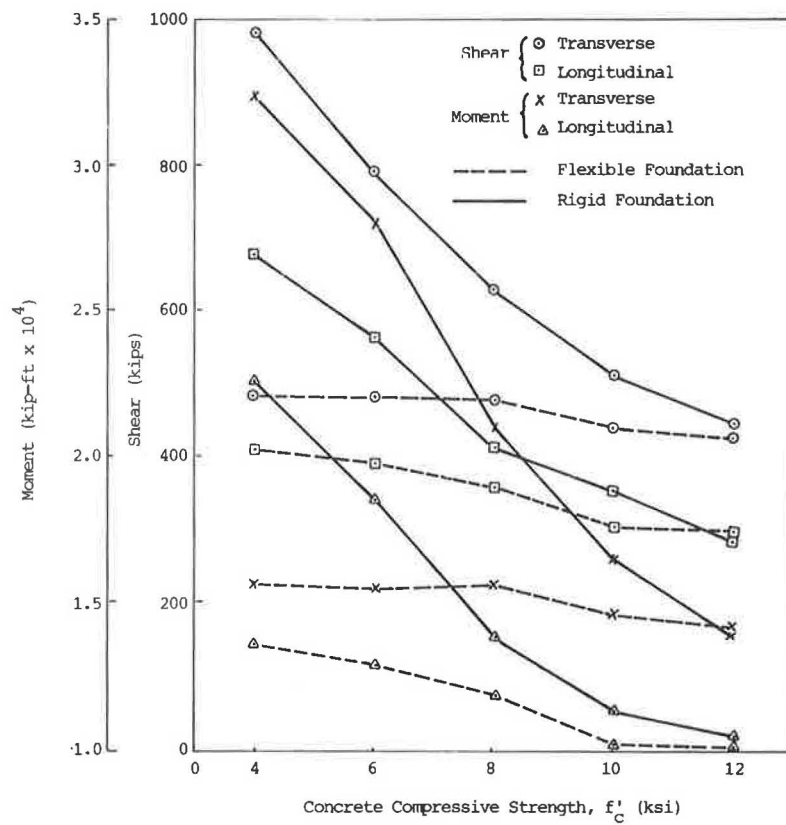
Additional research and small-scale testing should be conducted to further study the behavior of HSC used in slender columns on rigid and flexible foundation systems when subjected to seismic motion and subsequent cost savings.



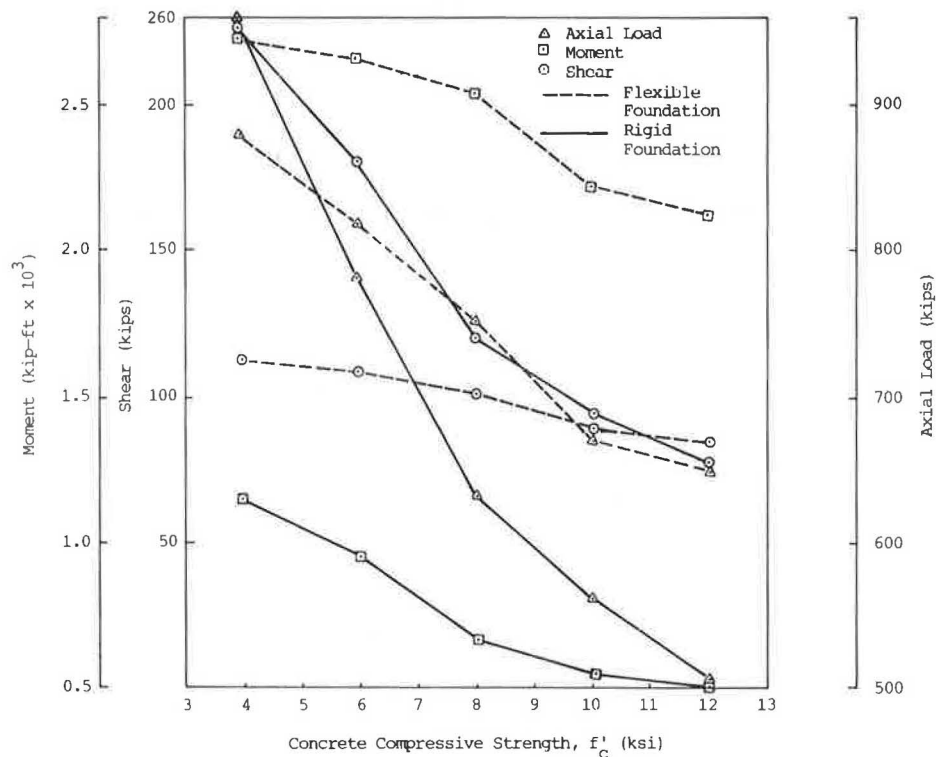
**FIGURE 7** Comparison of vibration characteristics of bridge structure for different pier concrete strengths.



**FIGURE 8** Comparison of CQC horizontal displacements at top of Pier 4 for different concrete strengths.



**FIGURE 9** Comparison of CQC forces at top of Pier 4 for different concrete strengths.



**FIGURE 10** Comparison of CQC forces to top of piles at Pier 4 for different concrete strengths.



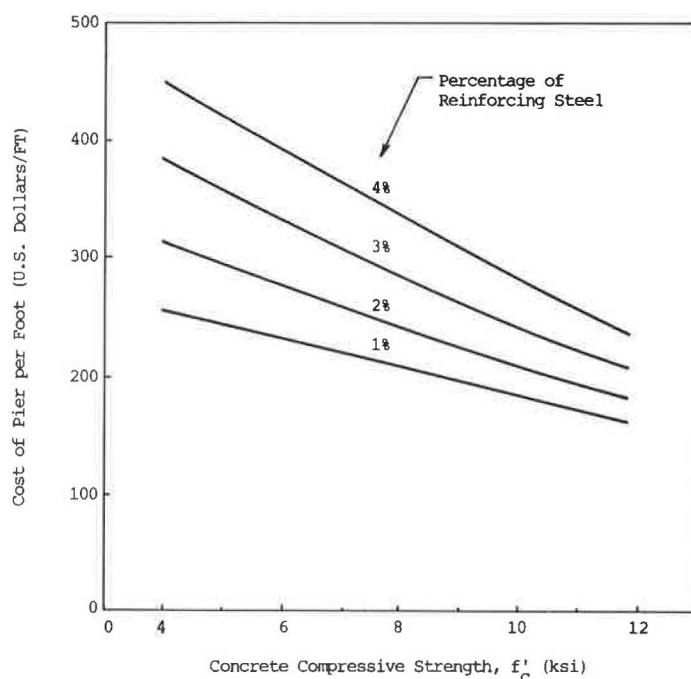


FIGURE 11 Material cost of piers for different concrete strengths and reinforcing steel ratios.

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## REFERENCES

1. Strong New Concrete Muscles into Market. *Engineering News Record*, March 19, 1987, p. 21.
2. *High Strength Concrete in Chicago High-Rise Buildings*. Task Force Report 5. Chicago Committee on High-Rise Buildings, Chicago, Ill., 1977, pp. 1-7.
3. H. G. Russell. *High Strength Concrete*. Special Publication SP-87. American Concrete Institute, Detroit, Mich. 1985, 278 pp.
4. A. J. Burgess, J. Ryill, and J. Bunting. High Strength Concrete for the Willows Bridge. *Journal of the American Concrete Institute*, Vol. 67, No. 8, Aug. 1970, pp. 611-619.
5. Mountain View Road Bridge. *Journal of the Prestressed Concrete Institute*, Vol. 29, No. 2, March-April 1984, pp. 148-151.
6. Tower Road Bridge. *Journal of the Prestressed Concrete Institute*, Vol. 29, No. 2, March-April 1984, pp. 144-147.
7. A. P. Grant. Pasco-Kennewick Bridge—The Longest Cable-Stayed Bridge in North America. *Civil Engineering—ASCE*, Vol. 47, No. 8, Aug. 1977, pp. 62-66.
8. S. B. Quinn. Record Concrete Box Girder Spans Houston Ship Channel. *Civil Engineering—ASCE*, Vol. 53, No. 11, Nov. 1983, pp. 46-50.
9. A. P. Grant. Design and Construction of the East Huntington Bridge. *Journal of the Prestressed Concrete Institute*, Vol. 32, No. 1, Jan.-Feb. 1987, pp. 20-29.
10. Hybrid Girder in Cable Stayed Debut. *Engineering News Record*, Nov. 15, 1984, pp. 32-36.
11. J. E. Carpenter. Applications of High Strength Concrete for Highway Bridges. *Public Roads*, Vol. 44, No. 2, Sept. 1980, pp. 76-83.
12. H. J. Jobse and S. E. Moustafa. Applications of High Strength Concrete for Highway Bridges. *Journal of the Prestressed Concrete Institute*, Vol. 29, No. 3, May-June 1984, pp. 44-73.
13. R. L. Carrasquillo, A. H. Nilson, and F. O. Slate. *The Production of High-Strength Concrete*. Report 78-1. Structural Engineering Department, Cornell University, Ithaca, N.Y., May 1978, 90 pp.
14. L. J. Parrott. *The Selection of Constituents and Proportions for Producing Workable Concrete with a Compressive Cube Strength of 80 to 110 MPa*. Technical Report 416. Cement and Concrete Association, Wexham Springs, Slough, England, May 1969, 12 pp.
15. S. Freedman. *High Strength Concrete*. Publication 15176. Portland Cement Association, Skokie, Ill., 1971, 19 pp.
16. R. L. Chen. Behavior of High-Strength Concrete under Biaxial Compression. Ph.D. dissertation. University of Texas at Austin, Nov. 1984, 299 pp.
17. ACI Committee 363. State-of-the-Art Report on High Strength Concrete. *Journal of the American Concrete Institute*, Vol. 81, No. 4, July-Aug. 1984, pp. 364-411.
18. S. P. Shah, U. Gokoz, and F. Ansari. An Experimental Technique for Obtaining Complete Stress-Strain Curves for High-Strength Concrete. *Cement, Concrete and Aggregates*, Vol. 3, No. 5, May 1981, pp. 21-27.
19. W. F. Perechio and P. Klieger. Some Physical Properties of High Strength Concrete. Research and Development Bulletin RD056.OIT. Portland Cement Association, Skokie, Ill., 1978, 7 pp.
20. ACI Committee 318. *Building Code Requirements for Reinforced Concrete*. ACI 318-83. American Concrete Institute, Detroit, Mich., 1983, pp. 29, 39.
21. S. P. Shah and S. H. Ahmad. Structural Properties of High Strength Concrete and Its Implications for Precast Prestressed Concrete. *Journal of the Prestressed Concrete Institute*, Vol. 30, No. 6, Nov.-Dec. 1985, pp. 92-119.

22. R. W. Poston, M. Diaz, and J. E. Breen. Design Trends for Concrete Bridge Piers. *Journal of the American Concrete Institute*, Vol. 83, No. 1, Jan.-Feb. 1986, pp. 14-20.
23. *Standard Specifications for Highway Bridges*, 13th ed. AASHTO, Washington, D.C., 1983.
24. ACI Committee 318. *Commentary on Building Code Requirements for Reinforced Concrete*. ACI 318-83. American Concrete Institute, Detroit, Mich., 1983, p. 45.
25. R. A. Imbsen et al. *SEISAB-I, Seismic Analysis of Bridges: User's Manual*. Manual Version 1.3.3. Engineering Computer Corporation, Sacramento, Calif., Aug. 1985.

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