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LIGHTWEIGHT CONCRETE FOR A SEGMENTAL BRIDGE

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Decreasing a structure's mass and increasing its flexibility mean better seismic survivability. Lightweight concrete can help, and a design for the proposed 1.2 mi long Benicia-Martinez Bridge across San Pablo Bay, Calif. shows how.

In the wake of the recent Northridge, Calif. earthquake, bridge engineers are evaluating the pluses and minuses of structural designs produced after the 1989 Loma Prieta earthquake in the San Francisco Bay area. One lesson learned is that the greatest seismic damage to long-span bridges comes from two phenomena: ground motions shaking the foundations of elevated deck superstructures and out-of-phase oscillation of the superstructure. Fortunately, both problems can be addressed with one material: lightweight structural concrete.

With this in mind, lightweight concrete was selected for the final design for the new 1.2 mi, $93.1 million Benicia-Martinez Bridge, which will carry the northbound half of Interstate Highway 680 across San Pablo Bay between the cities of Benicia and Martinez, Calif. The new bridge, which is also likely to carry heavy-rail traffic, is designed to remain in service after an earthquake on the nearby Hayward fault measuring 7.3 on the Richter scale, the area's maximum credible earthquake. Construction could begin as soon as 1996.

Because it reduces the mass of the superstructure up to 20% and is more flexible, lightweight structural concrete can help minimize the forces induced by seismic excitation of the superstructure. Designers have ordinarily failed to take advantage of this because lightweight concrete is usually considered too expensive compared to viable alternatives, such as steel or normal-weight concrete.

However, studies for the new bridge show that lightweight concrete can be both economical and advantageous for long spans subject to strong seismic loadings. This is particularly true if the design takes advantage of the material's high strength and performance characteristics.

A lightweight-concrete box-girder bridge was one of four different conceptual plans developed in the preliminary phase of the project. The other three were a steel truss bridge with a concrete deck, a steel box girder bridge and a cable-stayed bridge. Most would require about three years to put together, except the cable-stayed bridge, which would need four. However, the lightweight-concrete option cost approximately $8 million–$42 million less than the others.

Structural lightweight concrete, also known as structural lightweight aggregate concrete, is defined as structural concrete that has a minimum compressive strength of 2,500 psi at 28 days with a corresponding air-dry unit weight not exceeding 115 lb/cu ft, and consists of lightweight aggregates such as expanded clay, shale, slate or furnace slags, or a combination of lightweight and normal-weight aggregates.

Structural lightweight concrete used in bridge applications is characterized by two requirements:

- The material uses natural sand and lightweight aggregate of rotary-kiln–expanded shale with a surface sealed by firing.
- Coarse aggregate is not crushed after firing except a small amount of aggregate, $^{3}/_{4}$ in. diameter and smaller, which may be crushed to produce proper grading.

Compared to normal-weight concrete, lightweight aggregate concrete offers bridge designers a number of advantages, including:

- Better protection to reinforcing steel.
- Comparable fatigue resistance.
- Superior abrasion resistance.
- Twice the thermal strain capacity.
- Lower initial modulus of elasticity.
- Ability to remain elastic to much greater strain.
- Greater resistance to microcracking and shrinkage cracks.

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Further, because strengths of 5,000 psi are easily achieved, the material is considered a high-strength concrete. Higher strengths, like 7,000 psi, require high-quality aggregate, and strengths around 11,000 psi require special admixtures, such as silica fume and superplasticizers. Of course, as always, the smaller the aggregate, the heavier and stronger the concrete.

However, compared to normal-weight concrete, the material does have some disadvantages for bridge design, including:

- Greater expense if high-quality manufactured aggregate is used.
- More cement required to achieve high strengths.
- Stricter control required of the moisture content, mixing and placing.
- More susceptible to local crushing than regular concrete.
- Increased confining reinforcement prestressing required in the design.

ONE CONCEPT, TWO DESIGNS

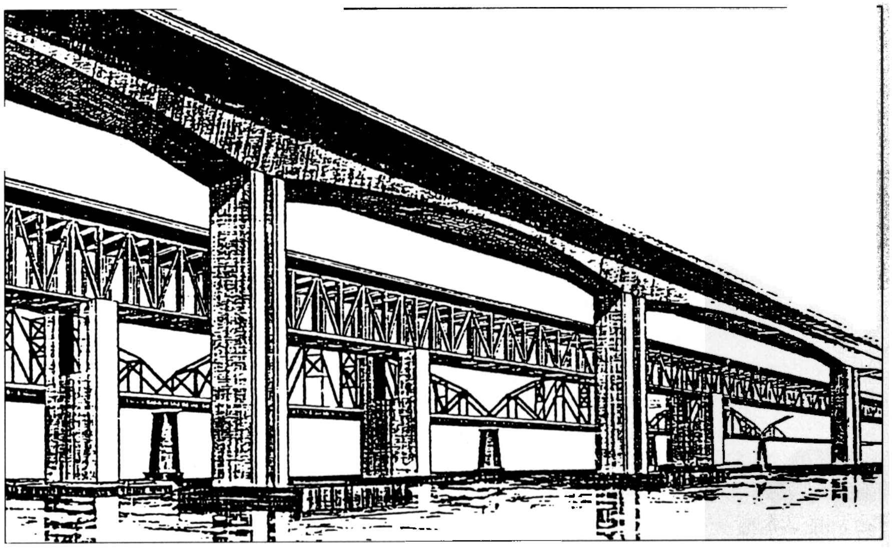
The horizontal and vertical alignment of the new bridge structure will be parallel to, and 120 ft east of, the existing alignment. T.Y. Lin International, San Francisco, performed two preliminary designs of concrete box girder superstructures, one using normal-weight concrete with a hard rock aggregate, the other using lightweight concrete with expanded shale coarse aggregate. The final design is to be performed by a joint venture of T.Y. Lin International and CH2M Hill, Sacramento, Calif.

Both alternative preliminary designs consist of nine main spans, 528 ft each, with 335 ft spans at each end for a total superstructure length of 5,422 ft. Both plans are based on an 83.5 ft wide deck, a single-cell box-girder cross section, a maximum girder depth of 25 ft and cantilever construction with cast-in-place segments. The width is likely to change, however, for a planned mass-transit rail line.

The overall bridge structure, substructure and superstructure is developed as a special moment-resisting frame that maintains its integrity and load-carrying ability after yielding to seismic stresses has been experienced in the piers, just under the superstructure. The existence of quarter-point span hinges to separate the continuous-span modules is a good structural seismic configuration, as it creates the optimum condition for superstructure flexural resistance to column plastic moment under longitudinal response.

Normal-weight concrete is used in both designs for the piers and foundations. The primary differences between the normal-weight– and lightweight-concrete options are the minimum girder depth at midspan, the prestressing requirements and the foundation component sizes.

The proposed superstructure cross section for both designs consists of a trapezoidal single-cell box girder with an 83.5 ft wide deck slab acting as the top flange. The basic dimensioning of the box girder is the same for the lightweight and normal-weight–concrete alternatives, but the maximum top-slab and bottom-slab thicknesses of the normal-weight alternative are slightly greater, to provide the additional strength required by the heavier structure.


AN ARTIST'S RENDERING DEPICTS THE SEGMENTAL CONCRETE DESIGN OF THE PROPOSED BENICIA-MARTINEZ BRIDGE ACROSS THE CARQUINEZ STRAIT, SAN PABLO BAY, CALIF. THE CURRENT BRIDGE, WHICH WILL CARRY SOUTHBOUND TRAFFIC, STANDS IN THE MIDDLE GROUND, AND A RAIL BRIDGE IS IN THE BACK. CONSTRUCTION COULD BEGIN IN 1996. DRAWING COURTESY T.Y. LIN INTERNATIONAL

The girder cross section for both designs varies from maximum depth at the face of the pier to minimum depth at midspan. The higher modulus of elasticity of normal-weight concrete permits a shallower depth at midspan while meeting the deflection criteria. However, lightweight concrete can produce more than twice the amount of deflection as regular concrete because it is more flexible. Accordingly, lightweight concrete requires more prestressing. The box girder is prestressed longitudinally with cantilever tendons in the top slab and continuity tendons in the webs, transversely in the top slab, and vertically in the webs.

The three-dimensional prestressing of the superstructure provides a relatively crack-free structure with good serviceability. The prestressing also creates a homogeneous material in keeping with the assumptions of the service load, which include highway traffic and a heavy-rail line on the edge of the cantilever.

All of the mild steel reinforcement used in the plans conforms to standard Caltrans design requirements. The girder cross-section reinforcement includes a grid of bars in each direction on each face of each structural element. Vertical post-tensioning in the webs consists of threaded bars at variable spacing. This allows the anchorages to be closer to the top and bottom of the girder, enhancing the prestress's control of principal stresses at critical locations.

Expansion joints are found only at the extreme ends of the structure and two intermediate points. The tall piers and deep foundations provide enough flexibility to accommodate the time-dependent strains and temperature strains of the concrete, accumulated over the 2,112 ft long maximum girder length between joints. In addition, building the bridge with long girders and few expansion joints reduces the damages caused by spans butting into each other during a seismic event.

All bridge piers are fixed to the girder and footings with monolithic, moment-resisting connections to provide maximum pier fixity, for continued serviceability under the required seismic excitation. The maximum total relative movement capacity required for the joints to accommodate creep, shrinkage and temperature movements is approximately 12 in. at the ends of the structure, and about 18 in. for the intermediate joints.

The configuration of the piers and the clear column behavior of the pier shafts allows a displacement ductility factor of 4, meaning that the structure can move up to four times beyond its displacement after yielding. The pier-superstructure connection, despite the substantial depth of the superstructure, is a problem area, particularly in light of our decision to carry the pier section up, unchanged, as the diaphragm.

Shear stresses in this section, where the moment must drop from a maximum at the soffit to zero at the deck slab, are very high and considerable transverse reinforcement is required. The continuity of moment and force transfer into the top slab will need to be carefully designed. The structure will have to resist the column plastic moment capacity, and moment redistribution of dead-load moments should be permitted for this. The superstructure will also be designed to resist the plastic pier moments elastically so that traffic can continue on the deck after a major seismic event.

The maximum force from out-of-phase support motion will be taken by seismic dampers in the internal movement joints. Seismic dampers at the expansion joints will allow slowly occurring displacements, but for seismic shock, no relative displacement can occur across the joint.

For both lightweight- and normal-weight–concrete designs, the foundations are 10 ft diameter drilled caissons of composite steel-and-concrete construction, supporting cast-in-place footings. The bottoms of the caissons are socketed 10 ft into the rock for the lightweight-concrete design and 12 ft for the normal-weight alternative. For the lightweight design, the caissons are arranged three across on the width of the footing, spaced 20 ft apart to provide maximum overturning resistance in the required direction, and two over on the length of the footing, 25 ft apart. The normal-weight–concrete design used a similar arrangement with stronger footings, due to the greater mass of the structure and induced seismic forces.

Each pier consists of four circularly tied reinforced concrete columns, 6.5 ft in diameter, located on a 21.5 ft by 9.5 ft rectangular plan, connected by reinforced concrete walls to form a hybrid cellular element. The design provides most of the advantages of the traditional box pier, along with the significantly improved ductility capacity and seismic resistance of the circularly tied columns.

All piers are fixed to the girder and the footings with monolithic, moment-resisting connections. However, under transverse seismic excitation, the piers behave as cantilevers, developing significant moments only at the bottom. For resisting longitudinal seismic excitation, the piers behave as members in a rigid frame with moments developed at both top and bottom.

The pier footing connection requires a three-dimensional strut and tie distribution to account for joint shear and transverse reinforcement requirements. It is important to fully develop the plastic capacity of the composite caisson steel case into the foundation. This is accomplished by extending the steel bars of the casing into the concrete footings.

SEISMIC ANALYSIS

The Carquinez Strait, site of the Benicia-Martinez Bridge at San Pablo Bay, has rock at comparatively shallow depths. As such, site amplification of ground-motion effects should be minor, and nonsynchronous excitation at different piers should not be significant. However, out-of-phase displacements will be recommended for final design of the bridge.

The soil profile of the site indicates that at the north and south ends of the bridge, bedrock is at or near the ground surface. However, in most of the Carquinez Strait, bedrock lies beneath soil cover of up to 95 ft. In the north and south parts of the strait, the cover usually consists of the soft, silty clays and clayey silts known locally as San Francisco Bay mud. Toward the middle of the strait, the soils are mostly loose, liquefiable sands. A layer of denser sands with gravels separates the superficial soils and the bedrock.

To assess the modifying influence of the soil deposits on ground motions, we made a nonlinear site response analysis of four soil columns representing the range of soil conditions along the bridge. Smooth response spectra of soil motions were developed from the analysis, indicating that the spectra content of ground motions at the bridge site may be expected to vary significantly at different locations. Accounting for the different inputs entering the structure and the induced seismic forces complicated the design.

From the site response analysis, acceleration time histories of soil motions were obtained corresponding to the input rock acceleration time histories for each maximum credible earthquake. The time histories of rock motions were modified to develop sets of spatially time-lagged incoherent rock motions along the length of the bridge. Five sets of rock motions were generated; they can be used as multiple support excitations to the bridge foundations in varying types of rock.

Additional special seismic design criteria will be implemented during the final design phase, including:

- Seismic loads for staged construction.
- Stand-alone analysis for individual frames.
- Displacement ductility assessment of the frames.
- Joint shear design.
- Use of A706 reinforcing steel to control the upper limit of plastic moments and provide for a steel more ductile than A615 reinforcing steel.

Using lightweight structural concrete on the design for the bridge affected all of these factors by decreasing the mass of the superstructure. Special consideration was also given to the effect of reversal cyclic seismic loads at high ductility demands with regard to the development length of the large-diameter bars proposed for the main column reinforcement of the pier shafts. The 25 ft depth of the superstructure seems more than sufficient to develop the column bars; however, this will need to be studied and probably supported by experimental research.

Our intent is to extend the pier walls as a solid diaphragm that is wide enough to allow the pier column reinforcement to project into the superstructure where it is confined by hoops. We found this was the best way to achieve bar anchorage, ductile behavior and shear transfer in a region that is critical to the structure's longitudinal seismic response.

Lightweight concrete can be used to optimize seismic design in regions of high seismicity. By reducing the mass and stiffness of the superstructure, lightweight concrete reduces the seismic effect. By combining ductile strength and structure tuning, the new Benicia-Martinez Bridge can comply with the desired seismic performance for San Francisco Bay–area bridges, which calls for the structures to survive the maximum credible earthquake without structural damage impairing their function.

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