BART aerial structures, creep and shrinkage control: part I: design

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BART Aerial Structures, Creep and Shrinkage Control
Part I: Design

La structure aérienne du BART — Contrôle du fluage et du retrait
Partie I: Projet

BART Hochbahnstrecken — Kriech- und Schwindkontrolle
Teil I: Vorkehrungen

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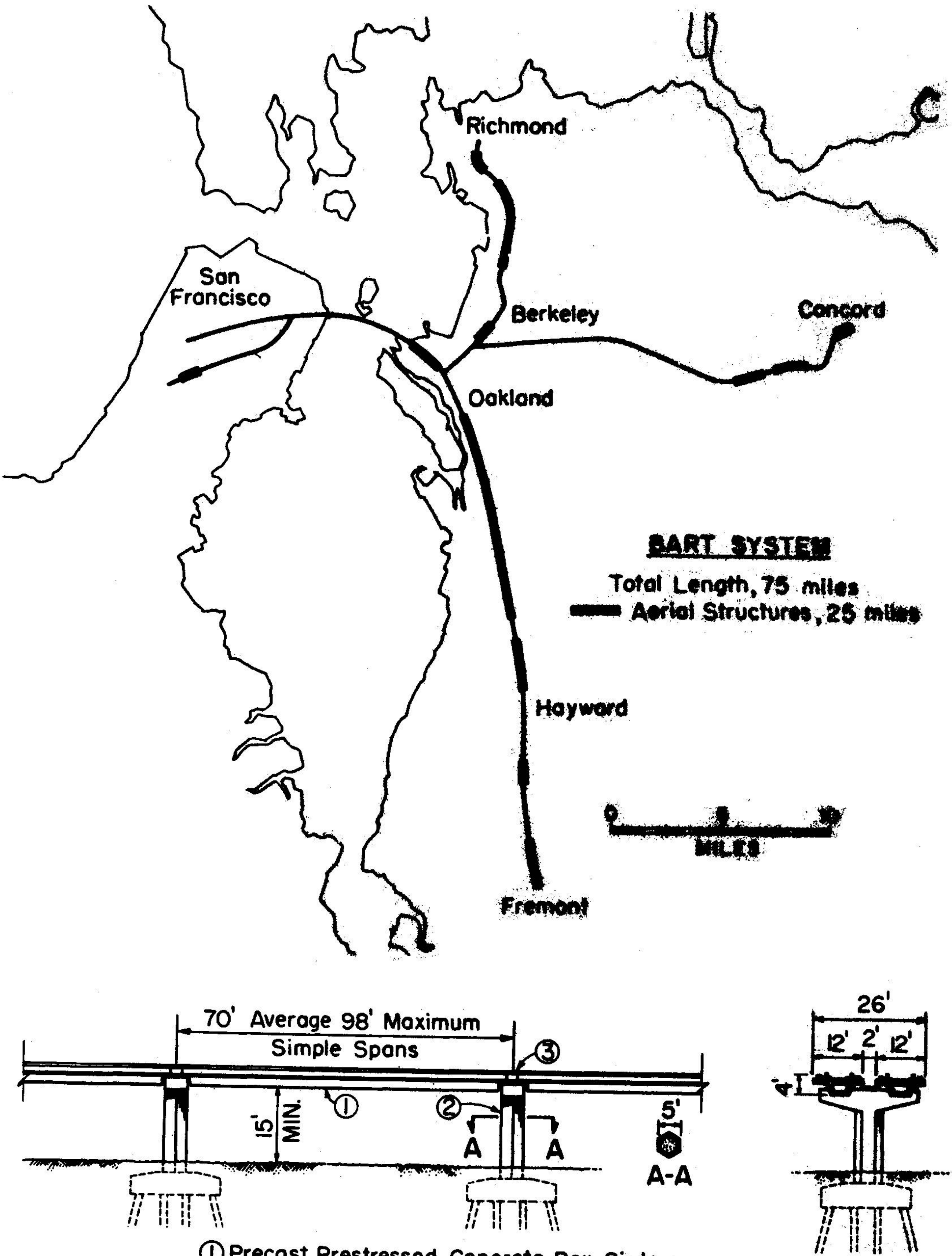
The San Francisco Bay Area Rapid Transit System, known as BART, comprises 75 miles of double-track construction. As shown on Fig. 1, one-third of this length is comprised of "Aerial Structures", including a single structure 10 miles long between Oakland and Hayward.

The typical aerial structure (Fig. 2) consists of twin precast, post-tensioned concrete box girders, each carrying a single track. The girders are supported on cast-in-place reinforced concrete piers. Simple span construction was chosen to simplify manufacture and erection of the girders, and an average span length of 70 feet was used to permit truck transportation from the casting yard to the site. Spans up to 98 feet long were used for street crossings, and required special permits and equipment to handle their 140-ton weight. The girders are connected by cast-in-place concrete closure strips, which also encase special earthquake anchorages. A uniform girder depth of 4'-0" was used for all spans to produce a "ribbon structure" architectural effect.

In order to eliminate the weight and cost of ballasted deck construction, as well as to secure a thin structure for architectural design, it was decided to fasten the running rails directly to the concrete deck. This made control of deformations of great importance, in order to provide a smooth-riding profile and to minimize future maintenance adjustments.

The history of concrete structures in the San Francisco area indicated that both shrinkage and creep would cause unacceptable deformations unless special precautions were taken. The predominant sources of concrete aggregates in the area are sandstones which form high-strength concrete, but with relatively large deformability.

Theoretical considerations indicated that limiting the free water content of the concrete mix would significantly reduce shrinkage, and using an



① Precast, Prestressed Concrete Box Girders
② Cast-in-place Reinforced Concrete Piers
③ Cast-in-place Concrete Closure Strip

BART AERIAL STRUCTURES
TYPICAL DETAILS

Fig. 2

aggregate with a high modulus of elasticity would reduce both shrinkage and creep. Since no accepted standards for these matters exist in the United States, it was necessary to devise special limitations and testing methods for the BART project. The aims were to screen out unacceptable materials without incurring excessive costs, and to set up performance tests that could be consistently repeated to provide a clear measure of acceptability.

The BART Standard Specifications for concrete include a limitation on free water content in pounds per cubic yard, with the allowable amount increasing with greater slump and smaller size aggregate. For the prestressed concrete box girders, both air-extraining and water-reducing admixtures were required. Both these ingredients promote workability of the mix, and this was recognized by further reducing the allowable free water content when admixtures were used.

The use of a large, well-equipped precasting yard was economically mandated by the size of the project – some 3,000 individual box girders comprising over 200,000 cubic yards of concrete. This implied careful layout of the prestressing tendons and the mild steel reinforcement in order to facilitate concrete placement, and efficient use of internal vibrators to ensure complete filling of the forms. In addition, the box girder webs were deliberately made a uniform 10 inches thick, and the bottom slab a uniform 8 inches thick, which exceeded the stress requirements, specifically to promote placement of the concrete.

By these means, the use of a relatively dry mix was secured despite the confined spaces inherent in a highly reinforced box girder section, with a great reduction in the free water content and resultant shrinkage. The actual mix used is shown in Table 1.

Table 1

BART SPECIAL CONCRETE

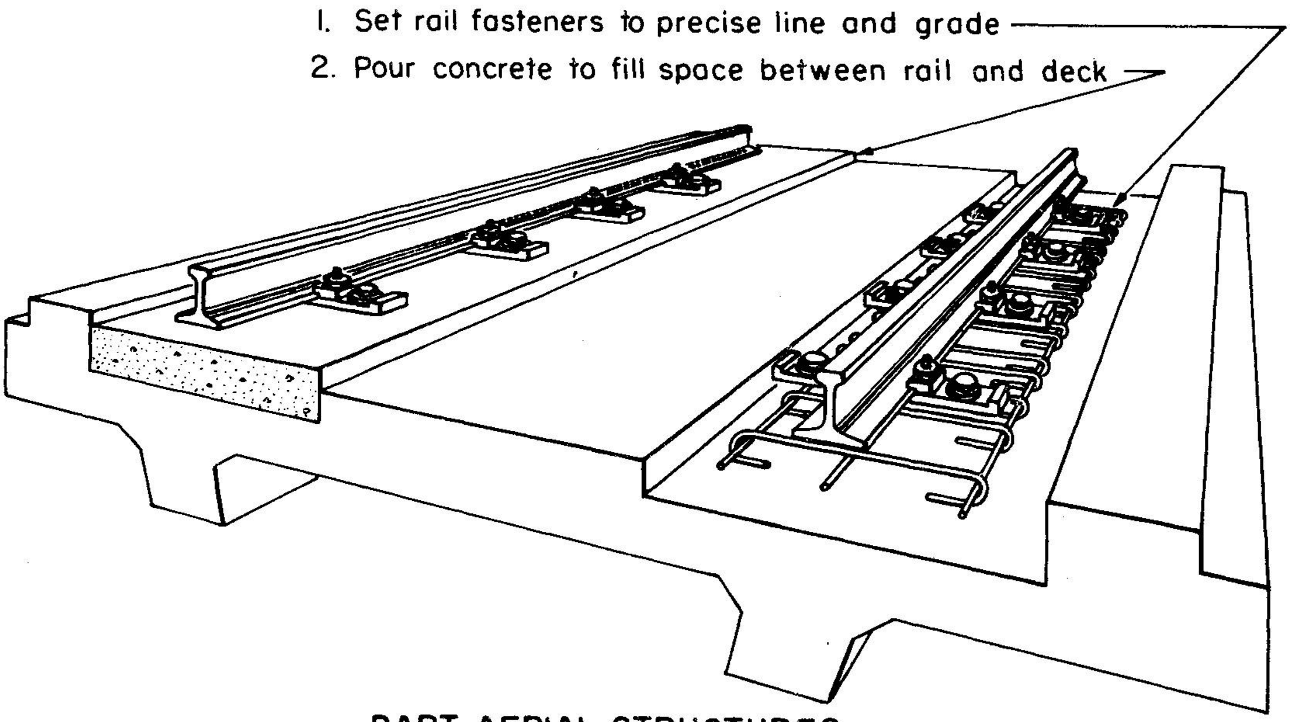
	Mix Proportions (Quantities)	
Material	1 Cubic Yard	1 Cubic Meter
Cement	699 pounds	415 kilograms
Water	298 pounds	177 kilograms
Fine Aggregate (1/4 inch max.)	1,163 pounds	691 kilograms
Coarse Aggregate (3/4 inch max.)	1,775 pounds	1,054 kilograms
Air-entraining admixture	9.0 fluid ounces	264 milliliters
Water-reducing admixture	1.49 pounds	850 grams

Beyond the general specification limits on proportions and on cleanness and soundness of materials, the construction contractors were permitted to select their own material sources and propose their own concrete mix. The proposed mix was tested against a control mix consisting of selected materials, with respect to compressive strength, modulus of elasticity, shrinkage, and creep. Specimens of the proposed mix were required to be within certain percentages of the performance of the control specimens. (Details of the tests are given below in Part II.)

Setting the limits on relative performance requirements was a delicate matter. If the limits were set too high, all local material sources would be excluded and the premium costs for importing aggregate from distant sources would be excessive. If the limits were too low, many sources could be qualified, and the lowest cost (and probably poorest quality) material would be used, with resulting increased deformation and its associated problems.

By judicious accommodation between desirable and practical limits, two relatively economical local aggregate sources (one granite, and one basalt) were qualified, and several proposed sandstone aggregate sources were rejected. An interesting development was a proposal for an alternative design using light-weight concrete made with expanded shale aggregate. This design showed economic advantages and adequate strength, but was eventually rejected because the proposed mix was greatly deficient in creep resistance.

In addition to requiring special control of materials, the designers limited creep deformations by providing substantial amounts of nonprestressed mild steel reinforcement in the top slab, which resist any tendency toward upward bowing. The girder forms were also cambered downward by an amount calculated so that after elastic deformation under its own weight and that of track construction, plus an allowance for creep deformation, the girder would be approximately level. The calculation of creep allowance was based on the assumption that total creep deformation would be about three times the elastic deformation. Provision was made to adjust this allowance when experience had been obtained with the first girders cast using the approved concrete mix.



BART AERIAL STRUCTURES
"SECOND POUR" TRACK BED CONSTRUCTION

Fig. 3

Finally, it was recognized that despite controlled pre-casting, the practical tolerance in girder manufacture would exceed the allowable tolerance in rail profile. Accordingly, the running rails were independently set to final profile slightly above the concrete deck, as shown on Fig. 3, and the variable intervening space was filled with a "second pour" of concrete to take up any variations.

The cost of the BART shrinkage and creep control program, including premium charges for special aggregates and all costs associated with developing and carrying out the special testing program, was somewhat less than 2% of the cost of the girders using the special concrete, or about 1% of the total cost of the aerial structures.

SUMMARY

For 25 miles of the BART system, twin precast, prestressed box girders are made of concrete conforming to special creep and shrinkage tests. Reduction of water content and use of aggregates with high elastic modulus were primary control methods. Running rails were independently set to accurate profile, and then attached to the girders through a "second pour" of concrete. The cost of creep and shrinkage control was 1% of the total cost of the structures using special concrete.

RESUME

Sur quarante kilomètres, le système BART se compose de structures aériennes: poutres en caisson jumelées, préfabriquées en béton précontraint soumis à des essais de fluage et de retrait. Les premières méthodes de contrôle ont été la diminution de la teneur en eau, et l'utilisation des agrégats à module d'élasticité élevé. On a posé indépendamment les rails sur le profil exact; ensuite, ils ont été fixés aux poutres au moyen d'une deuxième coulée de béton. Le coût du contrôle du fluage et du retrait s'est élevé à 1% du coût total des structures utilisant le béton spécial.

ZUSAMMENFASSUNG

Für 40 Kilometer der BART Anlagen wurden doppelt vorgegossene, vorgespannte Kastenträger aus Beton hergestellt, die auf besondere Prüfungen für Kriechen und Schwinden abgestimmt waren. Die wesentlichsten Kontroll-Methoden waren Reduzierung des Wassergehaltes und Verwendung von Aggregaten mit hohem elastischem Modul. Die Schienen wurden unabhängig genau nach Profil gelegt und dann durch einen zweiten Betonguss mit den Trägern verankert. Die Kosten der Kontrolle über Kriechen und Schwinden bei Verwendung dieses Spezial-Betons beliefen sich auf ein Prozent der Gesamtkosten für das Bauwerk.

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