Urban interchanges on elevated structures

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Urban Interchanges on Elevated Structures

Echangeurs routiers en milieu urbain

Neuartige Kreuzungen innerstädtischer Hochstrassen

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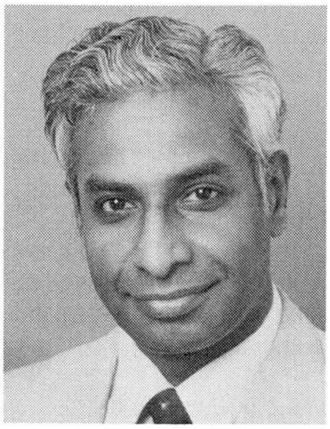

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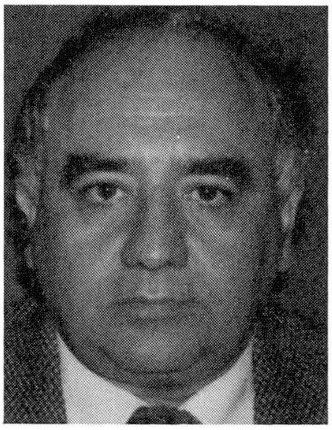

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SUMMARY

This paper illustrates the design and construction in Phoenix, Arizona, of a novel type of urban interchange on elevated structures. This approach can often be implemented at a lower cost and on smaller sites than traditional multilevel interchanges.

RÉSUMÉ

Cet article illustre la conception et la construction à Phénix, Arizona, d'un nouveau type d'échangeur routier en milieu urbain, situé au-dessus de structures élévées préexistantes. Cette approche peut souvent s'appliquer de façon plus économique et sur des surfaces plus restreintes que les solutions traditionnelles d'échangeurs à plusieurs niveaux.

ZUSAMMENFASSUNG

Dieser Vortrag behandelt den Entwurf und die Konstruktion neuartiger Kreuzungen innerstädtischer Hochstrassen. Diese Lösung kann oft mit geringeren Kosten und mit geringerem Landverbrauch als bei den üblichen mehrstöckigen Kreuzungen erreicht werden.

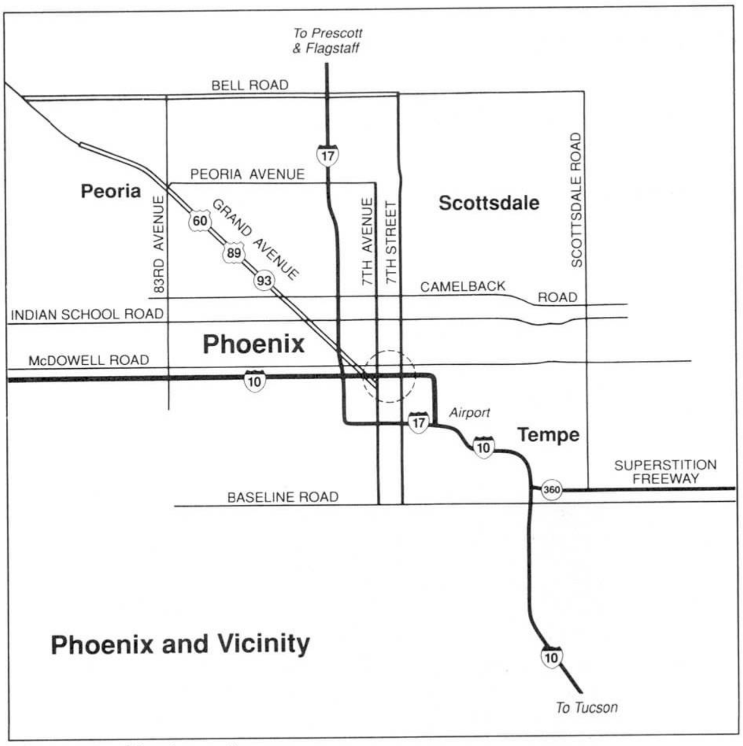

Figure 1. Site Location

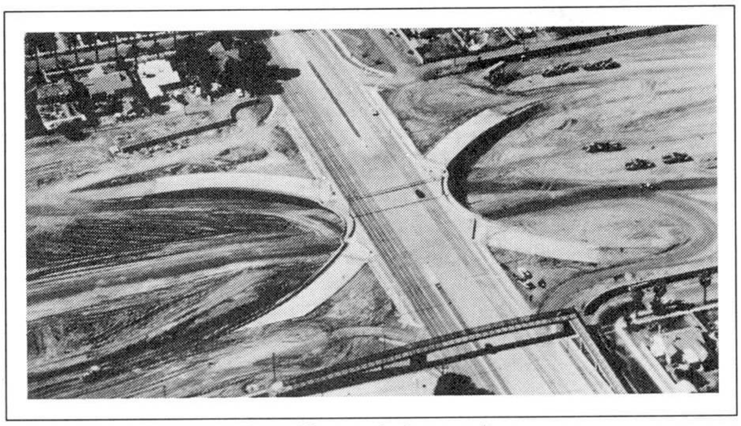

Figure 2. Bird's eye view (Seventh Avenue)

INTRODUCTION

In Phoenix, Arizona, two prestressed concrete interchanges of complex geometry have proved an appropriate structural solution for compressing highway structures into the cramped urban landscape. The elevated structures, linking the north-south arterials Seventh Street and Seventh Avenue to the new depressed highway I-10, are neither full multilevel elevated interchanges with on/off ramps on independent structures, nor completely ground level interchanges. They are in essence compact urban interchanges that have been partly elevated, with certain ramps compressed right into the main structure to reduce the ordinary four levels of an elevated interchange to two.

This paper examines the choices of analytical approach and of construction methods that made rapid (one-year) design and construction possible despite the complexity: finite element analysis of the structures, and postprocessing of results into formats directly useful to engineers.

At these sites, where I-10 was to be connected through the heart of metropolitan Phoenix (Fig. 1), right-of-way could be costly, and lengthy construction disruptive. The Arizona Department of Transportation therefore favored an urban interchange over a multilevel interchange. It was found, however, that the scarcity of land would force the ends of certain ramps to fall *on structure*, with motorists executing their turns on the structure itself (Fig. 2).

MAKING THE INTERCHANGE CONCEPT WORK

Fusing into the main structure four of the usual eight on/off ramps achieved compactness, but at the cost of generating ramp-structure interactions that challenged analysis. The ramps rest on curving projections of the mainspans, making a flared shape, wider at the abutments to accommodate the ramps (Fig. 2). Each structure would look from above like an hourglass, wide at the abutments and narrow at the central pier—the waist of the hourglass. The concept was simple, but the design and construction of such unusually shaped structures would not be.

What makes the urban interchange on structure so complex for design and analysis is the interactive load transfer among all these parts that rest on one another. The loads of the four curved and skewed prestressed concrete ramps, for example, would have to be transferred onto the prestressed concrete mainspan late in construction—when a small error might easily make a ramp rotate from its own weight instead of uniformly sitting on the bearings. The interactive stresses of the entire odd-shaped concrete structure would have to be understood at each stage of construction and load transfer if the structures were to survive the hard-to-predict stresses of their own construction. The final simplicity would be achieved at the price of a major analytical effort, individualized at each of the two sites.

UNUSUAL STRUCTURES/UNUSUAL ANALYSES

Unusual structures require unusual analysis techniques. State-of-the-art finite element technique with up to 2,000 elements of various shapes was employed to model the structures, and greatly assisted in understanding the interactive stresses and the true behavior of the ramp structures with their extreme skews.

The main part of the structures at both locations is a two-span continuous post-tensioned concrete structure supported on concrete abutments at both ends and supported through the midsection by concrete columns erected in the median of I-10. The curved ramp structures are of concrete box section, each of a different length and different skew to the main structure (Fig. 3). The portion that is on structure rests at one end on a protrusion on the side of the main structure (Fig. 4). The triangular gaps resulting from the peeling off of the ramps from the main structure in front of the abutments also had to be covered—to support landscaping in these visually important spots. Both structures included separate pedestrian walkways, with ramps for disabled persons.

In part, the design was driven by aesthetic needs, and planned to be visually pleasing for users and neighbors alike. Seen from above it flares out like a great concrete hourglass, wide at the ends. Seen in profile by I-10 motorists, its notched curves arc powerfully against the sky. Driving up the ramps, motorists discover landscaping high above ground level, thanks to hidden structural elements that take the weight of earth and plants.

To meet our aesthetic goals, we streamlined the fascia to present a smooth, aesthetically pleasing appearance to the travelling public on I-10, with canopied fences that offered smooth transitions at their ends and at the intersections of the ramps and the main structures. Even landscaping requirements affected structural design: the final landscaping decision to plant shrubs into the triangular areas formed between the ramp structures, main structure, and abutments was not a decision calculated to make life easy for the structural designer. We would need to support a layer of soil at least a foot deep and accommodate a maintenance

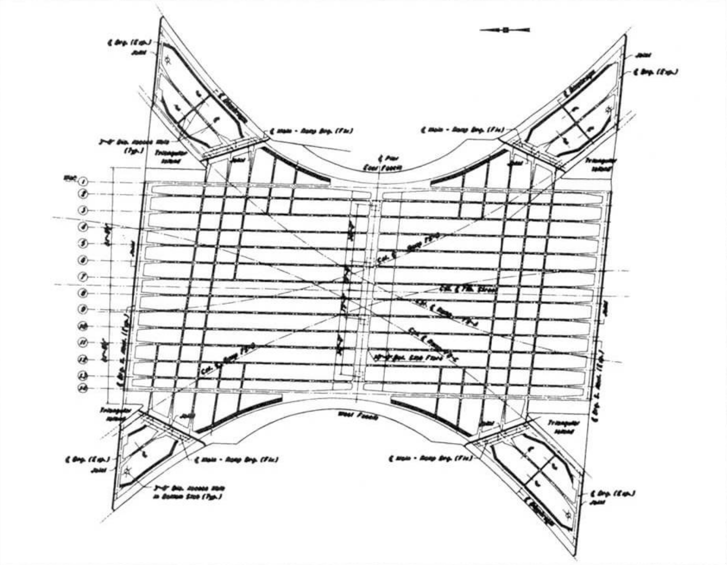

Figure 3. Typical framing (Seventh Street)

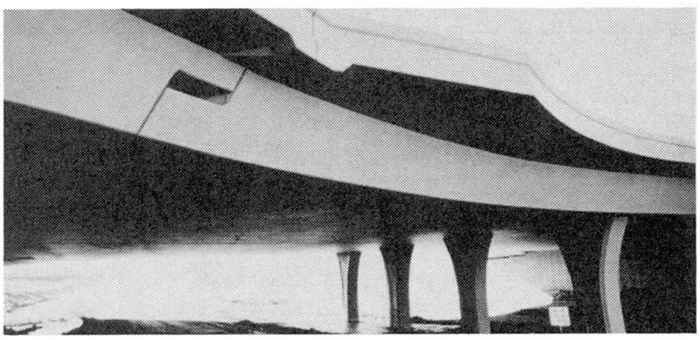

Figure 4. Ramp (left) sitting on the main structure (right)

THE STRUCTURES AT A GLANCE		
	Seventh Street Structure	**Seventh Avenue Structure**
Main Structure		
-Span lengths ft	121' & 121'	141' & 129'
-Width ft	260' & 280' at abutment & 125' at piers	360' & 400' at abutments & 130' at piers
-Type	Cast-in-place post-tensioned concrete with curved fascia	Cast-in-place post-tensioned concrete with curved fascia
Ramp Structures		
-Span lengths ft	Vary, 60'-85'	Vary 110'-170'
-Width ft	32'	32'
-Type	Cast-in-place curved reinforced concrete	Cast-in-place curved post-tensioned concrete
Foundation	Spread footings on S-G-C (sand, gravel, and cobbles) material	Spread footings on S-G-C material
Triangular areas	Cantilever slabs with 29' max. overhang	Cantilever slabs with 27' max. overhang coupled with pretensioned concrete beams

vehicle live load right in the gap between structures. Bridging this gap to support that load threatened to create major structural problems by imposing heavy loads on the ramps. By cantilevering the abutment wall up to about 25 feet, however, much of the triangular area load was relieved off the ramps and transferred directly to the abutments. At Seventh Avenue, the cantilevering alone was insufficient to cover the entire triangle, and the gap beyond the cantilevers had to be covered using precast concrete elements. Before placing the fill for landscaping, we waterproofed the top of the cantilever and precast elements.

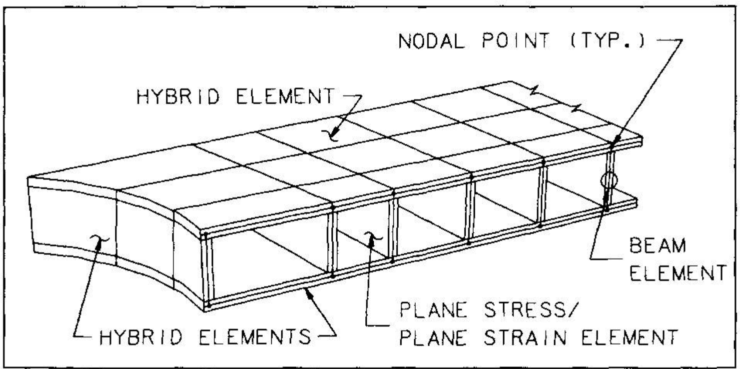

Figure 5. Finite elements of main structure

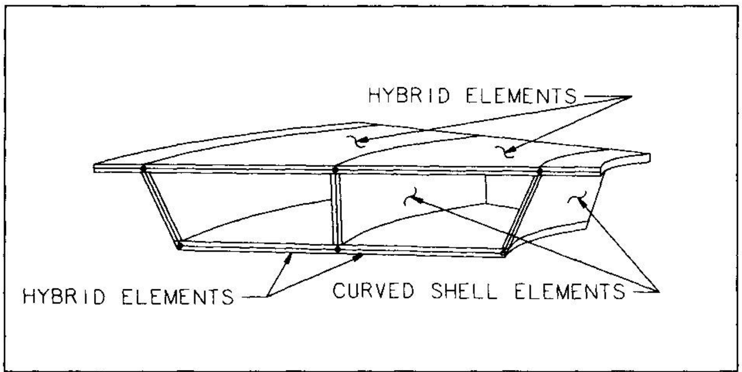

Figure 6. Finite elements of ramps

FINITE ELEMENT APPROACH

The Seventh Street and Seventh Avenue structures were similar in concept but would have to be analyzed independently because of their unique shapes, geometric nonsimilarities, ramp-structure variations, span length variations, etc. What mathematical modeling method we chose for all this analysis might well determine what questions we could ask effectively.

Surveying the available methods, we closed in on two finalists. The space grid method simplifies the structure into a Tinkertoy-like skeleton of lines and nodes; the finite element method has similar nodes, but connects them by surfaces instead of lines. Thus a real three-dimensional beam would be represented as either a single line (space grid) or as a set of surfaces, as if boxing-in the beam (finite element).

Before embarking on the most appropriate method, we critically compared the two candidate methods as to their ability to reflect the true behavior of such difficult features as transfer of torsional loads, transverse stress distribution, temperature gradient, post-tensioning forces, skewed ends, and curved surface areas. The evaluation showed the finite element procedure to be superior.

Before applying the finite element concept to the entire structure, we evaluated discrete structural models for the various element shapes and applied loads. Once a 'level of comfort' was achieved, the full-structure model was pursued.

The main structure required about 1,700 finite elements for the Seventh Avenue structure and 1,400 finite elements for the Seventh Street structure. Each of the ramp structures was individually analyzed and required about 160 elements. The types of elements were quite varied, including trapezoidal and triangular hybrid for slabs, diaphragms, and curved fascia webs of the main structure; curved shell for webs of ramps; and plane-stress/plane-strain for the longitudinal webs of the main structure. Beam elements were introduced between adjacent plane-stress/plane-strain elements (Figs. 5, 6).

Transient loads, such as live loads, were applied on the top slab as surface pressures. After careful evaluation of alternative modeling approaches, post-tensioning loads were applied as equivalent loads using the parabolic curve approach along the webs and concentrated loads at the ends of the elements. The vertical, lateral, and axial components of the post-tensioning forces were input.

In order to fathom the finite element run output in easy-to-understand terms, we developed a postprocessing program that reduced the stresses at any particular nodal point to shear and moment forces. This proved a tremendous help in verifying the behavior of the structure.

DESIGN OF PERIPHERALS

The principle that unusual structures exhibit unusual behaviors affects not only the design of the structure itself, but also the design of such important peripherals as bearings and deck expansion joints. Each of the peripherals had to be carefully evaluated, and systems selected and designed to function properly within these unusual structures.

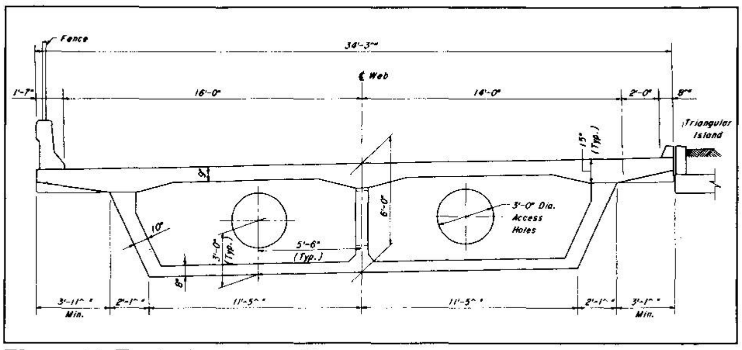

Figure 7. Typical ramp section

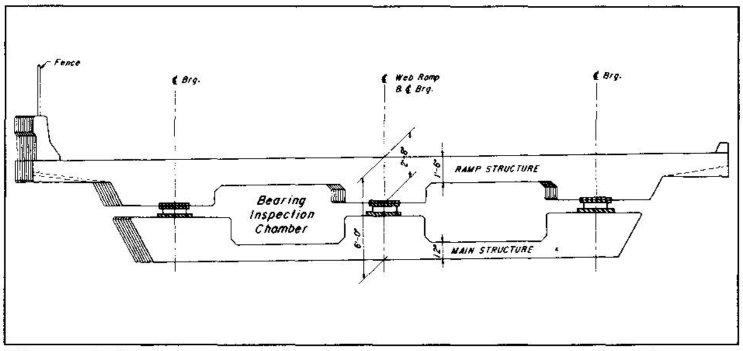

Figure 8. Cross-section through bearing inspection chamber

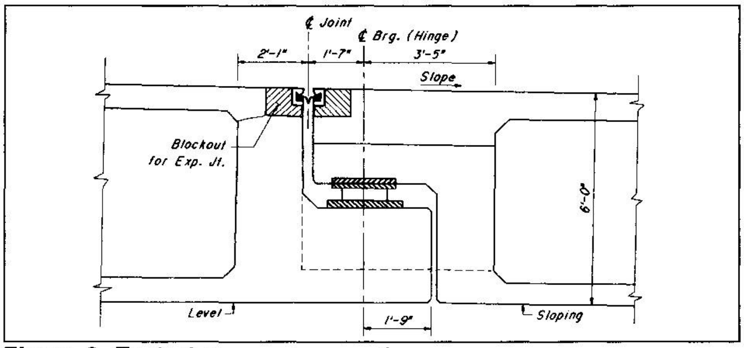

Figure 9. Typical ramp cross-section

Pot bearings were selected, as they provided multidirectional rotational capability. The bearings were designed incorporating the direction and amount of thermal movements, axial shortening during post-tensioning, shrinkage, and creep given by the finite element analysis, together with AASHTO seismic requirements. To spare the bearings from having to resist high transverse earthquake forces, side shear walls at the two abutments provided the resistance.

A special issue in bearing selection was the presence of uplift forces at the center bearing because the ramp structures were so long and transversely stiff at the bearing lines. In a first attempt to control this, the hinged-end articulated diaphragm was optimized for the gravity loads. However, this proved difficult from the viewpoint of thermal loads, making uplift bearings necessary.

Bearings had to be accessible for inspection and replacement if necessary. At the abutment, the access is easy from below the structure, but at the hinges, where the ramps sit on the main structure, the access requirements imposed a design challenge. We met it by providing entrance to the ramps through an access manhole at the ramp soffit and through ports in the ramp hinge articulation (Figs. 7, 8, and 9).

Deck joints, too, needed careful attention since the unusual shape of these structures imposed unusual movements on the deck joints. Finite element analysis indicated that thermal, creep, shrinkage, and post-tensioning movements would be severe both transversely and longitudinally. After evaluation, a strip seal deck expansion joint was selected as providing the necessary movements in two directions.

CONSTRUCTION

No design is complete if the designer, who knows all the problems and concerns in the design of such complex structures, does not communicate those concerns to the contractor and field engineers. This is especially critical where a particular design is bid by several contractors. Giving the contractor a suggested detailed sequence of construction is helpful. Our design did not try to dictate a construction method, but opened the door for the contractor's initiative by incorporating in the construction documents a suggested sequence of construction together with notes that highlighted the designer's concerns at various stages. It proved very beneficial; contractors for both structures mostly used the suggested methodology—with some improvements, which were acceptable to us.

Close coordination between the designer and the contractor is a must: both benefit from the interaction, and this experience benefits their future projects as well. On these two projects, such cooperation was realized to be essential, and with the timely cooperation of the client, problems as they were perceived and encountered were solved to every party's satisfaction.

In Arizona, most concrete box girder superstructures are poured directly on a 'mud slab' as the base form. The mud slab is a thin unreinforced concrete slab poured to grade on a stabilized fill (the 'mud'). Both these projects benefited from the method, which allowed pouring the deck slabs without recourse to the scaffolding commonly used in other regions.

CONCLUSION

However difficult the analysis and design, the concept of an urban interchange on structure has proved quickly and economically constructible. The \$2.6 million Seventh Street structure (\$62/square foot) and the \$3.6 million Seventh Avenue structure (\$63/square foot) were each built in about a year, and cost considerably less than comparable multilevel interchanges.

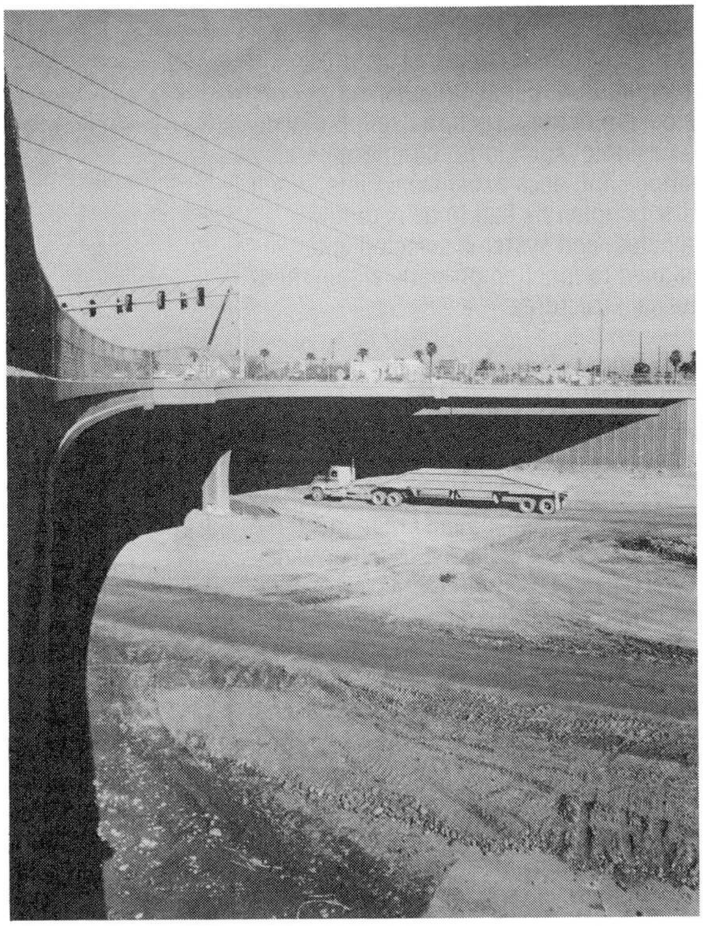

Figure 10. A driver's view from I-10 (Seventh Avenue)

Phoenix's new urban interchanges on structure, and the design and construction that made them possible, offer a new option for cities seeking to thread highways and interchanges through the already dense urban fabric (Fig. 10).

CREDITS

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Arizona Department of Transportation

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Structural Engineer
Parsons Brinckerhoff Quade & Douglas, Inc.

Contractors
Tanner Construction (Seventh Street Structure)
McCarthy Construction (Seventh Avenue Structure)

Portions of this paper appeared, in different form, in *Civil Engineering* (September 1988), published by the American Society of Civil Engineers, and are reused here with their permission. These structures have received engineering awards from the American Concrete Institute (Arizona), Post-Tensioning Institute, and American Consulting Engineers Council (Arizona).