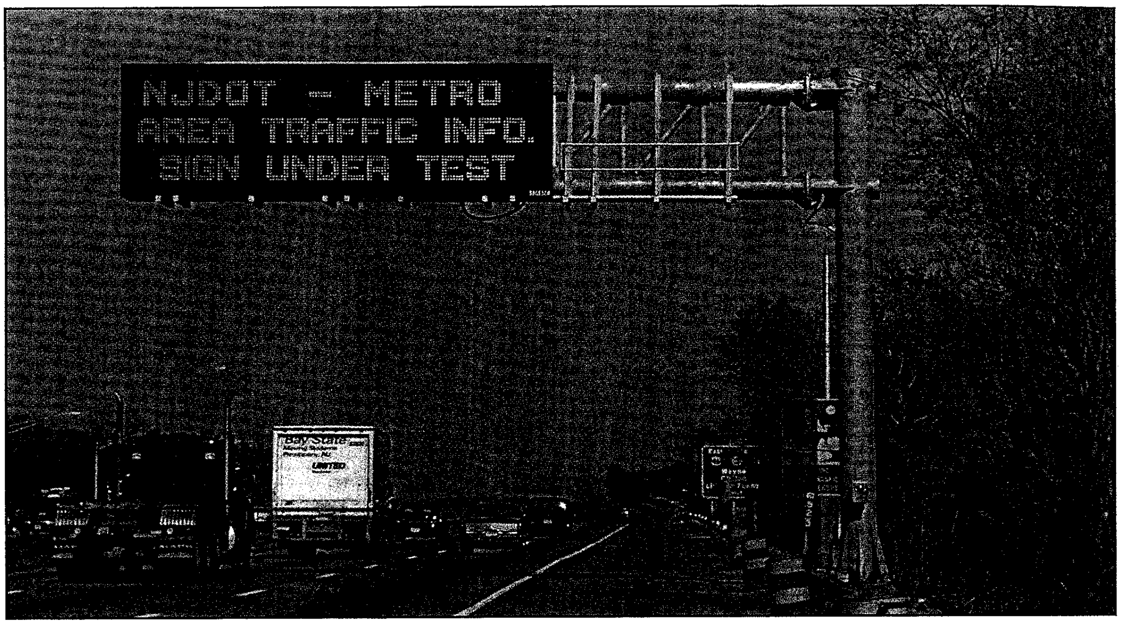

Smart Sign
SUPPORT

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Structural investigation enables engineers from Lehigh University and the New Jersey Department of Transportation to develop design criteria for cantilever sign support structures.

The showcase intelligent transportation system (ITS) project for the state of New Jersey, Route I-80-MAGIC (Metropolitan Area Guidance, Information, and Control), is taking shape along 72 mi (116 km) of highway. Starting near New York City at the George Washington Bridge, it continues west along Interstate 80 and terminates west of the interchange with I-287. Portions of various state routes and of the New Jersey Turnpike also form part of the project.

The ITS is made up of multiple traffic surveillance and information networks controlled and monitored by a central computer system. Thirty-seven closed-circuit television (CCTV) cameras provide visual coverage of the roadway to the New Jersey Department of Transportation (NJDOT) operations personnel, who may also operate the cameras manually. More than 150 radar units will provide traffic volume and speed information, while five weather stations will monitor weather conditions. Computer software will monitor all of this information and advise the NJDOT operations personnel of changes in road conditions. The software automatically determines traffic incidents by analyzing real-time traffic information collected from the radar detectors and verified by CCTV camera operators. Once an incident is verified, the computer software will recommend diversion routes, determine the need to dispatch police and emergency medical services, and determine the appropriate messages to be broadcast to motorists over five

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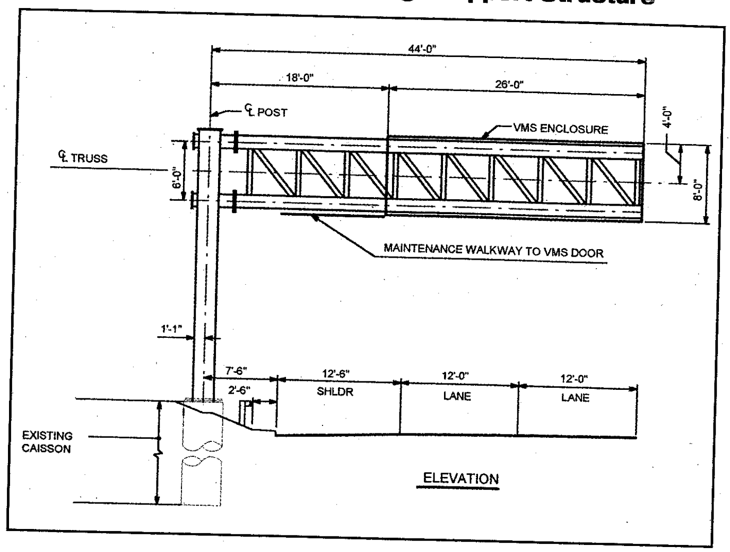
synchronous highway advisory radio transmitters. In addition to radio bulletins, there are 35 variable-message signs (VMSs) located in the approach to interchanges and along selected diversion routes to keep motorists informed. Most of the signs will be supported by steel cantilever support structures, but existing design specifications do not adequately ensure the safety of such structures. New design and construction research were needed to determine a safe design standard.

Construction on the Route I-80-MAGIC project began in 1994 but stopped in the spring of 1997 when the project was about 60 percent complete. One of the major items of work completed was the concrete caisson foundations for the VMS cantilever support structures. Not all of the structures, however, had been fabricated. About that same time, the Federal Highway Administration (FHWA) expressed concern about the use of the support structures. Other states have used this type of support structure and experienced such problems as large vibrations and fatigue cracking. The NJDOT echoed the FHWA's concerns because of the poor structural performance of a prototype VMS cantilever sign structure installed on the project during the original construction.

Faced with need to relet the project using revised contract documents and to obtain a new contractor, the NJDOT took advantage of the extended schedule to evaluate the vibration and cracking concerns. Harry A. Capers, Jr., a New Jersey State bridge engineer, and the project manager, Robert DiBartolo, thought that a structural engineering research project might help determine the effects of wind uplift on the fatigue design of VMS cantilever support structures. The work was done at Lehigh University, where structural research was conducted by Mark Kaczinski, James VanDien, Kevin W. Johns, and Robert J. Dexter.

The NJDOT had chosen VMS enclosures that could display either three or four lines of text, and had chosen a walk-in design that would allow maintenance personnel to repair the signs internally without having to close the traffic lanes beneath them. The common dimensions for these signs are

Fig. 1 Typical VMS Cantilever Sign Support Structure



26 ft (7.9 m) in length and about 4 ft (1.2 m) in depth, with the three-line VMS about 8 ft (2.4 m) in height and the four-line about 10 ft (3 m) high. Most of the VMSs would be supported by steel cantilever support structures.

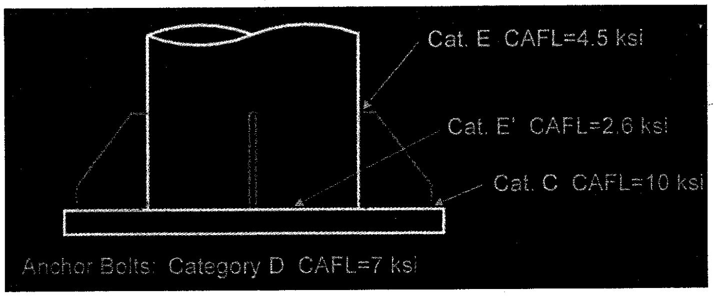
Cantilever structures were selected because they are more economical than the overhead (bridge) type of sign support structure. They were to be fabricated from steel pipe, to have a maximum truss span of 44 ft (13.4 m), and to be hot-dipped galvanized. Each is supported by eight anchor bolts that attach the single-column steel post to the concrete caisson foundation. The anchor bolts for the structures are 3 in. (76.2 mm) in diameter and are produced from A-36 steel threaded rods. At most locations, the VMS has been placed at the extreme free end of the cantilever truss.

The original design was based on the "Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals," which was published in 1985 by the American Association of State Highway and Transportation Officials (AASHTO). Additional design criteria were provided by the NJDOT. Because this project was the first for the NJDOT in which a walk-in VMS enclosure would be used, the original construction contract called for one prototype cantilever structure to be fabricated and erected with a VMS by the contractor. The VMS used was the larger, four-line type, and the performance of the structure was assessed over active highway traffic.

Almost immediately after the prototype was installed, the structure moved vertically as well as horizontally when trucks passed underneath. The structure oscillated for many cycles after the passage of tractor-trailer trucks, which also induced wind gust loads on the frontal area, the underside of the members, and the attachments mounted on the truss. The FHWA and the NJDOT were concerned that this uplifting movement would affect the structure' s fatigue life. After about nine months of in-service performance, the anchor bolt nuts on the baseplate of the column post loosened. When that happened, the structure was immediately removed.

Cantilevered support structures are much more sensitive to vibration than span-type or overhead support structures. The single support significantly increases the flexibility of the cantilevered structures, and the flexibility of these structures has increased over the years owing to the longer span lengths used to accommodate a greater number of traffic lanes and the desire to set the column farther away from the road to increase motorist safety. The ratio of stiffness to mass consistently gives these structures a

Fig. 2 Typical Baseplate-to-Column Connection



low natural frequency, about 1.0 Hz. Such structures also have extremely low critical damping ratios, typically less than 1 percent. These characteristics make cantilever support structures particularly susceptible to large-amplitude vibration and to fatigue cracking caused by wind loading.

Wind-induced vibration of the structures was part of the research program at Lehigh University. The results of this research are included in Report 412 of the National Cooperative Highway Research Program (NCHRP), "Fatigue-Resistance Design of Cantilevered Signal, Sign, and Light Supports." Researchers found that excessive vibration of the sign and signal support structures may be caused by three distinct phenomena, possibly acting together at times: buffeting by natural wind gusts, buffeting by gusts caused by trucks passing under the structure, and "galloping."

Galloping, also known as Den Hartog instability, is an aeroelastic phenomenon caused by wind-generated aerodynamic forces acting on a structure in combination with structural vibrations. Galloping-induced oscillations primarily occur in flexible, lightly damped structures with nonsymmetrical cross sections. Natural or truck-induced wind gusts fluctuate, and it is the fluctuation of their resulting aerodynamic forces that is important for fatigue design specifications.

Galloping and natural or truck-induced wind gusts may give rise to large-amplitude displacement ranges and associated fatigue-causing stress ranges. Because of this, typical stress ranges resulting from these three factors must be considered in designing these structures to resist fatigue.

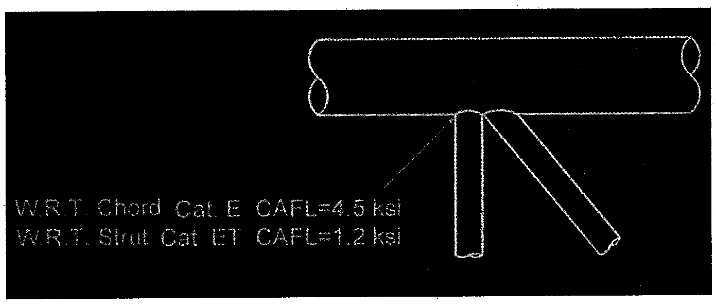
Trucks passing beneath cantilevered support structures tend to induce gust loads on the frontal area and the underside of the members, as well as on the attachments mounted on the mast arms. The magnitude of the pressure from a natural wind gust is much larger than the horizontal pressures from truck-induced loading, so for purposes of fatigue design truck-induced wind loads normal to the sign are not critical.

VMSs are particularly susceptible to truck-induced wind gusts because of their relatively large width in the direction parallel to traffic flow. Cantilevered VMS support structures have been observed to vibrate in the vertical plane, and vertical pressure acting on the horizontal area seems to be the primary cause of vibrations on cantilevered VMS support structures.

Many VMSs across the nation have had problems with excessive vibration and fatigue cracking, and failures have occurred in other states. In California VMS structures mounted on supports of the monotube or J-tube type were affected by galloping. A typical truss-type structure similar to the one used by the NJDOT for the Route I-80-MAGIC project is torsionally stiff and apparently not as susceptible to galloping as other sign support structures. Wind buffeting from natural gusts and truck-induced wind uplift, however, are serious design considerations.

To design sign structures for fatigue that take into consideration wind buffeting effects, design criteria containing an equivalent static pressure needed to be developed. The equivalent static pressure corresponds to load range; when the pressure is applied to a structural model, the computed stresses represent the total stress range, or, twice the amplitude of the stress. For the fatigue design the team used an equivalent static pressure in lieu of actual dynamic pressures. This equivalent also represents the largest load ranges—those that occur for only a few hours every year. The engineers designed the new VMS cantilever sign support so that the stress ranges computed using the equivalent static pressure are below the threshold for fatigue cracking of the various details. This conservative approach ensures an essentially infinite fatigue life. The structures' useful life will be governed by factors other than fatigue, such as the life of the galvanization.

Fig. 3 Typical Connection of Diagonal Members to Truss Chord



To determine the equivalent static pressures for fatigue loads on cantilever sign support structures, the Lehigh team installed instrumentation on a cantilever VMS sign structure on I-80 and continuously monitored it for three months. The structure was fitted with strain gauges, pressure transducers, and an anemometer. The measurements included pressures near the VMS and strains at all critical locations. Transducers then measured the pressure of upward gusts of air produced by trucks passing at high speed under the VMS sign. Short-term testing was also performed on the structure to determine such dynamic characteristics as stiffness, natural frequency, and percent of critical damping. Results of the short-term tests indicated that the first- and second-mode natural frequencies were 0.87 and 1.22 Hz, respectively, and that the percentages of critical damping for the first and second modes were 0.57 percent and 0.25 percent, respectively.

Long-term monitoring was performed to capture the structure's response to natural wind gusts, galloping, and truck-induced wind gusts. During the three months of monitoring the structure did not experience galloping. The natural wind speeds and associated stress ranges from natural wind gust responses were never that large.

The maximum response measured during the three-month period was caused by truck-induced wind gust loading. In NCHRP Report 412, an equivalent static pressure range of 37 psf (1,772 Pa) was recommended based on the displacement amplitude of vibration that had been observed in several structures prior to failure. This pressure range is multiplied by a drag coefficient for the type of surface; the AASHTO specifications include a table of drag coefficients. The appropriate coefficient for a rectangular box shape is given as 1.45. This design pressure range represents both the upward and the downward part of the loading cycle. Drag coefficients are given for rectangular shapes with larger lengths than widths along the wind direction, and these are much higher than 1.45—of the order of 1.7, depending on the aspect ratio. These larger drag coefficients may actually be more appropriate for the VMS boxes with wind coming from underneath and flowing upward. However, since the design pressure of 37 psf (1,772 Pa) was derived assuming a drag coefficient of 1.45, using the higher drag coefficients in applying the design pressure may prove to be too conservative.

The maximum stress ranges measured during the three-month monitoring period were consistent with an equivalent static pressure range of 11 psf (527 Pa), assuming a drag coefficient for the VMS of 1.45. It is unclear how much the response can vary if the conditions are different, for example, if there is more natural wind at the same time or if the trucks are in different lane positions relative to the sign location. The displacement amplitudes at the I-80 location were never near those reported when the original prototype structure was in service on Route 17. It is unclear if the worst-case conditions had been observed during the monitoring on I-80.

The team recognized that the optimum design criterion is somewhere between 11 and 37 psf (527 and 1,772 Pa). The recommendation was for New Jersey to use the more conservative pressure range recommended in NCHRP Report 412. Another modification that was used in the New Jersey design criteria was a gradient for the truck-induced gust design pressure. The measurements indicated that the truck gust load is full strength for elevations of 18 ft (5.5 m) or less and decreases linearly to zero at a height of 30 ft (9 m).

The research for the NJDOT also addressed the tightening of the anchor bolts and the connection between the truss and the column post. There was not much guidance available on the proper tightening procedure for the size of bolt used. Improper tightening of the anchor bolts can cause changes in the dynamic characteristics of the sign support structure.

All of these criteria—in addition to 1994 AASHTO specifications—were used to redesign the sign support structures when the Route I-80-MAGIC project was relet. The consulting engineering firm Edwards and Kelcey, of Morristown, New Jersey, designed the new VMS sign support structures to the new criteria and prepared the contract documents with the revised specifications.

Reletting the project gave the NJDOT the time to work with the research team at Lehigh University to perform structural investigations and to develop refined structural design criteria that properly consider fatigue. The work also permitted the NJDOT to ensure the proper installation of the bolts during the sign structure erections. With an improved support structure design that could use the existing in-ground concrete caisson foundations, the NJDOT saved taxpayers about $3 million and reduced the overall construction time by four to six months. Construction should be completed by the end of this year.

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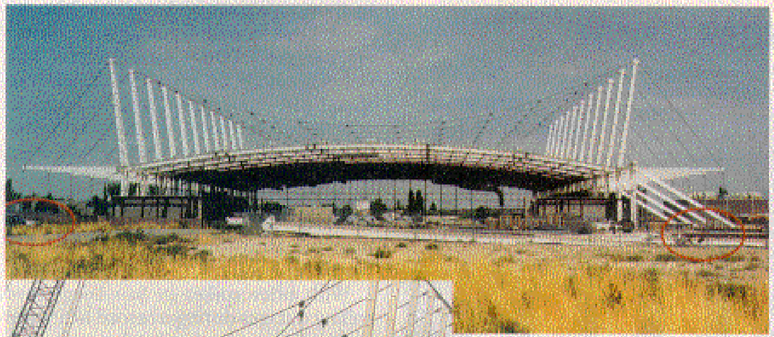
AASHTO has recently sponsored several research projects through the NCHRP to develop new design specifications for support structures. The first phase of this research has been completed, and an AASHTO subcommittee has approved a 2000 version of the 1985 specification, and the new version should soon be available. Research to refine these specifications is continuing at the University of Minnesota under Associate Professor Dexter's direction and at the University of Alabama at Birmingham. ▼

Robert J. Dexter, Ph.D., P.E., M.ASCE, is an associate professor of civil engineering at the University of Minnesota. Kevin Johns is now an engineer with Modjeski and Masters, Inc., in Mechanicsburg, Pennsylvania, and was a member of the Lehigh University team. Robert DiBartolo, P.E., M.ASCE, is a project manager and structural engineer with the New Jersey Department of Transportation.

Repairs

PILE CAPS AT SALT LAKE CITY RINK ARE 'ENCAGED' AFTER BOLT FAILURE



RINK Fix, after failure (left), has cables attached to steel cages over pile caps (circled).

AFTER A THREE-MONTH STALL IN CONstruction triggered by the collapse of one suspension bridge-like element, a $2-million fix is under way on the exterior cable-supported roof of Salt Lake City's $27-million 2002 Winter Olympics skating arena. Work calls for fitting steel cages over all the driven H-pier pile caps that, like tent stakes, anchor the roof's 12 suspension cables. The fix also includes replacing the snapped cable and the portion of roof damaged by the April 19 failure, which injured three workers.

A two-month probe by Geiger Associates Consulting Engineers, New York City, which included bolt material tests at Lehigh University in Bethlehem, Pa., confirmed the suspicion that pile-cap anchor bolts sheared to initiate the partial collapse (ENR 5/15 p. 16). The cause was "design of the cable attachment to the foundation and the serviceability of the anchor bolt materials at that attachment," says Mitt Romney, president of the Salt Lake Organizing Committee (SLOC).

The exposed support for the 655 x 310-ft building resembles a series of steel suspension bridges. The 3.5-in.-dia main suspension cables are strung from 12 pairs of 109-ft-tall masts, 50 ft on center, and anchored back to pile caps topping 75-ft-deep piles, 69 ft from the building's side walls. Roof beams with metal decking hang from the cables.

Like a larger shoe box being placed over a smaller one, the 2 x 4-ft new steel cages, which vary in height, will be installed over the tops of the piles and pile caps, after some excavation. Workers will then bolt the cages to the pile caps. The suspension cables will attach to the cages. The fix is expected to take one month, according to the skating rink's contractor, Layton Construction Co., Salt Lake City.

The intent is to beef up the system's ability to withstand horizontal forces, says Ove Arup & Partners, New York City, project structural engineer.

SNAPPED. The eight 1.5-in.-dia. anchor bolts that sheared had stayed a cable strung just two days before it snapped. The other 11 had been up for as long as two months.

Though "an error was clearly made," Romney says the Olympics organizers are not interested in assessing blame. Rather, they want construction of the Oquirrh Park Oval to be completed in time for Olympic speed skating events.

SLOC has left it to the principal designers to work out payment for the repairs. Consequently, the cost is being negotiated between the members of the design and construction team and their respective insurers. These include local architect Gillies, Stransky, Brems and Smith; Layton; structural engineers Arup and its partner Martin/Martin-Utah Inc. Consulting Engineers, Salt Lake City.

"We're not pointing fingers at any one," says Alan Rindlisbacher, a spokesman for Layton. "We're going to work to resolve these issues." He characterizes the negotiations as friendly and says a payment decision is likely soon.

The design for the interior column-free arena was initially hailed for its cost-effectiveness and unobstructed views of the rink from the 7,000 seats. The exterior cable-supported roof would eliminate unused under-ceiling volume, thereby reducing heating and cooling costs.

Originally set to open by October, the arena is now slated for completion by January. That would make it difficult for skating's U.S. National Championships, set for early December, to be held there as planned. ❑

By Tony Illia in Salt Lake City

Clean Air

PLANTS TO SPEND MILLIONS ON FIXES

THE U.S. ENVIRONMENTAL PROTECTION Agency and Justice Dept. have reached agreements with three industrial firms that could generate record spending on air pollution fixes at 25 U.S. plants.

Petroleum refiners BP Amoco and Koch Petroleum Group agreed July 25 to spend a total of $600 million for improvements at 12 sites to head off possible enforcement. In addition, BP Amoco will pay a $10-million fine and Koch $4.5 million for violations of the Clean Air Act.

EPA, in the midst of a "sector-by-sector" new source review of industrial pollutants, says at least three other refiners "have expressed an interest in coming to the table" rather than face penalties for nitrogen oxide and sulfur dioxide emissions and release of volatile organic compounds and benzene. The agency has also targeted coal-fired utilities and paper manufacturing facilities.

Just days before, Portland, Ore.-based Willamette Industries Inc., agreed to pay $11.2 million in clean air penalties, the largest for air pollution emissions. The wood products firm will install pollution controls at 13 facilities in four states and spend $8 million more on other environmental projects.

BP Amoco and Koch initiated talks with EPA this spring in exchange for the promise of "a clean slate" with regard to past violations. The plants specified in the agreements account for 15% of U.S. refining capacity. ❑

PHOTO BOTTOM: RICK EGAN