While bridge superstructures and substructures are often designed separately, a holistic design approach can increase the efficiency of both.

bridge crossings

ALL TOGETHER NOW

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THE FOUNDATION to any truly great steel bridge design includes a consistent and economical approach to both the superstructure and the substructure. And while the superstructure and substructure act in concert to form the structure, each is often analyzed for separate loads and isolated from the other as much as possible both physically and analytically—and this can lead to an inefficient steel design.

Efficiency can be improved if the substructure and superstructure are compatible with respect to economic, structural and aesthetic demands. When alternate designs are prepared, the substructure for the steel design must be evaluated and designed concurrently with the superstructure. In addition, for cases where the chosen substructure form dictates the use of bearings, consideration should be given to the use of less expensive bearings such as elastomeric ones, where the calculated movements and rotations are within the tolerable limits of these bearings.

Form Follows Function

Bridge substructures are designed to safely transfer lateral loads as well as vertical loads. Some loads are applied directly to the substructure, but most loads are transferred to the substructure from the superstructure through the bearings, shear keys or integrally. While the superstructure generally must resist vertical loads far in excess of lateral loads, the substructure is subjected to a wide range of lateral load effects. As a result, the form of the most efficient substructure must be deduced from its many functions, while remaining consistent with the existing soil conditions.

The substructure must be designed according to the specification for various combinations of the force effects. The specification may either provide for increased allowable stresses or call for reduced load factors for each force effect to account for the reduced probability of the individual design forces occurring simultaneously.

Multiple column shafts provide more than one path for the vertical loads to reach the foundation. The total vertical capacity of the substructure is usually greater than the sum of the vertical loads in these cases; thus, the substructure would be designed for more than the total vertical load.

When pile foundations are employed, the objective is to minimize the number of piles. The number of piles cannot be less than the number required to resist the fully factored vertical load. Lateral loads create an increased downward force on some piles, but not an increase in the total vertical force. Therefore, if more piles are required to resist lateral loads than are necessary to resist the vertical loads, it can be hypothesized that an improved substructure design and/or pile arrangement may be possible.

To minimize the number of piles, consideration should be given to employing a single-shaft pier. Single-shaft piers are non-redundant, which may eliminate the need to investigate multiple live-load positions to determine the maximum vertical live load on the pier. The smaller footprint of single-shaft piers may also be advantageous in certain situations, such as when a single-shaft pier might eliminate a skewed pier. Of course the height of the pier, width of bridge and under-clearance dictate the practicality of single-shaft piers, as well as any aesthetic considerations.

Torsional behavior of the superstructure can be used to reduce overturning effects on single-shaft piers. When a single-box cross section is used, the loads on the extreme of the deck are transferred by torsion in the box to the pier by a couple in

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the reactions. This technique greatly reduces the pier bending by allowing the superstructure to handle the eccentric loads, and is employed to great advantage with single-box segmental concrete bridges. This can also be accomplished with a single steel box or two I-girders with bottom flange lateral bracing.

More typically, the steel superstructure consists of multiple girders supported on single-shaft piers consisting of hammerhead pier caps. Hammerhead pier caps can be designed to be integral with the girders. These are often employed to improve under-clearance. Many skewed piers have been eliminated in this manner. Not only is a long pier minimized, but the skew is also eliminated.

Fixed bearings can distribute load to several piers. Piers integral to the superstructure transmit longitudinal forces, such as ice, to many piers, which can resist the forces in reverse bending (double curvature), reducing the base moment. Integral connection of steel superstructure and substructure is usually not practical, but distribution of longitudinal and transverse forces via fixed bearings to several piers is still economically beneficial. These arrangements of fixed bearings are particularly useful in mitigating thermal forces in longer multi-span bridges. Such designs obviously require consideration of the interaction at design.

Careful treatment of skewed supports permits the design of efficient elastomeric bearings in cases where the computed girder rotations are small enough to be accommodated by such bearings. Lateral forces in the bearings can be immense at skewed supports. They can often be alleviated by judicious selection of bearing releases and constraints. The forces in the end diaphragms can also be reduced to tolerable levels.

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Span Optimization

The optimum span arrangement for a steel design is usually different from the optimum span arrangement for a concrete structure. In competitive situations, it is important to optimize spans for both materials when possible. The cost of any additional borings is usually offset by the economy gained. The versatility of steel permits it to be used in span arrangements optimal for concrete. If a single-span arrangement is chosen, it is usually one that is optimal for concrete. An alternate steel design for those spans can be made, but it will not be optimal. Span lengths should preferably be arranged to yield approximately equal maximum positive dead-load moments in the end and center spans. These balanced span arrangements (end spans approximately 80% of interior spans) result in balanced moments and deflections, while reducing the likelihood of uplift in short end spans or inefficient interior spans if the end span is too long. Such span arrangements result in optimal depth of the girder in all spans, with nearly the same moments and deflections and a more efficient and aesthetic design.

In situations where there are severe depth restrictions or where it is desirable to eliminate center piers (e.g., certain overpass-type structures), it may be desirable to provide short end spans. However, in cases where there are no such restrictions, it is often economical to extend the end spans to provide a balanced span ratio, avoiding costs associated with the need for tie-downs at end bearings, inefficient girder depths and additional moment in the interior spans. In curved structures, extension of the end spans may also permit the use of radial supports where skewed supports might have otherwise been necessary. Elimination of skewed abutments and piers reduces the cost of the substructure and reduces the effects of torsion on the superstructure design.

For major, long bridge projects, superstructure and substructure cost curves should be developed for a series of preliminary designs with different spans. Because the concrete deck costs are constant and independent of span length, they need not be considered when developing these curves. The optimum span arrangement lies at the minimum of the sum of the superstructure and substructure costs. These curves should always be regenerated to incorporate changes in unit costs that may result from an improved knowledge of specific site conditions, particularly the pier costs.

The specifications do not limit the length of jointless bridges. Elimination of joints provides savings by reducing or optimizing the number bearings, the cross-frame, expansion devices and less efficient end-spans. By attaching the superstructure to several piers with fixed longitudinally restrained bearings and forcing the piers to flex, less expensive elastomeric fixed bearings often can be used. Longitudinal forces are then distributed to several piers in proportion to their relative stiffnesses. Multiple-span steel girder bridges more than 2,000 ft long, with expansion joints only at their ends, have been successfully built in moderate to cold climates.

Integral and Semi-Integral Abutments

Integral and semi-integral abutments have the characteristic of having no deck-joint at the abutments. This is done to reduce maintenance by reducing the amount of water that enters the abutment area. Integral abutments resist end rotation of the girders and longitudinal force. The restraint of rotation causes negative end moments that must be resisted by the girder connection to the abutment and by the girders. Vertical loads on the girders cause negative end moments in the girders. These moments generate tension in the deck and compression in the bottom flange which may be problematic.

A single row of piles is generally used to increase flexibility. Steel piles, concrete-filled pipe piles and concrete piles have also been employed. There are several ways more flexible piles can be obtained. A sleeve may surround the pile; predrilled piles may be used with granular material surrounding the pile; or fixed base piles may be used. Integral skewed abutments are problematic but have been used. The piles at the acute angle tend to unload, which increases the force on the piles at the obtuse angle. Hence, an increased number of piles are required. The unequal loading on the piles causes restoring shear in the concrete deck and in the connections to the girders. Integral abutments with steel girder bridges up to about 400 ft in length have been successfully constructed.

To extend the span range for bridges without deck joints, some states use a semi-integral abutment concept. In these abutments, elastomeric bearings are typically introduced under the girders to provide a horizontal flexible interface at the bridge seat to separate the superstructure from the abutment and allow rotation of the girders. Semi-integral abutments are easier to construct than fully integral abutments.

Integral abutments introduce issues that may be deleterious to both the substructure and the superstructure. As the bridge attempts to lengthen or shorten due to temperature changes, forces are generated in the abutment and the superstructure. The approach slabs often rest on a polyethylene sheet (or some similar material) to minimize friction. Measurements of the coefficient of friction between the slab and the soil indicate that it varies between 0.9 and 1.9.

A Holistic Approach

Steel is an inherently versatile material and it can be adapted to most any substructure and span arrangement. When the site dictates difficult span arrangements and pier designs, steel is often the only material of choice. However, its efficiency often suffers when designed to conform to foundations developed for other materials. The foundation of a good steel bridge design lies in a holistic approach that encompasses the site demands, aesthetics and economics. MSC

This article was originally published in the January 1998 issue of MSC *as No. 13 in a series that is being updated and reissued by the authors and NSBA.*