Design of Components or Systems?

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In the current American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*,[1] design is based on the consideration of individual structural components such as beams, columns, tension members, and connections. For each component, the specifications require that the load-carrying capacity exceed the design load, with the appropriate load and resistance factors applied. This concept is easy to understand, and it works well for simple structural systems such as simply supported girder bridges. The load per girder is calculated and compared with the calculated load-carrying capacity or resistance of the girder. In LRFD codes, the factors applied to loads and resistance are established using the statistical variability of load and resistance for a type of element to obtain an acceptable target reliability index. A reliability index is calculated using statistical parameters of load and resistance.

Bridges, however, are usually complex structures, and a design approach that only considers isolated elements may be overly conservative, especially for bridges such as single- or multiple-cell box girders, or even for slab bridges. Certain questions that seem straightforward for simply supported girder bridges can be difficult to answer for complex structures. Examples include, "What is the load for a bridge?" and "What is the structure's capacity or resistance?" To answer these questions more completely and accurately, the behavior of a bridge *as a system* must be considered. This article discusses the issues related to system-level versus component-level behavior and design.

Load and Resistance

For this discussion, it is assumed that the major load components are dead load and live load. The definition of live load for a girder in a multigirder bridge involves either applying truck and lane loads using girder distribution factors or a refined analysis to determine the distribution of live loads. The load is expressed in terms of a moment or shear force, or stress and strain. However, in practice, the definition of live load can be much more complex because the load is not necessarily a single truck—it can include multiple vehicles in different lanes and side by side. The effect of live load depends not only on the weight of the trucks but also on their transverse (distance from curb) and longitudinal position. The availability of an extensive weigh-in-motion (WIM) database provides a sufficient basis for the development of statistical parameters of live load for not only girders but also whole bridges.

Even more complex than the definition of bridge live load is the definition of bridge resistance, even on a component level. Girder resistance is defined as the moment-carrying capacity, shear capacity, or maximum allowable stress. The load-carrying capacity of a girder is generally well understood and can be evaluated analytically and confirmed by laboratory testing of components. Test results provide information about the statistical parameters of resistance

A statically determinate truss bridge is an example of a bridge than can be considered a series system, where failure of one element may result in failure of the system. All Photos: Modjeski and Masters

A multigirder bridge is an example of a bridge that behaves as a parallel system, where the load previously carried by a failed element can be distributed to other elements without causing system failure.

in typical girders designed according to the current specifications. However, girders do not exist in isolation; they are interconnected with other components through deck slabs and diaphragms or bracing. In structure types other than multigirder bridges, the interconnection between components can be even more complex. As the load increases and the system deforms, load is distributed to and shared by other components. The ability of a bridge to share load between components is strongly affected by ductility and redundancy. Therefore, prediction of the load-carrying capacity for the whole bridge requires consideration of multiple load paths, and the deformation behavior of all involved components into the nonlinear regime, typically requiring a three-dimensional (3-D) nonlinear analysis or perhaps proof-load testing.

Ductility and Redundancy

Ductility can be described as the ability of a structure or component to undergo considerable deformation before ultimate failure. The load-deformation (strain or deflection) relationship for a ductile component typically has a pronounced plateau where deformation increases with little or no additional load. An example of a ductile material is low-carbon steel, and an example of a ductile component is a reinforced concrete beam with a low reinforcement ratio.

Redundancy is the ability of a system of structural components to share the load through multiple load paths. When a structural component is overloaded and close to reaching its ultimate capacity, load is transferred to other components. Therefore, in a redundant structure, overloading of a single component does not typically result in failure.

Structural Systems

A useful way of thinking about structural systems is to classify them as series or parallel systems.

In a series system of elements, overloading/failure of any one element triggers a failure or collapse of the total system. An example of a series system is a chain, as its strength is determined by the strength of the weakest link. Statically determinate trusses are also series systems (when ignoring 3-D behavior).

A parallel system of ductile components has an ability to resist the load even after one or more elements reach their ultimate capacities. An example of a parallel system is a cable that consists of multiple wires, or a multigirder bridge with a reinforced concrete deck that helps distribute the live load from an overloaded girder to adjacent girders.

Most bridges are a combination of components or elements connected in series and in parallel, so an accurate system model can become very complicated. In addition, an important factor that affects the reliability of bridge systems is the degree of mutual relationship or connection between elements, which can be represented by a coefficient of correlation. In general, quantification of correlation is very difficult because of a lack of data. It can involve answering questions such as, "Are there considerable differences between components with regard to quality of materials and workmanship?" A high degree of correlation is helpful for series systems, but undesirable in parallel systems.

Code Calibration

The reliability-based calibration of design specifications involves the development of statistical parameters for load and resistance, development of a reliability analysis procedure, selection of the target reliability index, and derivation of load and resistance factors. However, the original calibration of the AASHTO LRFD specifications was performed for individual bridge components, and not for the system as a whole. In general, the reliability of the whole bridge is higher than the reliability of a single girder, but whether this is true in a specific case depends on the structural type, ductility, redundancy, and correlations.

Given improvements in analytical capabilities, system reliability-based calibration is now feasible. It would require the selection of a wider set of representative bridges, adoption of live-load models from the available WIM database, development of statistical parameters for system load and system resistance, development of an analytical procedure for modeling failure scenarios, selection of the system target reliability index, and, finally, derivation of load and resistance factors for the considered bridge systems.

However, there are issues to be considered when contemplating a shift to system calibration. When engineers speak of redundancy, they generally mean the ability of a structure to accommodate component damage or failure. Such accommodation typically requires a member loss analysis, which is not necessarily the same as a system calibration. System calibration involves consideration of the behavior of the bridge system under increasing loads and how those loads are redistributed as members approach their ultimate resistance, as well as consideration of system reliability procedures. When ductile behavior is assumed, an unintended consequence of using a system reliability design approach may be a reduction in required individual member resistance when compared with the component-level design approach. This difference can negatively affect the ability of a structure to accommodate unanticipated member damage or loss.

This effect is similar to the effect of using refined analysis rather than approximate methods during the design. The end result of a refined analysis is typically less required resistance in the constructed component due to less conservative analysis results, and the previously stated approach to the target reliability index. The Federal Highway Administration's *Manual for Refined Analysis in Bridge Design and Evaluation*[2] provides a more thorough discussion on this topic. To ensure that the intended outcome is achieved, consideration needs to be given to what the ultimate goals of a system calibration approach would be.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.
2. Adams, A., N. Galindez, T. Hopper, T. Murphy, P. Ritchie, V. Storlie, and J. Weisman. 2019. *Manual for Refined Analysis in Bridge Design and Evaluation*. FHWA-HIF-18-046. Washington, DC: Federal Highway Administration. https://www.fhwa.dot.gov/bridge/pubs/hif18046.pdf.