Perspectives on Structural Behavior and Redundancy:
Load Path Redundancy

by Dr. Oguzhan Bayrak, University of Texas at Austin

EDITOR'S NOTE ON STRUCTURAL BEHAVIORS SERIES

Robustness, redundancy, resiliency, and ductility of concrete bridges are being discussed by Dr. Bayrak in a series of Perspective articles that began in the Summer 2020 issue of ASPIRE®*. This series is seen by* ASPIRE *as an important discussion for the concrete bridge community as it begins to consider new materials. These new materials have properties that differ significantly from conventional materials, which may lead to different element behavior. For example, some of the new materials exhibit ductile behavior, whereas others do not. These differences require new approaches to design, but the framework necessary for establishing these new design approaches is not clearly defined by current design specifications.*

It should be noted that not all potential failure modes considered in the American Association of State Highway and Transportation Officials' AASHTO LRFD Bridge Design Specifications *are ductile failure modes, so ductility should not be considered as the only criterion for acceptable bridge designs. For example, concrete breakout failure for embedded anchors is quite brittle, which is recognized in calibration of the applicable equations in the AASHTO LRFD specifications. Furthermore, a more complete understanding of the actual capacity of a bridge is provided when the system-level robustness is considered. Different types of redundancies are inherent in concrete bridges, such as load transfer between girders; these contribute to the overall robustness of the bridge by providing multilayer protection against sudden failure. However, quantifying the contribution of these redundancies is not easy. Current AASHTO LRFD specifications have simplified bridge design by considering only element behavior. Therefore, they do not consider overall system behavior and the redundancies that contribute to it.*

This article, which is the final article in this series, focuses on alternate load paths and structural behavior at all levels, from section- to system-level behavior.

My article in the Summer 2020 issue of *ASPIRE®* initiated a discussion on structural, load path, and internal redundancies. My subsequent articles in the Winter 2021 and Spring 2021 issues focused on various aspects of redundancy, resiliency, and robustness of concrete bridges. This article continues the discussion by focusing on load-path redundancy and structural response at the section, member, and structure levels.

Load-Path Redundancy

Load-path redundancy in bridges is the existence of multiple ways in which applied loads can be transferred to the supports. To facilitate a discussion of load-path redundancy, let us consider a couple of examples, beginning with a scenario involving a three-span continuous post-tensioned bridge. **Figure 1** shows the cross section of this two-cell, post-tensioned concrete box-girder bridge. Although the superstructure was designed to handle a variety of different loads and load combinations, an accidental vehicle strike damaging one of the two cells was not explicitly considered in design.

Let us assume an overheight vehicle striking the bridge would damage all internal and external tendons of one cell at the positive moment region in one of the three spans. In the event of such extensive damage, this bridge would benefit from the high torsional strength and stiffness that the undamaged cell possesses. In the damaged span, one-half of the superstructure would be supported as a cantilever from the undamaged cell and use an alternate load path that would aid in the transfer of the weight of the damaged portion,

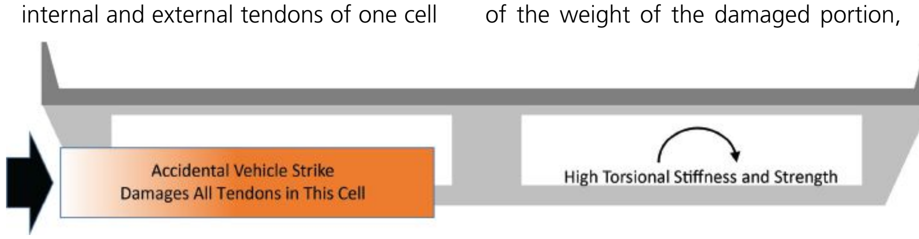
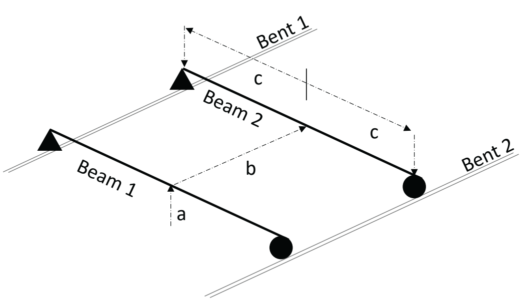


Figure 1. If one cell of a two-cell, three-span continuous post-tensioned concrete box girder is extensively damaged, the bridge would benefit from the high torsional strength and stiffness of the undamaged cell and continuity in the longitudinal direction. Figure: Dr. Oguzhan Bayrak.

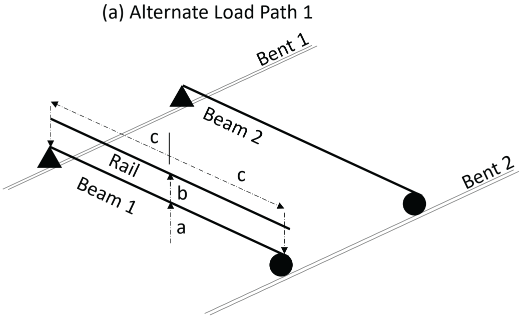
Figure 2. Severe damage to a two-cell, post-tensioned concrete box-girder bridge from an overheight vehicle strike. The stiffness of the remaining box-girder superstructure prevented structural collapse. Photo: Kansas Department of Transportation.

and any loads placed on it, into the supports. Although this bridge was not designed to accommodate such a loading scenario, a vehicle strike would likely not result in collapse. The alternate load path is facilitated by continuity in the longitudinal direction, by the well-distributed post-tensioning layout, and by the torsional stiffness and strength of the undamaged cell.

Figure 2 shows an example similar to that described in Fig. 1; in this example, the boom of an excavator that was being transported by truck severed the great majority of the longitudinal reinforcement near a support. In this case, the stiffness of the box-girder superstructure as well as the concrete bridge rail served to mobilize alternate load paths that prevented structural collapse.



(a) Alternate Load Path 1



(b) Alternate Load Path 2

Figure 4. As a result of redundancies, two alternative load paths are available after a fascia girder, represented in the figure as beam 1, is heavily damaged near midspan. Figure: Dr. Oguzhan Bayrak.

In the next example, let us consider a precast and prestressed concrete girder bridge with the deck supported on four girder lines. The simply supported span was damaged by an overheight vehicle strike, severely damaging the bottom flange and web of the fascia girder (**Fig. 3**). The adjacent girder was damaged to a lesser extent. **Figure 4** illustrates two alternate load paths that likely helped the bridge survive the vehicle strike and associated damage that was not explicitly considered in the original design.

Alternate load path 1 (Fig. 4a) requires the deck to work as a cantilever to pick up the load (from the location marked as "a" in Fig. 4a) that was originally supported by the fascia girder (beam 1) and transfer it to beam 2 (along the path marked as "b" in Fig. 4a). Beam 2 subsequently carries the load to bents 1 and 2 (using the paths marked as "c" in Fig. 4a). Alternate load path 2 (Fig. 4b) involves the overhang portion of the deck taking the load (from the location marked as "a" in Fig. 4b) that was originally supported by the fascia girder (beam 1) over to the bridge rail (along the path marked as "b" in Fig. 4b). The bridge rail now works as the new fascia girder carrying the load to bents 1 and 2 (along the paths marked as "c" in Fig. 4b, although the load may also go back into the girder and into the supports at undamaged locations). In reality, the load will be shared by a combination of both of these alternate load paths. The member that displays the larger stiffness will attract a greater portion of the load that was originally carried by the fascia girder.

Undoubtedly, the distribution of forces is a function of material strengths as well as the bridge geometry—for example, beam spacing, girder depth, and bridge rail geometry. Depending on the aforementioned factors, the rail may play a more or less important role compared to the slab cantilevering to pick up the load. Having acknowledged that subtlety, we must recognize two important points. First, bridge decks are never designed for this type of loading.

Figure 3. Severe damage to a prestressed concrete beam bridge caused by an overheight vehicle strike. Load-path redundancy within the multibeam system prevented collapse. Photo: Mark Bloschock.

The reinforcement details, use of partial-depth precast concrete panels, and the like, are all controlled by applicable service and strength limit states of the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*.[1] However, when called upon, the top and bottom mat reinforcement in the deck will serve to reinforce the cantilever to transfer the load. Second, bridge rails are designed for vehicle impact, and their design purpose is to keep vehicles on the bridge. To meet their intended design function, the rails are crash-tested to verify their design. Once again, when the need arises, as it does in this vehicle-strike scenario, the rails can serve as a substitute for the fascia girder and provide an alternate load path, even when the rails are jointed.

In summary, a bridge's actual behavior is dictated by the structural details provided in that bridge. For example, in the aforementioned case, deck reinforcement that is primarily intended to resist cracking caused by volume changes due to temperature and shrinkage can readily serve as flexural reinforcement in a cantilever. There is no replacement for good structural details, robust reinforcement detailing, and good conceptual designs.

Section-, Component-, and System-Level Responses

Previous articles in this series focused on the relationship among the sectional response, the response of a potential plastic hinge, and the member-level response. We also examined the influence of structural redundancy on overall response. The previously discussed overheight vehicle strike cases provide the framework for our thinking regarding primary (intended) and secondary (alternate or backup) load paths in cases where unexpected conditions challenge a bridge's ability to support permanent and applied loads. The presence of primary and secondary load paths results in a robust structural response where a concrete bridge can make use of a variety of different load paths under different loading or damage scenarios. Ultimately, the system-level response is the most important. With that said, there are a variety of ways to obtain an abundantly redundant concrete bridge system displaying a robust structural response. The cases discussed previously provide good examples of robust structural response where local damage was contained and did not progress into structural collapse.

The AASHTO LFRD specifications were calibrated using a reliability-based methodology to ensure a reasonably uniform level of component safety. For typical concrete bridge systems ranging from simple to complex, there is a relationship between the component-level and system-level responses. In a reliability-based framework, accurate capacity estimations with minimal statistical bias, both for load and deformation capacities, will lead to better estimations at the system level.

The importance of minimizing statistical bias cannot be overemphasized. Engineers are typically predisposed to making decisions on the safe side, and understandably so. In many cases, and especially within the context of behavioral failure modes at the element level, this approach is easy to follow. If one decides to play on the safe side for every step of the evaluation moving from a cross section to a plastic hinge, then to a component, and finally to the system level, an accumulation of conservative assumptions may introduce considerable statistical bias in estimating the system-level response.

Alternatively, and as was done in the AASHTO *Guide Manual for Condition Evaluation and Load and Resistance Factor Rating (LRFR) of Highway Bridges*,[2] a more systematic approach aimed at minimizing statistical bias and targeting appropriate levels of reliability (as measured by reliability index β) for the inventory (design) rating (β = 3.5) and operating (load rating) rating (β = 2.5) can be used. Concepts underpinning the philosophy adopted in the AASHTO LRFR, and later in the AASHTO *Manual for Bridge Evaluation*,[3] are discussed in many publications. Weed[4] provides a concise discussion of this topic. There are a number of additional guidance documents that acknowledge and implement a reliability-based framework to load rate concrete bridges. For example, the Florida Department of Transportation commissioned studies to establish rational load-rating procedures for their segmental and spliced girder bridges.[5,6]

Implementation of System-Level Behavior

The preceding discussion describes how our design and load-rating specifications have recognized the importance of structural, load-path, and internal redundancies for quite some time. Next, let us explore an example that demonstrates the implementation of these concepts in our specifications, such as the load rating of segmental bridges (See the Spring 2021 issue of *ASPIRE* for an article on load rating segmental bridges.). **Table 1** shows that the system factor ϕ_s, in this case for post-tensioned segmental concrete box-girder bridges, is a function of several variables, including the bridge type and construction method. In effect, the system factor is intended to reflect the presence of alternate load paths and give credit to more-redundant structural systems. The second column shows that the determinacy (structural redundancy) influences the system factor, with the third column explicitly indicating the reasoning. For example, a statically determinate span needs to form one hinge to establish a collapse mechanism; an end span of a continuous unit needs to form two. (For details on plastic hinges, see the article in this series in the Winter 2021 issue of *ASPIRE*.) With respect to internal redundancy, as seen in the last columns of the table, as the number of tendons in each web increases, so does ϕ_s. Furthermore, the impact of this redundancy on ϕ_s is quite significant and is nonlinear, as can be

Table 1. System factors for single-cell, post-tensioned segmental concrete box-girder bridges

Bridge type	Span type	Number of hinges to failure	System factors (ϕ_s)			
			Number of tendons per web			
			1	2	3	4
Precast balanced-cantilever, Type A joints	Interior span	3	0.90	1.05	1.15	1.20
	End or hinge span	2	0.85	1.00	1.10	1.15
	Statically determinate	1	n/a	0.90	1.00	1.10
Precast span-by-span, Type A joints	Interior span	3	n/a	1.00	1.10	1.20
	End or hinge span	2	n/a	0.95	1.05	1.15
	Statically determinate	1	n/a	n/a	1.00	1.10
Precast span-by-span, Type B joints	Interior span	3	n/a	1.00	1.10	1.20
	End or hinge span	2	n/a	0.95	1.05	1.15
	Statically determinate	1	n/a	n/a	1.00	1.10
Cast-in-place balanced-cantilever	Interior span	3	0.90	1.05	1.15	1.20
	End or hinge span	2	0.85	1.00	1.10	1.15
	Statically determinate	1	n/a	0.90	1.00	1.10

Note: For box-girder bridges with three or more webs, table values may be increased by 0.10. Adapted by Dr. Oguzhan Bayrak from references 2, 5, and 6.

expected from a complex bridge. Finally, and importantly, the system factors listed in the table were developed for a single-cell box. In cases where there are three or more webs (that is, two cells or more, or two box girders), the values in the table can be further increased. This last fact is driven by the load-path redundancy introduced by additional webs. While this table was specifically developed for post-tensioned segmental box-girder bridges, similar trends in the system factor could be expected for pretensioned concrete multigirder bridges, although such a table has not yet been developed.

Conclusion

Structural indeterminacy, load-path redundancy, and internal redundancy serve as three layers of robustness for concrete bridges. All three types of redundancies have been discussed in this series of articles. The discussions covered a wide range of topics, including the theoretical background and definitions, the design framework employed in the AASHTO LRFD specifications, and real-world examples. As illustrated in this article, the presence of all types of redundancies leads to alternative load paths and gives concrete bridges multiple lines of defense in the event they are subjected to extreme events. Bridge designers should also resist the inclination to include too many conservative assumptions into the design of components or elements in an attempt to improve the redundancy or robustness of the whole bridge. Attempting to enhance the redundancy or robustness of a bridge system by introducing more and more conservatism into the design of individual components or elements will not necessarily achieve the desired levels of redundancy or robustness.

References

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