Resilience of Concrete Highway Bridges

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The new I-35W Bridge across the Mississippi River in Minnesota provides continuity throughout the bridge and state-of-the-art smart bridge technology that monitors bridge behavior in real time. Photo: FIGG Bridge Engineers.

Highway and transportation agencies are adopting innovative methods, technologies, and materials. They are using systematic preventive maintenance, bridge management systems, and asset management principles to balance demands and resources, while maintaining a high level of safety in highway bridges. This article summarizes a framework to achieve more resilient highway bridges.

Resilient Highway Bridges

Resilient concrete highway bridges have the capability to withstand unusual or extreme forces without collapse or loss of lives. They are able to recover from distress or major damage with minimal disruption to traffic and essential services. Three key factors affect the resilience of highway bridges: ductility, redundancy, and operational importance.

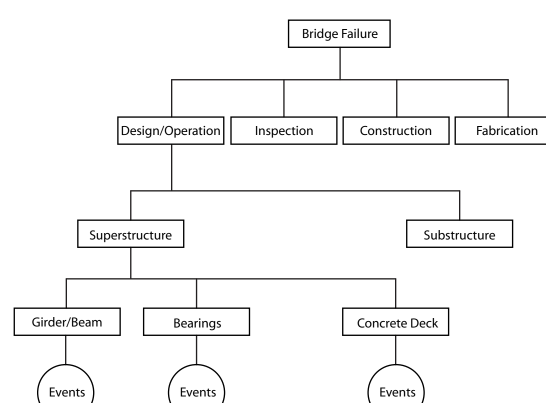
- Ductility in a structural system is characterized by development of significant and visible inelastic deformations before failure.
- Redundancy may be defined as the capability to continue to carry loads after the failure of one of its components. In other words, a redundant bridge system has multiple-load paths for distributing the loads when a component fails.
- Operational importance relates to the consequences of loss of use of the bridge. Rapid emergency response is important for the survival of people and the security of the incident scene.

The *AASHTO LRFD Bridge Design Specifications* recognizes the significant effects of ductility, redundancy, and operational importance on the resilience of concrete highway bridges. The *LRFD Specifications* accounts for these effects on the load side of the limit states equation. It recommends the use of multiple load paths and continuous bridges, unless there are compelling reasons for not doing so. The National Cooperative Highway Research Program (NCHRP) Reports 406 and 458 contain discussions and recommendations on quantifying redundancy in highway bridge superstructures and substructures, respectively. There is an ongoing NCHRP Project 12-86 "Bridge System Safety and Redundancy" for developing a methodology to quantify bridge system reliability for redundancy. The project is scheduled for completion in July 2012 with recommendations for updating the *LRFD Specifications* and the AASHTO *Manual for Condition Evaluation*.

The FHWA publication titled *Framework for Improving Resilience of Bridge Design*, Publication No. FHWA-IF-11-016, introduces the fault-tree methodology for performing failure analysis during design. A bridge designer goes through a fault-tree analysis mentally in making sure that the design is devoid of weaknesses or trouble spots that could lead to bridge closure or failure. This is generally adequate for simpler and more common types of concrete bridges. For more complex bridges, it is desirable to perform a fault-tree analysis to systematically determine all potential contributing factors or events that could lead to a bridge failure. The contributing factors or events can then be considered and carefully addressed in the design.

Fault-Tree Analysis

A fault-tree analysis can be carried out using a fault-tree diagram. The diagram is a graphic model that shows parallel and sequential failure paths that can lead to an undesirable outcome; in this case a bridge failure. The fault-tree diagram is helpful in determining potential failure modes and their interactions. A fault-tree diagram is developed in a top-down direction. In this application, the top event is the failure of the bridge. The events immediately beneath the top event lead to the execution of the top



Portion of the girder bridge fault tree. Diagram: Federal Highway Administration.

event. Successor events and conditions that most directly lead to the predecessor events are then determined. This process is repeated at each successive level of the fault tree until the diagram is complete.

Utilizing a fault-tree diagram, a bridge is modeled to determine the critical failure paths. The fault-tree diagram illustrates the structural component interactions, redundancy, actions/causes, and environmental impacts. The failure paths depicted in the fault-tree diagram are intended to provide bridge designers with a means to improve bridge designs. If bridge designers understand critical failure modes related to the particular bridge, they will be able to employ additional analyses to assess and rectify issues not typically addressed during the design phase.

The Don E. Wickstrom Bridge over the Green River in Kent, Wash., features fully continuous, post-tensioned spans and integral piers. Photo: BergerABAM.

Girder Bridge Failure Analysis Framework

A general fault tree for the case of a bridge failure is developed and presented in this section. Failure may be considered as a total collapse of the bridge system or an event that results in a critical defect.

The fault tree is established with the top event, the Bridge Failure. The failure can develop from four different categories: Design/Operation, Inspection, Construction, or Fabrication. Not all of the conditions will necessarily apply to the bridge designer, but the designer should be aware of all of the events on the fault tree. These aspects are presented here so bridge designers understand and take into account the whole process of the design, fabrication, construction, inspection, and operation of the bridge.

The *Design/Operations* category alludes to the fact that a failure, either a collapse or critical defect, can occur while the bridge is in service. *Inspection* refers to the fact that there may be a problem with the routine inspection such that the design does not permit inspection of some of the bridge components. A failure can also occur during the *construction* of the concrete girder bridge. The *fabrication* process is also subject to errors and omissions. The bridge designer should be aware of, and give due consideration to the events in these categories.

Design/Operation Category

While in service, a bridge failure can result from either a failure of the superstructure or substructure.

A failure of the concrete girder superstructure can be caused by a failure in any one of the superstructure components, but mainly the girders, bearings, or concrete deck. A failure of the superstructure will trigger an operational failure of the bridge. After identifying the critical events or components, the bridge designer can take steps to ensure the resilience of the design for safety, durability, and economy. Detailed discussions of each of the main components and events are given in the FHWA Publication No. FHWA-IF-11-016, *Framework for Improving Resilience of Bridge Design*.

Closing Remarks

The fault-tree analysis is applicable to highway bridges of all types of construction materials. Fortunately, concrete has a track record of high performance. The application of fault-tree analysis in the design and evaluation of major and complex concrete highway bridges will further enhance the design of resilient concrete highway bridges.

EDITOR'S NOTE

The FHWA Publication No. FHWA-IF-11-016, Framework for Improving Resilience of Bridge Design *may be downloaded from www.fhwa.dot.gov/bridge/pubs/hif11016/hif11016.pdf.*

An accident caused by an over height load on I-29 in Iowa, resulted in the destruction of all bottom flanges of this precast, prestressed concrete I-girder bridge without its collapse, illustrating the redundancy in these concrete structures. Photo: Iowa Department of Transportation.