Perspectives on Structural Behavior and Redundancy: Structural, Load Path, and Internal Redundancies

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Concrete bridges have long been a preferred solution for bridge owners due to their adaptability, versatility, durability, and reliability. An important attribute of concrete bridges relates to their redundancy, which can be defined as the ability of a concrete bridge at either its system level or the component level to develop alternate load paths at the strength limit state or under extreme loads. This article focuses on redundancy, with the intent of providing a succinct discussion about the effects of redundancy on structural behavior.

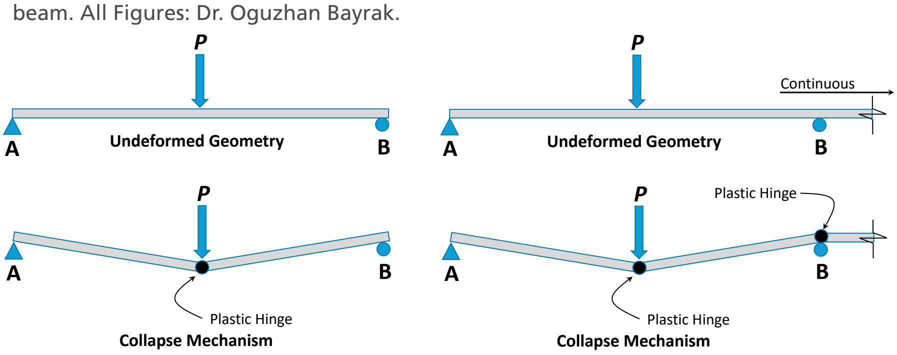
Structural Redundancy

At its most basic level, redundancy can be described by the level of indeterminacy present in a structure. The level of structural indeterminacy controls the behavior of a structure as it is gradually loaded to failure. To facilitate a discussion of collapse mechanisms as a function of redundancy, consider a reinforced concrete beam with ample shear capacity for which flexure is the controlling failure mode.

If a simply supported reinforced concrete beam supporting a concentrated load at its midspan is loaded to failure (**Fig. 1a**), the beam develops a plastic hinge at the section of maximum moment. At this point a plastic mechanism forms and the beam collapses. The beam fails in this manner because the beam is statically determinate.

If the same beam is continuous at support B (**Fig. 1b**), the beam is statically indeterminate—that is, there are more support reactions than the number of equilibrium equations that can be written to determine the support reactions. In this case, under a gradually increasing load *P*, the first plastic hinge will form either at midspan or at support B. The location where the first hinge occurs is a function of the magnitude of the applied moments at those sections, as well as the respective flexural capacities of the reinforced concrete beam at the maximum positive and negative bending moment sections. Regardless of its location, the beam does not collapse at the formation of the first plastic hinge. A second plastic hinge is needed to complete the collapse mechanism shown in Fig. 1b. The incremental load needed to form the second plastic hinge gives an opportunity for engineers, inspectors, and the general public to observe the structure in distress and take necessary actions.

Figure 1. The formation of plastic hinges in a determinate beam and an indeterminate beam. All Figures: Dr. Oguzhan Bayrak.



(a) Simply Supported Span (b) Continuous at One End

Load Path Redundancy

To discuss load path redundancy, let us focus on a bridge with five girder lines (**Fig. 2**). In this case, assume that the bridge span under consideration is simply supported. That is to say, the reinforced concrete deck is supported on five simply supported pretensioned concrete girders that are supported on bearing pads and are free to rotate at the supports. In this case, the superstructure has load path redundancy, which is explained in the following discussion.

If one of the fascia girders shown in Fig. 2 were to be hit by a truck at location 1 and all prestressing strands were severed, we can assume that the fascia girder has failed because it has no positive moment resistance. If the reinforced concrete deck has top and bottom mat reinforcement in longitudinal and transverse directions at location 2 of Fig. 2, the load that can no longer be supported by the failed fascia girder can be transferred to the adjacent girder—with the slab serving as a cantilever to pick up the weight of the fascia girder and deck. The system of remaining girders can then transfer the load to the supporting bents at location 3 of Fig. 2. In this scenario, the superstructure has load path redundancy and can therefore support the deck. In other words, local failure in one of the supporting girders does not trigger disproportionate failure that would lead to the collapse of the total structure. In this context, the term "disproportionate failure" is used to signify total collapse of a

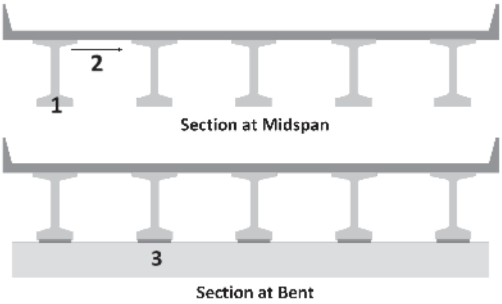


Figure 2. Load path redundancy in a pretensioned concrete girder bridge with a reinforced concrete deck.

structure that is out of proportion with the local damage experienced in one component.

It has also been observed that the bridge rail, originally designed for different loading conditions, may serve as a beam that stiffens the edge of the bridge deck, helping to carry the load to the supports. As an aside, when trucks collide with fascia girders, the superstructures often can be repaired and then kept in service. Such repairs are commonplace and routinely conducted nationwide.

Internal Redundancy

The third type of redundancy is internal redundancy of structural components. Reinforced and prestressed concrete components designed and detailed to comply with the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] possess a significant amount of internal stress redistribution capability (internal redundancy). To illustrate this concept, let us focus on a simply supported deep beam. Such elements are to be designed in accordance with the strut-and-tie modeling (STM) design provisions of the AASHTO LRFD specifications. Because STM is a lower-bound, plasticity-based method, the resulting designs are quite conservative. This conservatism can be attributed to the calibration of the efficiency factors[2] and the nature of all lower-bound plasticity methods.

Experienced structural designers commonly make decisions to optimize their designs. **Figure 3** shows a classic deep beam example. Most bridge designers would use the solution presented in Fig. 3a. The 45-degree struts and logical placement of flexural reinforcement A_s (primary tie) result in an efficient design. With that stated, let us assume another designer chooses the model shown in Fig. 3b. If that model is used, the unusual location of the longitudinal reinforcement appears awkward at first pass. The strut inclination in this model is 26.5 degrees and, as such, doubles the force in the primary tie and results in twice as much reinforcement. Both of the structural components designed by STM will support the design loads safely. The use of crack-control reinforcement (0.3% reinforcement in each direction, as per the AASHTO LRFD specifications) will facilitate the internal redistribution of the stresses, and both models (a) and (b) envisioned by the designers will form at the strength limit state. In other words, the reinforcement detailing within the member will control the behavior of that member and hence control the development of a load transfer mechanism consistent with that reinforcement detailing. With that stated, the use of model (a) will result in the best service performance because this model more closely resembles internal compression and tension fields in an elastic model. The in-service performance is important, particularly as we aspire to design our bridges to have 70- to 100-year service lives.

To understand the internal redundancy of deep beams like the one shown in Fig. 3a, consider the test results from two deep beam tests conducted at Phil M. Ferguson Structural Engineering Laboratory at the University of Texas[2] (**Fig. 4**). The photographs in Fig. 4 focus on the portion of the beam between the load point and the left support. Support and loading plates are drawn to provide better visualization. The two test specimens depicted in Fig. 4 have different reinforcement details. The specimen shown on the left does not have any crack-control reinforcement, and the specimen shown on the right contains 0.3% crack-control reinforcement in both directions in compliance with the AASHTO LRFD specifications. All other details of these specimens were kept constant to facilitate a direct comparison. Figure 4 shows that the specimen with no crack control reinforcement developed fewer cracks as the loading was gradually increased to failure. The specimen that contained 0.3% crack-control reinforcement in the vertical and horizontal directions developed extensive flexural and shear cracking before it ultimately failed. Therefore, it can be concluded that crack-control reinforcement facilitated internal redistribution of stresses and associated cracking. As mentioned earlier, reinforced concrete elements designed to meet the requirements of the AASHTO LRFD specifications possess a fair amount of internal redundancy and the ability to form cracks to distribute and redistribute internal stresses prior to failure.

Conclusion

Concrete bridges have the advantage of possessing to varying degrees all three types of redundancy discussed in this article. Structural indeterminacy, load path redundancy, and internal redundancy serve as three layers of protection for concrete bridges. These redundancies lead to the presence of alternative load paths and give concrete bridges different lines of defense if they are subjected to extreme loading conditions during their service lives. As we move forward in the 21st century, bridge engineers must give due consideration to redundancy when introducing new structural systems, technologies, and construction methods.

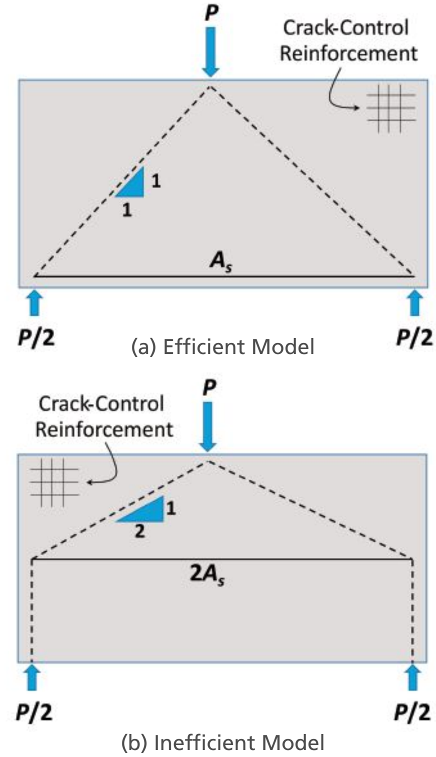


Figure 3. Internal redundancy of a member accommodates two different strut-and-tie model designs.

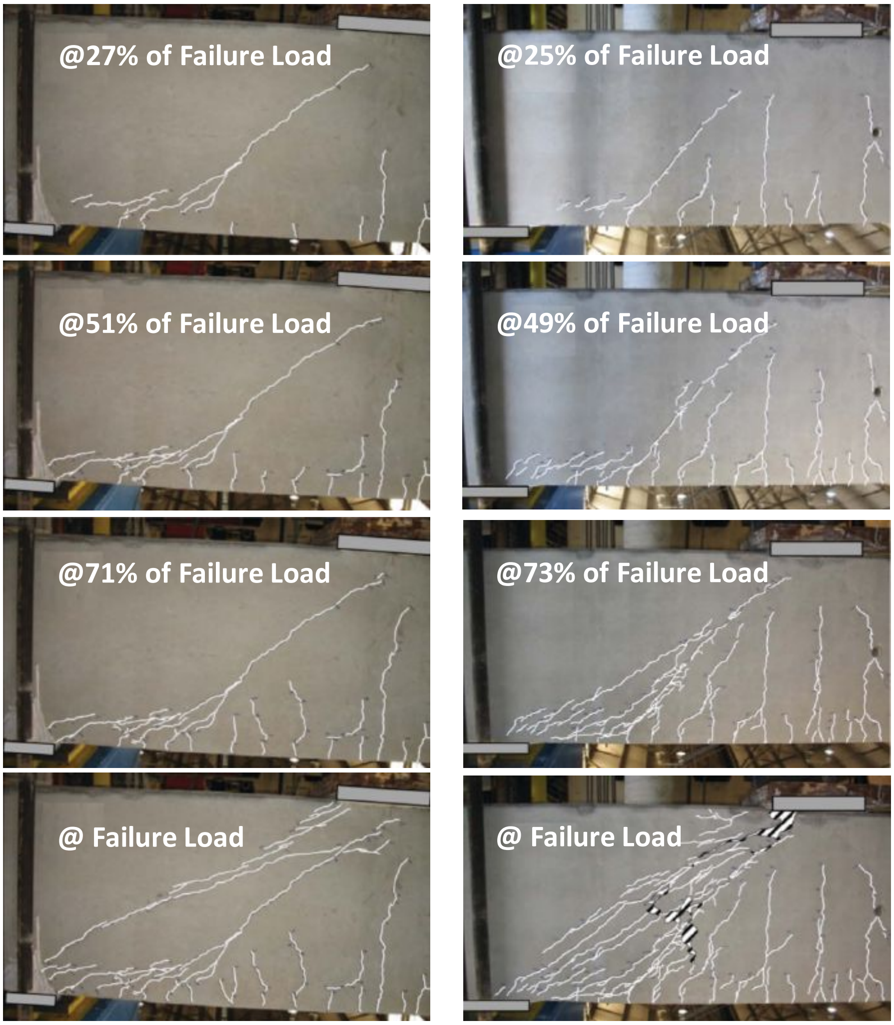


Figure 4. Redistribution of internal stress (internal redundancy) is illustrated by the different cracking behaviors of two deep beams with different reinforcement. The specimen on the left does not have any crack-control reinforcement, whereas the specimen on the right contains 0.3% crack-control reinforcement in both directions.

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2017. ***AASHTO LRFD Bridge Design Specifications***, 8th ed. Washington, DC: AASHTO.
2. Birrcher, D.B., R.G. Tuchscherer, M.R. Huizinga, O. Bayrak, S.L. Wood, and J.O. Jirsa. 2009. ***Strength and Serviceability Design of Reinforced Concrete Deep Beams***. Technical Report 0-5253-1. Austin: Center for Transportation Research, Bureau of Engineering Research, University of Texas at Austin.

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