PROJECT SUMMARY REPORT

0-7114: Re-examine Minimum Reinforcement Requirements for Shear Design

Background

Minimum shear reinforcement requirements are crucial for the structural integrity of prestressed concrete girders. However, current design standards often rely on past experimental data, which may not account for new materials, such as high-strength concrete and steel, or larger girder sections. The significant differences in minimum shear reinforcement requirements often provided by different standards further increase uncertainty, highlighting the need for a comprehensive evaluation.

What the Researchers Did

A comprehensive literature review was performed, which studied shear failure modes and shear transfer mechanisms, and identified design parameters that affect shear capacity and minimum shear reinforcement requirements. Subsequently, minimum shear reinforcement provisions in major design codes were comparatively evaluated. These design codes include the 2020 American Association of State Highway and Transportation Officials (AASHTO) *LRFD Bridge Design Specifications*, ACI 318-19, and design standards adopted by different U.S. states. The available literature was further reviewed to identify studies from shear tests on prestressed girders, and a comprehensive dataset including data from 87 experimental studies was compiled. Exploratory data analysis on this dataset was then performed to identify trends, patterns, and correlations among major design parameters and to inform the selection of girder specimens for an experimental program that would complement the compiled dataset.

The executed experimental program included shear testing of 22 Texas Department of Transportation (TxDOT) prestressed concrete girder designs within 11 girder specimens (Figure 1). These designs included two cross-section depths (Tx54 and Tx70), three shear span-to-depth ratios (2.5, 3, and 4), straight and harped tendons, standard (GR60) and high-strength stirrups (GR80), different axial prestressing ratios, and various stirrups spacings and shear reinforcement ratios that resulted from different design assumptions. Additionally, parametric finite element analyses were conducted to provide information on girder designs that were not included in the dataset or the test specimens. The compiled dataset, complemented by the data from the executed experimental program on Tx54 and Tx70 girders, was used to derive mechanics-informed data-driven models using nonlinear regression and genetic programming to predict the shear capacity of girders at the onset of diagonal cracking and at failure. These models, along with existing models in design standards, were used within a proposed reliability analysis framework to derive minimum shear reinforcement requirements accounting for uncertainty in model predictions. The derived requirements were included within proposed design guidelines.

Figure 1. Shear Testing of Full-Scale Girder.

Research Performed by:
Texas A&M Transportation Institute

Research Supervisor:
Petros Sideris, TTI

Researchers:
Anna Birely, TTI
Mary Beth Hueste, TTI
Stefan Hurlebaus, TTI
Maria Koliou, TTI
Stephanie Paal, TTI
Nikhil Potnuru, TTI
Wonsuh Sung, TTI
Suhaib Alfaris, TTI

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What They Found

Major observations and findings include:

- The reserve shear strength (RSS), which is defined as the ratio of the strength at shear failure over the strength at the onset of diagonal cracking, was the key parameter in determining minimum shear reinforcement requirements. Commonly, the minimum shear reinforcement ratio is derived using a preselected value of RSS. Because it accounts for prestressing effects, ACI 318-19 was found to require larger minimum shear reinforcement ratios than the AASHTO LRFD specifications. Typical TxDOT girder designs adhere to AASHTO standards, including a maximum stirrup spacing of 12 in. for Tx28 to Tx34 girders and 18 in. for Tx40 to Tx70 girders.
- Exploratory data analysis revealed that most gaps in research were associated with the limited tests on larger girder depths, which led to adoption of Tx54 and Tx70 girders in the executed experimental studies. The full-scale tests showed that unless full composite action is achieved, the presence of a deck slab may not significantly affect the shear strength of the prestressed girder. Lower stirrup spacing increased RSS, as did the use of high-strength stirrups. Harped strands increased shear capacity and RSS, particularly in the case of larger stirrup spacings. Higher prestressing ratios and larger concrete strengths improved shear performance, with more closely spaced diagonal cracks and increased shear strengths. However, higher prestressing ratios and larger concrete strengths reduced RSS, implying that larger minimum shear reinforcement would be needed. Lower shear-span-to-depth ratios resulted in higher RSS, and this difference increased for lower stirrup spacing. Larger cross-section depths (Tx70) exhibited lower RSS, implying that they would need larger minimum shear reinforcement ratios. Except for one design with a Tx70 girder that achieved an RSS of 1.28, all selected stirrup designs achieved an RSS of 1.35 or higher. The findings of the finite element analyses aligned with the experimental observations. Particularly for the presence of deck slab, the finite element analyses showed that when interfacial sliding is prevented, higher shear strength and RSS can be achieved.
- The development of mechanics-informed data-driven models showed that solely data-driven modeling may not be efficient due to the inherently low number of data points in this type of application. The use of physics-based conditions was found to improve the predictive capabilities of such models. While selection of appropriate RSS values has often been somewhat subjective, the formulated reliability analysis framework enabled connecting RSS values with probability limits that are associated with model uncertainties. For a 5 percent probability limit, an RSS of 2 is obtained for the AASHTO minimum shear reinforcement ratio equation, while an RSS of 1.33 is obtained for a minimum shear reinforcement ratio equation derived using the mechanics-informed data-driven models. Most importantly, this reliability analysis framework provides a way to connect minimum shear reinforcement ratios derived from different models by accounting for model-specific uncertainties.
- Using both models in design examples, researchers observed that the minimum shear reinforcement ratios produced by the data-driven model and by the modified reliability model based on the AASHTO LRFD specifications (with an RSS of 2) were close. The former resulted in slightly lower reinforcement requirements due to its higher accuracy. However, both models required more shear reinforcement than that required by the current AASHTO LRFD specifications. This new minimum shear reinforcement ratio, together with a new maximum spacing based on girder depth, aligned well with TxDOT's standard drawings and the ACI 318-19 provisions.

What This Means

TxDOT I-girders make up a significant portion of the Texas bridge inventory. Current design codes often require different minimum shear reinforcement for a given girder section, creating uncertainty. A new minimum shear reinforcement ratio equation is proposed that accounts for model uncertainty, that is, the capability of the model to predict experimental data. The adopted models account for a wide range of test data including the data produced from the executed tests on large TxDOT girders. An updated maximum stirrup spacing is also proposed based on girder depth so that a minimum of two stirrups cross each diagonal crack.

For More Information

Project Manager:
Jade Adediwura, TxDOT, (512) 486-5061

Research Supervisor:
Petros Sideris, TTI, (979) 845-2708

Project Monitoring Committee Members:
Zoran Umicevic, Steven Austin, Courtney Holle, Niyi Arowojolu, Lianxiang Du, Yi Qiu, and Joe Roche

Research and Technology Implementation Office
Texas Department of Transportation
125 E. 11th Street
Austin, TX 78701-2483

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