CENTER FOR TRANSPORTATION RESEARCH

PROJECT SUMMARY

Texas Department of Transportation

0-7039: The Development of Knowledge in the Application of Strut-and-Tie Method

Background

The strut-and-tie method (STM) is a simple and widely used method for designing D-regions in reinforced concrete members. Despite its incorporation into major design codes and continuous refinement over the past century, there are still areas that require further research. These include the use of 3D strut-and-tie models for designing drill shaft footings under eccentric axial loads, the use of curved-bar nodes in closing knee joints, the provision of appropriate confinement to enhance nodal strength, and the relaxation of the "d/4 limit" on crack control reinforcement spacing based on experimental data. Addressing these knowledge gaps would improve the applicability and cost- effectiveness of STM in reinforced concrete deep member design.

What the Researchers Did

To bridge these knowledge gaps, the research team conducted a thorough review of past studies and design codes relevant to the application of the STM and identified research needs and design parameters. Based on the results of the literature review, the research team developed four large- scale structural experimental programs, each of which aimed to expand the applicability of the STM on one of the four design scenarios aforementioned.

The first experimental program was to investigate the anchorage behavior of drilled shaft reinforcement under tri-axial tension in the 3D STM. Two drill shaft specimens, each of which had two test regions, were designed to resist a stress flow that could be represented by a 3D strut- and-tie model in which tri-axial tension affecting the development of the drill shaft reinforcement. Test variables included the anchoring mechanism: straight bars versus headed bars, and the surface reinforcement ratio: 0.3% versus 0.15%.

The second experimental program was developed to investigate the behavior of curved-bar nodes. In this experimental program, nine portal specimens, each had two knee joints, were tested under closing moments that formed a curved-bar node at the outside of the joints. Test variables included the bend radius, the diagonal strut angle, and the arrangement of the longitudinal reinforcement.

The third experimental program included three deep beam specimens, each of which had two test regions. Under shear force, each test region had a strut connecting a CCC node and a CCT node and therefore the test was to evaluate the strength of the strut when the CCC node or both nodes were confined. The amount of confinement reinforcement also varied.

The fourth experimental program also included three deep beam specimens, each of which had two test regions. Each test region, similar to the third experimental program, was tested under shear load. The test regions were assigned the minimum required orthogonal crack control reinforcement ratio but with either the horizontal spacing or the vertical spacing relaxed.

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For each of the experimental programs, finite element analysis (FEA) was employed to provide supplement insights into the behavior of the test specimens before or after the actual structural testing.

What They Found

Based on the test results, the researchers made several primary findings as follows:

1. Test results of the drill shaft specimens showed that the design recommendation of Project 0-6953 regarding anchorage checks using a fan-shaped compression zone for the drilled shaft reinforcement is still valid and found to be conservative, even if the surface reinforcement does not comply with the minimum required crack control reinforcement.
2. Further, test results of the closing knee joints indicated that enlarged bend radii per the given equation for radial stresses in curved-bar nodes are needed to develop ductility and avoid compromised strength in closing knee joints whether the diagonal strut angle is 45-degree or not. On the other hand, the equation that addresses circumferential bond stresses appears to be overly conservative and unnecessary.
3. Tests of the deep beams in the third experimental program found that confining the CCC and CCT nodal zones of a strut simultaneously enhances its strength by 10% when effective confining reinforcement of 1.0% is provided in both directions.
4. Tests of the deep beams in the last experimental program revealed that relaxing the requirement of spacing leads to a slight reduction in the strength of the strut. Nevertheless, the STM still is still valid and delivers conservative design.

What This Means

The findings provide valuable insights into the behavior of drilled shaft reinforcement under tri- axial tension, the effect of the bend radius at the outside of the frame corner on joint shear capacity, the effect of nodal zone confinement on nodal strength, and the effect of relaxed spacing requirement for crack control reinforcement. The researchers recommended design guidelines and provided a design example based on the test results and data interpretation. In addition, the researchers provided thorough procedure of using the STM on reinforced concrete deep members that appear in this research. The information presented in the research significantly expand the availability of the STM and will be useful to structural engineers in the field of reinforced concrete design and will lead to more efficient and cost-effective design solutions for reinforced concrete deep members. In addition, the researchers proposed code provisions that are ready to be implemented for AASHTO LRFD and TxDOT. However, the results of the research indicate that there are still test variables that require further research and experimental data to optimize the use of the STM.

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