Design of Deep Beams with Openings using Strut-and-Tie Models

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Summary

An experimental study was initiated to observe the strength of reinforced concrete deep beams with openings. Six beams were designed using three strut-and-tie models (STMs) developed according to ACI 318-05. For the first three beams, only the principal reinforcement required for equilibrium was placed in the specimens in general. For the final three beams, minimum distributed reinforcement was placed throughout the specimen, additional anchorage lengths were provided for critical ties, and confining spirals were added to highly-stressed nodal regions. The failure loads of the first three beams ranged from 75 to 84% of the nominal strength requirement. The failure loads of the final three beams ranged from 112 to 160% of the nominal strength requirement. Based on the test results, it was evident that the use of unreinforced bottle-shaped struts and the improper detailing of critical regions of the STM contributed to the unconservative failure loads.

Keywords: Strut-and-tie models, detailing, minimum reinforcement

1. Introduction

In strut-and-tie modelling, a truss composed of compressive struts, tension ties, and nodes is developed to design reinforced concrete structures with loading or geometric discontinuities [1]. According to the design method, the forces in the truss must satisfy equilibrium and the material strength of the truss members must not be exceeded. In addition, adequate detailing, especially in regards to anchorage and bearing locations, is essential to achieve satisfactory results.

2. Experimental Program

Three strut-and-tie models were developed to design the reinforced concrete beam depicted in Figure 1-(a). A finite element analysis (FEA) was used as a starting point for the development of each STM (Figure 1-(b). The struts, ties, and nodes of each STM were checked according to ACI 318-05 Appendix A.

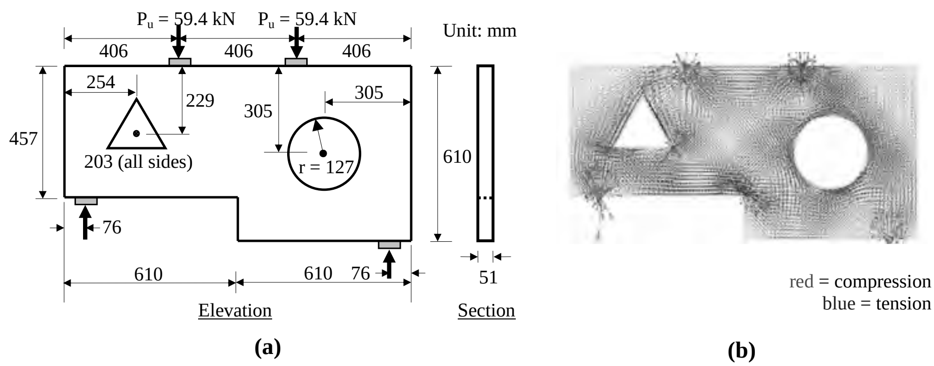

Figure 1: (a) geometry and loading conditions of specimen. (b)FEA results

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Two beams were fabricated according to each STM. For the first beam (Series 1), only the minimum principal reinforcement required for equilibrium was used in general. For the second beam according to each model (Series 2), design improvements were made based on the test results of the first beam. The improvements consisted of adding minimum distributed reinforcement (0.25% in both orthogonal directions), increasing anchorage lengths of critical ties, and placing confining spirals in highly-stressed nodal regions.

3. Results

The failure loads of the six test specimens are depicted with the nominal strength requirement in Figure 2. It is clear that the Series 1 beams did not reach the required strength. Beam 1-1 and 2-1 failed prematurely because bottle-shaped struts with either no or little distributed reinforcement, as allowed in ACI 318-05, failed before their design strengths were reached. Beam 3-1 failed prematurely due to insufficient anchorage.

All of the Series 2 beams (1-2, 2-2, and 3-2) failed at higher loads than the nominal strength requirement. Premature anchorage and bearing failures were avoided with proper detailing. Also, the distributed reinforcement in the bottle-shaped struts enabled the full design strength of these struts to be reached. In fact, for all of the Series 2 beams, the failures were instigated by the crushing of a concrete strut.

The higher failure loads of the Series 2 beams were also affected by distributing the minimum reinforcement throughout the specimen. Alternate load paths were created that were not accounted for in the original STM. Schlaich et al. recommended the use of overlapping, determinate strut-and-tie models to produce a redundant structure that is simple to analyze [1]. The minimum reinforcement in the Series 2 specimens provides this same simplistic redundancy.

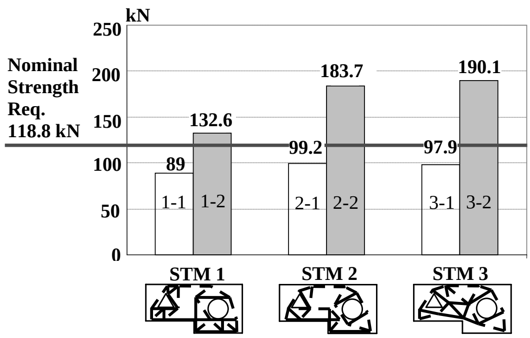

Figure 2: Failure loads

4. Concluding Remarks

Based on the results of the six deep beams tested in this study, the following observations were made:

1). Bottle-shaped struts with little (less than 0.15% in each direction) or no reinforcement did not reach their design strength according to Appendix A of ACI 318-08

2). Minimum distributed reinforcement in bottle-shaped struts (0.25% in each direction)

- Allowed the design strength of all struts to be reached.
- Provided redundancy to the structure without the use of an indeterminate STM or overlapping STMs.
- Restricted shrinkage cracking.

3). Proper detailing in regards to anchorage and bearing locations is essential to achieve the required design strength of the STM.