Topology Optimization for Reinforced Concrete Design using Bilinear Truss-Continuum Material Models

Yang Yang[1], Andrew T. Gaynor[1], James K. Guest[1], Cris Moen[2]

[1] *Department of Civil Engineering, Johns Hopkins University, Baltimore, MD, USA*
yyang61@jhu.edu, agaynor1@jhu.edu, jkguest@jhu.edu,

[2] *Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, USA*
cmoen@vt.edu

Abstract

Strut-and-tie models are a useful tool for designers of reinforced concrete structures and structural members. For a concrete component of general shape with general loading and support conditions, the quantity and location of steel reinforcement can be rationally and conservatively determined with a simple truss model. Although equilibrium is satisfied in a strut-and-tie solution, the flow of tension and compression forces (i.e. the location and geometry of the truss members) must be assumed by the designer. With an infinite number of possibilities, selection of an efficient truss solution that yields minimum steel requirements becomes a challenging task, particularly for complex design domains such as structural domains with cutouts. Topology optimization has therefore been promoted as means of automating the development of highly efficient reinforced concrete truss models. Typically, the concrete and steel phases are assumed to have identical properties and optimization progresses under the assumption of linear elastic mechanics. It can be shown, however, that this assumption leads to solutions that fail to properly account for secondary tensile stresses; that is, the case where the major principal stresses are compressive and minor principal stresses are tensile.

To overcome this shortcoming, a hybrid truss-continuum topology optimization scheme has been developed. The design domain is discretized with both truss and continuum elements sharing nodes to enable force transfer. The stiffness of these elements are then formulated such that truss elements carry only tensile forces and thus represent straight steel rebar, while the continuum elements carry only compressive forces and thus represent the concrete load paths. This is achieved for the truss elements by using a bilinear Young's modulus that is large magnitude in tension and small in compression. For the continuum elements, a stress-dependent orthotropic material model is assumed that is stiff in directions corresponding to compressive principal stresses and compliant in directions corresponding to tensile principal stresses. The resulting governing mechanics model is bilinear, stress and rotation dependent, and thus design dependent. The design goal is then to optimize the truss areas (tensile load paths) and continuum volume fractions (compressive load paths). The algorithm is demonstrated on several benchmark design examples including beams with cutouts, hammerhead bridge piers, and three-dimensional domains. Consideration of construction costs is also discussed. Results are shown to produce high quality steel reinforcing patterns that are load direction dependent and properly capture and address the development of minor principal stresses in tension.