Abstract

Plane reinforced concrete (RC) elements are used in a large variety of structures. Their principal function is to carry forces that act in the plane of the element, but external actions and connections to other structural elements generally introduce additional out-of-plane forces. In practice, the design of such elements is often performed in a simplified manner, neglecting the interaction between these different internal forces. However, especially for existing structures the need for more precise and kinematically consistent analysis tools arises. This thesis provides novel tools based on the elastic-plastic stress field (EPSF) method to investigate the interaction between in-plane and out-of-plane forces in plane RC elements in general and the effect of transverse bending on the longitudinal shear resistance of beams in particular.

A general multi-layered (ML) EPSF approach is developed. Applied to a unitary web segment, in-plane shear-transverse bending interaction diagrams are established and compared to existing rigid-plastic (RP) interaction models. In general, it is found that the influence on the shear resistance is less pronounced, especially in case of small transverse moments. The shear transfer actions admitted in RP models that consist in a shift of the compression field to the bending compression side and a rearrangement of the stirrup forces are confirmed. However, it is shown that the stress field is highly non-linear in the transverse directions (stress/strain distribution and inclination) and strongly depends on the intensity of the applied transverse moment. The concrete strength reduction factor η_ε is generally higher and high shear reinforcement ratios or asymmetric layouts allow equilibrating small moments without disturbing the stress field in the concrete. This increases the predicted shear resistance. The longitudinal deformation is shown to have a non-negligible effect on the overall interaction and ultimate resistance.

A simplified verification method for beams in practice is proposed. Based on the EPSF finite element method (FEM), it considers the influence of the transverse moment by means of a reduced web width and an effective shear reinforcement ratio. Validation with tests from the literature gave safe but not overly conservative results and consistent predictions of the failure modes. The method provides enhanced lower-bound solutions.

Plane EPSF analyses of experimental tests suggest that the influence of the transverse bending moment in beams is less pronounced than predicted by interaction models, especially if ductile failure modes occur. However, more experimental data is required to validate this observation.

A non-linear FEM based on the ML-EPSF is developed. It aims to extend the field of application of the EPSF FEM by accounting for in-plane (normal and shear) and out-of-plane (bending and shear) actions in plane RC elements. Concrete is modelled by ML in-plane elements that are combined with out-of-plane shear elements. Reinforcing steel is modelled separately by bar elements. Benchmark tests and validation with experimental data show that the proposed FEM is a promising tool for the design and assessment of plane reinforced concrete elements primarily subjected to combinations of in-plane forces and out-of-plane bending moments.

Keywords

Reinforced concrete flat shell elements, elastic-plastic stress fields, multi-layered stress fields, shear resistance, interaction of in-plane shear and transverse bending, non-linear finite element method.