

Finite Element Analysis of Shear Critical Thin-Walled Reinforced Concrete Structures: A Review

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Abstract: Reinforced concrete wall-type structural elements are widely used in large-scale construction due to their high strength-to-mass and stiffness-to-mass ratios. To reduce material consumption and self-weight, these structures are designed as thin-walled systems, making accurate analysis essential. Finite Element Analysis (FEA) is commonly employed to predict their behavior by modeling them as assemblies of plane stress elements. The effectiveness of FEA depends on robust material models capable of capturing nonlinear behaviors such as stiffness degradation. These elements are extensively applied in critical structures such as bridge piers, shear walls, deep beams, and containment vessels. This study highlights the importance of efficient design and advanced modeling techniques for ensuring the structural performance and reliability of thin-walled reinforced concrete systems..

Keywords: Reinforced Concrete, Wall-Type Structures, Thin-Walled Systems, FEA, Plane Stress Elements.

I. INTRODUCTION

The FEA of reinforced aggregate components constitutes a mathematical challenge due to the irregular nature of the fundamental interactions of both reinforcing and cement. The response of RC structural elements depends on the composite material action of steel and heterogeneous concrete each of which has its own individual characteristics. Hence, a clear understanding on the element level material response of RC structures is very essential. Scientists established numerous logical mathematical 2-D (2D) frameworks over the past 50 years to comprehensively analyse the elemental activity and examine the full curvilinear response of reinforced concrete (RC) walls systems. However, majority of these models cannot predict the complete nonlinear behaviour in all damage stages (which includes pinching effect, post peak strength degradation, stiffness degradation and shear contribution of concrete) and has limited applications. Besides, models such as Equilibrium Plasticity Truss Model also do not fit into the finite element analysis framework since they were developed based on the force equilibrium equations and neglected the compatibility conditions. Several researchers developed finite element tools and implemented some of these models in frameworks such as Vector (Polak and Vecchio 1993 and Hrynyk 2013), FEAP (Taylor 2014), ABAQUS (Abaqus 2011), OpenSEES (McKenna et al. 2009) etc. In the present study, C++ based finite element framework, Open S.E.E.S had being used as the primary tool for analysing RC wall type structures with the proposed material models.

Variable Angle Truss Model

45° Truss model was modified by Kupfer (1964) by considering the orientation of the diagonal cracks as an unknown parameter as shown in Figure. The additional unknown parameter introduced into the equilibrium equations was derived from energy principles assuming both concrete and steel materials as linearly elastic materials.



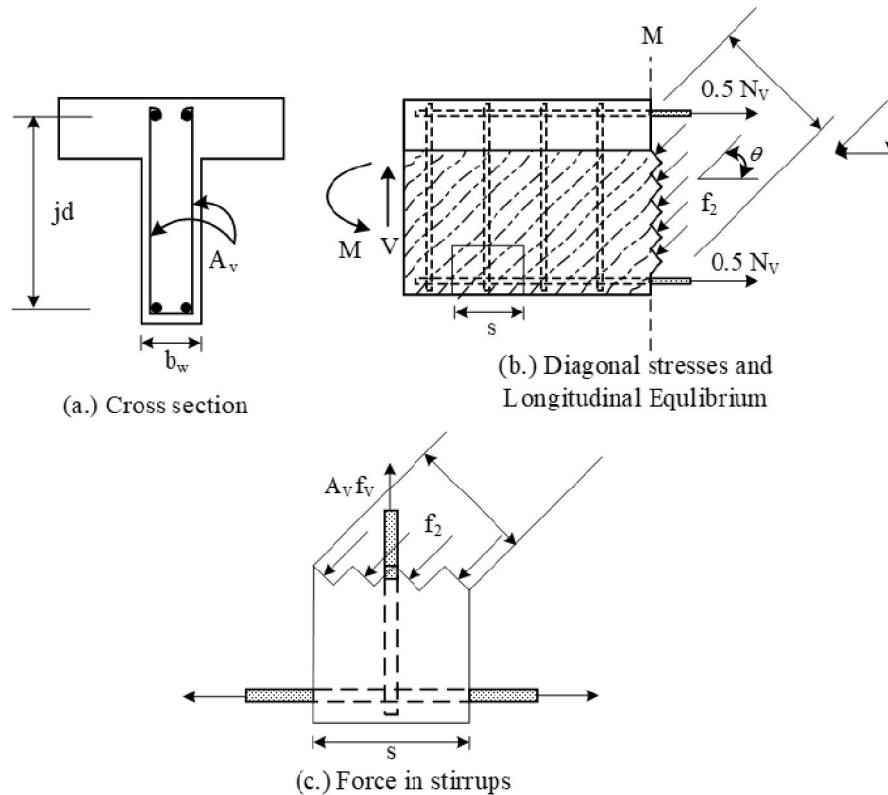


Figure 1. Variable Angle Truss Model Considerations

Where, V is the shear force, j is the lever arm factor and d is the effective depth of the cross section, b_w is the width of the web, A_v is the area of shear reinforcement, N_v is the force in the reinforcement bars, f_2 is the effective principal compressive stress, f_v is the force in the shear stirrups and s is the stirrup spacing.

In this system, the stress equilibrium eqⁿ were derived from Navier's first principle of mechanics of materials by assuming the transverse and longitudinal steel were smeared between the diagonal cracks. The tensile stress in concrete between the cracks was neglected. The orientation angle αr of the diagonal cracks and the shear stress in concrete was obtained by considering an element in pure shear and assuming the transverse and longitudinal steel yield at failure. This model is primarily used for calculation of ultimate strengths in 2D RC elements and cannot be used for predicting complete load deflection curves of 2D RC elements.



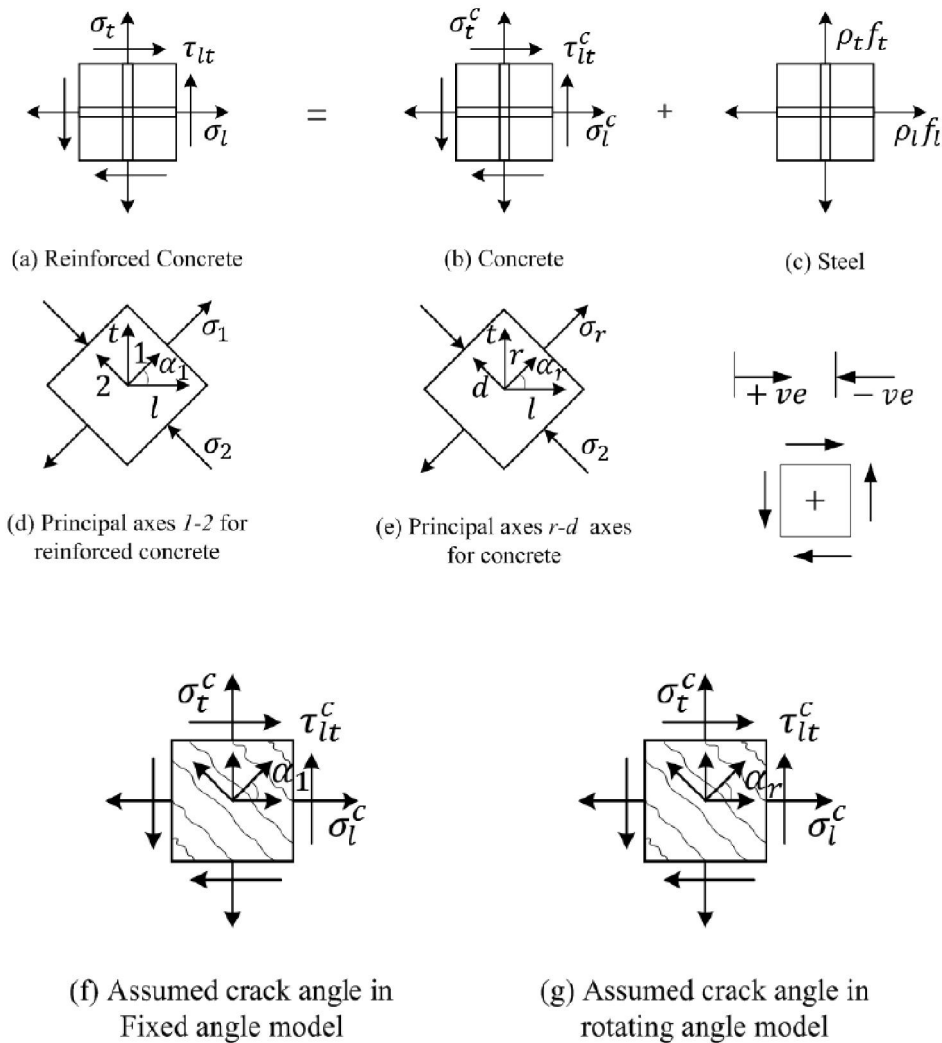


Figure 2. Element Stresses in Reinforced Concrete, Concrete and Reinforcing Steel Materials

Mohr Matching Torsion Framework

The balance Polymer Truss System excluded stress tolerance as well as the deterministic relationships of substances. Strain suitability formulas were initially formulated by Nagel (1972) and Phillips (1973). Phillips (1978) formulated the Murphy Compliance Truss System by developing a comprehensive set of formulae based on load balance, tension adequacy, & Hooke's rule. This framework determined the rotation angles of the horizontal cracks by employing strained compatible equations rather than relying solely on a purely shearing stress situation. The orientation angle r of the diagonal cracks was determined using Eqn . The strain in steel was taken to be the constitutive relationships of steel and concrete were assumed linear and tensile strength of concrete was neglected. Mohr Compatibility Truss Model was more realistic in comparison to the Equilibrium Plasticity Truss Model as the orientation of the diagonal cracks in this model coincided with the principal compressive stress direction in concrete.



As linear constitutive relationships were used for both concrete and steel, this model is applicable for analysis of RC elements under monotonically applied service loads and cannot predict the post peak strength as well as stiffening degradation & pinching effects via cyclic loading. The concrete contribution to shear also cannot be predicted using this model. Thus, the Mohr Compatibilities Truss system followed a more generalised approach compared to the previous one.

The direction of principle compressive stress was assumed to be equal to the direction of principle compressive strain. Thus, the orientation of the diagonal cracks was expressed in terms of principle compressive strain in this model. The softening of the principal tensile strains was first observed by Robinson and Demoreix (1968). However constitutive relationship incorporating the softening of concrete was first proposed by Vecchio and Collins (1981) using the results of RC panels tested using a shear rig apparatus at the University of Toronto. CFT could well predict the behaviour of RC elements up to the ultimate load as it considered the softened stress strain curve of concrete. However, CFT overestimated the deformation of RC elements because it assumed the principle tensile stresses in concrete to be zero & proposed in the CFT are shown in Figures 3 and 4.

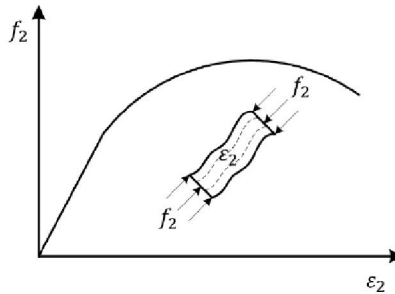


Figure 3. Constitutive Relationship of Concrete Used in CFT

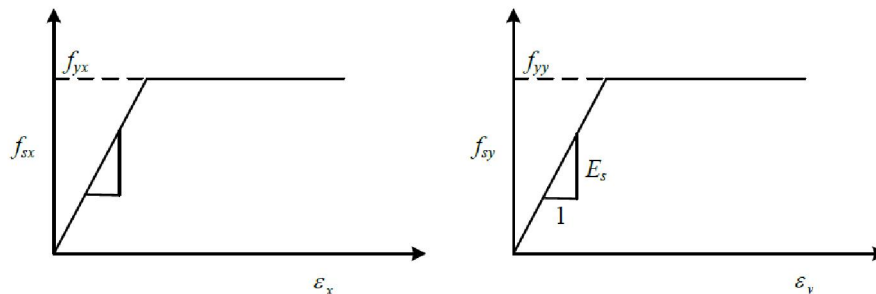


Figure 4. Constitutive Relationship of Transverse and Longitudinal Steel Used in CFT

II. CONCLUSION

The existing image processing and ML originated crack detection have limited performance due to irregular crack shapes, branching patterns, overlapping, and complex concrete structures. The existing image processing-optimized methods primarily focused on the detection of cracks without extracting the proper ROI. The ML crack detection models rely heavily on handcrafted features such as texture, edge, or colour descriptors that increase human intervention and computation error. The availability low resolution noisy crack images dataset is another main issue that hinders the overall efficacy of existing methods. The manual parameter tuning has been used in image processing-initiated methods, which makes the overall process more iterative and complex. The DL-based crack detection methods suffer from overfitting due to a limited and imbalanced dataset. The image processing-based crack detection has illustrated only qualitative analysis to judge the effectiveness of the method. The DL-based crack detection and



localization methods have difficulty in handling small and hairline cracks that often occupy a tiny portion of the image. The literature reveals that very few web tools or GUI are available for real time crack assessment.

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