(V－66) THREE - DIMENSIONAL MODELLING OF REINFORCED CONCRETE MEMBERS SUBJECTED TO TORSION

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1. INTRODUCTION

The objective of this study is the full three-dimensional simulation of plain concrete and reinforced concrete members subjected to torsion. Concrete and the reinforcing bars are combined to a composite finite brick element. A concept of 3D RC-zoning and anisotropy of strain softening/stiffening is discussed. The whole torque-twist relationship up to the ductility limit can be numerically simulated in a uniform manner and agrees well with the one experimentally obtained.

2. RC BRICK ELEMENT

2.1 GENERAL CONCEPT

By combining the constitutive laws of average stress and average strain for concrete and reinforcement [8], respectively the RC brick element has been constructed [2]. Concrete is, separated by crack initiation, treated in an un-cracked or a cracked concrete routine. In the pre-cracking range the triaxial elasto-plastic and fracture model for concrete [5,2] is employed. After the introduction of cracks 3D continuity is assumed to be broken and smeared crack modelling of 3D based on cracked concrete in-plane constitutive law is employed [6]. The crack analysis routine is composed of tension stiffening/softening model across cracks, compression softening model parallel to cracks and shear transfer model along cracks [8]. For reinforcement orthogonal arranged in space distributed representation without dowel shear stiffness had been adopted. The localisation of initial steel plasticity close to cracks and bond slip effect are considered in computing the mean stress-strain relation based on the local bond-slip behaviour [8].

2.2 RC-ZONING AND ANISOTROPY OF SOFTENING

To consider the different post-cracking behaviour of concrete close and far from reinforcing bars, RC-zoning [1] is used. In the RC-zone, cracking is highly controlled by bond with reinforcement hence stiffening models are employed, while in the plain concrete zone sharp softening is assumed. RC-zoning is applied in all three directions of the orthogonal reinforcement system, respectively [2]. In order to avoid spurious mesh dependence plain concrete softening has to be defined by means of fracture mechanics requirement. Softening is obtained from fracture energy in association with the reference length on which the average softening stress-strain relation of the smeared crack element is deterined. The reference length is defined depending on the 3D crack inclination [2]. Stiffening in the RC zone, on the other hand, had been found to be independent of the FE mesh [8]. However, if a control volume contains reinforcement only in one or two directions the average softening/stiffening behaviour depends on the crack inclination relative to the bar. A crack normal to reinforcement will exhibit stiffening due to bond while the other parallel crack would be softening. Consequently, a crack which is neither parallel nor normal to a reinforcing bar but discretionary inclined must show a mixed softening/stiffening behaviour (Fig. 1). It might be opportune to call this dependency of reinforced concrete post cracking behaviour on the crack orientation with respect to reinforcement anisotropy of softening. An interpolation scheme based on released fracture energy [2] is employed to define the softening/stiffening behaviour of an arbitrary inclined crack.

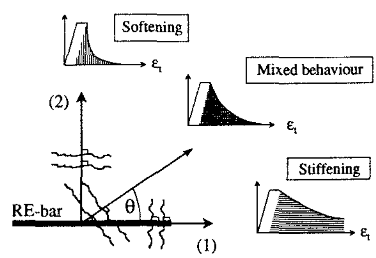

Figure 1 Anisotropy of softening

3 APPLICATIONS & VERIFICATIONS

To verify the general analysis frame of concrete and mesh objectivity in inclined cracking situations, unaffected from reinforcement, RC-zoning or tension stiffening formulations, a plain concrete torsion beam [3] with square cross section is analysed. Three different meshes are investigated: a coarse, standard and fine mesh. The results (Fig. 2) indicate an acceptable prediction of cracking and ultimate torque. The required objectivity with respect to mesh refinement seems to be given.

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The concept of 3D RC-zoning and anisotropy of softening are to be scrutinised by analysing torsion beams with full three-dimensional load bearing mechanisms. In the general formulation of strain softening model, coupling of tension and shear softening had been assumed. Taking into account that hoop reinforcement may confine the specimen, preventing shear transfer loss along cracks, shear softening is assumed to be less significant in 3D and negligible rather than in 2D. The results of computed torque-twist relationships are compared with experimental data [7] in Fig. 3, indicating that neglecting shear softening is reasonable.

To further solidify the analysis scheme solid and hollow torsion RC beams are utilised. From an abundance of tested beams [4] four with solid (VH-series) or hollow (VQ-series) square cross sections, respectively were selected. For all beams axial and lateral reinforcement ratio coincide. Specimens VH2 and VQ4 are distinguished from specimens VH1 and VQ1 by a 50% higher amount of reinforcement. The results of numerical simulation are compared with experimental data in Fig. 4. For both reinforcement ratios the numerically obtained torque-twist relationship of the solid section agrees fairly with the experimental one up to the ductility limit. It should be noted that for the low reinforcement ratio the ultimate capacity of hollow and solid beams almost coincide while for the higher reinforcement ratio the hollow specimen is correctly predicted to have a slightly higher ultimate torsion capacity. This can be explained by the higher deformability of the hollow beam which is, unlike the solid specimen, not constrained by a core without post-cracking resistance contribution.

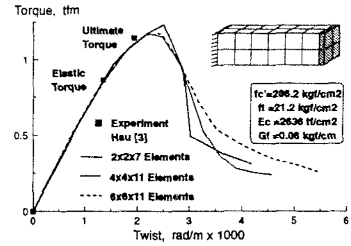

Figure 2 Plain concrete torsion

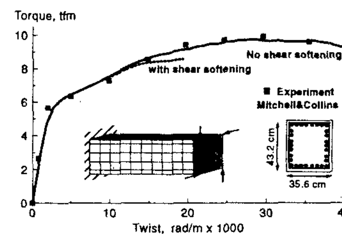

Figure 3 Torsion RC beam

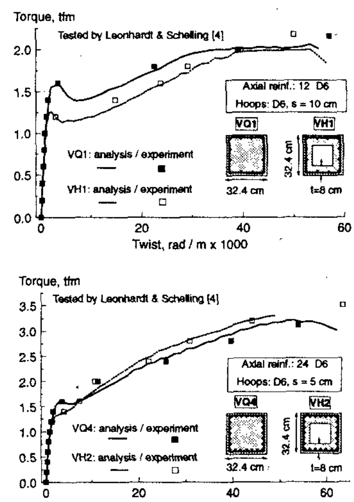

Figure 4 Solid + hollow torsion RC beam

4. CONCLUSIONS

Full three-dimensional analysis scheme of reinforced concrete was presented for RC solids with multi-directional cracks, and their applicability under monotonic forces was examined. The mesh independence of the formulation was shown. Accounting for anisotropy of tension softening in the 3D domain, a method of three-dimensional RC-zoning and softening parameter interpolation was presented. The proposed framework of 3D nonlinear analysis was successfully applied to the numerical response prediction of torsion beams.

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