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Numerical simulation for seismic performance evaluation of fibre reinforced concrete beam–column sub-assemblages

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ABSTRACT

In the present study, performance of exterior beam–column sub-assemblages designed using normal concrete (NC) and steel fibre reinforced concrete (SFRC) is investigated. Nonlinear finite element method is adopted to analyse the sub-assemblages under reverse cyclic loading. To suit the material models for SFRC, available concrete model is judiciously modified. Cyclic behaviour of reinforcement, concrete (both normal and fibre reinforced) modeling based on fracture energy, bond–slip relations between concrete and steel reinforcement have been incorporated. The study also includes numerical investigation of crack and failure patterns, ultimate load carrying capacity, strain comparisons and formation of plastic hinges, load displacement hysteresis, energy dissipation and ductility. Experimentally validated numerical models are used to study the influence of various parameters on the performance of the beam–column sub-assemblage. Results obtained from experimental investigation were used for numerical validation. The influence of several parameters such as concrete strength, number of stirrups in the joint and amount of steel fibres on joint shear behaviour and strength of beam–column sub-assemblages are investigated. It is found that the failure mode cannot be favourably changed by adding fibres, if the compressive strength of the matrix is too low. It is also observed that the influence of fibre contribution to improve the residual tensile strength and fracture energy is significant and inter-dependent. Further, increase in residual tensile strength of FRC is found to be linear with increase in joint shear strength. In the present study, relationship for strength degradation depending on joint shear deformation for FRC has been established.

1. Introduction

Till recently, numerous earthquakes have caused severe damage or have led to collapse of many structures. Seismic performance of the old structures is extremely alarming. As a consequence, design provisions of different standards are stipulated to use large amount of reinforcement in disturbed regions (D-regions) of newly built structures to attain the required level of ductility insure required structural performance against earthquakes. For instance, beam–column sub-assemblages which are treated as one of the most crucial structural components during earthquake, are required to have very high stirrup reinforcement ratio in the joint region to provide adequate confinement and ductility. On one hand, congestion of reinforcement in joint region brings the difficulty in concrete compaction at site and on the other hand, large diameter and higher percentage of reinforcement bars in beams are difficult to be adequately anchored within slender column widths. Therefore, the application of steel fibre reinforced concrete (SFRC) could be one of the promising alternatives to avoid reinforcement congestion in joint region for confinement and therefore, has the potential to facilitate smooth construction and desired performance under cyclic loading. Further, joint strength, energy dissipation and joint integrity could be improved by taking advantage of confining effect and enhanced mechanical properties provided by fibres. Hence, it is utmost important to evaluate the performance of the beam–column sub-assemblages constructed using normal concrete (NC) and steel fibre reinforced concrete (SFRC), and to find out realistic models (geometric- and material-models, bond–slip, etc. along with other computational issues) for further studies.

Few investigations were carried out for evaluating the performance of beam–column subassemblages using FRC. Henager et al. [1] conducted experimental investigations on concrete joint using fibre reinforced concrete and it was aimed to minimize unwanted steel congestion common to seismic-resistant building

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Nomenclature

c_{ts}	tension-stiffening factor
f_c	concrete compressive strength (cylinder)
f_{ct}	axial tensile strength
$f_{ct,fl}$	flexural tensile strength
$f^f_{ct0,u}$	axial residual tensile strength according to DAfSt Richtlinie Stahlfaserbeton
$f^f_{cflk,L2}$	flexural residual tensile strength according to DAfSt Richtlinie Stahlfaserbeton
$f^f_{ctR,u}$	axial residual tensile strength according to DAfSt Richtlinie Stahlfaserbeton (design value)
$f_{t,res}$	residual tensile strength according to Gebekken et al.
f_{yh}	yield strength of stirrups
G_f	fracture energy
l_e	theoretical bond length of the fibre
l_f	fibre length
V_f	fibre content
w	crack opening
β_u	empirical factor according to DAfSt Richtlinie Stahlfaserbeton to consider application of FRC in combination with reinforcement bars
η_{Vol}	steel fibre volume
$\eta_{\theta l}$	fibre orientation factor.
k^f_F	fibre orientation factor
κ^f_G	geometry factor
ρ_w, ρ_{sw}	volumetric stirrup ratio
$\sigma(W)$	crack opening law
σ_τ	fibre stress at bond failure

joints. It was reported that the modified joints were more damage tolerant and crack resistant than the conventional joints. Filiatrault et al. [2] brought out the potential usage of fibre reinforced concrete for providing more cost-effective ductile beam–column joints subjected to seismic loading. It was found that by reducing the amount of confinement reinforcement in the joint regions and by compensating for the required shear strength by steel fiber reinforced concrete, better performance can be achieved. Bayasi and Gebman [3] pointed out that application of FRC in joint region would lead to increase in hoop spacings within the joint region and reduction in lateral reinforcement in beams and columns, without negatively affecting the performance of the joints under cyclic loading. Parra-Montesinos et al. [4] developed a procedure for damage tolerant beam column joints using high performance FRC composites (HPFRCC). It was emphasized that HPFRCC beam–column joints perform satisfactorily under large shear reversals and the joints were able to sustain a drift of 5.0% with beam rotation capacities of about 0.04 rad. An experimental investigation was carried out by Ganesan et al. [5] to study the effect of hybrid fibres on the seismic performance of beam column joints. Crimped steel fibres and polypropylene fibres were used in hybrid form and high performance concrete was designed for the beam column joints. It was observed that addition of fibres in hybrid form improved many of the engineering properties such as the first crack load, ultimate load, energy dissipation, less stiffness degradation and ductility factor of the composite. Further, efficacy of HPFRCC on improvement of deficient low strength reinforced concrete exterior beam–column joints under reverse cyclic loading was examined by Bedirhanoglu et al. [6]. Maya et al. [7] attempted to develop a methodology for providing connection of precast elements using ultra high performance fibre reinforced concretes (UHPFRC). It was aimed to avoid the typical complex reinforcing details and inefficient construction processes. It was claimed that the proposed configurations using UHPFRC avoids the interference between longitudinal and transversal reinforcement and provides an efficient construction process. An exclusive experimental program was conducted by Caballero-Morrison et al. [8] to study the behaviour of columns subjected to combinations of constant axial and lateral cyclic loads and to assess the role of slenderness, axial load level, transverse reinforcement ratio, and volumetric steel-fibre ratio on the maximum load and deformation capacity of the columns.

The behavior of beam–column sub-assemblages is influenced by several parameters. Further, usage of nonconventional materials such as FRC in beam column joint significantly increases the number of key parameters. Hence, the investigations on the influence of various parameters on the behaviour of beam–column sub-assemblages under cyclic loading cannot be fully studied through experimental investigations. Therefore, validated numerical models are required to study the behaviour of beam–column sub-assemblage with different variables which would pave the way for achieving the better and optimally designed structures.

Lee and Liang [9] proposed a computational model to predict the effective mechanical behavior and damage evolution in fiber reinforced cellular concrete (FRCC). The effective moduli of the FRCC are estimated using micromechanics proposed by Eshelby. Damage mechanics based constitutive model was implemented into a finite element code to predict the performance of typical fiber reinforced concrete. Numerical investigations on the influence of column axial load on the joint shear strength of the exterior beam–column joints were carried out by Haach et al. [10]. It was pointed out that the column axial load made the joint more stiff. It was further observed that a more uniform stress distribution in the joint region was obtained when the stirrup ratio was increased. Shannag et al. [11] formulated a nonlinear static procedure to model the behavior of interior beam–column joints under lateral cyclic loading. It was concluded that the nonlinear static analysis (termed as pushover analysis) seemed to be an efficient tool to predict the structural behavior parameters such as load–deflection and moment–curvature responses of beam–column joints. Papanikolaou and Kappos [12] developed computational framework of three-dimensional nonlinear finite element analysis of reinforced concrete bridge pier sections for providing convenient transverse reinforcement arrangements to enhance both the strength and ductility. An emphasis was given for modelling of constitutive laws for materials and confinement effects. To simulate the structural responses of the reinforced concrete specimens with severe geometric and material nonlinearity, Yu and Tan [13] proposed a component-based joint model. Macro model-based finite element analysis with fiber elements was adopted and bond–slip behavior under large tension was simulated using series of springs. Masi et al. [14] numerically analysed the beam column joints. Numerical simulations were used to evaluate the stress distribution in the joint panel as a function of the axial load and to quantify the beam rebar deformations. Collapse mode due to the failure of beam longitudinal rebars was investigated. Numerical investigations on behaviour of steel fibre reinforced concrete beam–column joints were carried out by Abbas et al. [15]. The joints were subjected to reverse cyclic loading and constant axial force was applied on the column. Further, parametric studies were carried out to evaluate the efficacy of introduction of steel fibres to compensate for requirement of conventional transverse reinforcement. Seismic performance of reinforced concrete rectangular hollow piers made of steel fiber reinforced concrete was investigated