FE analysis of behavior of steel fibre reinforced Ultra-high strength concrete columns Under reversed cyclic loading

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SUMMARY:

Although ultra-high strength concrete with steel fibre has been widely used for civil and architectural engineering, from the difficult of production of ultra-high strength concrete, very little test data was available for the study of characteristics of this material. Therefore, this paper presents results of FE modelling of failure behaviour of steel fibre reinforced ultra-high strength columns under slowly reversed cyclically induced lateral load(hysteric load), for the defining the characteristics of ultra-high strength concrete at various details. High strength concrete was modelled with elasto-plastic model using isotropic hardening and softening because ultra-high strength concrete have small sized-aggregate with homogeneity. Plasticity damaged model was used for the constitutive law for compression and tensile regime. For the simulation of compressive behaviour of ultra-high strength concrete, three uniaxial stress-strain relation and test data were used (AFGC, JSCE and Obata model). Uniaxial tensile behaviour was modelled with two bi-linear model(AFGC, JSCE) and one exponential model(Mansur model). These models well predict compressive and tensile behaviour of steel reinforced ultra-high strength concrete. Steel rebars were modelled with an elasto-plastic constitutive law with Von Mises yield criterion. The FE model was calculated using FEM code, ABAQUS. FE model was compared with previously conducted test data of fibre reinforced columns under reversed cyclic loading. Although FE model predicted high initial stiffness, ultimate load and other characteristics, such as crack propagation and strain concentration at the column-base surface was satisfactorily described. Using proposed FE model, parametric study was conducted. The main parameters are compressive strength of concrete, steel reinforcement ratio and axial load level. Higher compressive strength of concrete reduced energy dissipation area compared with normal strength concrete. Axial load increase lateral load capacity of column but reduce the ductility ratio. For more ductile manner optimal reinforcement was found in the case of 200MPA compressive strength of concrete.

Keywords: ultra-high strength concrete, steel fiber, stress-strain model, FEM

1. INTRODUCTION

Ultra-high strength concrete have been developed through these concurrent decades. Although concrete can endure the severe compressive load, because of the lack of researches, engineered hard to use this material. However, the needs for ultra-high strength material have become higher due to the increase of vertical load of concurrent high-rise buildings. Because high-rise buildings have very high vertical load and self-weight, it is very vulnerable to the earthquake excitation. Generally, high strength concrete have shown very brittle failure and this is very dangerous under shear load. Brittle characteristics of ultra-high strength concrete should be changed to more ductile, enduring severe earthquake excitation. Brittleness of ultra-high strength concrete can be reduced using the steel fibre. Using ultra-high strength concrete of 200MPa compressive strength and Choi et al(2012) carried out the experimental study for stress block parameters and compression behaviour of ultra-high strength concrete of 150MPa. Verification of shear strength and flexural strength of ultra-high strength concrete with steel fibre was verified extensively, there are a few studies for the cyclic loading. Therefore, in this study, analytical study was conducted for the

ultra-high strength concrete with steel fibre using FE analysis, describing material characteristics of ultra-high strength concrete(UHSC) and FE model.

2. CHARICTERISTICS OF STEEL FIBRE REINFORCED UHSC

Because characteristics of steel fibre reinforced UHSC can be changed variously, definition of material properties are very important. In this chapter, compressive behaviour and tensile behaviour of steel fibre reinforced UHSC was investigated.

2.1. Compressive Behaviour

Generally, stiffness reduction of matrix of concrete was occurred by the propagation of micro cracks in the matrix and sliding between aggregate and cement matrix. This failure mechanism causes the severe nonlinearity of concrete behaviour under compression. However, UHSC have no coarse aggregate or very small sized aggregate for the homogeneity of matrix. And silica fume and micro silica can be used for increase the density of UHSC. UHSC has the linear strength strain relation until failure. However, very brittle failure would be occurred, because there was no friction between aggregate and matrix. According to this characteristics, stress-strain relation was defined by high elastic modulus and linear relation with sudden drop of stress. Several researchers suggested the stress-strain relation of UHSC and they were illustrated in Table 2.1 and Fig. 1.

Researcher	Equations
Obata(2003)	$\sigma = E_c \varepsilon + (E_c - \varepsilon_m) (\varepsilon / \varepsilon_m)^2, E = 33.5 (\lambda / 2.4)^2 (\sigma_B / 60)^{1/3} [MPa]$
Graybeal(2007)	$\varepsilon_c E$
	$f_c = \varepsilon_c E(1-\alpha), E = 3840\sqrt{f_c'}, \alpha = 0.001e^{0.24f_c'} - 0.001 \text{[MPa]}$
JSCE(2008)	$\sigma_c = \varepsilon'_c E_c$ for $\varepsilon'_c < 0.85 f'_{ck} / E_c \gamma_c$, $\varepsilon'_{cu} = 0.0035$
	E_c could be decided by appropriated test, 50000 MPa could be used for the gereral case
AFGC, Setra(2002)	$f'_{b} = \varepsilon'_{b,el} E_{c}$, E_{c} could be decided by appropriated test, $\varepsilon'_{b,u} = 0.0035$

 Table 2.1. stress-strain relation under compression



Figure 1. Stress-strain relation of UHSC under compression(compared with test data)

Investigating previously suggested method predicting the stress-strain relation under compression, new elastic modulus equation was built for each relation. Guideline did not describe the post failure region however researchers suggested the post peak behaviour.

2.2. Tensile Behaviour

Steel fibre used for the compensate the defect of concrete, low tensile strength. Steel fibre increase the direct tensile strength and flexural strength. Especially, preventing the brittle failure of UHSC, which have no coarse aggregate, steel fibre mixed with UHSC. Tensile properties of steel fibre reinforced UHSC(SF-UHSC) was characterized in JSCE guideline and AFGE Setra Guideline for the SF-UHSC. Because SF-UHSC have higher tensile strength compared with plain concrete, tensile properties would be considered for design of members. The stress-strain relation of SF-UHSC under tension was defined in Table 2.2 and Figure 2. These relations were characterized according to the strain softening or hardening effect.

Researcher	Equations
RILEM(2003)	$\sigma_1 = 0.7 f_{ctb,fe}(1.6 - d), \ \sigma_2 = 0.45 f_{R1} k_h, \ \sigma_3 = 0.37 f_{R4} k_h, \ E_c = 9500 (f_{ctm})^{1/3}$
	$\varepsilon_1 = \sigma_1 / E_c$, $\varepsilon_2 = \varepsilon_1 + 0.0001$, $\varepsilon_3 = 0.025$
JSCE(2008)	σ_3 and $\sigma_1 = f_{tk} / \gamma_c$, $\sigma_2 = 0$
	$\varepsilon_{cr} = \left(f_{tk} / \gamma_c\right) / E_c, \varepsilon_1 = \varepsilon_{cr} + w_{1k} / L_{eq}, \varepsilon_2 = w_{2k} / L_{eq},$
	$L_{eq} / h = 0.8 \left\{ 1 - \frac{1}{\left(1.05 + 6h / l_{ch} \right)^4} \right\}$
AFGC, Setra(2002)	$\varepsilon = \frac{\Delta L}{L_{ch}}, L_{ch} = 2H/3, \varepsilon_{b,el} = f_{b,el}/E, \varepsilon_{b,w1} = w_1/L_{ch}, \varepsilon_{b,w2} = w_2/L_{ch}, \varepsilon_{b,u} = l_f/3L_{ch}$

Table 2.2.	stress-strain	relation	under	compression





3. FE ANALYSIS OF SF-UHSC COLUMNS UNDER CYLCIC LOADING

The test of SF-UHSC columns are very hard to conduct because they need very high compressive strength for simulating the real structural response. Therefore, in this study, FE analysis was used for the verification of structural performance of the member with SF-UHSC.

3.1. Material Models

Simulating inelasticity of ultra-high strength concrete, plasticity based constitutive low would be needed for accurate calculation of finite element model. Important relation of constitutive law for concrete was shown in Table 3.1. SF-UHSC has similar value of compressive strength to

tensile strength ratio and similar behavior in multi-axial stress state, damaged plasticity model, which was shown in Table 3.1, was used. Constitutive model for steel reinforcement was isotropic plasticity model since isotropic homogeneous property was maintained. Material properties of concrete and reinforcements were defined by using their standard properties. For concrete, compressive strength was main parameter. Elastic modulus of concrete was defined by the equations suggested before. Poisson's ratio was 0.2 according to the test results. Other relation was controlled by previously suggested equations. Reinforcements were modeled with approximate bi linear curve which have clear yield point.

For the use of ABAQUS(2010), uniaxial stress-strain relation would be needed for the simulating the material behavior. Simulating more realistic behavior of ultra-high strength concrete, we use the various stress-strain relation for SF-UHSC. These were shown in Figure 1 and 2.

Parameters	Model
Effective Stress	$\overline{\sigma} = D_0^{el} : (\varepsilon - \varepsilon^{pl})$
Invariants	$\overline{p} = -\frac{1}{3} trace(\overline{\sigma}), \overline{q} = \sqrt{\frac{3}{2}(\overline{S}:\overline{S})}$
Flow rule	$G = \sqrt{\left(\varepsilon\sigma_t \tan\psi\right)^2 + \overline{q}^2} - \overline{p}\tan\psi$
Yield criterion	$F = \frac{1}{1 - \alpha} (\overline{q} - 3\alpha \overline{p} + \beta(\widetilde{\varepsilon}^{pl}) \langle \overline{\sigma}_{max} \rangle - \gamma \langle -\overline{\sigma}_{max} \rangle) - \overline{\sigma}_{c}(\widetilde{\varepsilon}_{c}^{pl})$

Table 3.1. Constitutive law for concrete

3.2. Elements

Solid elements were used for concrete elements. C3D8R elements were used because SF-UHSC have been induced the large vertical force and hoop shape is important to column behavior. And there were not enough length of column specimen describing 2D plain stress model. Reinforcements were modeled with the truss elements, T3D2. Generally, reinforcements in concrete member transfer the axial stress in reinforcements, we modeled the reinforcements as truss elements. ABAQUS provide the embedded element. This is a technique used to place embedded node at desired locations with some constraints on translational DOF on embedded elements by the host region. Both the longitudinal reinforcements and hoops were embedded in concrete using this modeling technique. Total model of FE analysis was shown ion Figure 3.



Figure 3. FE model of lateral load inducing columns

3.3. Loads

Loads were induced to the model through two steps. Axial load was induced according to the load control. After inducing axial load, lateral load was induced with displacement control. Displacement control was induced according to the boundary condition. Lateral load was induced with slowly reversed cyclic loading. Cyclic frequencies were defined with the same method of test procedures.

3.4. Verification of FE model

Verifying the FE model, specific test program was selected. H. Kimura(2007) tested columns with 200 MPa compressive strength concrete with SF-reinforced with. 3-dimensional model was built and test loading history was used to FE analysis. Characteristics of test specimens were depicted in figure 4.



Figure 4. Test specimen for verification

4. RESULTS OF FE ANALYSIS

Results of FE analysis was analyzed in this chapter. The first step of analysis is verification of used FE model. The second step is parametric study for SF-UHSC columns. Investigated parameters are compressive strength of concrete, axial load ratio, reinforcement ration of longitudinal steel. The main comparative data are strength and ductility ratio of column.

4.1. Results of verification

Analysis results were shown in Figure 5 with important failure patterns and load-displacement relation. Well behaved Material model were Graybeal equation(2007) under compression and RILEM(2003) equation under tension. Because shear-span to depth ratio was 4 and relatively high vertical force was induced to specimen, the main failure pattern was flexural failure. Cover of bottom of column was spalled-off and longitudinal reinforcements were yielded at the same location. This aspect was also shown in FE analysis results as shown in Figure 5. Crushing area of column was also well illustrated in FEA results. Cyclic behaviour of analysis was compared with test results. Although initial stiffness was slightly higher than test results, ultimate strength only have 5% of differences. However post-peak behaviour of FE model was more brittle than test results.

4.2 Effect of Concrete Strength

FE analysis utilizing various compressive strength was carried out. Investigated range of compressive strength of concrete was 50 to 200MPa. Because HSC column induced relatively high axial load, vertical load was determined to 40% of axial capacity of columns. Volume fraction of steel fiber was 2% for all analysis cases. According to the Analysis results relatively linear increase of lateral load capacity was shown. Analysis for the effect of concrete compressive strength was shown in Figure 6.

4.3 Effect of Axial Load

For the flexural and shear behaviour of reinforced concrete column, axial load is very important because axial load close the flexural and shear crack. Consequently it increases the lateral load capacity of columns. Finding axial load boundary which causes the increase of lateral load capacity, FE analysis utilizing various axial load was carried out. Investigated range of axial load ratio was 10 to 60% of axial load capacity of column. As a results of FE analysis, --% of axial load induced specimen has shown largest value of lateral load capacity. However, ductility was dramatically reduced because more higher compressive stress was induced to the same area of column. The results of axial load effect was illustrated in Figure 7.

4.4 Effect of Reinforcement Ratio

Ductility is very important factor for the reinforced concrete members with high strength material. Although fibre reinforcement can provide the very high strength under shear, their reinforcing effect to



Figure 5. Verification of Test Results(compressive strength of concrete)



Figure 6. Results of parametric study(compressive strength of concrete)

flexural is relatively lower than shear. Therefore appropriate steel reinforcement ratio should be investigated. According to the parametric study for reinforcement ratio, the optimized reinforcement ratio was in the range of the 1 to 2%. Reinforcement strain was reduced with increasing reinforcement ratio and this cause the strength degradation effect.



(a) Stress distribution difference between 10% and 60% axial load ratio



(b) Lateral load capacity variation according to the axial load ratio

Figure 7. Results of parametric study(axial load ratio)



(a) Typical Drift Angle-Strain relation

(b) Lateral load capacity variation according to the reinforcement ratio

Figure 8. Results of parametric study(reinforcement ratio)

5. CONCLUSION

Verifying the performanace of SF-UHSC under lateral cyclic loading, finite element analysis was conducted. Proposed FE model was compared with test results and verification process was carried out. Parametric study about the compressive strength of concrete, axial load ratio and reinforcement ratio was conducted for finding design boundary of SF-UHSC. The results obtained from the analysis on SF-UHSC columns using 200MPa concrete with steel fibre were summarized here.

- 1. From the verification process, the well predicted material model were Graybeal and RILEM equation for compression and tension respectively. Good agreement was shown in the pre-peak region however, sudden drop of lateral resisting load was shown after peak load. However, conventional analysis can be carried out using proposed FE model.
- 2. Compressive strength of concrete was affect to the lateral load capacity relatively linear relation. However, strength about the negative drift cannot shown the linearity of strength

increase.

- 3. Axial load cannot increase the strength of column dramatically. However, SF-UHSC can endure the half of axial strength with lateral load resistance. However, stress concentration was occurred at bottom of column it may occurred the ductility reduction.
- 4. Strength ratio was reduced increasing reinforcement ratio. Because fibre contribute to the tensile strength of column, balance reinforcement ratio would be lower than conventionally designed column. Providing the yielding strain to reinforcements, design boundary of reinforcement ratio should be re-calculated.

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