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- Technical Paper -

SHEAR CAPACITY OF ULTRA HIGH PERFORMANCE FIBER REINFORCED CONCRETE BEAM

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ABSTRACT

The sensibility of the tension softening model and compression model for the simulation of ultra high performance fiber reinforced concrete (UHPFRC) beams is shown. Then, a new attempt for a combination of the constitutive models in FEM for UHPFRC is introduced in the present study. In the analysis, the shape of tension softening model for each UHPFRC element becomes depending on the inclination angle of that element. Finally, the advantage of simulation by the proposed technique compared with current FE methods and available test results are demonstrated.

Keywords: ultra high performance fiber reinforced concrete, shear capacity, 3D FEM

1. INTRODUCTION

FEM in combination with an appropriate material model may serve as a suitable tool to analyze the structural performance of Ultra high performance fiber reinforced concrete (UHPFRC). On the small size specimen level, available constitutive models are installed into the 3D FE program. However, the constitutive model derived from the small size specimen level does not necessarily provide the correct post-cracking relation for the use in the simulation of structural members. One of the main reasons for possible errors is a deviation in preferred orientation and distribution between the fiber reinforcement in small size specimens and the fiber reinforcement in structures. Consequently, the effectiveness of fiber reinforcement in structures strongly depends on the actual fiber orientation relative to the orthogonal direction of the occurring stress. The fiber restriction from geometrical boundaries and pouring direction of concrete are considered as an important issue influencing the fiber orientation number in the hardened state. A sensibility analysis is conducted to evaluate the effect of the material parameters on the predicted beam behavior. The comparisons between the numerical and the experimental results are performed to confirm the applicability of the proposed models on the specimen level.

2. OUTLINE OF FE ANALYSIS

In the present study, a 3D nonlinear FE program (CAMUI) developing at the Hokkaido University was used. In this analysis, 20 node iso-parametric solid elements, with 8 Gauss's points were adopted for the representation of fiber reinforced concrete elements. The nonlinear iterative procedure was controlled by the modified Newton-Raphson method.

2.1 Analyzed Specimens

Data of six I-shaped beams made from reactive powder concrete with 200N/mm^2 compressive strength and 12N/mm^2 tensile strength, which is one of the UHPFRC are used in this paper [1]. The details of their dimensions, arrangement of reinforcing steel and loading condition are shown in Fig.1. The properties of steel fiber used are given in Table 1.

2.2 Constitutive Models

The 3D elasto-plastic and fracture model [2] was used for the concrete model before cracking. The adopted failure criteria follow Niwa's model and Aoyanagi and Yamada's model [3].

Table 1 Properties of steel fiber

Volume (V_f)	Tensile strength (f_t)	Diameter (ϕ)	length (l)
2%	2700MPa	0.2mm	15mm

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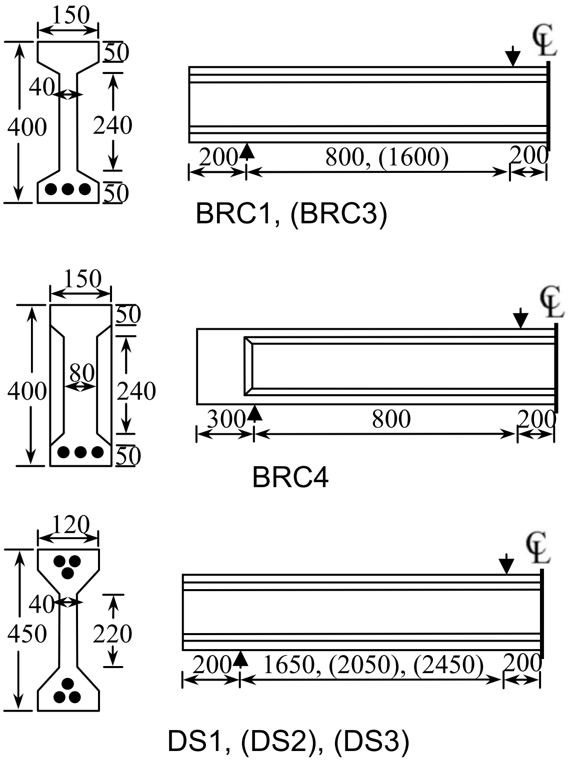

Fig.1 Section of test data [1]

When the first crack occurs, the strains in the global coordinate system are transformed into the strains in the local coordinate system (called crack coordinate system) as shown in Fig.2. Constitutive models were applied in the directions parallel and normal to the crack planes. After calculating stresses from the strains in the crack coordinate system, the stresses are retransformed into stresses in the global coordinate system and superimposed.

To consider the effect of fiber, the current tension softening model for concrete element was replaced. The one-dimensional tension softening model reported by Fukuura et al. [1] is adapted to a stress-strain relationship of fiber reinforced concrete in the direction normal to cracks (Fig.3). The model is expressed as the following relationship between σ, the tensile stress carried by concrete, and δ, the crack opening displacement.

$$\frac{\sigma}{f_t}=\frac{(\delta_0-\delta)}{(\delta_0-\delta_{ck})} \tag{1}$$

where δ_0 = the critical crack opening (crack width at zero stress), 4.3 mm; δ_{ck} = displacement that tension stiffening starts; and f_t = concrete tensile strength

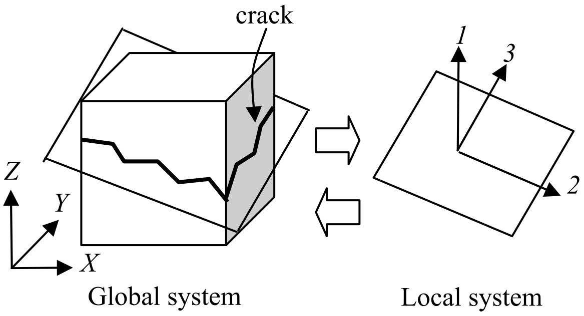

Fig.2 Coordinate system on crack plane

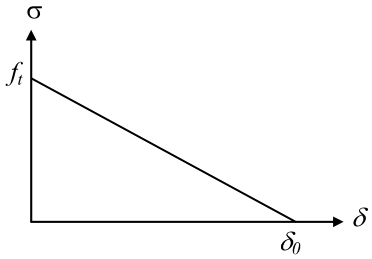

Fig.3 Tension softening model [1]

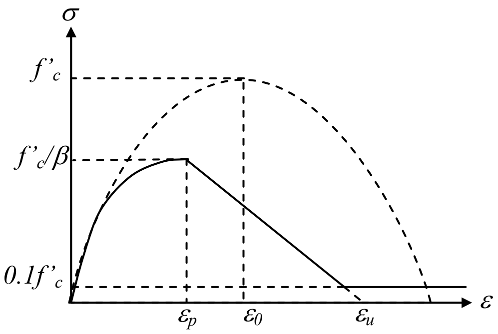

Fig.4 Compression model

The ascending part of the Vecchio & Collins model [3] was applied for the 2D concrete model in a plane parallel to the crack as shown in Fig.4. Compressive strength is reduced according to the magnitude of tensile strain in the direction normal to the crack. After peak stress, the effect of crack on compression-softening is considered by the linear descending line (Fig.4). In this model, compressive stress is reduced to zero at limited strain ε_u. However, the reduced stress has a limit that is 10% of the compressive strength. The gradient of strain softening is defined by the compressive fracture energy (G_{fc}) determined by Nakamura's equation [4].

$$G_{fc}=0.88\sqrt{f_c^{'}} \tag{2}$$

The limit strain for compression (ε_u) is [4],

$$\varepsilon_u=\frac{2G_{fc}}{\sigma_{peak}\cdot l_{eq}}+\frac{\varepsilon_p}{2} \tag{3}$$

where ε_p = compressive strain at peak stress; $\sigma_{peak} = f'_c/\beta$; and l_{eq} = equivalent length assumed to be the width of element, 50 mm

Shear transfer stresses were calculated using model proposed by Li & Maekawa [2]. However, the use of high performance concrete having very high concrete compressive strength induced a smooth crack surface. As a result, the stress transfer equation can be simplified by multiplying the shear transfer envelop of the contact density function model that assume rough crack surface of normal strength concrete by a reduction coefficient A [2] (A = 0.25 for this paper).

2.3 Experimental and Numerical Results

The calculated load-deflection curves with and without modified constitutive models are compared with test results for specimens BRC series (Fig.5). It can be seen that, without any modification of constitutive models, the load-deflection curves of numerical results become lower than that of the test results after shear cracking. Moreover, the shape of curves is almost identical for test and both FE results before shear cracking. This indicates that fiber show no effect on beam behavior before the occurrence of crack. After the installation of models that can consider the effect of fiber, the predicted load-deflection curves can be improved but the overestimation of ultimate load can be observed for all specimens (Fig.5). On the other hand, the predicted curves of specimens DS series (Fig.6) do not show the overestimation of results. This can be explained by the failure mode that might be different due to the long length of shear span of specimens DS series.

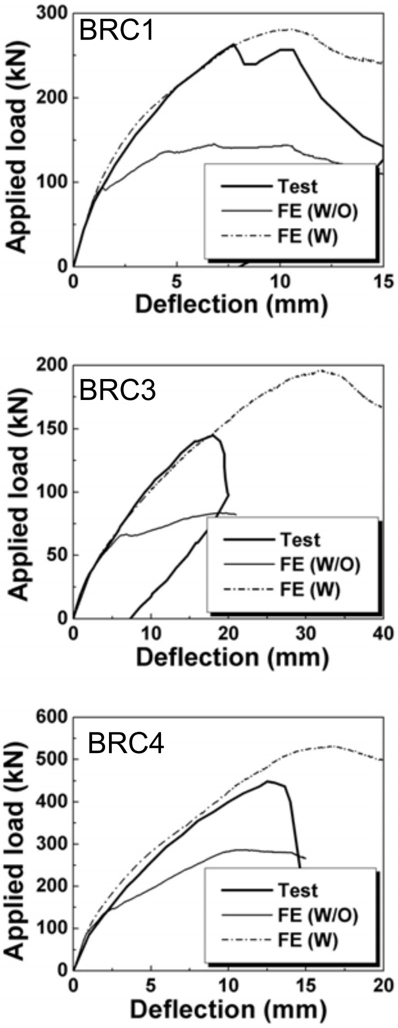

Fig.5 Predicted curves of BRC series

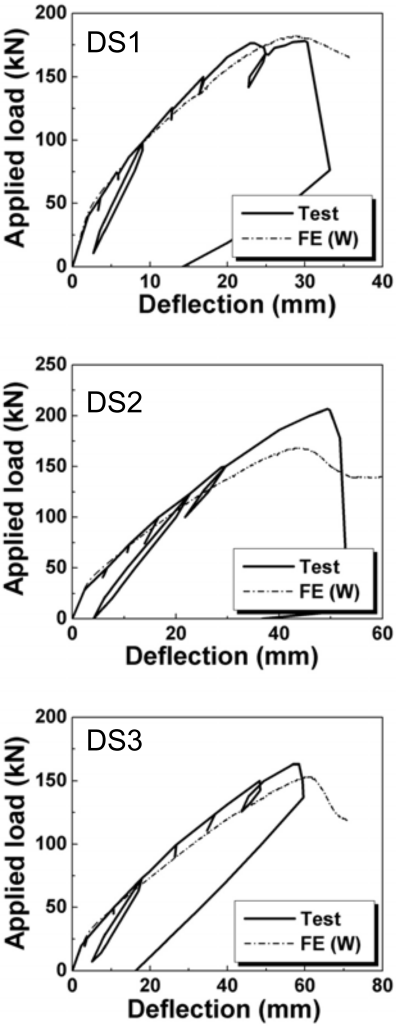

Fig.6 Predicted curves of DS series

3. SENSIBILITY OF MODELS

The overestimation of predicted ultimate load with some modified constitutive models in Fig.5 is not reasonable because the effect of steel fiber still did not consider in some constitutive models, for example, the compression model for UHPFRC and the tension stiffening model for UHPFRC with steel bars. Consequently, the more rational predicted ultimate load should be lower than that of experimental results. The sensibility of the constitutive models can be considered as one of the major subject having an effect on the overestimation of the simulated ultimate load.

3.1 Tension Softening Model

The installed tension softening model (δ_0 = 4.3 mm, see Fig.3) was selected as the representative of the scattering of experimental results and back analyses [5]. Minimum and maximum of the possible critical crack opening (δ_0 = 2.0 and 5.0 mm, respectively) are reanalyzed instead of δ_0 = 4.3 to show the sensibility of tension softening model. The tensile strength is simply kept constant throughout the investigation.

Fig.7 shows the load-deflection curves of experimental and FE results with varying the critical crack opening (δ_0 = 2.0, 4.3 & 5.0 mm). It can be observed that the calculated ultimate load is changed with the variation of the critical crack opening. Larger value of the critical crack opening gives higher value of the predicted ultimate load. Furthermore, it can be said that the simulated results with smaller value of the critical crack opening become closer to the experimental results. This finding might be considered by the fact that the tensile stress-crack width relationships in Fig.3 were derived from many bending tests of 100 mm-depth small beams [5]. Base on these relations, it seems quite easy to recommend permissible tension softening model, taking the scatter in test data into account by averaging the test results. However, the post-cracking behavior derived from small test specimens does not necessarily provide the correct post-cracking relation for the use in structural level. One of the main reasons for possible errors is a deviation in preferred orientation and distribution between the fiber reinforcement in small size specimens and the fiber reinforcement in structures. It could be observed from the test results reported by Grunewald [6] that the fiber orientation number in small beams determining with an image analysis is higher than that in large beams. It can be concluded that the appropriate tension softening model for the FE analysis of UHPFRC structural member should not be the averaged responds from the bending test of small beams but it should be lower than that to capture the decrease of orientation number in large-scale structural members in practice.

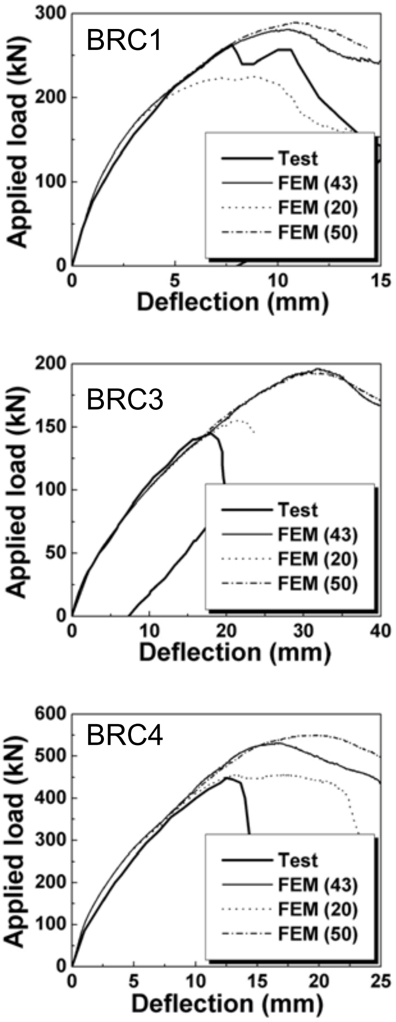

Fig.7 Sensibility of tension softening models

3.2 Compression Model

There is almost no report on the compressive fracture energy of UHPFRC but there are many works on the toughness of high-strength fiber concrete. The toughness index (*TI*) is defined as the area under the stress-strain curve of fiber concrete up to a certain strain level divided by the area under the stress-strain curve of plain concrete with the same peak stress up to the same strain level. Based on the empirical equations reported by Taerwe & Gysel [7], *TI* can be calculated. The calculated *TI* is only the approximate value showing the effect of steel fiber on the compression model because the material properties of specimens BRC1, 3 & 4 are beyond the valid range of the considering Equations [7]. In order to estimate the limited strain $\varepsilon_u(fiber)$ of UHPFRC by calculated *TI*, the toughness index is roughly assumed to be equal the area under the stress-strain curve of UHPFRC divided by the area under the stress-strain curve of plain concrete. Finally, the limited strain $\varepsilon_u(fiber)$ can be obtained using the calculated *TI* and ε_u. The limited strain $\varepsilon_u(fiber) \approx 7\times\varepsilon_u$ is installed into the compression model for fiber concrete elements without steel reinforcing bars and specimens are reanalyzed. Fig.8 shows the comparison between test results, simulated results with and without modified limited strain $\varepsilon_u(fiber)$. It can be said that the effect of steel fiber assuming by adjusted descending line after peak stress on the load-deflection curves is quite small. There is a small change of curve after peak load while the predicted ultimate load is almost constant for all specimens (Fig.8).

4. INFLUENCE OF FIBER ORIENTATION IN FE ANALYSIS

The angle of inclination of each fiber strongly influences both its own behavior and the response of the surrounding matrix when a load is applied to the composite. The behavior of fibers inclined at varying angles to the direction of the stress, i.e. so-called inclination angle, becomes an important factor which determines the overall strength of a composite with short random fiber reinforcement. Fig.9 shows the effect of this inclination angle on the tensile load-bearing capacity of a single fiber, embedded in a cementitious matrix [8]. It can be seen that, as the inclination angle increases, the efficiency of a single fiber decreases depending on the fiber type.

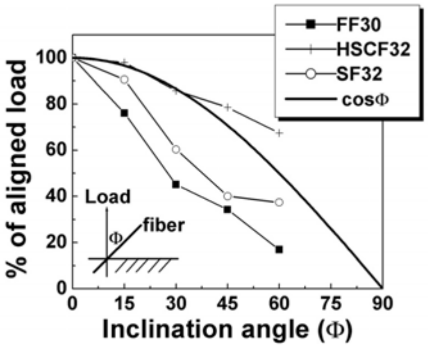

Fig.9Effect of inclination angle on aligned load

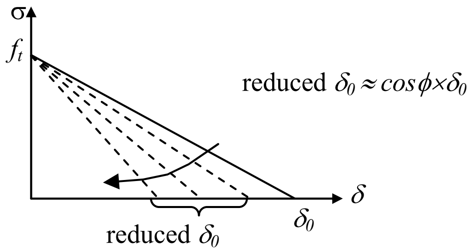

Fig.10 Modified tension softening model due to inclination angle

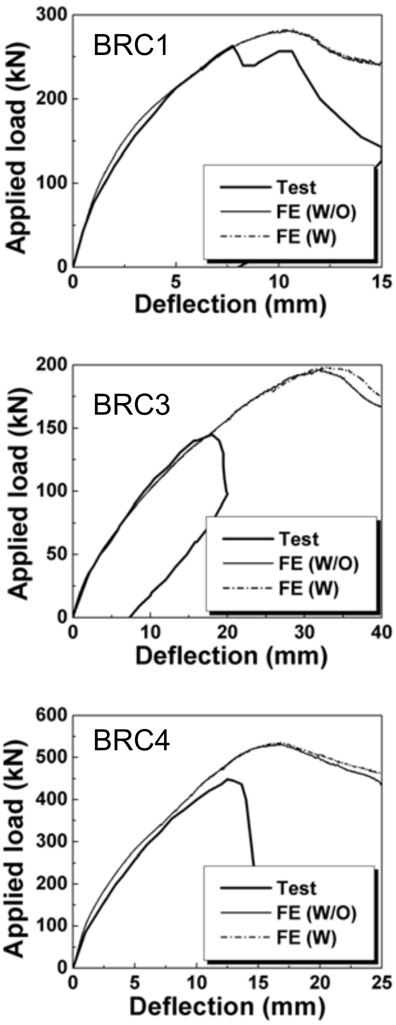

Fig.8 Sensibility of compression models

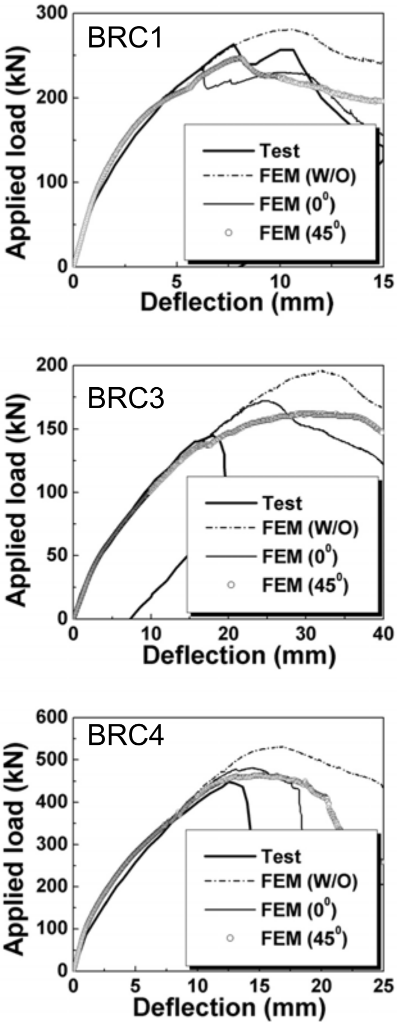

Fig.11 Effect of varied tension softening model

As mentioned before, the calculation of stress with constitutive models in the current FE program is performed on the local coordinate system (crack coordinate system) as shown in Fig.2. Correspondingly, the tension softening model is normally calculated in the direction normal to crack plane. When a load is applied to the beam, crack can propagate not only in the direction normal to main bar but also diagonal direction. In the case of diagonal crack that makes calculated direction inclined to major direction of fiber, it may have an effect on the tension softening behavior of cracked UHPFRC in the calculation process.

In order to take the effect of angle between calculated direction and major direction of fiber into account, the simplified idea of the modification of tension softening model is proposed. First, the major direction of fiber in UHPFRC member is simply assumed as 0° and 45° (clockwise) to direction of main reinforcing bars. Following the pulling results of single fiber that the efficiency of a single fiber decreases with the inclination angle increases (Fig.9), the critical crack opening (δ_0) is simply reduced as shown in Fig.10. The reduction factor is assumed to be $cos\Phi$ (Fig.9) that can be easily obtained by the angle between axis X and axis 1 (for major fiber direction = 0°) and the angle between axis $X\text{-}45^{\circ}$ and axis 1 (for major fiber direction = 45°) in the calculation process (Fig.2). Finally, the shape of tension softening model for each UHPFRC element becomes depending on the crack angle of that element in the FE calculation.

Fig.11 shows the load-deflection curves of experimental and FE results without and with the modification concept of tension softening model (assumed major direction of fiber = 0° & 45° to main bar) for all specimens. It can be observed that the calculated ultimate load is reduced with the variation of the critical crack opening. Moreover, the effect of fiber angle (0° & 45°) on the ultimate load of predicted results is small but the difference in post-peak behavior can be observed. The simulated results became closer to the experimental results indicates that current simplified idea may suitable for the analysis of a UHPFRC member. However, concretely modeling of the reduction factor remains as a future task.

5. CONCLUSIONS

With the available constitutive models, the effect of fibers on the analysis of UHPFRC can be considered. Because of the overestimation, the appropriate tension softening model for the FE analysis of UHPFRC structural member should not be the averaged responds from the bending test of small beams but it should be lower than that to capture the decrease of orientation number in large-scale structural members. For the compression model, there is almost no effect of steel fiber on the overall load-deflection of UHPFRC members. Finally, the current simplified idea that the shape of tension softening model for each UHPFRC element becomes depending on the crack angle of that element in the FE calculation may suitable for the analysis of a concrete member with short random fiber reinforcement. However, concretely modeling of the reduction factor remains as a future task.

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