

# Fracture simulation of fiber reinforced concrete by visco-elasto-plastic suspension element method

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**ABSTRACT:** In this paper, a simulation of direct tension test and bending test of fiber reinforced concrete is carried out by VEPSEM has been applied for the fracture simulation of plain concrete under various conditions. The fiber in fiber reinforced concrete is simulated by dynamic elasto-plastic element between nodal points. As the result, the analytical result comparatively expresses the experimental result in which the maximum load becomes high and the descending portion after maximum load becomes ductile.

## 1 INTRODUCTION

Fiber reinforced concrete is added fibers to improve the brittle fracture behavior of plain concrete. It is studied by many researchers and fiber reinforced concrete that has ductile fracture behavior is widely used in concrete construction work. The fibers used in fiber reinforced concrete are steel fiber, glass fiber, carbon fiber and so on, and the other kinds of fiber have been developed. However, in order to grasp the fracture behavior of fiber reinforced concrete used a new fiber, many experimental examinations by tensile test, bending test and so on should be carried out actually. Because the relationship between the fracture behavior of fiber reinforced concrete and the property of fiber is not necessarily grasped.

Therefore, the theoretical study on this relationship between fracture behavior of fiber reinforced concrete and fiber and on the mechanism of reinforcing by fiber has been carried out. Generally, the mechanism of becoming ductile by fiber is called bridge effect, because fibers in concrete construct bridge internal cracks, and many models on the basis of this mechanism are proposed. However, the bridge effect of fiber is influenced by mechanical properties of concrete and fiber and bond property between concrete and fiber. The model that can be applied for all fiber reinforced concrete is not proposed.

The authors have proposed a visco-elasto-plastic suspension element method (VEPSEM). This analytical method has two characteristics. One is the use of a simple non-continuum model consisted of aggregates and matrix. The other is the dynamic analysis by the solution of the equation of motion. The authors have carried out the simulation of concrete under various conditions, and investigated the applicability of this analysis.

In this paper, in order to investigate the fracture

behavior of fiber reinforced concrete, a simulation of direct tension test and bending test of fiber reinforced concrete is carried out by VEPSEM. The fiber is simulated by dynamic elasto-plastic element between nodal points. In case of fracture of matrix between nodal points, this fiber element constructs bridge. The constitutive law of this fiber element consists of the yield stress and Young's modulus. The effects of number, length, direction, yield stress and Young's modulus of fiber elements on the fracture behavior of fiber reinforced concrete is investigated.

## 2 ANALYTICAL METHOD

The visco-elasto-plastic suspension element method (VEPSEM) has been proposed to simulate the fracture behavior of concrete by the authors. The main characteristics of this analytical method are to use a simple non-continuum model consisted of aggregates and matrix, and to be able to carry out the dynamic analysis by using the equation of motion. The details of this analytical method were reported in the previous papers. In this chapter, the improvement of fiber element for analysis of fiber reinforced concrete is explained in detail.

Figure 1 shows the concept of fiber element. As shown in this figure, the previous analytical model is structured nodal point and mortar element. If the stress of mortar element reached the strength, the mortar element is disappeared. This disappearance of mortar element expresses the crack of mortar element. The fiber element with dynamic elasto-plastic property is added between nodal points for this analytical model. In case of the existence of this fiber element, the stress is transmitted between nodal points by the fiber element when the mortar element is disappeared. The bridge effect of fiber is simulated by adding this fiber element.

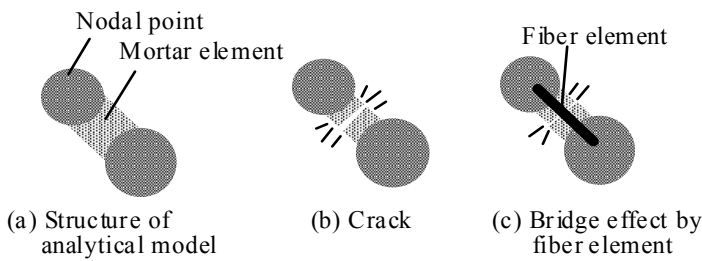


Figure 1. Concept of element.

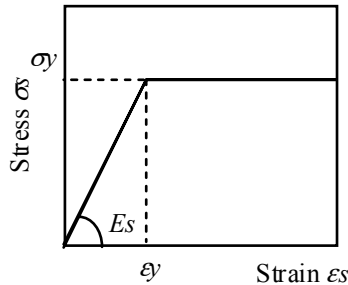


Figure 2. Constitutive law of fiber element.

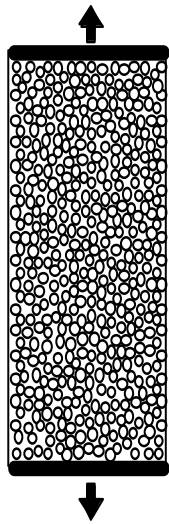


Figure 3. 440B model (For direct tension test).

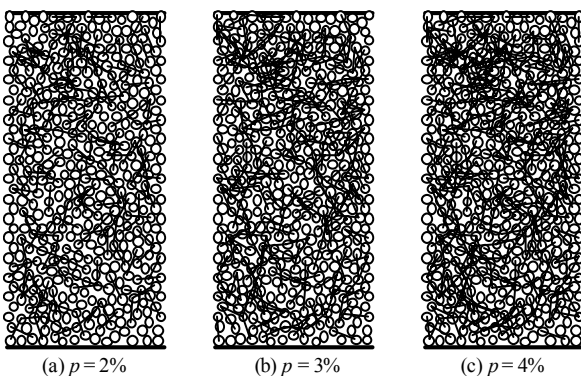


Figure 4. Analytical model (Effect of volume fraction of fiber  $p$ ).

The constitutive law of fiber element is shown in Figure 2. The simple bi-linear stress-strain curve is used for the constitutive law of fiber element. The constitutive law is consisted of yield stress  $\sigma_y$  and Young's modulus  $E_s$ . In this analysis, the yield force and stiffness are actually necessary. These input data are obtained by multiplying yield stress  $\sigma_y$  300N/mm<sup>2</sup>

and Young's modulus  $E_s$  210kN/mm<sup>2</sup> of general steel by the section area of fiber respectively. The volume fraction of fiber  $p$  is represented by the volume of fiber divided by the volume of analytical model. The volume of fiber is multiplied the section area of fiber by the length of fiber.

### 3 SIMULATION OF DIRECT TENSION TEST

In this chapter, the results of simulation of direct tension test are shown.

Figure 3 shows the analytical model of direct tension test consisted of 440 nodal points. The loading board is moved to direction of arrow sign to simulate direct tension test. Table 1 shows the input data of mortar.

Table 1. Input data of mortar.

tan	Ft	E	$\eta$	v	d	H	D
0.1	2.0	13	0.5	0.2	5.0	200	100

$\phi$  : Angle of internal friction, Ft : Pure tensile strength (MPa), E : Elastic modulus (GPa),  $\eta$  : Viscosity (MPa s), v : Shear loading rate (mm/s), d : Diameter of nodal point (mm), H : Height of specimen (mm), D : Width of specimen (mm)

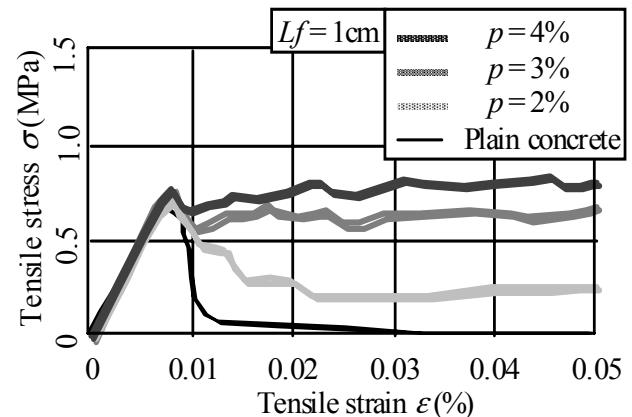


Figure 5. Tensile stress-strain curve (Effect of volume fraction of fiber  $p$ ).

#### 3.1 Effect of volume fraction of fiber

The analytical models which have each volume fraction of fiber are shown in Figure 4. The effect of volume fraction of fiber is investigated by using these models. Figure 5 shows the effect of volume fraction of fiber on tensile stress-strain curve. As shown in this figure, the stress of plain concrete suddenly decreases after the stress reaches the maximum stress. It is shown that the fracture behavior of plain concrete is brittle. On the other hand, though the maximum stress of fiber reinforced concrete is not changed compared with that of plain concrete, the descending portion in tensile stress-strain curve becomes gentle with increase of volume fraction of fiber. It is shown that the fracture behavior becomes ductile with adding the fiber element.

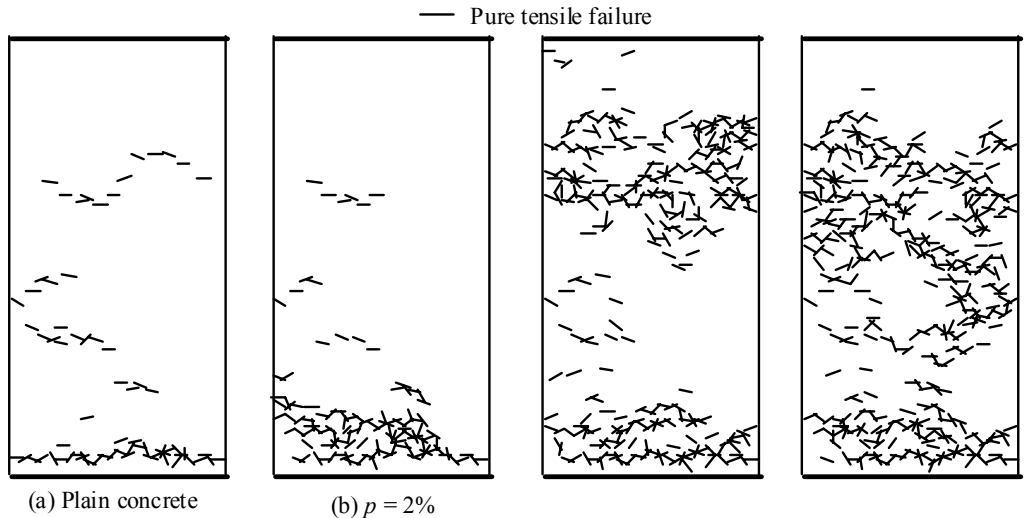


Figure 6. Internal cracks (Effect of volume fraction of fiber  $p$ ).

Figure 6 shows the last state of internal cracks. The internal cracks of plain concrete occur in the lower concentrated part of specimen. On the other hand, the internal cracks of fiber reinforced concrete occur in the whole part of specimen. These results show the bridge effect of fiber element, that is, the stress is transmitted by bridge effect of fiber element when the internal cracks occur in mortar element. This bridge effect increases with increasing of volume fraction of fiber.

Figure 8 shows the results of strain measured in the range shown in Figure 7. As shown in this figure, the strain of plain concrete increases only in Nos.1 and 2. Because the internal cracks occur only in the lower part of specimen as shown in Figure 6. However, in the case of fiber reinforced concrete, all strains increase. It is shown that the strain increases in whole specimen by the bridge effect of fiber element.

### 3.2 Effect of length of fiber

Figure 9 shows the analytical models in which the lengths of fiber element are varied in the three levels of 1, 2 and 3cm. The volume fraction of fiber is the

same by adjusting number of fiber element. Figure 10 shows the analytical results. The effect of length of fiber on stress-strain curve is small, and the increasing of tensile strength and ductile fracture behavior is observed at all length of fiber element in this figure.

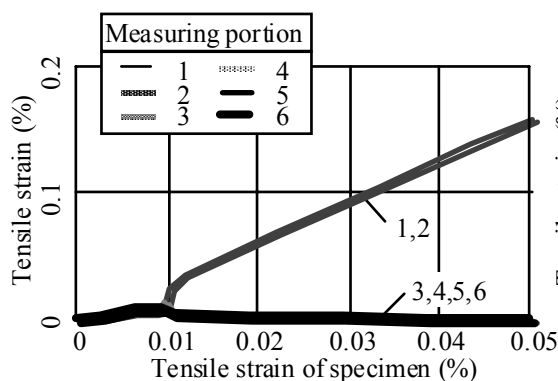
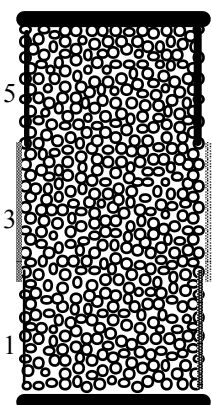
### 3.3 Effect of direction of fiber

It is said that the direction of fiber affects the fracture behavior of fiber reinforced concrete. Therefore, the effect of direction of fiber is investigated.

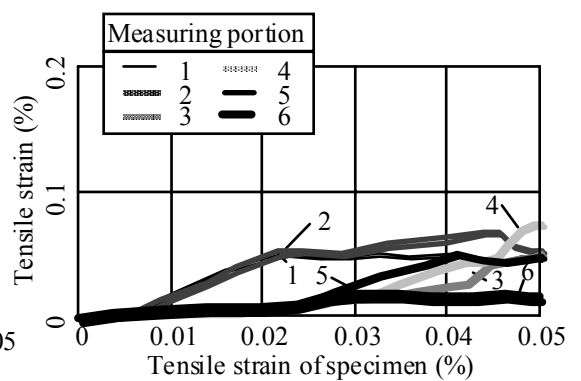
Figure 11 shows the analytical model which has only horizontal fiber element and another one which has only vertical fiber element. Figure 12 shows the analytical result obtained by these models. The result by only vertical fiber element is almost same as that by all fiber element. On the other hand, the result by only horizontal fiber element is almost same as that by plain concrete. These results show the effect of direction of fiber on direct tension test almost depends on only vertical element.

### 3.4 Effect of properties of fiber

The fibers that have been used in fiber reinforced



(a) Plain



(b)  $p = 4\%$

Figure 7. Measuring range of strain.

Figure.8 Strain of surface of specimen.

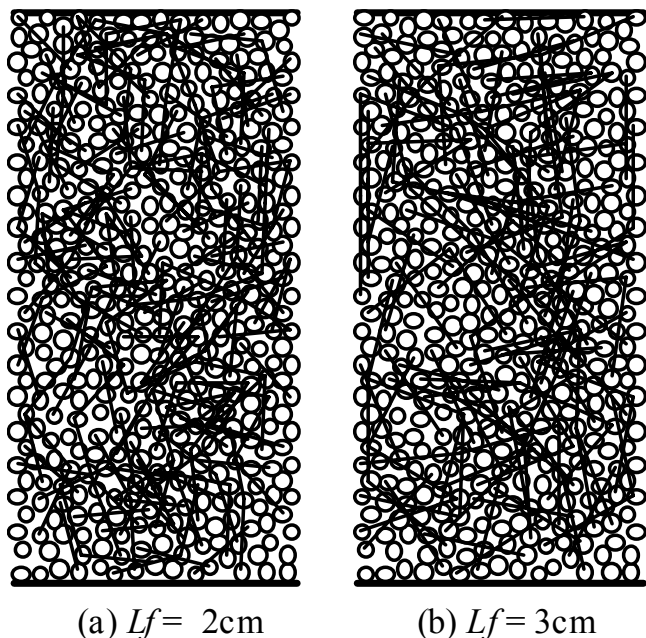


Figure 9. Analytical model (Effect of length of fiber  $L_f$ ).

concrete are glass fiber, carbon fiber, vinylon fiber, aramid fiber and so on besides steel fiber. In this chapter, the effect of properties of fiber on the fracture behavior of fiber reinforced concrete is investigated by changing yield stress  $\sigma_y$  and Young's modulus  $E_s$  which are input data for constitutive law of fiber element.

Figure 13 shows the effect of yield stress  $\sigma_y$ . The result of 3000 MPa is same as that of 300 MPa. It is shown that the effect of yield stress is nothing, if yield stress is over 300 MPa. Figure 14 shows the effect of Young's modulus  $E_s$ . The tensile strength increases and the fracture behavior becomes ductile with increasing of Young's modulus. It is shown that the effect of Young's modulus is large. These results mean that the increasing of reinforcement by fiber at early loading improves the fracture behavior of fiber reinforced concrete but that at later loading doesn't affect the fracture behavior.

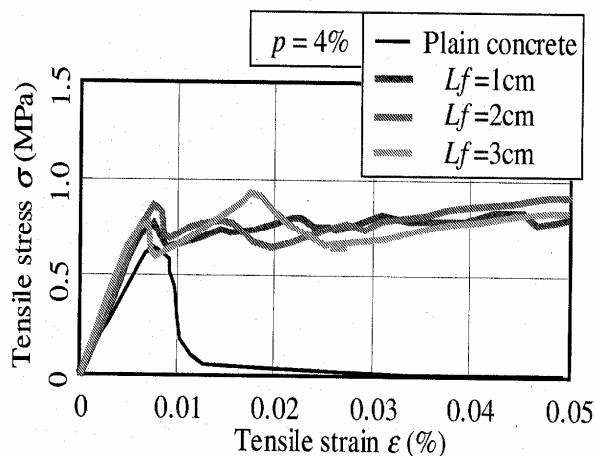


Figure 10. Tensile stress-strain curve (Effect of length of fiber  $L_f$ ).

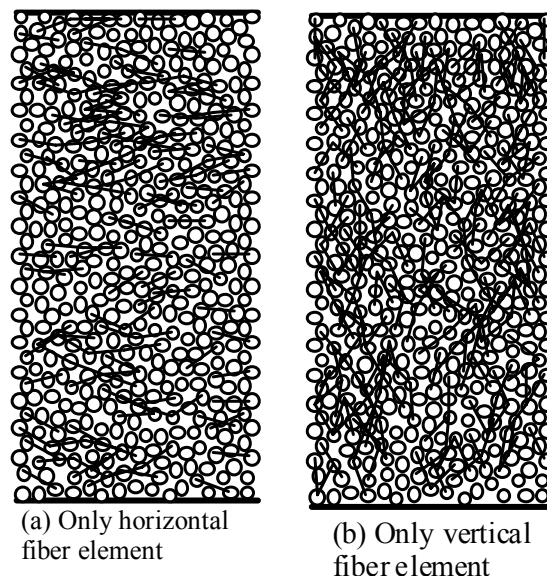


Figure 11. Analytical model (Effect of direction of fiber).

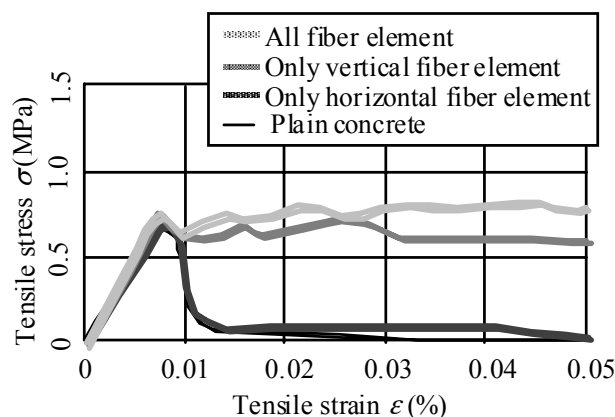


Figure 12. Tensile stress-strain curve (Effect of direction of fiber).

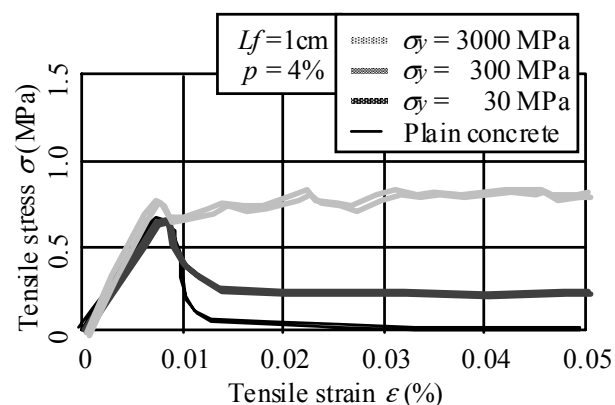


Figure 13. Tensile stress-strain curve (Effect of yield stress of fiber  $\sigma_y$ ).

#### 4 SIMULATION OF BENDING TEST

In this chapter, the results of simulation of bending test are shown.

Figure 15 shows the analytical model consisted of 650 nodal points to simulate center-point loading bending test. Table 2 shows the input data of mortar.

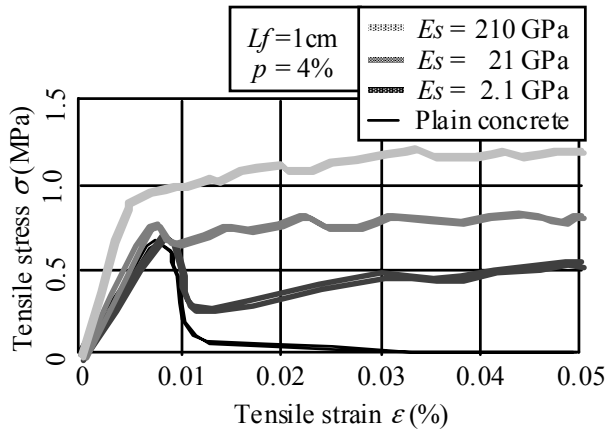


Figure 14. Tensile stress-strain curve (Effect of Young's modulus of fiber  $E_s$ ).

Table 2. Input data of mortar.

tan	Ft	E	$\eta$	v	d	H	D
0.3	3.0	19.6	0.05	0.5	5.0	100	300

$\phi$ : Angle of internal friction, Ft: Pure tensile strength (MPa), E: Elastic modulus (GPa),  $\eta$ : Viscosity (MPa s), v: Shear loading rate (mm/s), d: Diameter of nodal point (mm), H: Height of specimen (mm), D: Width of specimen (mm)

#### 4.1 Effect of volume fraction of fiber

Figure 16 shows the analytical model in which the volume fraction of fiber is varied. Figure 17 shows the load-deflection curve by using these models. In case of plain concrete, the load after reaching maximum load decreases suddenly. However, in case of fiber reinforced concrete, the maximum load increases and the load after reaching maximum load hardly decreases. These tendencies become obviously with increasing the volume fraction of fiber. These results are explained by Figure 18 which show the internal cracks. The internal cracks of plain concrete occur in one straight line only at center of specimen. This is the reason of sudden decrease of

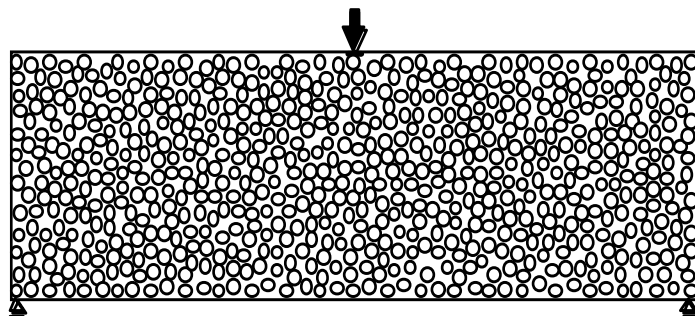


Figure 15. 650B model (For center-point loading bending test).

load after maximum load. On the other hand, the internal cracks of fiber reinforced concrete occur in large area of specimen especially at high volume fraction of fiber. It is thought that these results express the bridge effect of fiber. The extension of crack

width is restrained by the bridge effect of fiber, and the occurrence of crack spreads in whole specimen.

#### 4.2 Effect of length of fiber

Figure 19 shows the analytical models in which the length of fiber element are varied in the three levels of 1, 2 and 3 cm and the volume fraction of fiber is same. Figure 20 shows the analytical results of the load-deflection curve. The effect of length of fiber

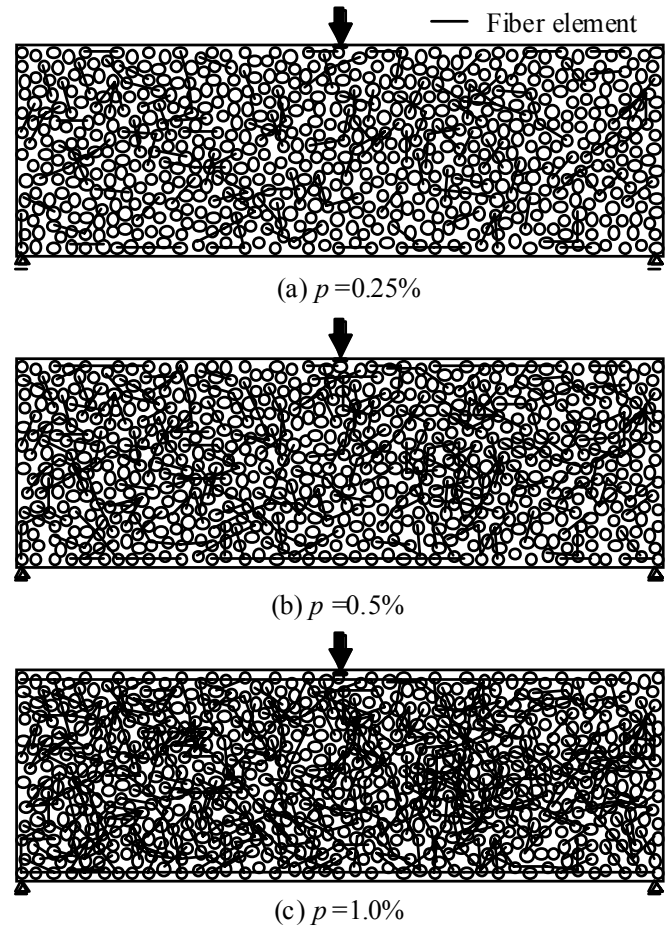


Figure 16. Analytical model (Effect of volume fraction of fiber  $p$ ).

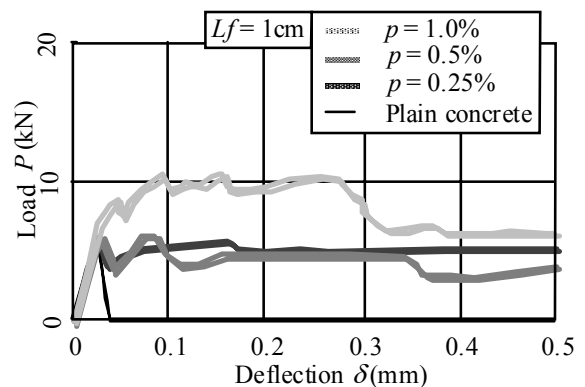


Figure 17. Load-deflection curve (Effect of volume fraction of fiber  $p$ ).

on load-deflection curve is small, and the ductile fracture behavior is shown at all length of fiber element in this figure.

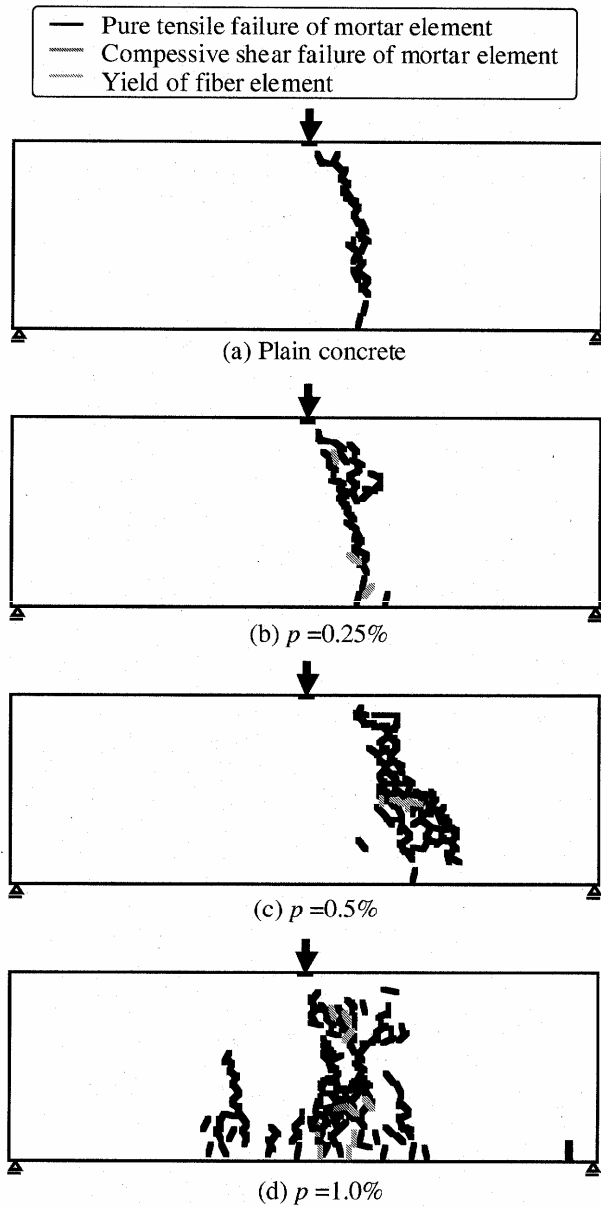


Figure 18. Internal cracks (Effect of volume fraction of fiber  $p$ ).

#### 4.3 Effect of length of fiber

Figure 19 shows the analytical models in which the length of fiber element are varied in the three levels of 1, 2 and 3cm and the volume fraction of fiber is same. Figure 20 shows the analytical results of the load-deflection curve. The effect of length of fiber on load-deflection curve is small, and the ductile fracture behavior is shown at all length of fiber element in this figure.

#### 4.4 Effect of direction of fiber

Figure 21 shows the analytical model which has only horizontal fiber elements and the analytical model which has only vertical fiber elements. Figure 22 shows the analytical result. The result by only vertical fiber element is almost same as that by plain concrete. The result by only horizontal fiber element is almost same as that by all fiber element. These results show

that the effect of horizontal fiber element is high and that of vertical fiber element is low in bending test.

#### 4.5 Effect of properties of fiber

In order to investigate the effect of properties of fiber on the fracture bending behavior, the simulation in which yield value  $\sigma_y$  and Young's modulus  $E_s$  is varied is carried out.

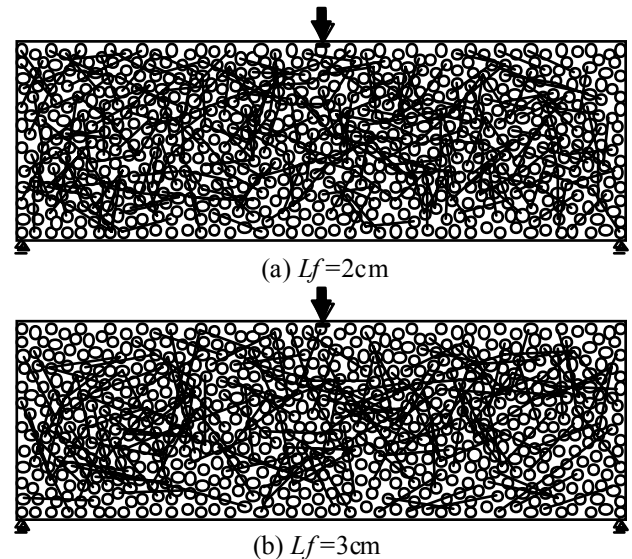


Figure 19. Analytical model (Effect of length of fiber  $L_f$ ).

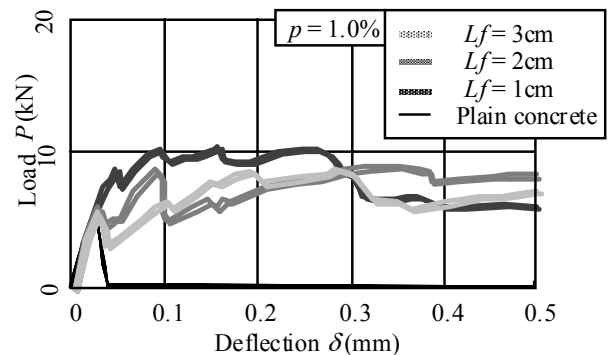


Figure 20. Load-deflection curve (Effect of length of fiber  $L_f$ ).

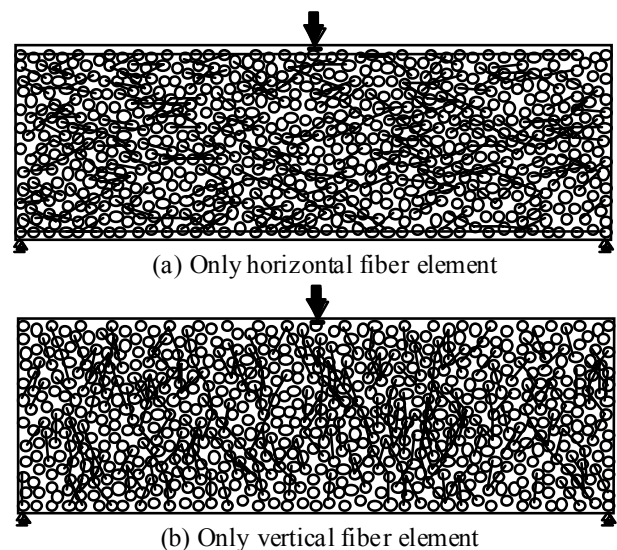


Figure 21. Analytical model (Effect of direction of fiber).

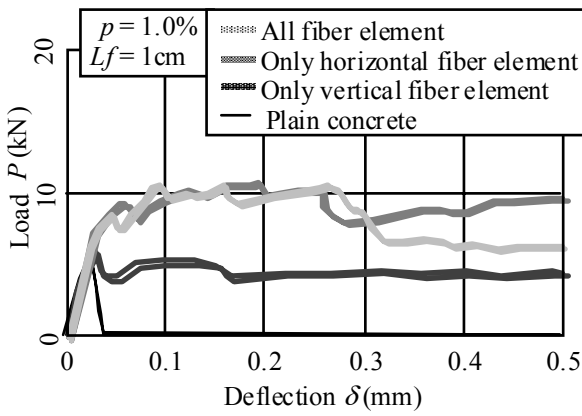


Figure 22. Load-deflection curve (Effect of direction of fiber).

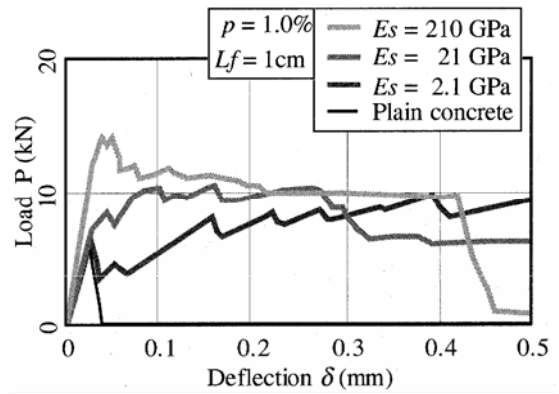


Figure 25. Load-deflection curve (Effect of Young's modulus of fiber  $E_s$ ).

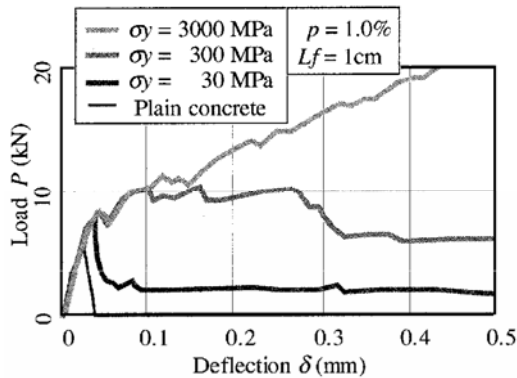


Figure 23. Load-deflection curve (Effect of yield stress of fiber  $\sigma_y$ ).

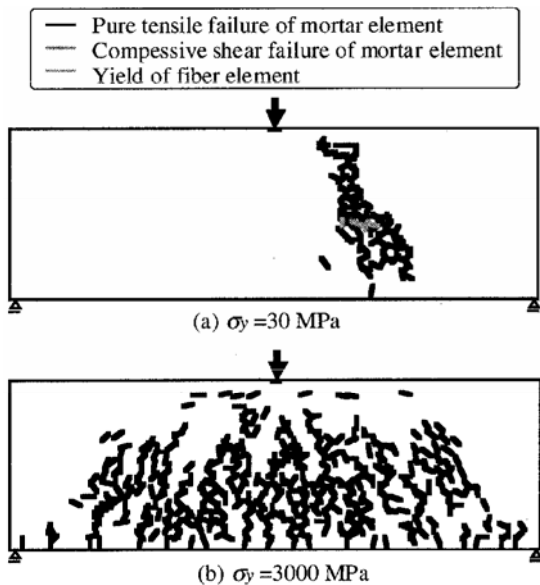


Figure 24. Internal cracks (Effect of yield stress of fiber  $\sigma_y$ ).

Figure 23 shows the effect of yield stress  $\sigma_y$  on load-deflection curve. The fracture behavior in case of 30MPa is brittle and almost same as that of plain concrete. However, the maximum load becomes high and the fracture behavior becomes ductile with increasing yield stress  $\sigma_y$ . Figure 24 shows the last state of internal cracks. The cracks occur at only center of specimen in case of 30MPa, and the fiber element yields. In case of 3000MPa, the cracks occur in large area of specimen, and the fiber element doesn't yield.

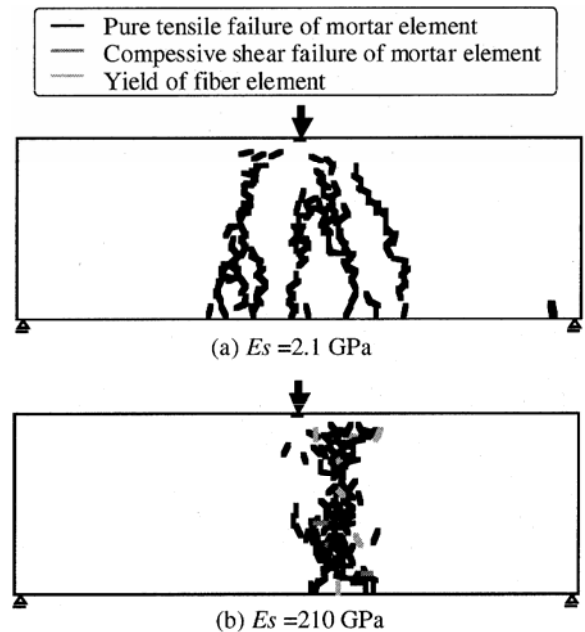


Figure 26. Internal cracks (Effect of Young's modulus of fiber  $E_s$ ).

Figure 25 shows the effect of Young's modulus  $E_s$ . The maximum load becomes high with increasing Young's modulus. However, the fracture behavior doesn't simply become ductile with increasing Young's modulus. The load after maximum load increases gradually in case of 2.1GPa. In case of 210GPa, the load after maximum load decreases and settles down. Figure 26 shows internal cracks. The cracks in case of 2.1GPa occur on a few lines at center of specimen. On the other hand, the concentrated cracks at center of specimen occur in case of 210GPa. It is thought that this difference in occurrence of internal cracks happens the difference of fracture behavior.

The effect of properties of fiber on the bending test is different from that on the direct tensile test.

## 5 CONCLUSIONS

In this paper, the fracture simulation of direct tension test and bending test of fiber reinforced concrete by using the visco-elasto-plastic suspension element

method was carried out. The effect of fiber element on the fracture behavior of fiber reinforced concrete was estimated by this analysis.

According to these results, it is obtained by considering fiber elements that the maximum load becomes high and the descending portion after the maximum load becomes ductile both in the result of direct tension test and bending test. These analytical results can comparatively express the experimental ones. The results of fracture behavior considering fiber elements show that the internal cracks and strains of specimen are dispersed compared with that of specimen of plain concrete. It is thought that the cause of these results can be explained by bridging effect of fiber element. It means that this analytical method has the possibility that can be applied for the investigation of fiber reinforced concrete.

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