

SHEAR BEHAVIOR OF FIBER-MESH REINFORCED PLATES

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ABSTRACT : To investigate the fundamental behavior of fiber-mesh reinforced plates, pure shear test is carried out for 11 specimens. Carbon and aramid fiber meshed in two, three and four directions are used as reinforcements for 300 × 300 × 15mm mortar panels. Test variables are fiber type, amount of fiber, mesh configuration, and mesh layers. From the test results, two failure processes, compression failure and rupture of fiber, are observed. Measured fiber strains correspond with the directions of fiber in regard to applied load direction. The analytical study is carried out based on the modified compression-field theory given by Collins. The shear stress versus shear strain relationships obtained by experiments show a good correlation with analytical results.

KEYWORDS: mesh, panel, configuration, pure shear, tension stiffening

1 INTRODUCTION

Continuous fibers, such as carbon and aramid fiber are materials with high strength and durability. However, all-elastic and brittle behavior have made it difficult to use as a substitute for steel reinforcement, especially in seismic areas. One of the effective use is in the development of composite structures consisting of concrete, steel reinforcement, and continuous fibers. In members of this type, ductile behavior should be given by the longitudinal steel reinforcement, while the high strength of continuous fiber is effective for use as shear and confining reinforcement. The fiber also has the merit of high durability when arranged at the surface of members.

Fig. 1 shows examples of the use of fiber-mesh reinforced panels as a shell for members. The panels are about 10-15mm thick, and used as a substitute for wooden forms. After concrete casting, the panels are not removed and become a portion of the member. These panels are expected to carry loads, especially for shear and confinement. Composite RC structures profiled by continuous fiber-mesh reinforced plate seem to be one of the most effective construction systems to utilize continuous fibers. In this paper, shear behavior of fiber-mesh plates, which is one of the fundamental properties, is investigated and evaluated through experimental and analytical studies.

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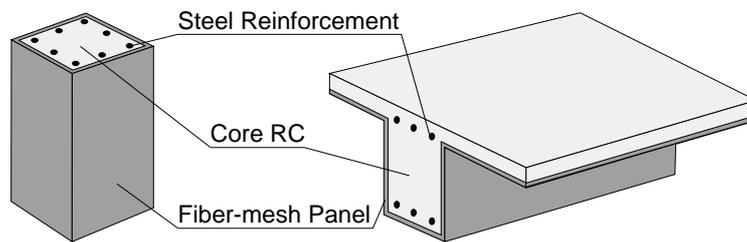


Fig. 1 Examples for effective use of fiber-mesh reinforced plates

2 TEST PROGRAMS

2.1 SPECIMENS AND LOADING

Specimens are 300mm square with a thickness of 15mm. Each specimen has a total of 24 holes along the edges to fix 12 attachment plates. Two oil jacks are connected to one attachment panel via pins. In this test, monotonic pure shear loading is achieved by applying equal pressures to 24 oil jacks. Fig. 2 shows the loading system and details of the setting.

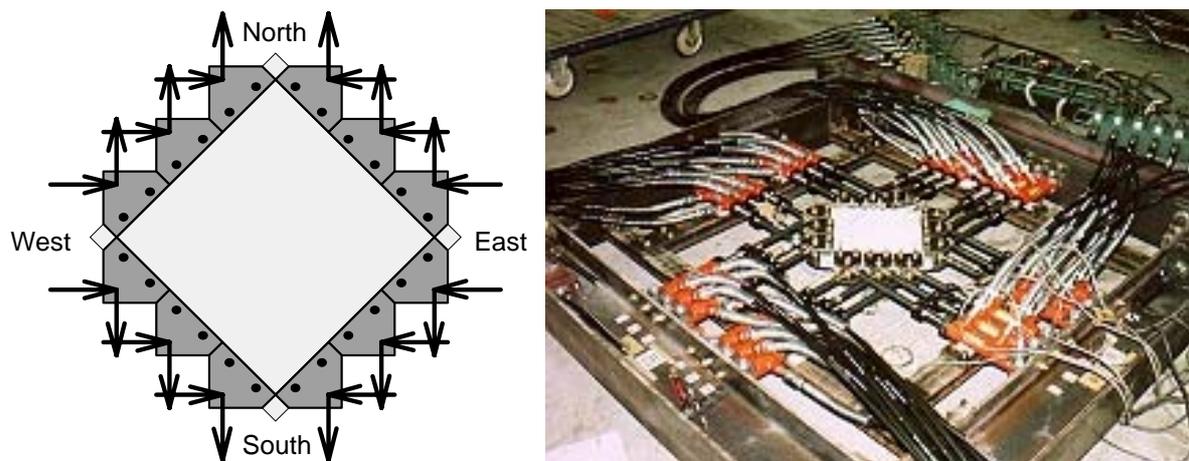


Fig. 2 Loading system and setting of specimen

2.2 MATERIALS AND TEST VARIABLES

Test variables are fiber type (aramid, carbon), filament number of yarn (2k, 4k, 6k), mesh configuration (2, 3, 4 directions) and mesh layers (1, 2 layers). Aramid fiber, which has 2k (30 denier) and 4k (60 denier) filaments, and carbon fiber with 6k filaments per one yarn are

Table 1 Mechanical properties of fiber (nominal values)

Fiber type	Elastic modulus (MPa)	Ultimate strength (MPa)	for one yarn		
			Filaments per one yarn	Sectional area (mm ²)*	Strength (N)
Aramid	70 000	3 500	2k	0.452	790
			4k	0.905	1 580
Carbon	230 000	3 500	6k	0.462	810

* includes binder volume

Table 2 Specimen identification

N4 - C A 30 x2				
				number of layers : nothing=1 x2=2
				amount of fiber : 30=2k 60=4k 06=6k
				fiber type : A=aramid C=carbon
				configuration : C=2 T=3 D=4 directions
mortar with 40MPa strength				

used as reinforcements. Mechanical properties of fiber are summarized in Table 1. These fiber are arranged in mesh with 2, 3 or 4 directions (see Fig. 4). The spacing of each yarn is fixed at 10mm. Epoxy resin is used for binder. Mortar with specified compressive strength of 40 MPa was cast vertically. The measured compressive strength at the loading was 55.1 MPa. By combining test variables, a total of 11 specimens are tested. The relationships between specimen identifications and test variables are shown in Table 2.

2.3 MEASUREMENTS

Load, displacements and fiber strains were measured. Load was obtained by a load cell set at an oil jack. Five displacement transducers were set up to four bolts fixed in the specimen as shown in Fig. 3. Four or six strain gages were attached as shown in Fig. 4.

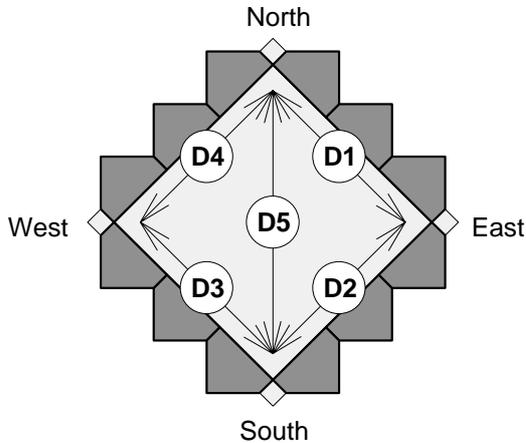


Fig. 3 Displacement transducers set up

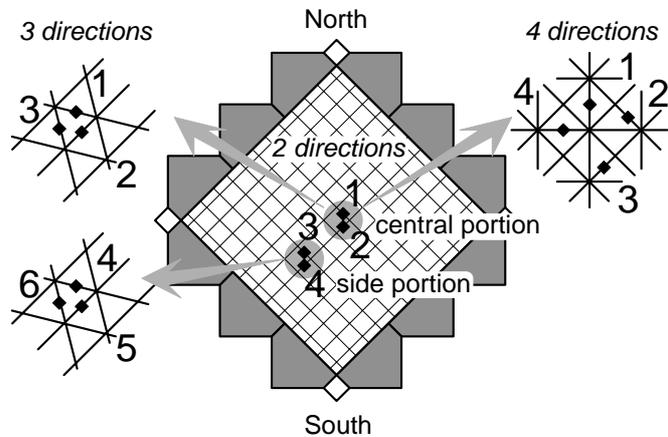


Fig. 4 Positions of strain gages

3 TEST RESULTS AND DISCUSSIONS

3.1 FAILURE PROGRESS

Test results are summarized in Table 3. In all specimens, first crack took place at over 2MPa of shear stress. Specimen N4-CC06 failed by rupture of fiber at essentially the first crack load. In other specimens, cracks took place step by step and diagonal displacement became larger. Two failure pattern were observed, rupture of fiber and compression failure of mortar. Two specimens that showed typical failure patterns, rupture and compression, and their shear stress versus shear strain curves are shown in Fig. 5.

Table 3 Test results

Specimen	Reinforcement		Shear stress at first crack (MPa)	Maximum shear stress (MPa)	Failure pattern
	Type	Aspect*			
N4-CA30	Aramid	2d-2k	2.11	2.45	Rupture
N4-TA30		3d-2k	2.43	3.25	Compression
N4-DA30		4d-2k	2.63	3.49	Rupture
N4-CA60		2d-4k	2.24	2.88	Edge failure
N4-TA60		3d-4k	2.42	4.01	Compression
N4-DA60		4d-4k	2.28	4.07	Compression
N4-CA30x2		2d-2k-2	2.66	3.42	Compression
N4-DA30x2		4d-2k-2	2.73	6.08	Rupture
N4-CC06	Carbon	2d-6k	2.24	2.26	Rupture
N4-TC06		3d-6k	2.31	2.50	Rupture
N4-DC06		4d-6k	2.03	2.71	Rupture

* direction - filament - layer

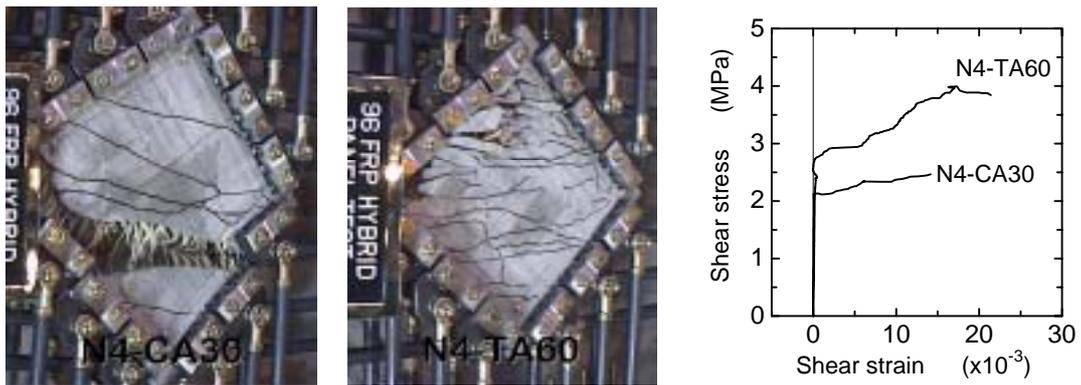


Fig. 5 Typical failures and shear stress - shear strain curves

3.2 STRAIN OF FIBER

Shear stress versus fiber strain curves of specimens using 4k-aramid are shown in Fig. 6. The left, middle and right graph shows specimen of 2-direction, 3-direction and 4-direction mesh, respectively. The numbers correspond with the gage numbers shown in Fig. 4.

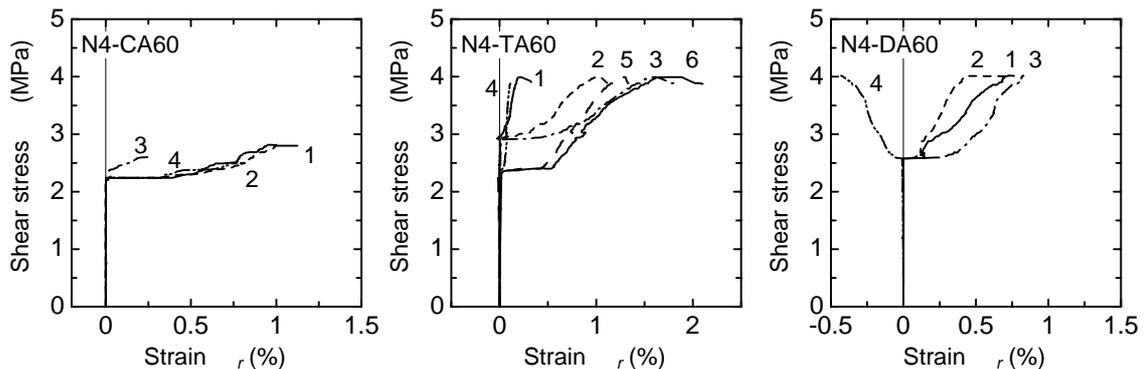


Fig. 6 Shear stress versus fiber strain curves

Since these specimens were not failed by rupture of fiber, maximum strains are smaller than the ultimate strain of 5%. In specimen N4-CA60, all strain-curves behave similarly. Fibers of 2 directions are under the same conditions to applied loads. On the other hand, each curve is different in specimen N4-TA60 and N4-DA60. These phenomena correspond with fiber direction to applied load. No.1 and 4 gages of N4-TA60 and No.4 gage of N4-DA60 are placed on fibers that run along the compressive direction (see Fig. 4). No.2 and 3 gages of N4-TA60 and No.1, 2, 3 gages of N4-DA60 show the same tendency.

4 ANALYTICAL PROGRAM

The analysis based on the “Modified Compression-Field Theory” proposed by Collins [1] is carried out to obtain shear behavior of fiber-mesh reinforced panels. Analytical relationship between shear stress and shear strain of panels can be obtained by solving compatibility conditions and equilibrium conditions using proposed stress-strain relationship for concrete. In addition, tension stiffening effect is also considered in this paper.

4.1 ANALYTICAL METHOD

The analysis is carried out according to the following process (notation is in appendix).

Step 1 : Choose principal tensile strain ε_1 to analyze.

Step 2 : Estimate average stress of reinforcement (fiber) f_r .

Step 3 : Calculate principal tensile stress of concrete f_{c1} by formula (1) (Fig. 7).

$$\left\{ \begin{array}{l} f_{c1} = \frac{2 \cdot f_c \cdot \varepsilon_1}{\varepsilon_c} \quad (\varepsilon_1 \leq \varepsilon_{cr}) \\ f_{c1} = \frac{f_{cr}}{1 + \sqrt{200 \cdot \varepsilon_1}} \quad (\varepsilon_1 \geq \varepsilon_{cr}) \end{array} \right., \quad f_{cr} = 0.33\sqrt{-f_c}, \quad \varepsilon_{cr} = \frac{f_{cr} \cdot \varepsilon_c}{2 \cdot f_c} \quad (1)$$

Step 4 : Calculate shear stress τ_{xy} from equilibrium (Fig. 8).

$$\tau_{xy} = f_{c1} + \rho \cdot f_r \quad (2)$$

Step 5 : Calculate principal compressive stress of concrete f_{c2} from equilibrium.

$$f_{c2} = f_{c1} - 2 \cdot \tau_{xy} \quad (3)$$

Step 6 : Calculate f_{c2max} for given ε_1 by formula (4).

$$f_{c2max} / f_c = 1 / (0.8 - \varepsilon_1 / \varepsilon_c) \leq 1.0 \quad (4)$$

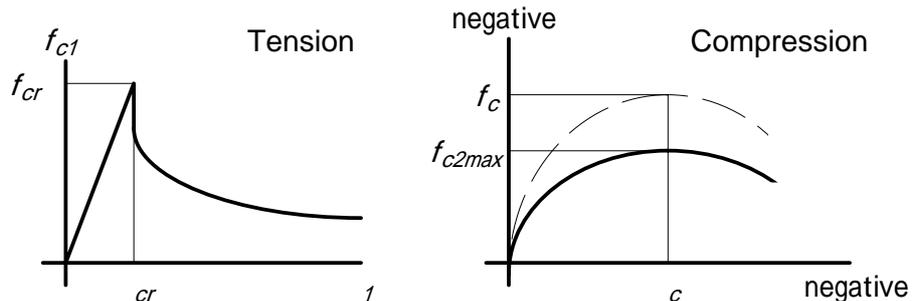


Fig. 7 Proposed stress-strain relationship for mortar

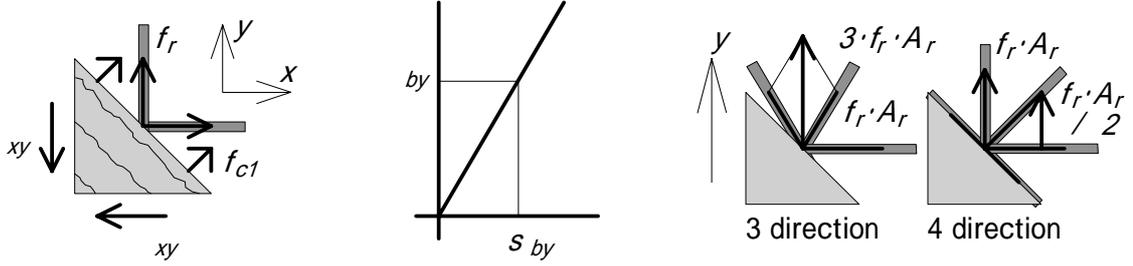


Fig. 8 Equilibrium conditions Fig. 9 Bond assumption Fig. 10 Effective area for

Step 7 : Calculate principal compressive strain ε_2 by formula (5) (Fig. 7).

$$\varepsilon_2 = \varepsilon_c \cdot \left(1 - \sqrt{1 - \frac{f_{c2}}{f_{c2\max}}} \right) \quad \therefore \frac{f_{c2}}{f_{c2\max}} = 2 \left(\frac{\varepsilon_2}{\varepsilon_c} \right) - \left(\frac{\varepsilon_2}{\varepsilon_c} \right)^2 \quad (5)$$

Step 8 : Calculate strain in y-direction ε_y ($= \varepsilon_x$) from geometry.

$$\varepsilon_y = (\varepsilon_1 + \varepsilon_2) / 2 \quad (6)$$

Step 9 : Calculate f_r .

$$f_r = E_r \cdot \varepsilon_y \quad (7)$$

Step 10 : Check if f_r calculated agrees with estimated f_r . If not, return to Step 2 with new estimate of f_r .

Step 11 : Check that $f_{c2} < f_{c2\max}$. If not, then mortar crushing by compression.

Step 12 : Calculate tensile force of reinforcement at a crack P_{rcr} (Fig. 9 [2]).

$$P_{rcr} = \frac{(1+n\rho) \cdot P_{rm} \cdot s_m}{n\rho \cdot s_m + 2/k \cdot \tanh(k \cdot s_m / 2)}, \quad P_{rm} = f_r \cdot A_r, \quad k = \sqrt{\frac{(1+n\rho) \cdot \tau_{by}}{E_r \cdot A_r \cdot s_{by}}} \quad (8)$$

Step 13 : Calculate tensile stress of reinforcement at a crack f_{rcr} .

$$f_{rcr} = P_{rcr} / A_r \quad (9)$$

Step 14 : Check that $f_{rcr} < f_{ru}$. If not, then reinforcement breaks (rupture of fiber).

Step 15 : Calculate γ_{xy} from geometry.

$$\gamma_{xy} = 2(\varepsilon_y - \varepsilon_2) \quad (10)$$

To obtain the complete stress-strain relationship, these calculations are repeated for a range of values of ε_1 , from small ε_1 and increasing until recognizing crush or break.

In this analysis, formula (4) is re-modified to adapt the reduction factor for concrete strength to 55MPa class mortar, because the reduction factor proposed by Collins was determined from test results of concrete with 27MPa strength. Formula (8) represents the effect of tension stiffening as the force in reinforcement at a crack is bigger than the average force. Reinforcement ratio, ρ , is calculated using the following formulas based on consideration of effective sectional area of yarns to y-direction (Fig. 10). Other common data for analysis are : $f_c = -55.1\text{MPa}$, $\varepsilon_c = -0.0035$, $n = 1.4$ (aramid), $n = 4.6$ (carbon), $\tau_{by} / s_{by} = 4300 \text{ N} / \text{mm}^2$

$$\begin{aligned} \text{2-direction} : & \frac{A_r}{s \cdot t}, \quad \text{3-direction} : \frac{\sqrt{3}A_r}{s \cdot t}, \quad \text{4-direction} : \frac{A_r (1 + 1/\sqrt{2})}{s \cdot t} \end{aligned} \quad (11)$$

Table 4 Comparison of analytical and test results

Specimen	Data for analysis		Analyzed maximum shear stress (MPa)	Ratio of test to analysis	Analyzed failure pattern
	(%)	s_m (mm)			
N4-CA30	0.301	20.0	2.20	1.11	Rupture
N4-TA30	0.522	15.0	3.21	1.01	Compression
N4-DA30	0.514	14.8	3.09	1.13	Rupture
N4-CA60	0.603	16.7	3.41	0.84	Compression
N4-TA60	1.045	14.8	4.24	0.95	Compression
N4-DA60	1.030	16.0	4.22	0.96	Compression
N4-CA30x2	0.603	12.1	3.41	1.00	Compression
N4-DA30x2	1.029	12.1	4.21	1.44	Compression
N4-CC06	0.308	100.0	2.20	1.03	Rupture
N4-TC06	0.534	20.0	4.34	0.58	Rupture
N4-DC06	0.526	18.2	4.60	0.59	Rupture

4.2 COMPARISON OF ANALYTICAL AND TEST RESULTS

The results of analysis are summarized in Table 4. Analyzed maximum shear stresses show a good correlation with test results especially for aramid specimens. The average of maximum stress ratio of test results to analytical values is 1.06 and 0.73 for specimens reinforced by aramid and carbon fiber, respectively. The analyzed failure patterns also correspond to test results. Fig. 11 shows comparisons of shear stress - shear strain curves between analytical and test curves. Though the reducing portion of curves is obtained by analysis, observation of this portion is not possible in the test program because of oil jack loading. It is considered that other portions are almost similar between analytical and test curves. However, the test curves of specimens reinforced with carbon fiber do not fit the analysis.

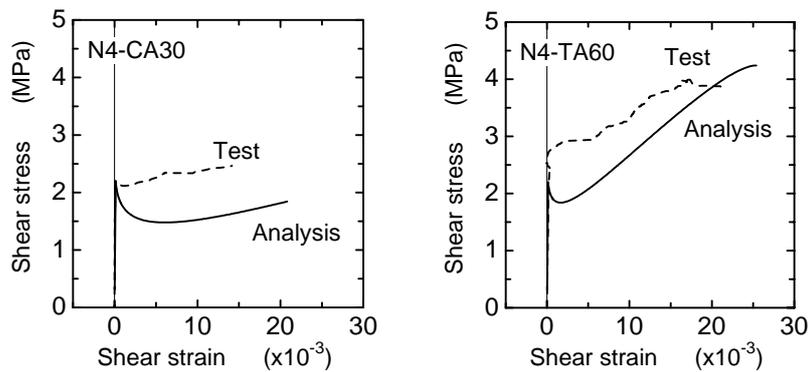


Fig. 11 Analyzed shear stress - shear strain curves

5 CONCLUSIONS

To investigate the fundamental behavior of fiber-mesh reinforced plates, pure shear test and analysis are carried out. The conclusions are summarized as follows.

- (1) Two failure processes, compression failure and rupture of fiber, are observed and can be

- accurately predicted from the analysis.
- (2) Measured fiber strains correspond with the directions of fiber in regard to applied load direction.
 - (3) Maximum shear stresses from analysis show a good correlation with measured values for the aramid fiber meshes.
 - (4) The shear stress - strain curves from testing agree with the analytical curves for the aramid fibers. Shear behavior of fiber-mesh reinforced panels can be predicted by the analysis based on the modified compression-field theory.

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REFERENCES

- [1] Vecchio, F. J. and Collins, M. P., "The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear," ACI Journal, March-April, 1986, pp.219-231
- [2] Muguruma, H. and Morita, S., "Fundamental Study on Bond between Steel and Concrete," Journal of AIJ, No. 131, January, 1967, pp.1-8 (in Japanese)

APPENDIX -NOTATION-

A_r : sectional area of reinforcement	s : spacing of reinforcement
E_c : elastic modulus of concrete	s_m : average spacing of cracks
E_r : elastic modulus of reinforcement	s_{by} : slip of reinforcement at τ_{by}
f_c : compressive strength of concrete	t : thickness of panel
f_{c1} : principal tensile stress of concrete	γ_{xy} : shear strain
f_{c2} : principal comp. stress of concrete	ε_1 : principal tensile strain
f_{c2max} : max. effective strength of f_c	ε_2 : principal compressive strain
f_{cr} : crack strength of concrete	ε_c : strain of concrete at f_c
f_r : average stress of reinforcement	ε_{cr} : strain of concrete at f_{cr}
f_{rcr} : tensile stress of reinf. at a crack	ε_y : strain in y-direction
f_{ru} : ultimate strength of reinforcement	ρ : reinforcement ratio
n : elastic modulus ratio = E_r / E_c	τ_{by} : bond stress per 1mm at s_{by}
P_{rcr} : tensile force of reinf. at a crack	τ_{xy} : shear stress
P_{rm} : average tensile force of reinf.	