EXPERIMENTAL STUDY ON CONTROL INDEX OF STRESS DROP FOR DESIGNING HYBRID FRP SHEETS

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Abstract

In the previous study, the authors proposed hybrid FRP sheets consisting of several types of fibers with various specific properties and investigated their mechanical properties. The observed stress drop due to the gradual rupture of higher modulus (HM) and/or higher ductility (HD) fibers is a concern and should be controlled. It was experimentally confirmed that integrative performance, including tensile strength, stiffness, and ductility could be thoroughly realized through appropriately hybridizing high modulus fibers, high strength fibers, and high ductility fibers for which the stress drop can be controlled within a required range. In this study, a control index for stress drop was designed to control the stress drop and it was investigated quantitatively with an experimental program. The effectiveness of the control index of the combination among different types of fibers to control the stress drop of hybrid fiber sheets was confirmed experimentally.

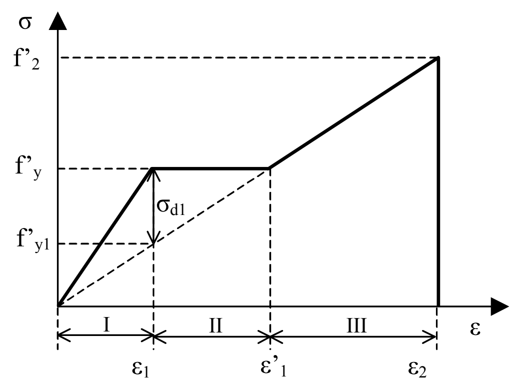
1 Introduction

In recent years, fiber reinforced polymer (FRP) sheets, especially carbon fiber reinforced polymers (CFRP) used as external reinforcements, have been increasingly applied in repairing, strengthening and upgrading deteriorated or deteriorating civil infrastructures due to their high strength and stiffness to weight ratios, high resistance against chemical corrosion, low density as well as for their other advantages. However, for structures strengthened with FRP sheets consisting merely of a single type of fiber sheet, their serviceability, such as the stiffness, steel yielding load, and crack resistance, cannot be markedly improved. Moreover, the premature debonding of FRP sheets, which occurs before tensile failure, is a serious problem for the FRP strengthening technique. To address these problems, the authors have proposed hybrid FRP sheets consisting of several types of fibers of different specific properties and investigated their mechanical properties. We found that the stress drop due to the gradual rupture of higher modulus (HM) and/or higher ductility (HD) fibers is a concern and should be controlled. It was experimentally confirmed that integrative performance, including tensile strength, stiffness, and ductility could be thoroughly realized through appropriately hybridizing high modulus fibers, high strength fibers, and high ductility fibers for which the stress drop can be controlled within a required level [1][2].

2 Control index of stress drop upon the rupture of the high modulus carbon fiber sheets

According to the mixture law of hybrid composites [3], the stress σ_L and the elastic modulus E_L of hybrid composites can be expressed [1] [2], as:

$$\sigma_L = \varepsilon\,(E_m A_m + E_d A_d)\,/A \qquad (1)$$

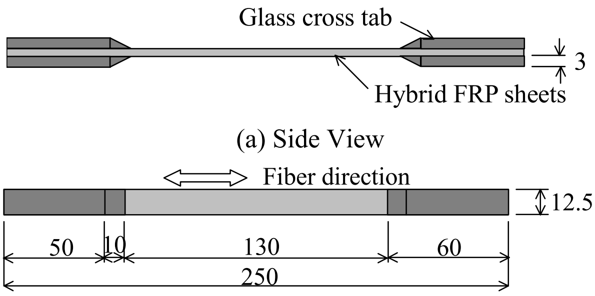


f'_y: Ultimate strength of HM
f'_2: Ultimate strength of HD
σ_d: Amount of decreased stress due to rupture of HM
ε_1: Rupture strain of HM
ε'_1: Strain at initiation of strain hardening
ε_2: Ultimate strain at rupture of HD

Fig.1 Identified tensile behavior of hybrid fiber reinforcements with two types of fibers

Table 1 Summary of Mechanical Properties of Different Fiber Sheets

Kind of FRP sheet	MC	SC	SP	DEG
Guaranteed tensile strength (N/mm^2)	1900	3400	3500	1500
Nominal elastic modulus (kN/mm^2)	540	230	240	80
Nominal rupture strain (%)	0.35	1.48	1.46	1.88
Nominal thickness (mm)	0.143	0.111	0.128	0.118
Unit weight of fibers (g/m^2/1 layer)	300	200	200	200



(a) Side View

(b) Top View

Fig. 2 Dimension of Specimen of CFRP Sheets

$$E_L = (E_m A_m + E_d A_d) / A \qquad (2)$$

where E_m, E_d, and A_m, A_d are the elastic modulus and cross-sectional areas of HM, and HD, respectively. A is the total cross-sectional area of the fiber sheets ($A=A_m+A_d$). Fig. 1 shows the identified tensile behavior of the hybrid fiber reinforcement. In our previous study [1], λ_c ($=\sigma_d/f'_y$) was defined as index of stress drop control upon the rupture of HM. Then, σ_d is the value of f'_y minus f'_{y1}, f'_y is the tensile stress just before the HM rupture, and f'_{y1} is the stress just after the HM rupture. In this study, the effectiveness of the control index to evaluate the stress drop of hybrid fiber sheets is confirmed experimentally.

3 Experimental program

3.1 Details of hybrid FRP specimens

To gain a clear insight into the mechanical behavior of different hybrid fiber sheets, a series of uniaxial tension specimens were tested by composing different types of fiber sheets. The fiber sheets included in the investigation were higher modulus carbon (MC), higher strength carbon (SC), higher strength Poly-p-phenylene-benzobisoxazole (SP), and higher ductility E-glass (DEG) FRP sheets with different proportions. The tensile properties of these

Table 2 Summary of mix ratio of hybrid FRP sheets

Specimen	MC layers	SC layers	Number
1MC0.4SC	1	0.4	5
1MC0.6SC	1	0.6	5
1MC1SC	1	1	5
1MC1.2SC	1	1.2	5
1MC1.4SC	1	1.4	5
1MC1.6SC	1	1.6	5
1MC1.8SC	1	1.8	5
1MC2SC	1	2	5
1MC2.2SC	1	2.2	5
1MC2.4SC	1	2.4	5
1MC2.6SC	1	2.6	5
1MC3SC	1	3	5
1MC5SC	1	5	5
Specimen	MC layers	SP layers	Number
1MC0.2SP	1	0.2	5
1MC0.3SP	1	0.3	5
1MC0.4SP	1	0.4	5
1MC0.6SP	1	0.6	5
1MC0.8SP	1	0.8	5
1MC1.0SP	1	1	5
1MC1.2SP	1	1.2	5
1MC1.4SP	1	1.4	5
1MC1.6SP	1	1.6	5
1MC1.8SP	1	1.8	5
1MC2.0SP	1	2	5
1MC3SP	1	3	5
1MC5SP	1	5	5
Specimen	MC layers	DEG layers	Number
0.5MC1DEG	0.5	1	5
0.5MC2DEG	0.5	2	5
0.5MC3DEG	0.5	3	5
0.5MC3.2DEG	0.5	3.2	5
0.5MC3.4DEG	0.5	3.4	5
0.5MC3.6DEG	0.5	3.6	5
0.5MC3.8DEG	0.5	3.8	5
0.5MC4DEG	0.5	4	5
0.5MC4.2DEG	0.5	4.2	5
0.5MC4.4DEG	0.5	4.4	5
0.5MC4.6DEG	0.5	4.6	5
0.5MC6DEG	0.5	6	5
0.5MC8DEG	0.5	8	5

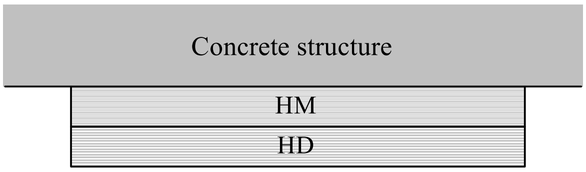


Fig. 3 Lay-up sequence of two types of FRP sheets

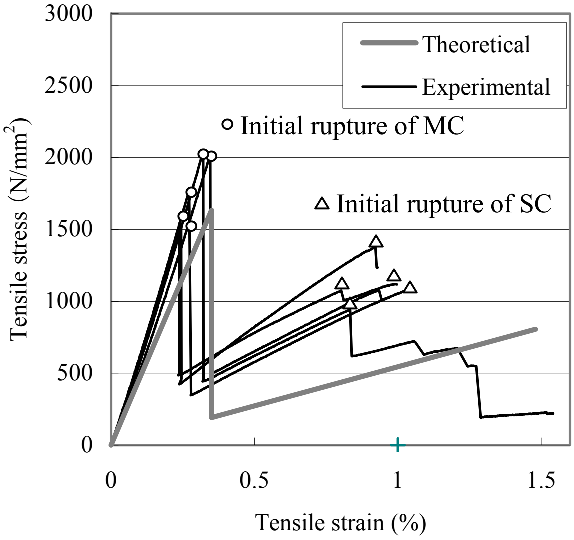


Fig. 4 Tensile stress-strain curves (1MC0.4SC)

types of FRP sheets are shown in Table 1. The hybrid ratios of the different types of fibers are indicated as the layer's ratio. The tension specimens of FRP sheets are manufactured through impregnation of epoxy resin according to the JSCE guideline (2001) [4], as shown in Fig. 2. The fiber volume content (V_f) of hybrid FRP sheets was set at 50%, based on the guideline. Continuous fiber sheets were impregnated with epoxy resin by hand and cured at room temperatures of about 25-27°C. The loading was controlled by displacement at a rate of 1 mm/min. The combinations of fibers used is as follows: (1) MC and SC, and (2) MC and SP. 39 cases of a mixed ratio of hybrid FRP sheets and 5 experiments were carried out for each mixed ratio, as shown in Tables 2 and 3. The total number of test specimens was 195. The lay-up structure of these FRP sheets was asymmetric, as shown in Fig. 3. This reasons for this are as follows: (1) the serviceability strengthening effect by MC fibers is effectively propagated to the concrete structure, and (2) the impact tolerance of high strength fibers at the MC rupture is increased by increasing the thickness of fibers remaining after the MC rupture.

3.2 Details of experimental program

The tensile tests of the hybrid FRP specimens

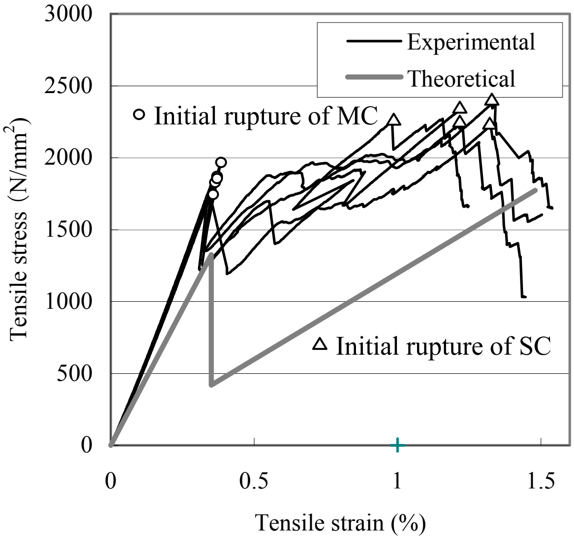


Fig. 5 Tensile stress-strain curves (1MC1.2SC)

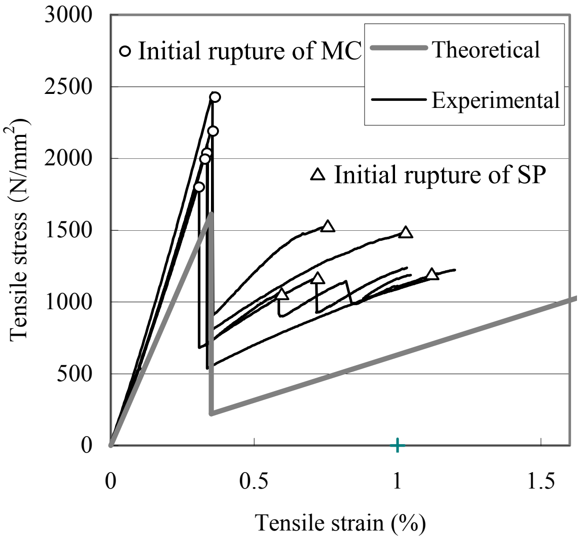


Fig. 6 Tensile stress-strain curves (1MC0.4SP)

were performed using an Instron 8502 series servo hydraulic testing machine with a 100kN capacity load cell. The rate of the loading was 1mm/min. The load and average FRP strain were measured with the electronic load cell and a 100mm-long extensometer that was attached to the mid-span of the specimen. Next, the values were recorded with wave maker software made by Instron co., ltd..

4 Experimental result and discussion

The tensile stress-strain curves of hybrid specimens whose mixture ratios of different fibers were SC/MC=0.4 and 1.2 are shown with a theoretical line in Figs. 4 and 5. The drop stress in

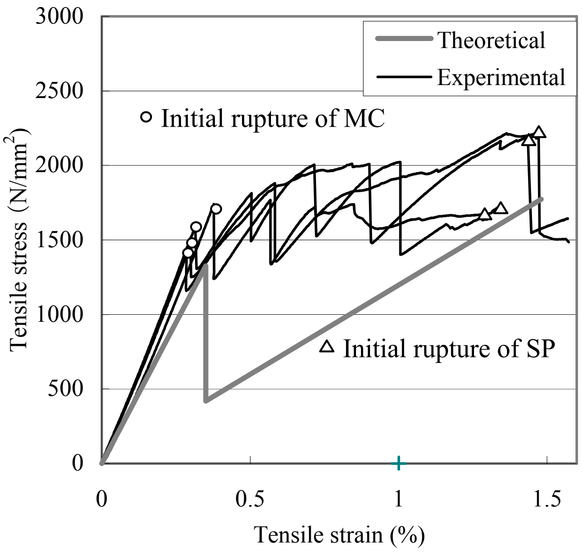


Fig. 7 Tensile stress-strain curves (1MC1.2SP)

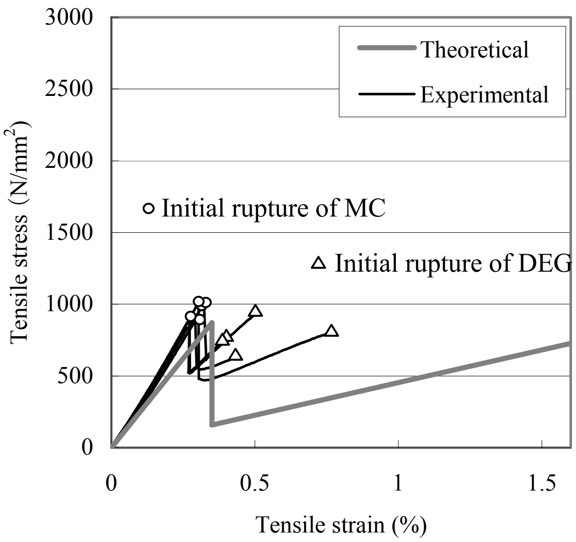


Fig. 8 Tensile stress-strain curves (0.5MC1DEG)

experiments was nearly same as that of theoretical curves in 1MC0.4SC specimens. The MC rupture occurred completely. Drop stress just after the initial rupture of MC fibers in these experiments was smaller than theoretical values in 1MC1.2SC specimens. The MC rupture occurred partially and stepwise, and the maximum strain reached the theoretical rupture strain of SC FRP. Therefore, the stress drop was found to be smaller with increasing the amounts of SC remaining after MC rupture. In contrast, tensile stress-strain curves of hybrid specimens whose mixture ratios of different fibers were SP/MC=0.4, 1.2 and DEG/MC=1 and 2 are shown with a theoretical line in

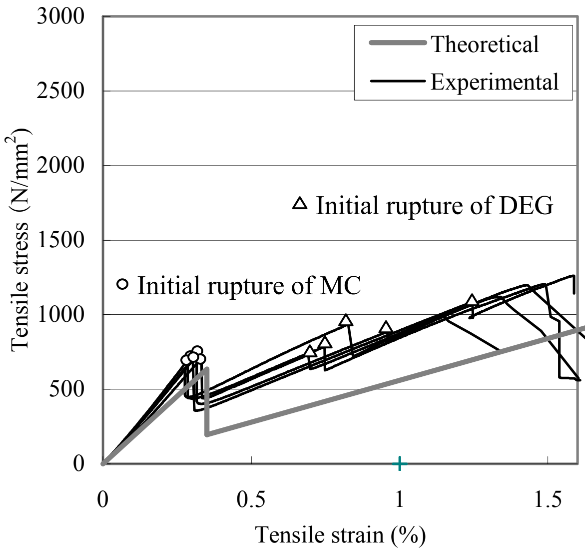


Fig. 9 Tensile stress-strain curves (0.5MC2DEG)

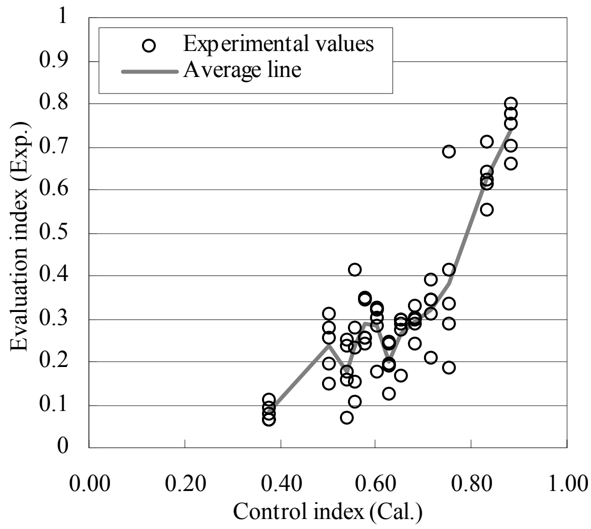


Fig. 10 Comparison between control and evaluation indices of MC-SC hybrid specimens

Figs. 6-9. The same behaviors were confirmed in MC-SP and MC-DEG hybrid specimens.

Comparisons between the control and evaluation indices of MC-SC, MC-SP, and MC-DEG hybrid specimens are shown in Figs. 10-12. Evaluation index λ_e is the value of the initial drop stress just after the initial rupture of the MC, σ_{de}, divided by the tensile stress just before the initial rupture of the MC, f'_{ye}. It appears that the evaluation index increases linearly when the control index increases from 0.4 to 0.7, and increases rapidly over 0.7 of control index. Thus, evaluation values of MC-SP hybrid specimens are located lower place than those of MC-SC and MC-DEG hybrid specimens.

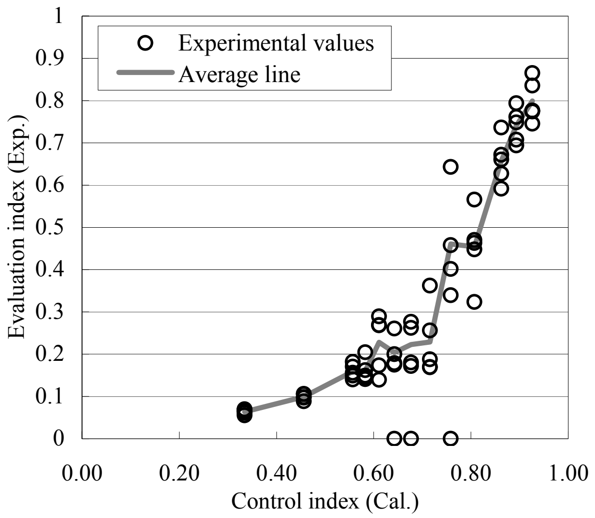


Fig. 11 Comparison between control and evaluation indices of MC-SP hybrid specimens

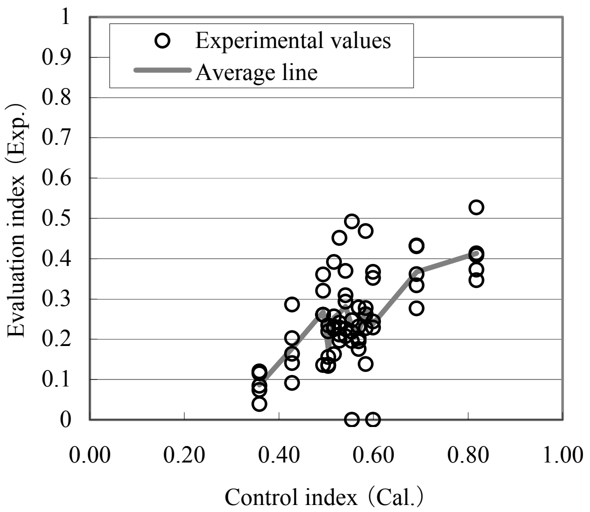
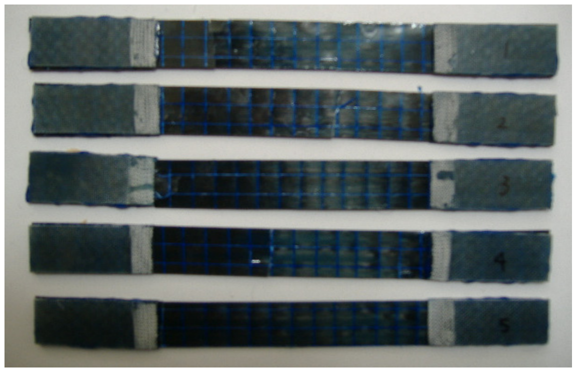
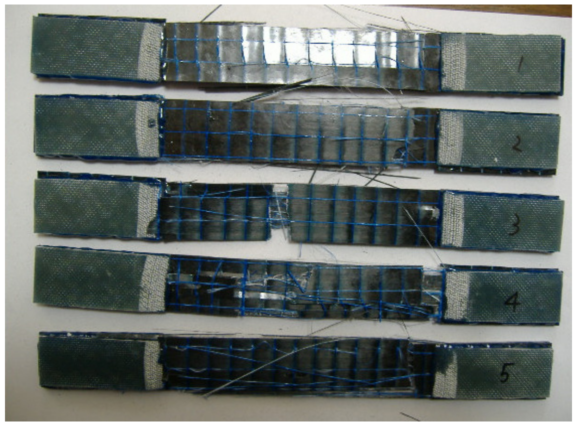


Fig. 12 Comparison between control and evaluation indices of MC-DEG hybrid specimens

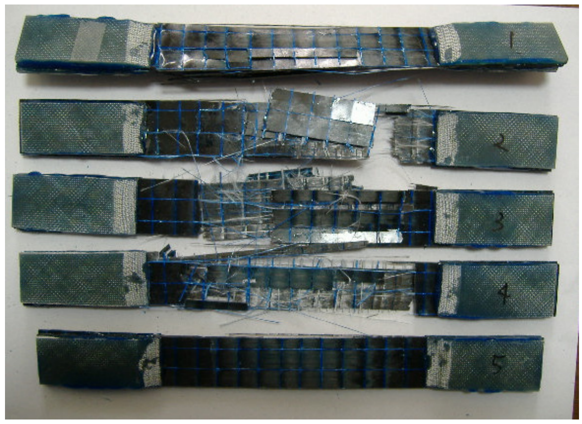
Moreover, dispersion of evaluation values of MC-SP hybrid specimens are smaller than those of MC-SC and MC-DEG hybrid specimens. The average value of standard deviation of evaluation index of MC-SC specimens is 6.89 and that of MC-SP specimens is 5.08. These effects are due to the fact that the energy absorption capacity of PBO fibers is higher than that of carbon fibers [5]. Many matrix cracks and partial ruptures appeared in hybrid specimens, including a larger amount of SC, as shown in Fig. 13. The impact force that occurred by MC rupture was found to become higher with the increasing amount of SC in the hybrid specimen. However, matrix cracks and partial ruptures are almost absent in the hybrid specimens, including the SP, as shown in Fig. 14.



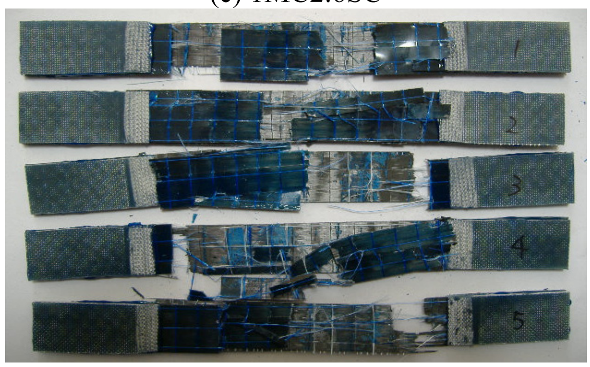
(a) 1MC0.4SC



(b) 1MC1.6SC



(c) 1MC2.6SC



(d) 1MC5SC

Fig. 13 Crack distribution of MC-SC hybrid specimens

The impact force scattered by the occurrence of micro cracks in MC is thought to be relieved by PBO fibers, and thus the occurrence of macro cracks is controlled.

5 Conclusion

The effectiveness of the control index of a combination of different types of fibers to control the drop stress due to rupture of HM in hybrid FRP was confirmed experimentally. Additionally, we found that PBO fibers function to decrease the stress drop of hybrid sheets by their own energy absorption capacity.

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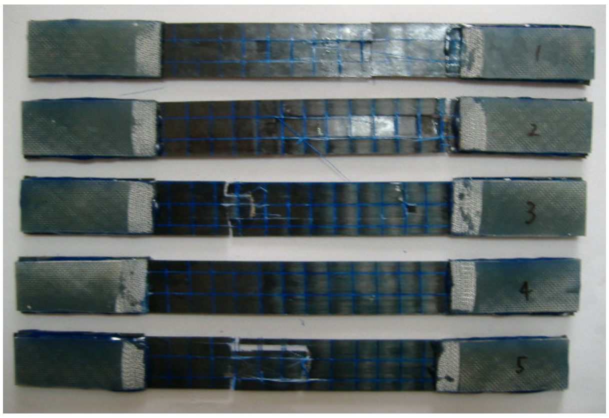
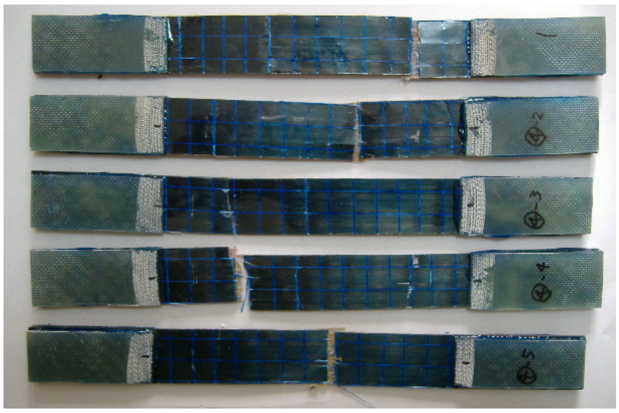
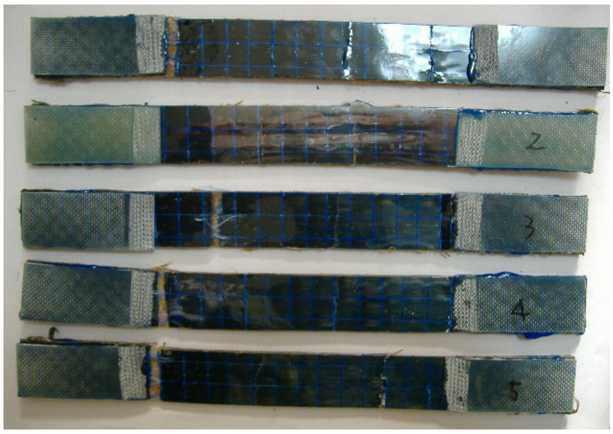


(a) 1MC0.3SP



(b) 1MC1SP



(c) 1MC3SP

Fig. 14 Crack distribution in MC-SP hybrid specimens