THE FRACTURED-BASED MODELING OF PULL-OUT PROBLEM WITH LONG EMBEDDED NYLON 600

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ABSTRACT

Fracture phenomenon happened during the pull-out process. Previous study of short embedded nylon 600 in cementitious matrix model has proved several new theories with main concern of fracture. Nevertheless, it is necessary to assure that the same theories can be applied accurately and consistently in the pull-out problem with long embedded nylon 600. The research conducts experiment method and analytical method. The experiment method applies pull-out test with long embedded nylon 600 in cementitious matrix and the analytical method is based on previous fractured based pull-out model. The pull-out specimens have embedded length of l_f = 110-180 mm. The results of experiment show that all specimens suffer fibers broken. The pull-out process explains several stages: (a) Pre-slip stage, (b) Slip stage, and (c) Strain-hardening stage. The pre-slip loads are found as 400-430 N and pre-slip displacements of no more than 0.1 mm. The slip loads have been observed in the same range of pre-slip loads with displacements of 3-30 mm. The maximum strain-hardening loads are found as 1600-1800N while the broken loads are observed as 1400-1700 N. The maximum displacements are ranged about 100-200 mm. The previous model for pull-out problem with short embedded nylon 600 is applied to the long embedded nylon 600. Clearly, the model has been proven fit to the experimental results. It is emphasized that the theories for the pull-out problem with short embedded nylon 600 are still accurate and consistent applied to long embedded nylon 600. This research meets conclusions: (a) The same theories of pull-out problem with short embedded nylon 600 in cementitious matrix can be applied accurately and consistently for long embedded nylon 600, (b) The unstable and stable fracture process phenomenon exist during the pull-out process, (c) Several stages exist during the pull-out process, (d) The equation of stable crack length of previous model can also be applied for long embedded nylon 600, (e) The equation of load of previous model can also be applied for long embedded nylon 600, (f) The possibility of crack arrester presence is bigger for the long embedded fiber length than the short ones, thus the strain-hardening part in load-displacement curve is longer for the long embedded fiber length.

Keywords: *model, fracture, pull-out, long, fiber, nylon*

INTRODUCTION

The fiber has been applied in the composites to increase the composite's performance since ancient period. Fiber existence in composites shows many advantages of crack delaying and resisting (Naaman, et. al, 1990). Hence, fiber takes an important role in determining whole "fiber-reinforced cementitious composite" (FRCC) performance.

The synthetic fiber has advantage in improving the FRCC performance. A good example to describe tensile ductility of FRCC is the using of nylon fiber. Nylon fiber is unique (Nadai, 1950). Nadai explains that nylon fiber will constrict many times and perform two moving surface waves along the fiber length during stretching condition. This phenomenon is called 'yield point elongation' which has magnitude of 200%-300% of initial fiber length. It should be noted that of the nylon viscosity will cause the load gradually decreasing while the fiber length becomes longer two or three times. The multiple constrictions of nylon fiber appeared by 'jagged' phenomenon of stress-strain or load-displacement curves (Nadai, 1950; Avarett, 2004; Susilorini, 2007a). Similar phenomenon is suffered by mild steel and aluminium alloy (Nadai, 1950).

A pull-out test is a characterization of the interface between fiber and cementitious matrix. Sun and Lin (2001) describes pull-out problem with interest on the mechanism of interface between fiber and matrix, strength, and stress distribution along the interface. Some models were built on pull-out problem. Those models are analytical models, fracture mechanics based models, and also micro fractural models. Several models have implemented shear stress and friction shear stress along the fiber. Unfortunately, some models neglect the Poisson's ratio (Wang, Li, Backer, 1988a, b; Li, Stang, 1997; Morrison, Shah, Jenq, 1988; Li, Chan, 1994; Sumitro, Tsubaki, 1997). It is only few researches (Naaman, et.al., 1990 and Bentur, et.al., 1996) consider the influence of Poisson's ratio and there is no research about stable crack length in the matrix.

Susilorini (2007a) states that the length of embedded fiber determines the performance of the composite by its fracture behaviour. Hence, the characteristic of long embedded nylon 600 will contribute specific performance in pull-out problem.

According to Susilorini (2007b), fracture based approach becomes a solution to prohibit a catastrophic failure of structure. By using fracture mechanics, the design will achieve more safety margin for structure and higher economic value and also structural benefit. When fracture emerged, crack propagation will be happened and the whole structure is going to failure. Therefore, according to Bazant (1992), the failure of concrete structures should consider the strain-softening phenomenon. The strain-softening phenomenon is related to distributed and localized crack. The crack is growing to larger fracture and bridging stresses at the fracture front. Hence, the suppression of fracture of concrete must be implemented by improving higher toughness and higher tensile ductility (Li and Wang, 2005). Some innovations have been applied to improve toughness and tensile ductility (Fischer and Li, 2004) such as Fiber Reinforced Concrete (FRC) and High Performance Fiber Reinforced Cementitious Composites (HPRFCC) which is known as Engineered Cementitious Composites (ECC). The performance evaluation of those innovations use fracture mechanics.

A comprehensive fractured based model is built to represents the pull-out problem of embedded nylon 600 (Susilorini, 2007a). Some aspects were considered by previous model of short embedded nylon 600. Hence, it is important now to know the result of model which is using long embedded nylon 600.

This research considers several aspects (Susilorini, 2007a): (1) Fracture capacity of embedded fiber is a function of Poisson's ratio of fiber, (2) Some stages exist during the pull-out and fracture pull-out process, (4) A 'jagged' phenomenon exists on strain-hardening part of load-displacement (P-δ) and stress-strain (σ−ε) pull-out curves, and (4) Unstable and stable fracture process phenomenon exist during the pull-out process.

There is a question, is the previous theories established by short embedded nylon 600 in cementitious matrix still accurate and consistent for model with long embedded nylon 600? This research tries to find whether the theories of pull-out problem with short embedded nylon 600 can be also applied to long embedded nylon 600.
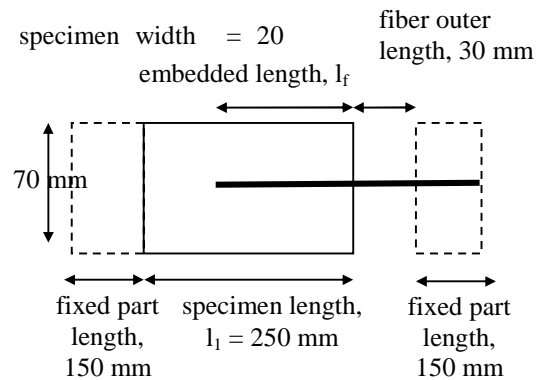
METHODS OF RESEARCH

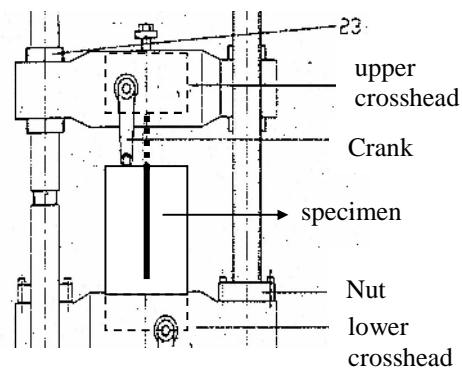Figure 1. Dimensions of Pull-Out

Figure 2. Pull-Out Test Set-Up

The research conducts experiment method and analytical method. The experiment method applies pull-out test with specimens described by Figure 1 while set up of the pull-out test by Figure 2. The pull-out specimens use long embedded nylon 600 fiber in cementitious matrix which is local made ("Golden Fish" brand) with 1.1. mm in diameter. The specimens have embedded length of 110, 150, and 180 mm. Mix design for cementitious matrix is 1:1:0.6 (cement : sand : water). The analytical method is based on previous fractured based pull-out model (with short embedded nylon 600). The model will be evaluated whether it is still accurate and consistent or not.

RESULTS AND DISCUSSION

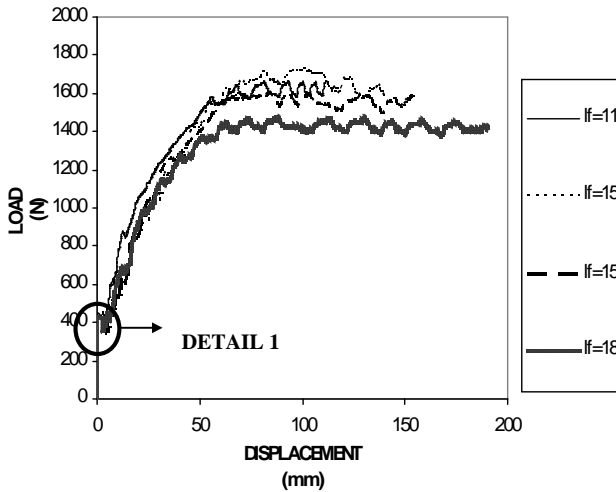### 1. Experiment Result

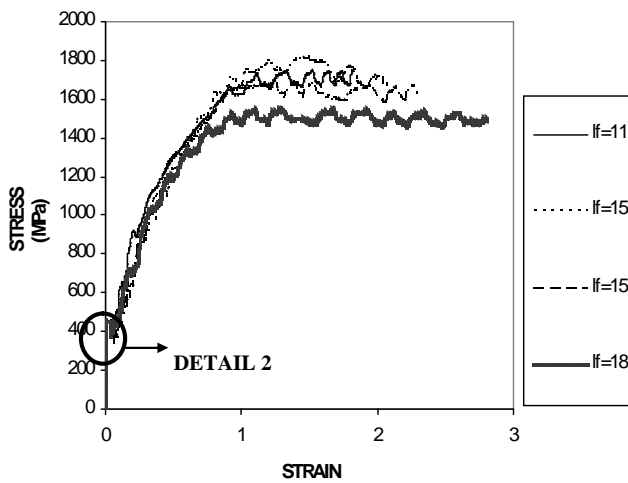Figure 3. Load-displacement relation of specimens with $l_f = 110 - 180$ mm

Figure 4. Stress-strain relation of specimens with $l_f = 110 - 180$ mm

The results of experiment show that all specimens suffer fibers broken. The pull-out process includes several stages: (a) Pre-slip stage, (b) Slip stage, and (c) Strain-hardening stage, as seen on Figure 3 and 4. The 'jagged' phenomenon exists at strain-hardening section of load-displacement and stress-strain curves (Figure 3 and 4). The pre-slip loads are found as 400-430 N and pre-slip displacements of no more than 0.1 mm. The slip loads have been observed in the same range of pre-slip loads with displacements of 3-30 mm. The maximum strain-hardening loads are found as 1600-1800N while the broken loads are observed as 1400-1700 N. The maximum displacements are ranged about 100-200 mm.
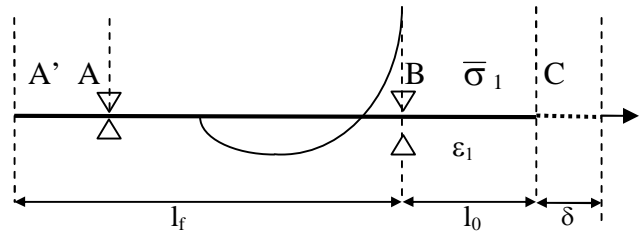
2. Modeling

Figure 5. Pull-Out Model at Elastic Stage

A piece of embedded fiber (A'A) with fiber end at A' is described by Figure 5. Fiber A'A is constrained at A and B but free at C. Free end fiber length named l_0 and embedded fiber end named l_f. A displacement of δ is applied at C. At this elastic stage, the condition of cementitious matrix and fiber are still composites. The displacement δ then will caused matrix stress σ_m. The value of matrix stress σ_m then increase until $\sigma_m = \overline{\sigma}_m = \sigma_m(\overline{\nu})$ reached. Hereby, the value of critical matrix stress $\overline{\sigma}_m$ is a bond capacity at the time of crack which represents the ultimate fracture tension capacity. The $\sigma_m(\nu)$ represents the matrix stress in Poisson's ratio function.

Thus, the strain and stress at BC will be expressed by:

$$\varepsilon_1 = \frac{\delta}{l_0} \qquad (1)$$

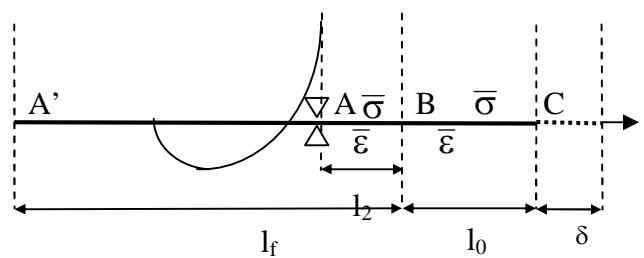$$\sigma_1 = \varepsilon_1 E_s \qquad (2)$$

Figure 6. Pull-Out Model at Unstable Fracture Process

Figure 6 explains that a crack will be performed when displacement δ keeps growing. This crack causes unstable fracture process. After a crack formed, the stress of composites condition then transferred to fiber. By crack formation, unstable fracture process phenomenon will release the constraint at B. Then, the crack length is growing until reach length of l_2. At that time, the constraint at

A is removed to left side. When the crack length l_2 is longer than embedded length l_f, then the fiber will be pulled-out.
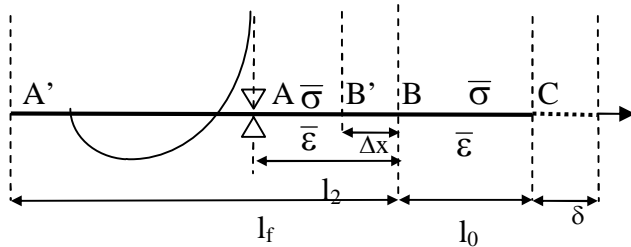

Figure 7. Pull-Out Model at Stable Fracture Process

Figure 8. Load-displacement Relation of Pull-Out Model

After unstable fracture process happened, the stable fracture process will exist. Assume that a crack has formed (Figure 7). The displacement δ increase and so do the strain σ_1 and stress σ_1 at B'B. One time, strain ε_1 and stress σ_1 increasing meets critical value of matrix stress $\overline{\sigma}_m$ and strain $\overline{\varepsilon}$. When those critical values are achieved, the displacement δ increasing is repeated at B'. In the same time, a new crack of Δx will be performed at the left side of fiber. It is happened continuously until constraint A is fixed. The constraint A then becomes crack arrester which is preventing crack growth. In this situation, the crack will be stopped to grow and crack length remains l_2. Once stable crack length l_2 achieved, and then strain at l_0 part is transferred to l_2 part. The stress and strain become:

$$\varepsilon_1 = \varepsilon_{12} = \varepsilon_0 = \varepsilon_r \qquad (3)$$

$$\sigma_1 = \sigma_{12} = \sigma_0 = \sigma_r \qquad (4)$$

$$_r = \frac{}{l_0 + l_2} \qquad (5)$$

When $\overline{\sigma}_m = \sigma_m(\overline{v})$ is achieved and strain at AC is $\varepsilon = \overline{\varepsilon}$, then $\delta = \overline{\delta}$. The strain can be expressed by:

$$\varepsilon = \overline{\varepsilon} = \frac{\overline{\delta}}{l_0 + l_2} \text{ where } \overline{\varepsilon} = \varepsilon(\overline{v}) \qquad (6)$$

The stable crack length is formulated as:

$$l_2 = \frac{\overline{\delta} - \overline{\varepsilon}l_0}{\overline{\varepsilon}} \qquad (7)$$
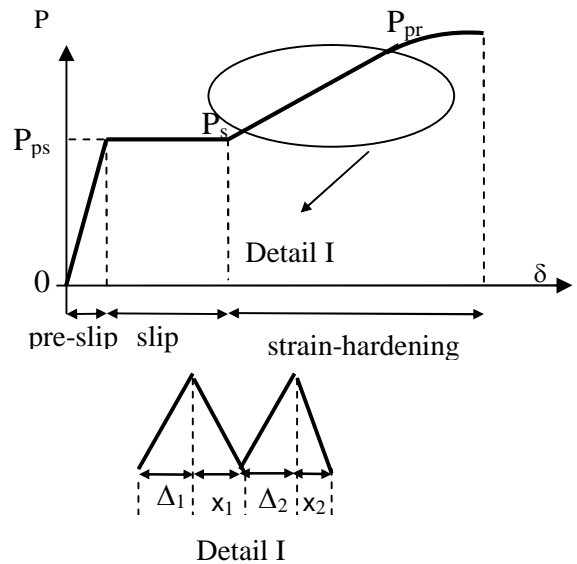
The pull-out modeling results a P-δ (load-displacement) curve (Figure 8) and formulation (Equation 8) that consists of 3 (three) stages: (a) Stage of pre-slip, (2) Stage of slip, and (3) Stage of strain-hardening.

During the stage of pre-slip, cracks have not been performed yet, and then the fracture process phenomenon doesn't exist. At the time of critical matrix stress $\overline{\sigma}_m$ exceeded, a lateral crack then performed and the stage of slip and unstable fracture process has just begun. The unstable fracture process keeps going. The crack length increases until stable crack length l_2 reached at the end of stage of slip. When the stable crack length l_2 is achieved, the unstable fracture process is changed to stable fracture process. The stable fracture process is followed by the stage of strain-hardening and 'a jagged' phenomenon exists. In this stage, the increase of the strain σ will increase the stress σ until the fiber is broken. This pull-out process can be defined as follow:

$$P_n = \left(r_{\Delta I} \frac{a_1}{a_2} E_{ps} A \right) + \left(r_{\Delta II} \frac{a_1}{a_2} E_s A \right) + \left(r_{\Delta III} \frac{a_1}{a_2} E_{pr} A \right) \qquad (8)$$

The range value of E_s, E_{ps}, dan E_{pr} for pull-out model is described by Table 1.

Table 1. Range value of E_s, E_{ps}, and E_{pr}

| l_f (mm) | STAGE OF PRE-SLIP | STAGE OF SLIP | | STAGE OF STRAIN-HARDENING |
| | | INITIAL SLIP | POST SLIP | |
	E_{ps} (x 10^3 MPa)	E_s (x 10^3 MPa)	E_s (MPa)	$E_{pr} = E_n$ (MPa)
110	500 - 650	2000 - 3000	500 -1500	400 - 2000
150	500 – 650	3000 – 4000	500 -1500	400 – 2500
180	500 - 650	4000 - 5000	500 -1500	400 - 2500

The analytical calculation has proved that the model fits to experimental results as shown by load-displacement curve (Figure 9). It is also proved that previous model of pull-out problem with short embedded nylon 600 is still accurate and consistent when it is applied to the long embedded nylon 600.
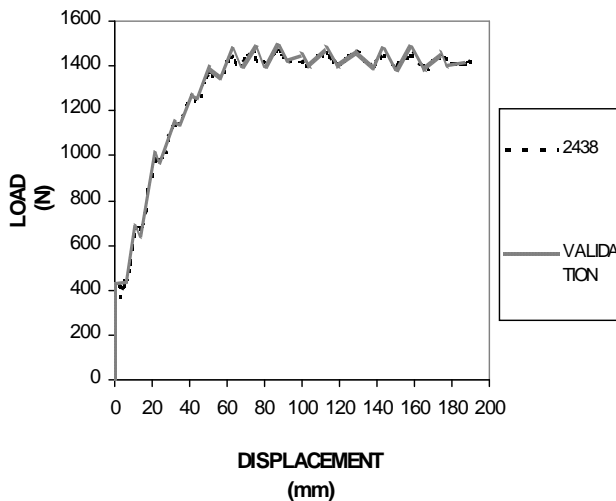

Figure 9. The Load-Displacement Relation of Pull-Out Model with l_f = 180 mm

3. Discussion

The 3 (three) stages which exist during the pull-out process need to be understood. Recall Figure 3 that describes the stage of pre-slip and stage of slip of load-displacement relation. Review the Detail 1 on Figure 10 and also the Detail 2 on Figure 11 below.

According to Figure 10, the stage of pre-slip of load-displacement curve (Figure 3) is represented by linear curve. The fiber and matrix both in composites condition in this stage. The load P at the end of stage of pre-slip is contributed by P of fiber (P_{pss}) and also P of matrix (P_{psm}), thus $P = P_{pss} + P_{psm}$. Figure 10 explains that P_{pss} is smaller than P_{psm} when displacement δ_{ps} is achieved. After crack performed, the fiber will be released from the matrix, and then the load 'jump' to become P_s. The lateral crack

performed instantaneously, so do the unstable fracture process. The initial P_s moves constantly until the post P_s is achieved at the end of stages of slip. The displacement δ_s at the end stages of slip. The part of stage of slip is horizontal-constant (similar to yield curve).
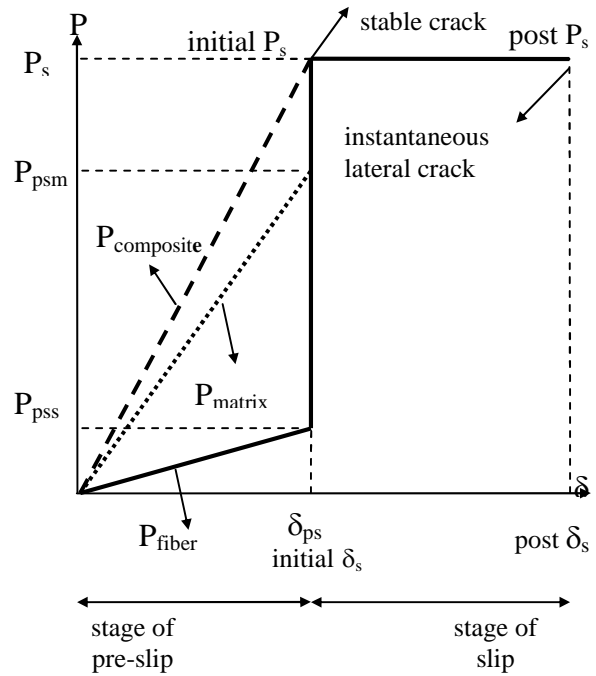

Figure 10. Detail 1 of Figure 3

The Figure 11 shows the Detail 2 of stress-strain curve (Figure 4). It should be noted that σ_{pss} is higher than σ_{psm} at the time ε_{ps} is achieved. The fiber and matrix are still in composites condition. After the crack performed, the stress jump to become σ_s. At this time, the starin ε_s is achieved. The stress of initial σ_s moves constantly until the stress of post σ_s achieved. It is also found that the part of stage of slip is horizontal-constant (similar to yield curve). When the strain of initial ε_{ps} is achieved, the crack will perform instantaneously and cause the establishment of stable crack.

The stage is the stage of strain-hardening (Figure 3 and 4) which shows 'jagged' phenomenon. This 'jagged' form is characteristic of nylon caused by the multiple constrictions during the pull-out process. The multiple constrictions is also generated by fiber yield point elongation (Nadai, 1950).
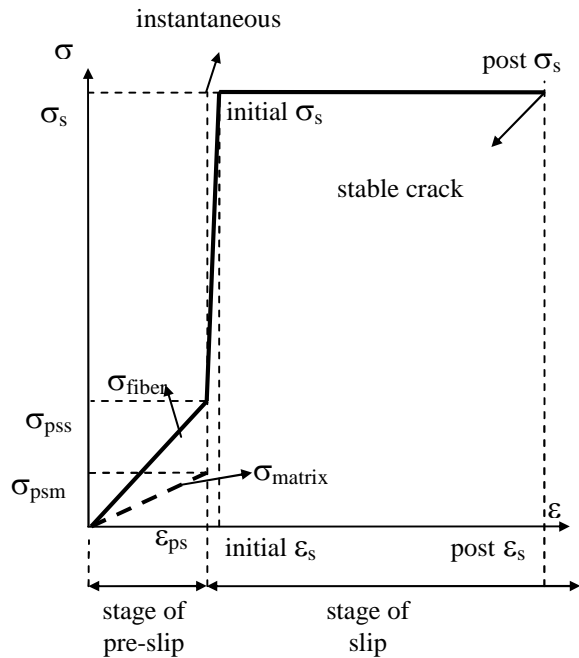
Figure 11. Detail 2 of Figure 4

It is emphasized by this research that stable crack length (equation 7) of long embedded nylon has distinction compared to the short one. It is shown that all specimens have their nylon fiber broken ($l_f = $ 110-180 mm). The reason of this phenomenon is stable crack length is bigger (Susilorini, 2007a) so that the possibility of crack arrester existence is bigger on the long embedded nylon than to the short one. It should be noted that because of the bigger possibility makes the strain-hardening part in load-displacement curve is longer for long embedded fiber length.

CONCLUSIONS

This research meets conclusions, they are:
a. The same theories of pull-out problem with short embedded nylon 600 in cementitious matrix can be applied accurately and consistently for long embedded nylon 600
b. The unstable and stable fracture process phenomenon exist during the pull-out process
c. Several stages exist during the pull-out process
d. The equation of stable crack length of previous model can also be applied for long embedded nylon 600
e. The equation of load of previous model can also be applied for long embedded nylon 600
f. The possibility of crack arrester presence is bigger for the long embedded fiber length than the short ones, thus the strain-hardening part in load-displacement curve is longer for the long embedded fiber length

NOTATION

A	fiber section area (mm^2)
E_{pr}	modulus of elasticity at stage of strain-hardening (MPa)
E_{ps}	modulus of elasticity at stage of pre-slip (MPa)
E_s	modulus of elasticity at stage of slip (MPa)
P, P_n	tension load (N)
a_1	total displacement of a stage (mm)
a_2	initial length of specimen or fiber that is specific for every stage (mm)
$r_{\Delta I}$	ratio of total free-end fiber displacement of free-end at stage of pre-slip
$r_{\Delta II}$	ratio of total free-end fiber displacement of free-end at stage of slip
$r_{\Delta III}$	ratio of total free-end fiber displacement of free-end at stage of strain-hardening
l_0	initial outer fiber length (mm)
l_2	stable crack length (mm)
l_f	embedded fiber length (mm)
ε_r	new fiber in the middle of right side of matrix
ε_1	fiber strain at the middle of right side of matrix (MPa)
σ_1	fiber stress at the middle of right side of matrix (MPa)
σ_{12}	fiber stress at l_2 part when stable crack length achieved (MPa)

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