FRACTURE BASED APPROACH FOR FAILURE ANALYSIS OF NYLON 600 FIBER

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ABSTRACT

The research purposes to implement fracture based approach in failure analysis of nylon 600 fiber and also partly embedded nylon 600 fiber in cementitious matrix. The methods are experiment and analytical by modeling. The experiment activities consist of tension test of nylon 600 fiber and pullout test of partly embedded nylon 600 fiber in cementitious matrix with length 150 mm and 180 mm. The research meets conclusions: (1) Whenever fracture takes place, it is always an unstable crack; (2) Stable cracks are established by the presence of crack arrester; (3) After the establishment of stable cracks, increasing strain beyond strain ε_1 will not increase stress σ_1, hence do not induce additional fracture; (4) Increasing of strain ε after the establishment of stable cracks in point g will increase stress, the second slip will not take place; (5) Broken nylon fibers have a longer embedded length because of the possibility of crack arrester presence is bigger than the shorter ones; and (6) Since the middle right side of matrix is at the intersection point with fiber acts as crack arrester in the beginning of pull-out process, then the load-displacement (P-δ) and stress-strain ($\sigma-\varepsilon$) curves of pull-out test will be the same as the load-displacement (P-δ) and stress-strain ($\sigma-\varepsilon$) curves of fiber tension test.

Keywords
Fracture, failure, nylon 600, pullout

1. INTRODUCTION

Nylon 600 fiber has great value of tension strength, elongation, tension strength, and also elastic modulus ([1], [2], [11]). The embedded nylon 600 fiber provides optimal stable crack length, and improves strain-hardening property ([1]-[11]). Because of its advantages, nylon 600 is believed to be applied into cementitious matrix to achieve best performace of cementitious matrix or concrete.

A popular approach to fracture problems is fracture mechanics. Fracture mechanics is very important in case of fiber cementitious composites. The improvement of fiber cementitious composites such as FRC, HPRFCC, and ECC seldom implements the fiber application such as nylon, which is categorized as synthetic fiber. It should be noted that fiber takes an important role in determining whole fiber-reinforced cementitious composite (FRC) performance. Previous researches have proved a better performance of ECC using various synthetic fiber surfaces [12], high performance as alike steel performance [13], and even higher compressive stress for irradiated nylon fiber by gamma [14]. The nylon fiber has a special characteristic of multiple constrictions at stretching condition [15] called 'yield point elongation' that has magnitude of 200%-300% of initial fiber length.

According to Bazant [16], the failure of concrete structures should consider the strain-softening related to distributed cracking, localized crack that grows to larger fracture prior to failure, and also bridging stresses at the fracture front. Therefore, the suppression of fracture of concrete can be implemented by improving higher toughness and higher tensile ductility [17]. Hence, the application of nylon 600 fiber into cementitious matrix is proper effort to achieve ductility performance.

It is important to recognize the properties of interfaces between fiber and cementitious matrices by a pull-out test and then takes failure analysis by fracture based approach. The research purposes to implement fracture based approach in failure analysis of nylon 600 fiber and also partly embedded nylon 600 fiber in cementitious matrix.

2. METHODS

This research conducts experiment and analytical methods. The experiment activities consist of tension test of nylon 600 fiber and also pull-out test of partly embedded nylon 600 fiber in cementitious matrix. The analytical method conveys pull-out modeling.

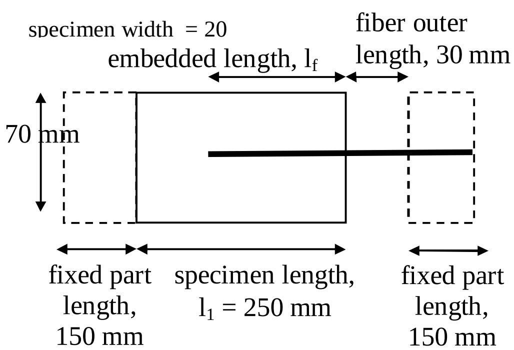

Figure 1: Dimension of specimen

The dimension of specimens is shown by Figure 1 while the setting of pullout test by Figure 3. The pull-out test is provided by computerized Universal Testing Machine "Hung Ta". The nylon 600 fiber is made in Indonesia with 1.1. mm in diameter and embedded length 150 mm and 180 mm for partly fiber embedded specimens. Mix design for cementitious matrix is cement : sand : water ratio of 1:1:0.6. Analytical method applied by modeling and formulation of theoretical model ([1], [2], [11]). The analytical models are built based on experiment result.

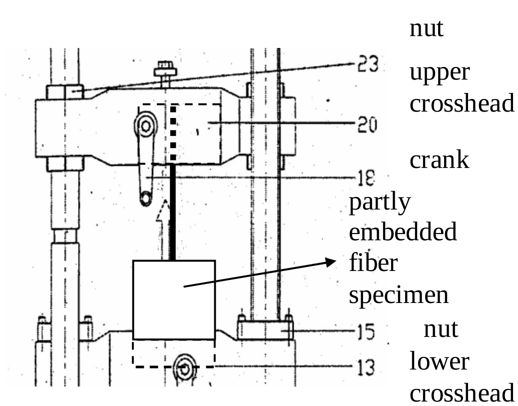

Figure 2 : Setting for pullout test

3. RESULTS AND DISCUSSION

3.1. Results

The results show that nylon 600 fiber has average maximum tension stress of 1471.21 MPa. Figure 3 shows relation of stress-strain of nylon 600 tension test with average maximum strain of 0.89, average maximum elongation of 84.11%, and average maximum tension load of 1398.13 N. A unique property of nylon fiber is shown by 'jagged' phenomenon on stress-strain (σ–ε) curves as also shown by Figure 3. This phenomenon is caused by the yield point elongation and the viscosity of nylon itself.

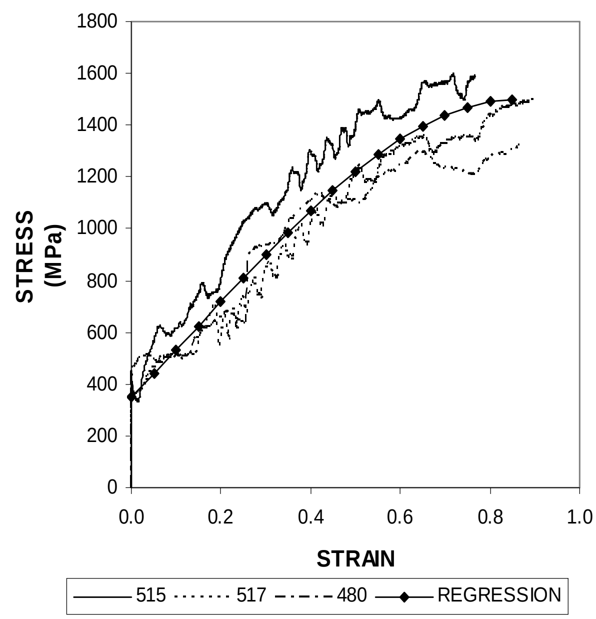

Figure 3 : Relation of stress-strain of nylon 600 tension test

The results of pullout test are shown below. Firstly, the experiment results show that the pullout test represent fracture phenomenon in some stages during pull-out process. Figure 4 describes the stages: (a) Pre-slip stage, (b) Slip stage, and (c) Strain-hardening stage. The pre-slip loads are about 400-430 N and pre-slip displacements are no more than 0.1 mm. The slip

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loads are in the same range of pre-slip loads with displacements of 3-4 mm. The strain-hardening loads are observed as 1300-1500 N and its displacement about 150-190 mm.

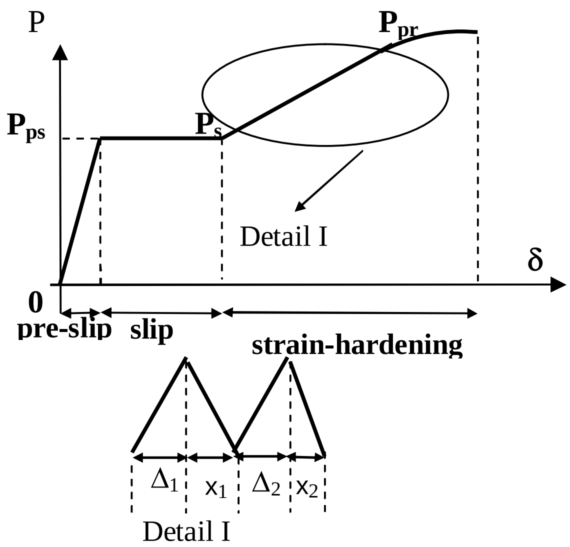

Figure 4 : The stages during pullout process

Figure 5 describes relation of load-displacement of specimen with embedded length (l_f) of 150 mm and 180 mm. Specimen 1025 and 1041 have embedded length l_f = 150 mm while specimen 2438 has l_f = 180 mm. Specimen with l_f = 180 mm has bigger displacement (190.2 mm) than l_f = 150 mm (140.08 and 154.76 mm). On the contrary, specimen with l_f = 180 mm has lower ultimit load (1400 N) than l_f = 150 mm (1500-1600 N).

Relation of stress-strain of specimen with embedded length (l_f) of 150 mm and 180 mm is described by Figure 6. Specimen with l_f = 180 mm has bigger strain (2.8) compared to l_f = 150 mm (2.06 and 2.28). On the contrary, specimen with l_f = 180 mm has lower ultimit stress (1500 N) than l_f = 150 mm (1600-1800 N).

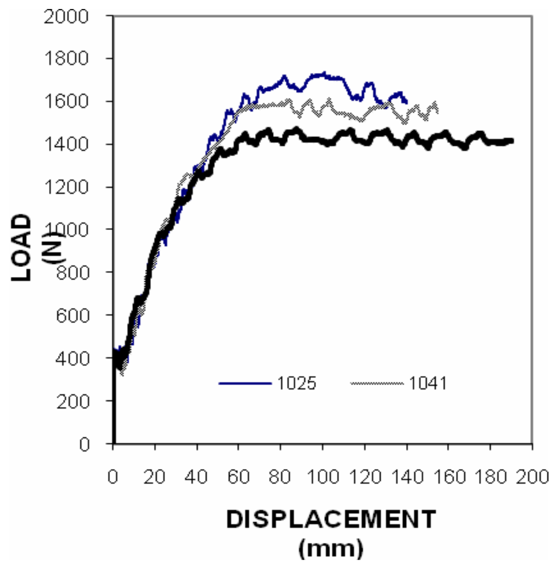

Figure 5 : Relation of load-displacement of specimen with embedded length (l_f) of 150 mm and 180 mm

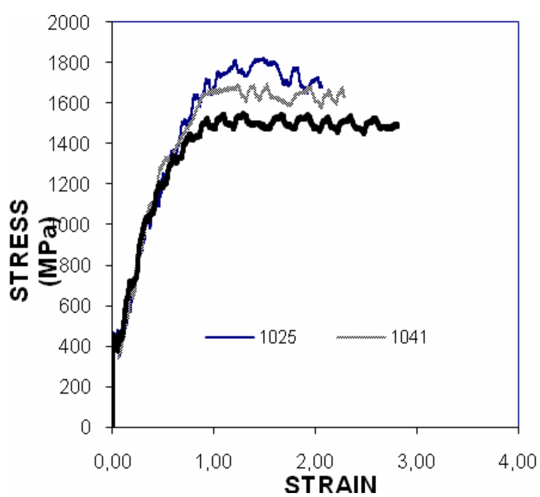

Figure 6 : Relation of stress-strain of specimen with embedded length (l_f) of 150 mm and 180 mm

The results were analyzed to become basis of pullout modeling. Several aspects have been considered in the modeling: (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) curves of pull-out, and (4) Unstable and stable fracture process phenomenon exist during the pull-out process.

Pullout modeling conceives a formulation of load which is a function of displacement that is expressed by Equation 1.

$$P_n = \left(r_{\Delta I} \frac{a_1}{a_2} E_{ps} A \right) + \left(r_{\Delta II} \frac{a_1}{a_2} E_s A \right) + \left(r_{\Delta III} \frac{a_1}{a_2} E_{pr} A \right) \quad (1)$$

Where:

P_n = load (N)
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)
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

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

Tabel 1 : Range value of E_s, E_{ps}, and E_{pr}

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

Pullout modeling also conveys a formulation for stable crack length as expressed by Equation 2.

$$l_2 = \frac{\bar{\delta} - \bar{\varepsilon} l_0}{\bar{\varepsilon}} \quad (2)$$

Where:

l_2 = stable crack length (mm)
l_0 = initial outer fiber length (mm)
$\bar{\delta}$ = fiber displacement at time of stable fracture achieved (mm)
$\bar{\varepsilon}$ = critical fiber strain

Stable crack length for each embedded length can be calculated based on experiment results as explained by Table 2.

Tabel 2 : Stable Crack Length of Specimens

l_f (mm)	l_2 (mm)
150	37,7375
180	37,7375

The pullout model then built based on experiment results and described by Figure 7-10 as follow.

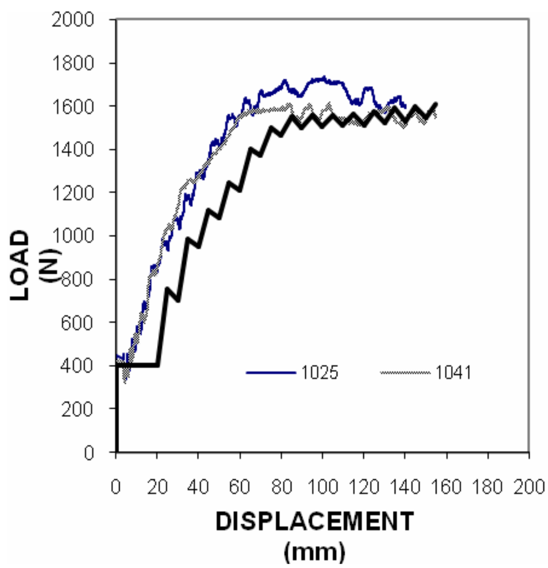

Figure 6 : Relation of load-displacement of experiment results and model with embedded length l_f = 150 mm

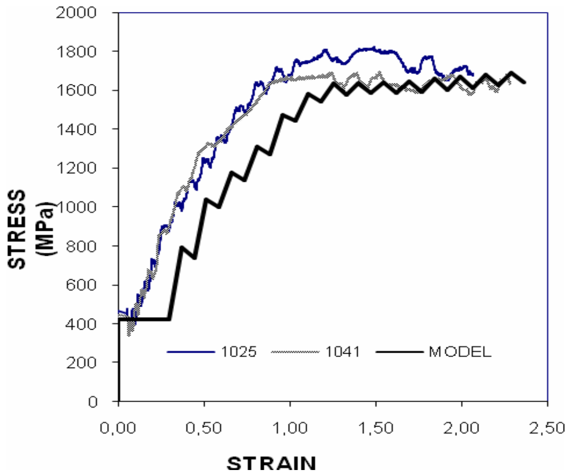

Figure 7 : Relation of stress-strain of experiment results and model with embedded length l_f = 150 mm

Figure 6 and 7 show that the model fit to the experiment results. For relation of load-displacement of experiment results and model with embedded length l_f = 150 mm (Figure 6), the model achieves stage of with load of about 400 N and stage of strain hardening with load of about 1500 N. Figure 7 shows that for stress-strain relation the model achieved stress at stage of slip with load about 400 MPa and stage of strain-hardening with load about 1600 MPa.

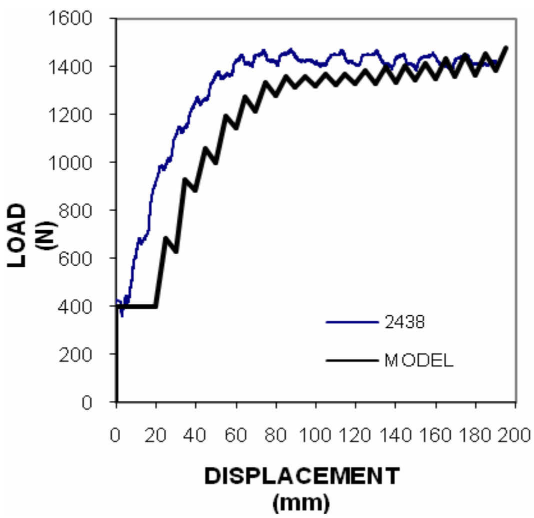

Figure 8 : Relation of load-displacement of experiment results and model with embedded length l_f = 180 mm

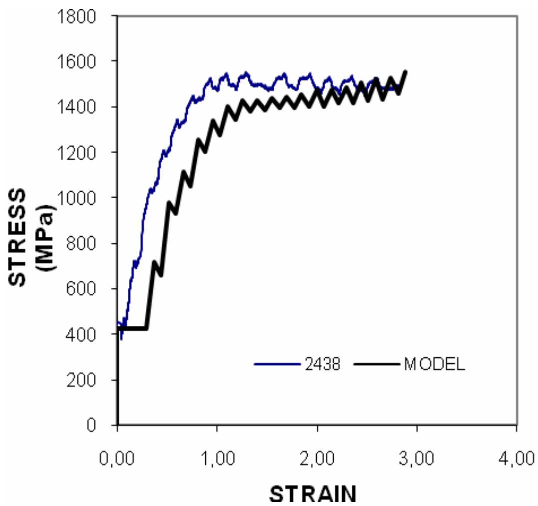

Figure 9 : Relation of stress-strain of experiment results and model with embedded length l_f = 180 mm

Figure 8 and 9 also describe that the model fit to experiment results. Figure 8 shows that the model also achieve stage of slip with load of about 400 N and stage of strain-hardening with load of about 1350 N. It is lower than the loads achieved by the specimens with embedded length of l_f = 150 mm.

The same phenomenon happened for stress-strain relation of Figure 9. The model achieve stage of slip with load of about 400 MPa and stage of strain-hardening with load of about 1400 MPa. It is lower than the loads achieved by the specimens with embedded length of l_f = 150 mm.

3.2. Discussion

Whenever fracture takes place, it is always an unstable crack. Unstable crack will change into stable crack with certain condition. Stable crack length will be occured when the crack arrester presents. It means, the phenomenon of unstable fracture that happened at the stage of pre-slip will change into stable fracture at the stage of slip.

It is interesting that the load and stress of embeded length l_f = 180 mm are lower compared to l_f = 150 mm. However, the displacement for embeded length l_f = 180 mm is bigger compared to l_f = 150 mm. It can be explained as follow. The long embedded length (150 mm and 180 mm) produces broken fiber when specimen gets failure. It should be noted that long embedded length of specimen is related to the possibility of crack arrester presence. Because of that bigger possibility makes the strain-hardening part in load-displacement curve is longer for long embedded fiber length. The stable crack length will be achieved in stable fracture.

For both embedded length l_f = 150 mm and l_f = 180 mm, the stable crack length are the same, l_2 = 37,7375 mm (Table 2). It can be seen (Figure 7-10) that they achieve same critical load and stress at the stage of slip that the stable fracture occured. Hence, the modeling represents the fracture phenomenon in appropriate way.

4. CONCLUSIONS

The research meets conclusions:

a) Whenever fracture takes place, it is always an unstable crack;
b) Stable cracks are established by the presence of crack arrester;
c) After the establishment of stable cracks, increasing strain beyond strain ε_1 will not increase stress σ_1 (the slip stage exists), hence do not induce additional fracture;
d) Increasing of strain ε after the establishment of stable cracks in point g will increase stress σ (the strain-hardening stage exist), the second slip will not take place;
e) Broken nylon fibers have a longer embedded length because of the possibility of crack arrester presence is bigger than the shorter ones;
f) Since the middle right side of matrix is at the intersection point with fiber acts as crack arrester in the beginning of pull-out process, then the load-displacement (P-δ) and stress-strain (σ–ε) curves of pull-out test will be the same as the load-displacement (P-δ) and stress-strain (σ–ε) curves of fiber tension test

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