

THE PERFORMANCE IMPROVEMENT of FIBER PULL-OUT of NYLON 600 by CLUMPED EMBEDDED FIBER END

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ABSTRACT: The fiber pull-out is an effort to characterize the fiber-cementitious matrix interface that becomes a basis for fiber reinforced cementitious composites design. Obviously, the fiber performance is influenced by embedded fiber end condition, especially for synthetic fiber such as nylon. The surface of nylon is very smooth and slippery that causes the low bond stress between fiber-cementitious matrix interface. Therefore, a strong effort to improve better fiber performance is very important to be done by implementing special treatment for embedded fiber end condition. The research purposes to show the performance improvement of nylon fiber by fiber pull-out experimental test and modeling. Fiber pull-out experimental test used fiber pullout specimens with fiber of nylon 600 made in Indonesia, 1.1 mm in diameter, and fiber embedded length l_f of 100 mm, and also vary with clumped and straight embedded fiber end condition. The clumped embedded fiber end condition was made by burning the end of fiber until the fiber's end change into clumped form. The modeling of fiber pull-out with clumped embedded fiber end is an improvement of Susilorini's previous model of straight embedded fiber end that is conducted analytically. The experimental and theoretical model has shown that all type of specimens were broken. Better performance shown by clumped embedded fiber end specimens that were reaching loads of 14-35% higher than straight embedded fiber end specimens, about 1200-1400 N. The research met conclusions of several theories that: (a) The clumped embedded fiber end condition generates higher shear-friction stress τ to against the fiber tension load will improve the specimen's pull-out load; (b) During the crack Δx formation to left side direction, the shear-friction τ along the embedded fiber gives contribution to against the displacement of fiber free-end; (c) The higher bond capacity $\bar{\sigma}_m$ is, the higher shear-friction stress τ will be; (d) The length of stable crack is determined by the position of crack arrester; (e) A new equation derived for load P_n for a model for fiber pull-out of nylon 600 with clumped embedded fiber end; and (f) The clumped embedded fiber end improves the pull-out load of nylon 600 fiber pull-out specimens.

KEYWORDS: pull-out, fiber, nylon, bond, clumped, model, pull-out load, shear-friction stress

1. INTRODUCTION

Fiber takes an important role in determining whole fiber-reinforced cementitious composite (FRC) performance. The fiber existence shows many advantages of crack delaying and resisting (Naaman, et.al,1991). In FRC, the interface behavior between fiber and matrix will be predicted by pull out tests. According to Sun and Lin (2001), the study of fiber-matrix interface is mainly to make certain about composites properties, to select the major ingredients of composites, and to predict the failure of composites. The using of synthetic fibers in FRC generates significant added values, that are strain-hardening property (Susilorini, 2007), higher tension strength, elastic modulus, and various fiber surfaces (Li, Chan, and Wu, 1994), high performance as alike steel performance (Clements, 2002), and even higher compressive stress for fiber concrete that its nylon fibers are irradiated by gamma (Martinez-Barera, 2006).

The nylon fibers itself, have a unique characteristic as mentioned by Nadai (1950). For stretching condition, nylon fibers will constrict many times and perform two moving surface waves along the fiber length. This phenomenon is called 'yield point elongation' that has magnitude of 200%-300% of initial fiber length. Because of the nylon viscosity, the load may gradually decrease 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. The same phenomenon can be found for mild steel (Manjoine, in Nadai, 1950), aluminum alloy (Elam, in Nadai, 1950), and nylon (Averett, 2004, and Susilorini, 2007). The application of local (Indonesia) made nylon fiber for concrete has established by previous researches (Suseno, et, al, 2000a,b, and Susilorini, 2007). Suseno,

et al. (2000a, b) used flexural beam and cylinder fiber concrete specimens with straight and clumped short fibers and found that flexural and splitting tensile strength of nylon fiber concrete is higher than the plain concrete. It was also investigated by Suseno, et, al, (2000a,b) that wider crack width is found on plain concrete. Susilorini (2007) established pull-out model using pull-out and fracture specimens with straight fibers that established many theories of unstable and stable cracks, the presence of crack arrester, equations for bond capacity $\bar{\sigma}_m$ and Poisson's ration of fiber relation, fiber stress σ_s and matrix stress σ_m relation at the time of failure, stable crack length, load for pull-out and fracture pull-out models, determination of bond capacity by using stable crack, existing of slip stage and strain-hardening stage, and also the possibility of crack arrester presence.

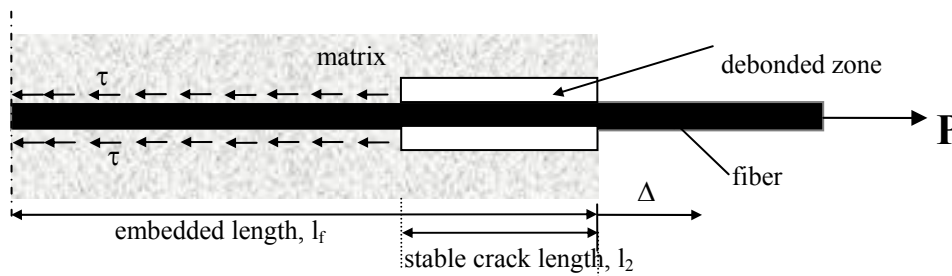


Figure 1 Pull-out Problem Description

The fiber pull-out is an effort to characterize the fiber-cementitious matrix interface that becomes a basis for fiber reinforced cementitious composites design. A description of pull-out problem is shown by Figure 1. In that figure, a tension load P is applied to fiber free end of a pull-out specimen. The applied load causes displacement of free end fiber of Δ . Some parts of the fiber are debonded from the cementitious matrix called debonded zone. The debonded zone then named stable crack length l_2 that created by fracture process during pull-out. It is difficult to determine stable crack length; however the crack length is formulated very well by Susilorini (2007). In general, previous pull-out models were built to represent the pull-out process, they are analytical models, fracture mechanic's based models, and micro-fractural models (Wang, Li, Backer, 1988a, b; Li, Stang, 1987; Morrison, Shah, Jenq, 1988; Kim, Zhou, Mai, 1992; Li, Chan, 1994; Sumitro, Tsubaki, 1997; Naaman, et.al. (1990); and Bentur, et.al. (1996). Some of those models used steel fiber, implemented shear stress and friction shear stress along the fiber, and neglected the Poisson's ratio. Among the previous models, there is no approach of stable crack length in the matrix but Susilorini's model (2007). Some of the models applied shear and friction-shear stress along the debonded zone. Those facts are contrary with Susilorini's previous theory which states that nylon fiber surface is slippery so that is shear established along the debonded fiber on the pull-out process (the establishment is along the embedded fiber so that the fiber and matrix are still in composite condition).

It was established by Susilorini (2007) that nylon fiber which is pulled out of the cementitious matrix will meet 'jagged' strain-hardening characteristic before it was broken. It is understood that the slippery property of nylon fiber has become an obstacle in reaching high pull-out load or stress. To reach higher pull-out load, it is important to apply clumped fiber end condition to generate shear-friction stress that also means bond property enrichment. It can be said that this paper want to deliver a model development of previous Susilorini's pull-out model (2007), that is a model for fiber pull-out of nylon 600 with clumped embedded fiber end. This research definitely purposes to show the performance improvement of nylon fiber by fiber pull-out experimental test and modeling.

2. METHODS

The research conducted two methods to reach final conclusions, experiment method and analytical method which are explained as follow. The experiment method applied pull-out test with specimens described by Figure 2 and set up of the pull-out test by Figure 3. This research used nylon 600 fiber local made ("Golden Fish" brand) with 1.1. mm in diameter and embedded length of 100 mm, several specimens use straight embedded fiber end and others use the clumped one. The clumped embedded fiber end condition was made by burning the end of fiber until the fiber end change into clumped form. Mix design for cementitious matrix is cement : sand : water ratio of 1:1:0.6. Analytical method applied by theoretical modeling that produces formulation. The model is a development model of

previous model (Susilorini, 2007) for fiber pull-out of nylon 600 pull-out with clumped embedded fiber end. The improved theoretical model then compared to experimental results.

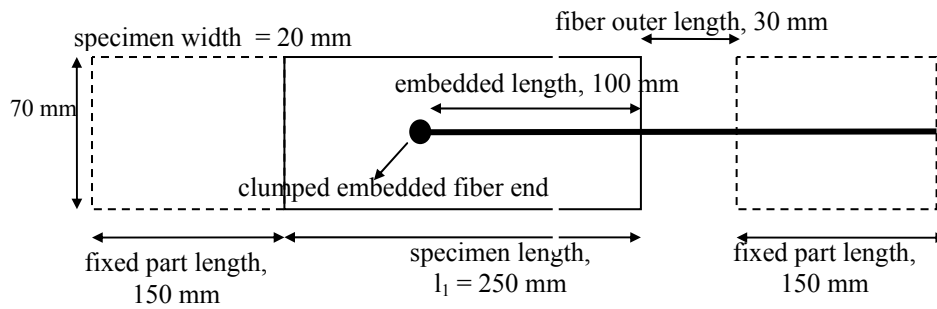


Figure 1 Dimensions of Pull-Out Specimen with Clumped Embedded Fiber End

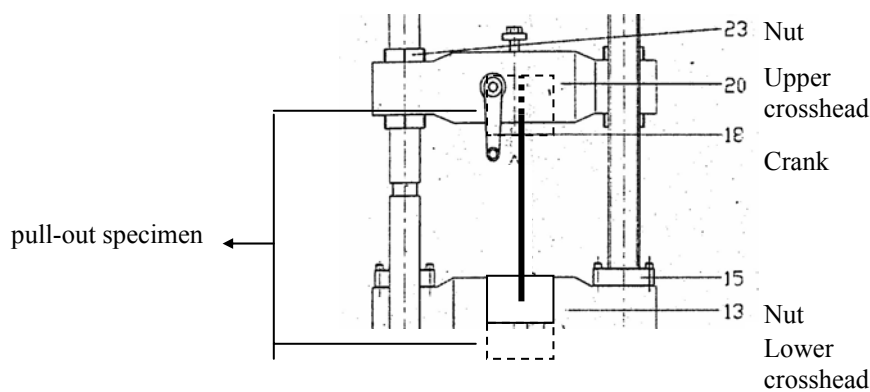


Figure 2 Pull-Out Test Set-Up

3. RESULT, MODELING, AND DISCUSSION

Result

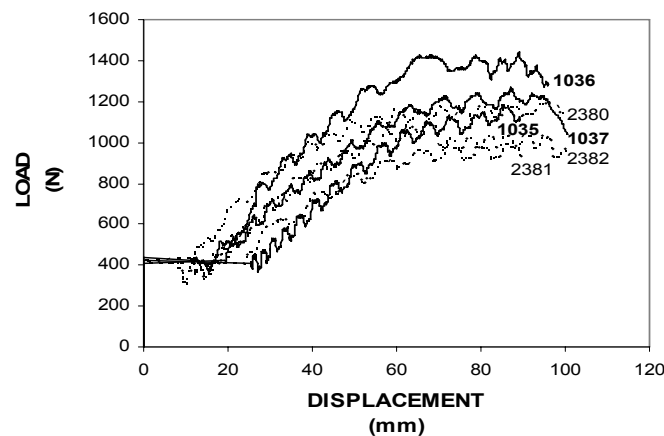


Figure 3 The Results of Pull-Out Test with Straight and Clumped Fiber End

The experiments observed that nylon fiber has had average maximum tension stress of 1471.21 MPa, 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 its load-displacement ($P-\delta$) and stress-strain ($\sigma-\epsilon$) curves that are caused by the ‘yield point elongation’ and the viscosity of nylon itself. For critical Poisson’s ratio of fiber of $\bar{\nu} = 0.47$, the critical strain of

nylon will reach $\bar{\varepsilon} = 0.29$. The results of pull-out test noted that both pull-out specimens with straight embedded fiber end and clumped ones showed several stages existence (Figure 3): (a) Pre-slip stage, (b) slip stage, and (c) Strain-hardening stage. The pull-out test results with straight fiber end (Figure 3) found pre-slip loads are about 400-430 N and pre-slip displacements of no more than 0.1 mm. The slip loads have been found in the same range of pre-slip loads with displacements of 3-30 mm. The strain-hardening loads are observed as 900-1200 N as regard. For pull-out test with clumped fiber end (Figure 3), pre-slip loads are ranged about 400-430 N with pre-slip displacements of no more than 0.1 mm. The slip loads had the same range of pre-slip loads with displacements of 3-30 mm. The strain-hardening loads are found higher than pull-out test with straight fiber end, which are about 1200-1400 N.

Modeling

A pull-out model has been derived by Susilorini (2007) for straight embedded fiber end. In this research, the previous model is improved for clumped embedded fiber end. This improved model considered many following aspects: (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.

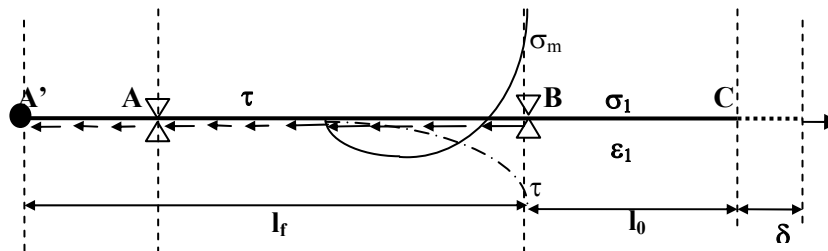


Figure 4 Pull-Out Model with Clumped Embedded Fiber End at Elastic Stage

Figure 4 shows a piece of embedded fiber (A'A) with clumped embedded fiber end at A' which is constrained at A and B but free at C. Free end fiber length named l_0 and embedded fiber end called l_f . A displacement δ is applied at C and both cementitious matrix and fiber are still in composites condition. The displacement δ will emerge matrix stress σ_m . The clumped fiber end will also generate the shear-friction stress τ existence along the fiber-matrix interface. The value of matrix stress σ_m increases until $\sigma_m = \bar{\sigma}_m = \sigma_m(\bar{\nu})$. The value of critical matrix stress $\bar{\sigma}_m$ is a bond capacity at the time of crack which represents the ultimate fracture tension capacity. Thus, the strain and stress at BC will be:

$$\varepsilon_1 = \frac{\delta}{l_0} \tag{1}$$

$$\sigma_1 = \varepsilon_1 E_s \tag{2}$$

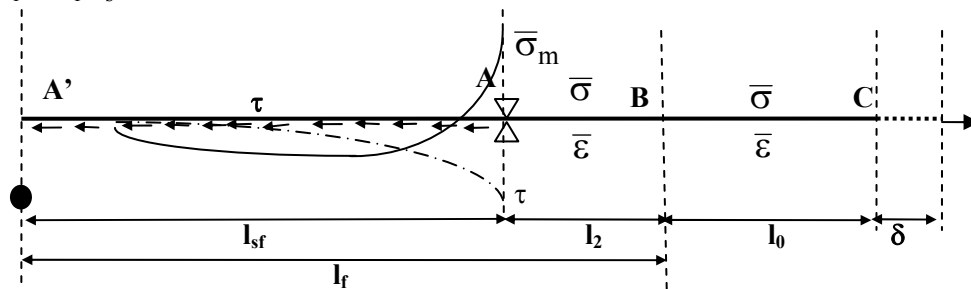


Figure 5 Pull-Out Model with Clumped Embedded Fiber End at Unstable Fracture Process

When displacement δ keep growing, then a crack will be formed. This crack emerges unstable fracture process. After a crack formed, the stress of the composite then being transferred to the fiber. By crack

formation, unstable fracture process phenomenon will release the constraint at B (Figure 5). The crack length is growing to be as long as l_2 and constraint at A still can remove to left side. When the crack length l_2 is longer than embedded length l_f , fiber may be pulled-out. The shear-friction stress τ is distributed along A'A, and then the length of shear-friction is called l_{sf} . The higher bond capacity is, the higher shear-friction will be.

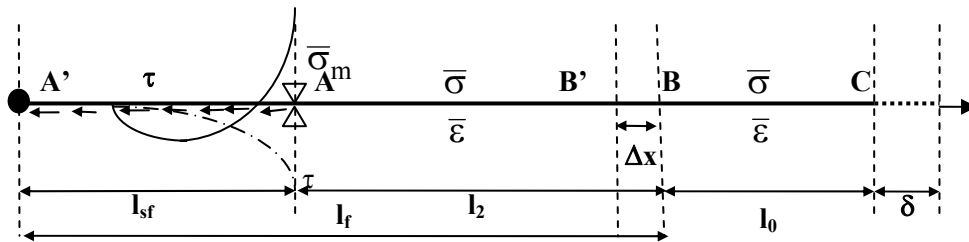


Figure 6 Pull-Out Model with Clumped Embedded Fiber End at Stable Fracture Process

An unstable fracture process may go the stable fracture process which is explained as follow. Assume that a crack formed as (Figure 6), then the increasing of displacement δ will also increase strain ε_1 and stress σ_1 at B'B. Those strain ε_1 and stress σ_1 increasing will cause the achieving critical value of matrix stress $\bar{\sigma}_m$ and strain $\bar{\varepsilon}$. Therefore, the displacement δ increasing repeated at B' at the same time a new crack of another formed Δx at the left side of fiber. During the crack Δx formation, the shear-friction τ gives contribution along the embedded fiber to against the displacement of fiber free-end. It happened continuously until constraint A is fixed. The constraint A becomes crack arrester which prevents crack growing. In this situation the crack will be stopped to grow and crack length remains l_2 . Once stable crack length l_2 achieved, then strain at l_0 part transfer to l_2 part. The stress and strain become:

$$\varepsilon_1 = \varepsilon_{l_2} = \varepsilon_0 = \varepsilon_r \quad (3)$$

$$\sigma_1 = \sigma_{l_2} = \sigma_0 = \sigma_r \quad (4)$$

$$\varepsilon_r = \frac{\delta}{l_0 + l_2} \quad (5)$$

When $\bar{\sigma}_m = \sigma_m(\bar{\varepsilon})$ is achieved and strain at AC is $\varepsilon = \bar{\varepsilon}$, then $\delta = \bar{\delta}$ and the strain will become:

$$\varepsilon = \bar{\varepsilon} = \frac{\bar{\delta}}{l_0 + l_2} \quad \text{where } \bar{\varepsilon} = \varepsilon(\bar{\varepsilon}) \quad (6)$$

The stable crack is formulated as:

$$l_2 = \frac{\bar{\delta} - \bar{\varepsilon}l_0}{\bar{\varepsilon}} \quad (7)$$

Formulation of the theoretical model is defined by equation (8). The model will result a P- δ (load-displacement) curve (Figure 7) 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 created, so that the fracture process phenomenon not exists. After critical matrix stress $\bar{\sigma}_m$ exceeded, a crack is formed, the stage of slip and unstable fracture process has just begun. The type of fracture in this stage is lateral fracture. The unstable fracture process keeps going and crack length increases until stable crack length l_2 reached at the end of stage of slip. Whenever the stable crack length l_2 achieved, the unstable fracture process changed to stable fracture process. The stable fracture process is going to be continued by the stage of strain-hardening, while 'a jagged' phenomenon caused by nylon multiple constrictions. In this stage, the increase of the strain ε will increase the stress σ until the fiber is broken. The clumped embedded fiber end condition generates higher shear-friction stress τ to against the fiber tension load will improve the specimen's pull-out load.

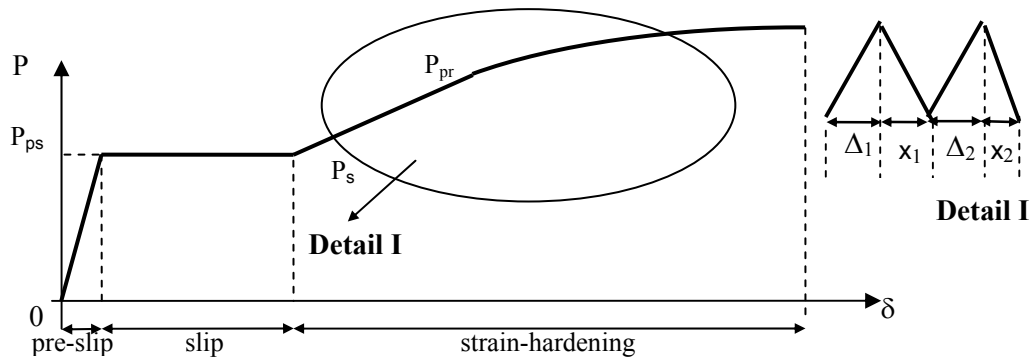


Figure 7 P-δ (load-displacement) Relation of Theoretical Pull-Out Model

$$P_n = \left(r_{\Delta I} \frac{a_1}{a_2} E_{ps} A \right) + \left(r_{\Delta II} \frac{a_1}{a_2} E_s A \right) + \left(C_1 r_{\Delta III} \frac{a_1}{a_2} E_{pr} A \right) - \left(\frac{r_{\Delta III} \frac{a_1}{a_2} E_{pr} A^2}{A_{fl}} \right) \quad (8)$$

where $C_1 = 2.3, C_2 = 2.6$, and the range value of E_s, E_{ps} , dan $E_{pr} = E_n$ for pull-out model is: $500000 \leq E_{ps} \leq 650000, 2000000 \leq E_{s \text{ initial}} \leq 650000, 500 \leq E_{s \text{ end}} \leq 1500, 400 \leq E_{pr} \leq 2000$. The theoretical model above has compared to experimental results. The P-δ (load-displacement) curves and σ-ε (fiber stress-strain) curve (Figure 8) and also the τ-ε (shear-friction stress-strain) curve (Figure 9) described as follow.

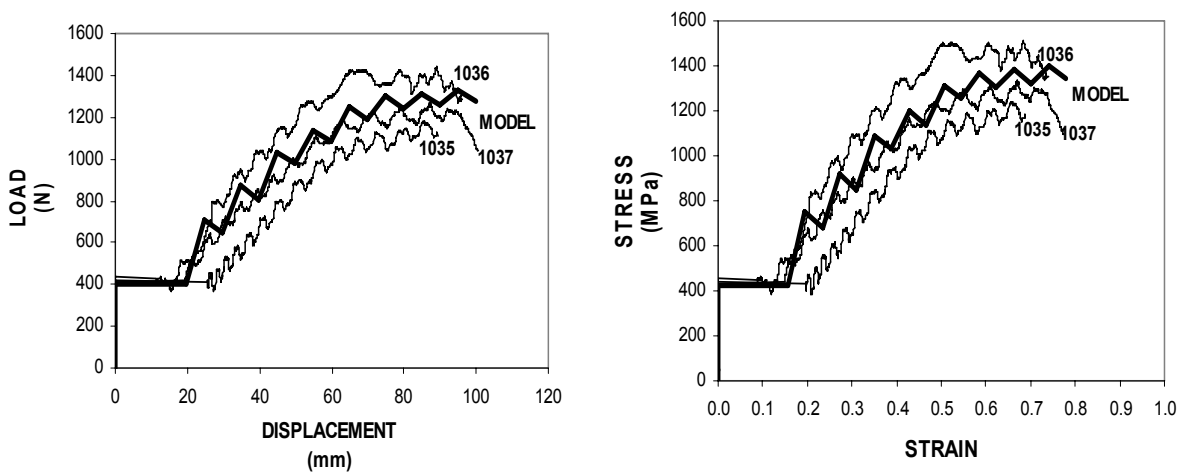


Figure 8 P-δ and σ-ε Relations of Model and Experimental Results

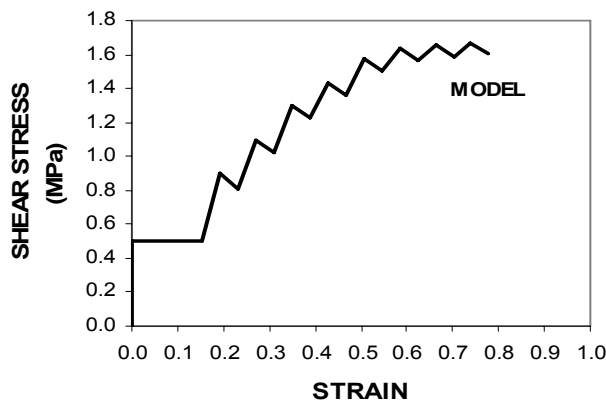


Figure 9 τ-ε Relation of Model

Discussion

Figure 8 shows that the model fit to the experimental results. The maximum strain of both model and experimental results (0.8) are lower than maximum strain of nylon fiber tension test (0.89). It is found that the pull-out load of clumped fiber end specimens is 14-35% higher than the pull-out load of straight embedded fiber end specimens. The reason of lower strain and the pull-out load improvement is because of the clumped embedded fiber end condition generates higher shear-friction stress τ to against the fiber tension load will improve the specimen's pull-out load. It should be noted that during the crack Δx formation to left side direction, the shear-friction τ distributed along the embedded fiber gives contribution to against the displacement of fiber free-end. A τ - ε (shear-friction stress-strain) curve is described by Figure 9. Thus, the higher bond capacity $\bar{\sigma}_m$ is, the higher shear-friction stress τ will be.

4. CONCLUSIONS

Several theories have been established by this research:

- The clumped embedded fiber end condition generates higher shear-friction stress τ to against the fiber tension load will improve the specimen's pull-out load
- During the crack Δx formation to left side direction, the shear-friction τ along the embedded fiber gives contribution to against the displacement of fiber free-end
- The higher bond capacity $\bar{\sigma}_m$ is, the higher shear-friction stress τ will be
- The length of stable crack is determined by the position of crack arrester
- A new equation derived for load P_n for a model for fiber pull-out of nylon 600 with clumped embedded fiber end
- The clumped embedded fiber end improves the pull-out load of nylon 600 fiber pull-out specimens

5. ACKNOWLEDGMENTS

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NOTATION

A	fiber section area (mm^2)
A_{fl}	fiber surface area (mm^2)
A_m	matrix surface area (mm^2)
D	fiber diameter (mm)
E_n, 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)
b	specimen width (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)
l_{sf}	length of shear-friction (mm)
x_i	relaxation length for n at stage of strain-hardening (mm)

- Δ_i free-end displacement for n at stage of strain-hardening (mm)
 σ_1 fiber stress at the middle of right side of matrix (MPa)
 σ_{l_2} fiber stress at l_2 part when stable crack length achieved (MPa)

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