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FULL PAPER

Basic study for drive mechanism with synthetic fiber rope - Investigation of strength reduction by bending and terminal fixation method -

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In this study, we investigate physical properties of synthetic fiber ropes for drive mechanism. First, we carry out experiment about the relation between tensile strength and bending ratio D/d, where D is pulley diameter and d is rope diameter. Although it is widely known that a metal wire rope gets strength reduction under small D/d, we newly detected that a synthetic fiber rope also gets strength reduction in the same way. Secondly, we evaluate the strength of various end fixation method of synthetic fiber rope. Knot fixation make rope strength half in all kinds of knot. Clamping fixation with enough pressuring force can get large strength even if a synthetic fiber rope has low friction coefficient. Although calking fixation and sewing fixation cannot change rope length easily, they can get the largest strength around 85 to 90 % of the rope strength in our experiment.

Keywords: Tendon-driven; Synthetic fiber rope; Mechanical design

1. Introduction

Recently, synthetic fiber ropes which have high tensile strength have been developed. Some of them have very high tensile strength as same, particularly lightweight as 1/5 to 1/8, much flexibility and lower coefficient of friction as metal wire ropes, e.g. stainless steel wire rope. Therefore, there is every possibility of developing lighter, smaller and higher load withstanding drive mechanism than existing one by using synthetic fiber ropes. Actually, taking advantage of such features, many researchers apply them for artificial muscles[1], tendon-driven robots[2][3][4] and active endoscopes[5].

Since a drive mechanism with a metal wire rope has been applied for robots, elevators, cranes and so forth for a very long time, many physical properties of metal wire ropes, e.g. tensile strength, are provided by International Organization for Standardization (ISO). Moreover, mechanical design guidelines with metal wire ropes are provided by books[6] or websites[7]. On the other hand, concerning synthetic fiber ropes, although manufacturers provide some properties and methods of experiment of original yarn[8], they also provide only tensile strength as physical properties when it is constructed as a rope. There are some researches which study about physical properties of synthetic fiber rope[9][10][11], however, there is no research which provide systematic design guideline as far as we know and there is less physical data to develop a truly practical drive mechanism now. Therefore, it is obscure for synthetic fiber rope to take the place of metal wire rope practically as a drive mechanism for robots. Advancing the study of physical properties of the synthetic fiber rope in the future, we can get great opportunity for developing new lightweight, compact and robust drive mechanisms which have not been achieved with conventional metal wire rope.

The ultimate goal of this research is developing a design methodology with a synthetic fiber

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rope, and this research would be a groundwork for all researches which use synthetic fiber ropes. In order to achieve the goal, we have to clarify physical properties of synthetic fiber ropes such as strength reduction by bending, terminal fixation method, transmission efficiency, durability, etc. As a first step of the research, in this paper, we clarify the relation between bending ratio and tensile strength in section 2 and consider the end part fixing method of synthetic fiber rope in section 3. This two properties are basic factors for the experiments to measure the other properties because we can carry out the experiments with compact and simple device which use necessity minimum size pulley and fixation by the result of the two properties. Finally, we make design guideline and conclude in section 4.

2. The Relation between Relative Curvature and Tensile Strength

In case of a drive mechanism using a rope, we often drive a rope with pulleys or wind it around a pin for end part fixing. If so, a rope inevitably has bending part. It is widely known that metal wire ropes get strength reduction by bending sharply when a ratio(D/d) of the rope diameter(d) to the pulley diameter(D) is getting decreased[7]. However, synthetic fiber ropes are much more flexible than metal wire rope and it needs less bending stress to bend them. Therefore, we often use synthetic fiber ropes under condition of small radius of curvature and aim at miniaturizing drive mechanism. In this section, we will investigate the relation between the bending ratio(D/d) and tensile strength.

2.1. Related Research

Actually, it is known that a metal wire rope decrease tensile strength when a ratio(D/d) of the rope diameter(d) to the pulley diameter(D) is getting decreased. As shown in Fig.1, many manufacturers and books show their own data as technical design guideline[6][7][12] or formulate strength efficiency E_B[13] as

$$E_B = 1 - \frac{0.5}{\sqrt{D/d}}. \tag{1}$$

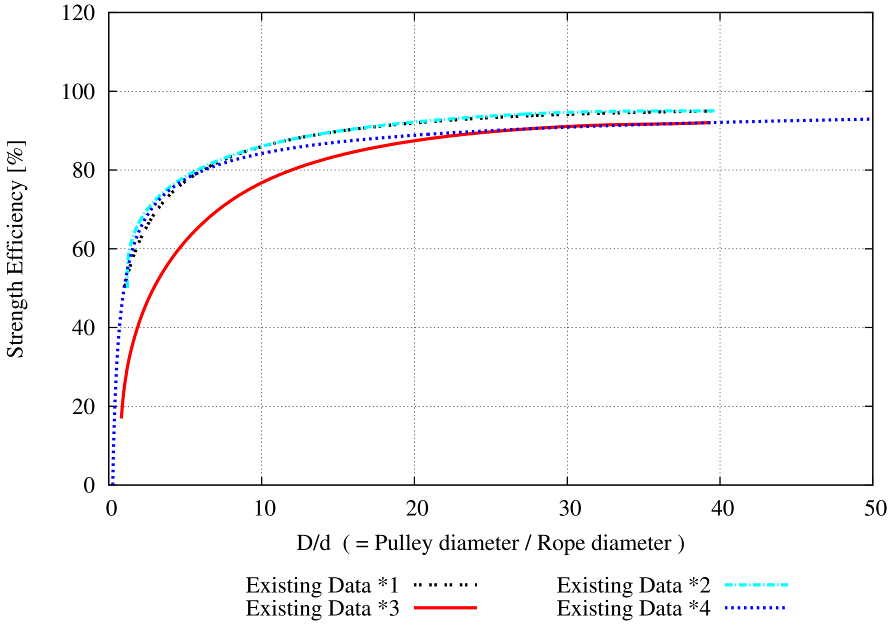
Here, strength efficiency is calculated as

$$\text{Strength efficiency} = \frac{\text{Broken tensile strength}}{\text{Ultimate tensile strength}}, \tag{2}$$

broken tensile strength is the reduced tensile strength by bending loss and ultimate tensile strength is the tensile strength of a stretched rope. In these data, we can see the large strength reduction where D/d is under 10. Therefore, drive mechanism using a metal wire rope have to be designed in consideration of the strength reduction derived by a pulley or a pin. However, since these curves don't have theoretical background as far as we know, it is unclear whether drive mechanism with synthetic fiber rope can be designed using these curves. Thus, in this study, we derive the relation between D/d and strength reduction of a synthetic fiber rope by doing a tensile testing experiment in a variety of D/d condition. Finally, we compare a synthetic fiber rope with a metal wire rope and derive a design guideline about D/d.

2.2. Experiments Description

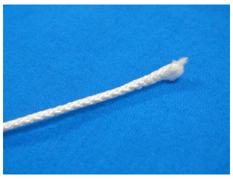
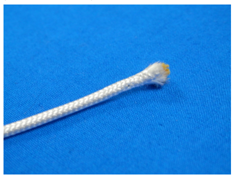
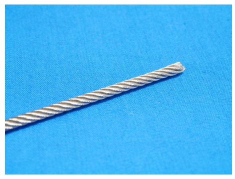
The relations between D/d and strength efficiency was derived by the tensile testing experiment which was carried out with three different types of ropes shown in Table 1. We chose Dyneema



*1 Mechanical Engineering Design[6]
*2 Edwards Wire Rope[7]
*3 Manchester Sling Company[12]
*4 Grommet shackle[13]

Figure 1. Strength efficiency of metal wire rope in existing research

Table 1. Specification of synthetic fiber rope and stainless wire rope used in this paper

	Dyneema rope 	Zylon-Dyneema rope 		Stainless rope 
Tensile strength	2.14 kN	3.22 kN		3.50 kN
Diameter	2 mm	2 mm		2 mm
		ZYLON part	Dyneema part	
Material	Polyethylene	PBO	Polyethylene	SUS304
Structure	1760 dtex ×8 strand	10020 dtex	770 dtex ×16 strand	7 × 19 Right Regular Lay
Wire Diameter (or Fineness)	1.11 dtex	1.7 dtex	1.11 dtex	0.13 mm
Type	SK-60	AS	SK-60	SUS304
Supplier	Fiber : TOYOBO Rope : Hayami industry			ASAHI INTECC

rope and Zylon-Dyneema rope among a number of types of synthetic fiber ropes because Dyneema rope is widely applied in robotics study (e.g. Kenshiro[4]) and other commercialized mechanism (e.g. string bike[14]) and Zylon-Dyneema rope consists of ZYLON® fiber which "has the highest tensile strength and tensile modulus among high-performance fibers"[15].

"Dyneema rope" is made of Dyneema®[8] which is Ultra High Molecular Weight Polyethylene Fiber. Dyneema rope has many advantages which are low cost, low friction coefficient, lightweight, water resistance and abrasion resistance but also disadvantage as large elongation. The rope which we use in this study consists of 8 strands.

"Zylon-Dyneema rope" is made of ZYLON[16] and Dyneema. ZYLON consists of poly(p-phenylenebenzobisoxazole, PBO) and has the highest tensile strength and smallest elongation among synthetic fibers. However, it also has low abrasion resistance and low light resistance, thus it is practical to cover ZYLON with Dyneema for protecting ZYLON against friction and light. The rope we used consists of ZYLON as core yarn and Dyneema as sleeve with 16 strands.

"Stainless rope" is one of metal wire ropes and made of SUS304. We also tested it to compare the results of synthetic fiber ropes.

Now, tensile strengths in the table are derived from the average of the results of tensile testing experiment on condition that large D/d (D/d =37.5 and 50 on Stainless rope and Dyneema rope and D/d =18.75, 25, 37.5 and 50 on Zylon-Dyneema rope), which means ropes were not broken due to strength reduction caused by bending loss.

In existing tensile testing experiment with synthetic fiber rope, for example Hayami Industry Co.,Ltd, each the end of the rope is pressured by some screws and two metal blocks after wound twice around a pulley whose diameter is 255 mm. This method aims that winding a rope around a pulley can generate frictional force which is derived by Euler's belt formula[17]:

$$T_2 = T_1 \exp(-\mu\theta) \tag{3}$$

T_1 : Tension before winding T_2 :Tension after winding μ : Friction coefficient θ : Winding angle

and get large fixation force in comparison to only screw pressuring force. However, even using this method which has a very large and heavy pulley, sometimes causes rope slipping or breaking at the pressuring point. Therefore there is no standard fixation method for a synthetic fiber rope which can exploit maximum tensile strength.

In this study, rope fixation was done along the same method. Eq.3 shows that the change of tension depends on winding angle, θ, and friction coefficient between a rope and a pulley, μ. Therefore, we fixed the rope against large tension by adjusting these parameters θ and μ. The experiment device is shown in Fig.2. Various D/d conditions are produced by changing pulley diameter($D = 6$ to $100\,\mathrm{mm}$) in the same rope diameter($d = 2\,\mathrm{mm}$). Two stationary pulleys are set on each the SUS303 base plates. Upper one "test pulley" is to make various D/d. We used 9 types

(a) Pulley and rope arrangement

(b) Tensile testing device (SHIMADZU:AG-I, maximum testing tension:100 kN)

Figure 2. Experiment device

of the diameters of pulleys that are 6, 10, 15, 20, 25, 37.5, 50, 75 and 100 mm. In addition, we also tested the strength of a knot which made in the middle of two pulleys as the data on $D/d = 1$. A rope is wound around test pulley in 3 to 8 times and the end of a rope is fixed by stainless steel block (SUS303) clamping. Lower one "fixed pulley" is to fix a rope under very high tension. Winding a rope around fixed pulley in 2 or 3 times can decrease the tension of the rope end. The diameter of fixed pulley is 100 mm which is larger than that of any test pulleys. The other end of a rope is also fixed by clamping. These two pulleys are made of SUS304 (only the pulley of 6 mm in diameter is made of alkaline blackening S45C, but it is almost the same as SUS304). Now, in case of synthetic fiber rope, the measurement of the strength was hardly done since a small friction coefficient cause slip on the clamping. Then, we covered pulleys with chloroprene rubbers as shown in Fig.3 in order to increase the friction coefficient. Since the point of the breaking of a rope is winding start point from a lower part around the test pulley, the rubber not covering in this point doesn't influence the testing of the relation between D/d and tensile strength.

During a tensile testing experiment, the distance between test pulley and fixed pulley was increasing in constant speed of 300 mm/min until the time of rope breaking as shown in Fig.4. We were sampling the rope tension from beginning to end and recorded the maximum tension as broken strength and calculated the strength efficiency by Eq.2. The experiment was carried out 3 times in the same condition and the experiment environment was shown in Table2.

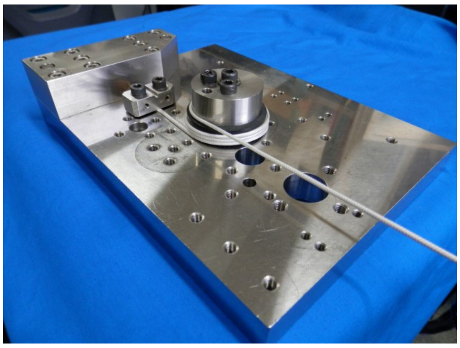


Figure 3. Pulley covered with rubber

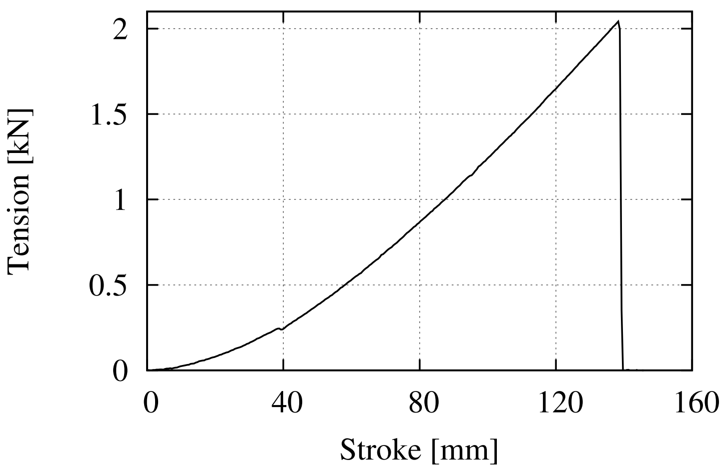


Figure 4. Stroke and tension in testing

Table 2. Experiment environment

Temperatures	23 – 24 °C
Humidity	55 – 65 %
Tension speed	300 mm/min.
Sampling period of tension	0.1 sec.

2.3. Results

Fig.5 is the result of the experiment about the relation between D/d and strength efficiency. From the figure, the strength reductions of synthetic fiber ropes trend larger with a drop of D/d as same as that of a metal wire rope. Therefore, an previous design guideline about the relation between D/d and strength efficiency can be also applied for synthetic fiber ropes. On condition that D/d values are 37.5 and 50 (and 18.75 and 25 besides in the case of Zylon-Dyneema), a rope didn't cause strength reduction because it broke in a straight position in the middle of the two pulleys. On the other small D/d values, the strength reduction which caused by bending can be observed because ropes broke in a start point of winding test pulley from straight position. Finally, the strength efficiencies of the synthetic fiber ropes become approximately 40 to 50 % on condition that D/d value is 1.

The result of the two synthetic fiber ropes, Dyneema and Zylon-Dyneema, can be approximated by the following empirical formula:

$$E = 1 - \frac{a}{(D/d)^b} \tag{4}$$

$$\begin{cases} a &= 0.585 \\ b &= 0.669 \end{cases} \Rightarrow \quad E = 1 - \frac{0.585}{(D/d)^{0.669}} \approx 1 - \frac{0.59}{\sqrt[3]{(D/d)^2}}, \tag{5}$$

which shows that the strength reduction is in proportion to the value of D/d to the power $-2/3$.

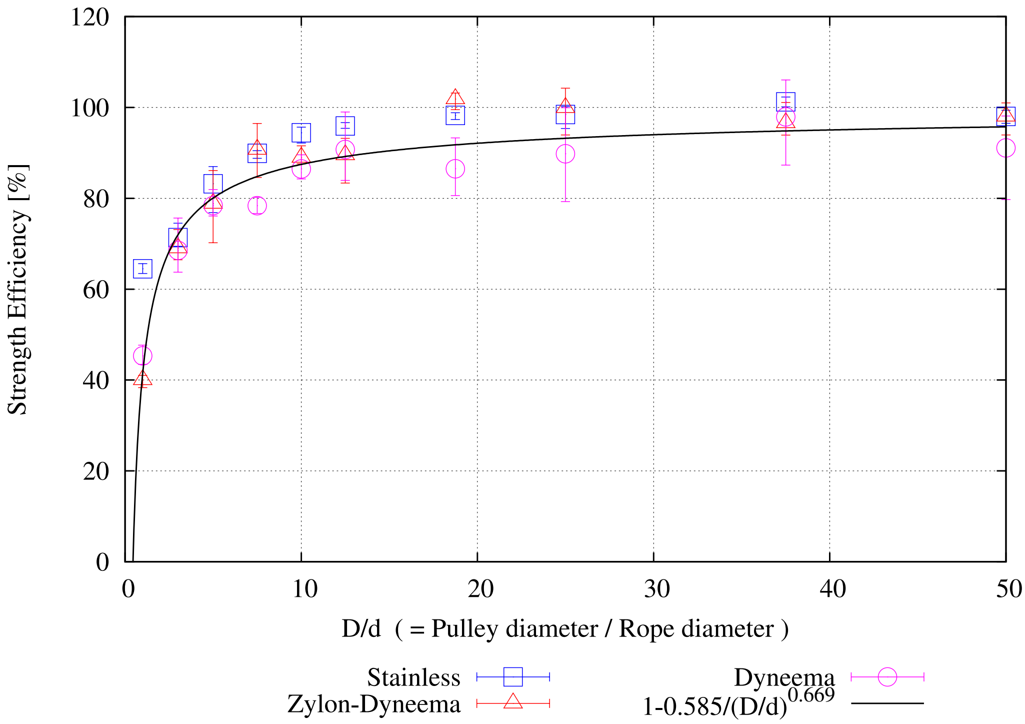


Figure 5. Relation between tensile strength and D/d ratio. Error bars show errors of three samples.

Table 3. Standard deviation of strength efficiency

Rope	Average standard deviation	Maximum standard deviation
Dyneema	4.90 %	8.44 % ($D/d = 25$)
Zylon-Dyneema	3.40 %	6.56 % ($D/d = 5$)
Stainless	1.55 %	4.50 % ($D/d = 5$)

We derived two parameters, a and b, by using Gauss-Newton method.

We show the standard deviations of the strength efficiencies in Table3. The standard deviations of the synthetic fiber ropes are larger than that of the metal wire rope, thus it became clear that synthetic fiber ropes has much more unevenness of strength efficiency than metal wire ropes. Moreover, the standard deviation of Dyneema is larger than that of Zylon-Dyneema. It is because Dyneema was made by only twisting eight strands and much affected by abrasion and manufacturing errors than Zylon-Dyneema whose core yarn is covered with sleeve.

In conclusion, even as the synthetic fiber rope which is more flexible than the metal wire rope, strength reduction occurs under condition of small radius of curvature. However, by using Eq.5, we can estimate the strength efficiency of a synthetic fiber rope which is wound around a pulley.

3. Fixation of Synthetic Fiber Rope

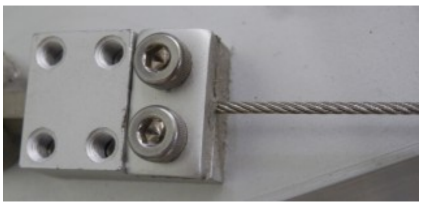
In previous section, synthetic fiber rope slipped on test pulley without covering pulley with rubber which can increase friction coefficient between synthetic fiber rope and pulley. This case shows that the low friction coefficient of synthetic fiber rope sometimes causes defective fixation, such as slipping from clamping or knot. Actually, slipping from clamping caused many failure in the experiment we did. On the other hand, metal wire rope has enough friction coefficient in order to be fixed with clamping or calking as shown in Fig.6.

Currently, making knot at the end of the rope is widely used as a method of fixation. Synthetic fiber ropes have a characteristic of flexibility and we can make knot very easily with synthetic fiber ropes. However, our research in previous section shows that strength reduction occurs under condition of small radius of curvature in the case of synthetic fiber rope. Therefore, from the result of the condition on $D/d = 1$, we can estimate the strength efficiency of the knot which is made on the end of a rope is only around 50 %.

In this section, we will measure the strength efficiency of fixation of synthetic fiber rope in various methods and suggest the suitable fixation depending on the purpose of use and a place.

3.1. Related Research

In case of metal wire rope, data of strength efficiency of fixation are shown in Fig.7 by [18]. These data show that fixation with open spelter socket has 100 % strength efficiency and many types of fixation have 90 % strength efficiency. These values are sufficiently large and we can make enough fixation easily. On the other hand, strength efficiency of knot fixation with synthetic fiber rope was investigated by [11] and it is around only 60 %. Moreover, the strength efficiency of clamping and



(a) Clamping

(b) Calking

Figure 6. Fixation of stainless wire rope

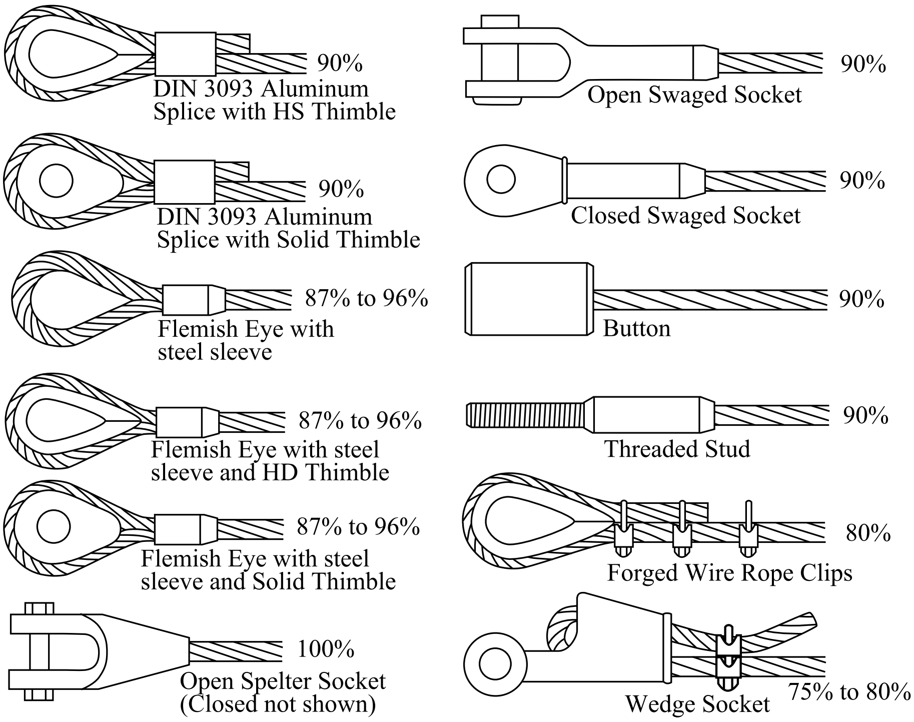


Figure 7. Several type of end terminations (created based upon data from [18])

calking, which are widely used with metal wire rope, with synthetic fiber rope can be estimated as small value because of low friction coefficient. Therefore, not same as metal wire rope, the fixation method for synthetic fiber rope with large strength efficiency is still unclear.

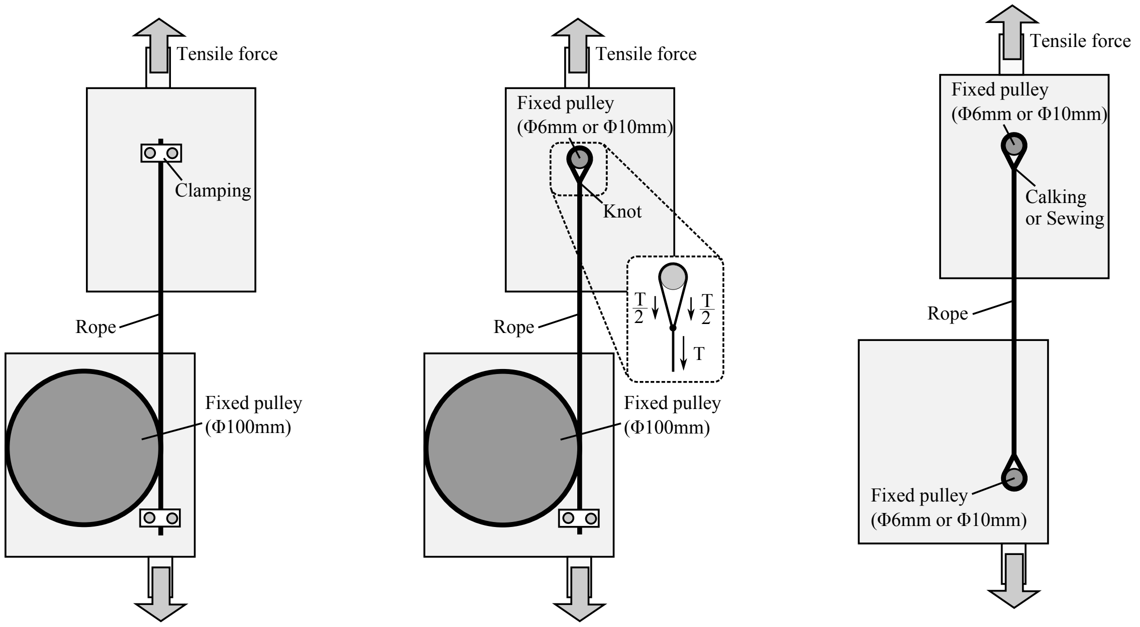
3.2. Experiments Description

In this study, we did experiment to measure strength efficiency of various fixations with synthetic fiber ropes. Experiment devices are the same as in previous section. Rope and pulley arrangement for fixation is shown in Fig.8 and the experiment aims at following fixations:

(1) Clamping
small, large, cylinder
(2) Knot
Bowline, Yosemite bowline, Double sheet bend, Figure-eight loop
(3) Calking
(4) Sewing

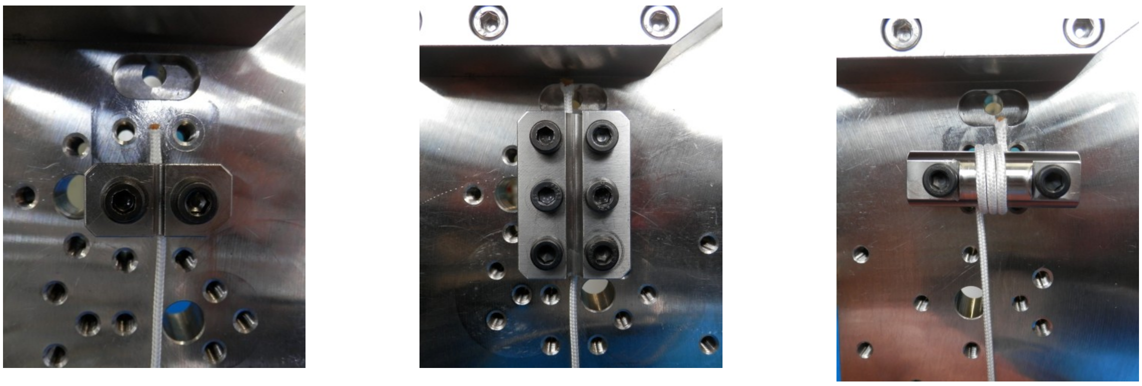
Clamping is putting a rope between stainless steel base plate (SUS303) and stainless steel block (SUS303) and pressing with some screws (M5) as shown in Fig.9. We used three types of stainless steel blocks, small block with two screws, large block with six screws and cylindrical block with two screws. In case of cylindrical block, rope can be wound around the block in order to increase friction force, and we tested under various winding turns. Here, tightening torque of each screw was 1.18 Nm and clamping forces are 7.08 kN with large block and 2.36 kN with small block and cylindrical block respectively.

Knots are making a loop at the end of a rope with various types of knots as shown in Fig.10. The loop is hitched to fixed pulley whose diameter is 6 mm. Here, the rope doesn't get strength reduction at the bending point because the tension in the loop becomes a half of testing tension as shown in Fig.8(b) although strength efficiency is around 72 % at $D/d = 6/2 = 3$ by Eq.5.



(a) Clamping (b) Looping (knot) (c) Looping (calking and sewing)

Figure 8. Fixation component arrangement

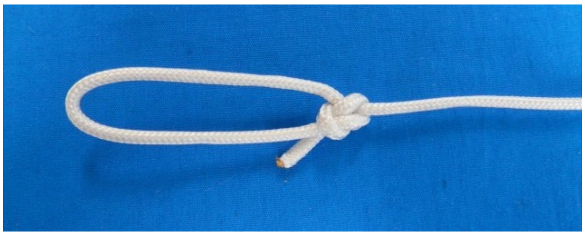


(a) Clamping with small block (H 15 mm × W 30 mm × T 10 mm) (b) Clamping with large block (H 45 mm × W 30 mm × T 10 mm) (c) Clamping with cylindrical block (D 15 mm × W 45 mm)

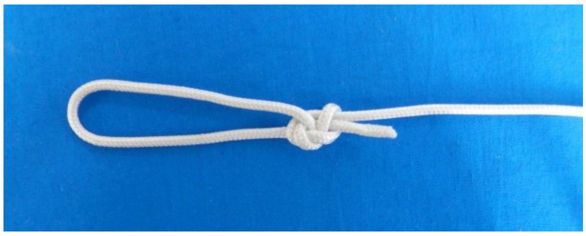
Figure 9. Clamping fixation types

Calking and Sewing are also making loop in the end of a rope and the loop is hitched to same fixed pulley as knot as shown in Fig.11. In the case of calking, we used SB-2 type[19], aluminum component, and tested strength efficiency with changing the number of SB-2 from one to three. In the case of sewing, we used Sewing Machine Processing[19] and sewing thread is made polyester. There are three types of the length of sewing are 10, 25 and 40 mm. Each of the length correspond with the length of calking with one, two and three SB-2.

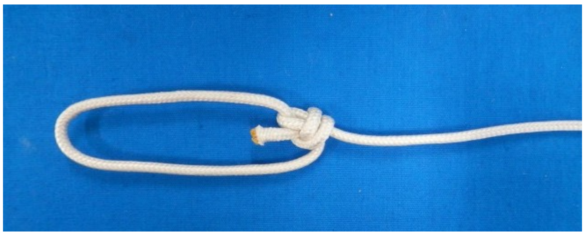
Ropes we used are Dyneema, Zylon-Dyneema and Stainless rope same as previous section, but only Zylon-Dyneema was another lot and its tensile strength was 2.99 kN. The experiment was done in the condition shown in Table4.



(a) Bowline



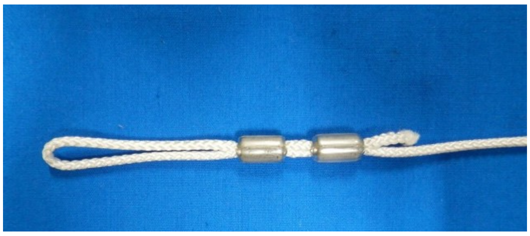
(b) Yosemite bowline



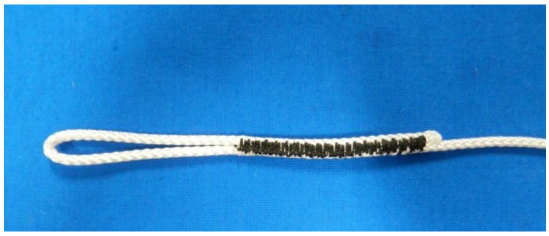
(c) Double sheet bend

(d) Figure-eight loop

Figure 10. Knot fixation types



(a) Calking



(b) Sewing

Figure 11. Calking and sewing fixation

Table 4. Experiment Environment

Temperature	18.6 – 19.6 °C
Humidity	55 – 61 %
Tension speed	300 mm/min.
Sampling period of tension	0.01 sec.

3.3. Results

The experiment was carried out 3 times in the same condition and we calculated strength efficiency of each fixation by taking average with following equation:

$$\text{Strength efficiency} = \frac{\text{Fixation strength}}{\text{Tensile strength}} \tag{6}$$

Table5 shows strength efficiency of each rope and fixation. Values whose background color is gray are the results that the fixation was broken by slipping rope from block or knot or breaking sewing thread. The others are the results that the fixation was broken by rope breaking on the point of fixation.

In the method of clamping, we tested various types of clamping blocks and methods. First, strength efficiencies of synthetic fiber ropes with small clamp were much smaller than the one of stainless wire rope because of slipping under low friction coefficient. However, as an effective means in such case, making knot at the end of clamping, like in Fig.12, can increase strength efficiency to 1.5 - 2 times.

Secondly, using large clamp, we can get large strength efficiency around 70% with even synthetic

Table 5. Strength efficiency of various fixation methods

		Dyneema	Zylon-Dyneema	Stainless
Diameter	[mm]	2	2	2
Tensile strength	[kN]	2.14	2.99	3.50
Clamping (small)	[%]	28.3	18.6	80.0
Clamping (small)*	[%]	42.9	37.3	-
Clamping (large)	[%]	65.0	72.3	90.2
Clamping (cylinder)	[%]	58.9	83.7	-
Bowline	[%]	47.1	36.6	63.1
Yosemite bowline	[%]	51.2	45.9	-
Double sheet bend	[%]	50.5	46.5	-
Figure-eight loop	[%]	50.9	53.2	73.6
Calking (1)	[%]	58.9	23.9	-
Calking (2)	[%]	89.6	47.8	-
Calking (3)	[%]	83.1	79.2	-
Sewing (10 mm)	[%]	48.8	34.1	-
Sewing (25 mm)	[%]	85.4	73.5	-
Sewing (40 mm)	[%]	81.3	90.8	-

*Making knot at the end of clamping.

(grey box): Slipping (white box): Rope breaking

fiber ropes. This is because the number of screw for fixing the clamp can increase in the case of large clamp, and large pressuring force of clamping can get large frictional force. However, ropes broke in the part of the beginning of clamping because of frictional wear of the rope. Therefore, it is difficult to get higher strength efficiency with this normal clamping method.

Thirdly, we tested cylindrical clamp. In addition to the frictional force caused by pressuring force with clamping, cylindrical clamping can get another frictional force caused by winding rope around clamp. Winding rope around cylindrical clamp in many times can increase winding frictional force even though clamping frictional force doesn't change. The change of tensions caused by winding frictional force is described by Eq.3. We show the result of experiment by changing the number of winding in Fig.13. Filled marks are the results of fixation breaking by rope breaking, and empty marks are the ones by rope slipping. There are different results between Dyneema and Zylon-Dyneema. The maximum value of strength efficiency of Dyneema is 58.9 % under 2 windings. In the case of Dyneema, strength efficiency become small according to increase of winding number. Moreover, all tested fixations were broken by rope breaking. This is because clamping force distribution by increasing winding number caused rope slipping and frictional wear, which got rope broken. In contrast, the maximum value of strength efficiency of Zylon-Dyneema is 83.7 %, which is the best value of clamping and almost same value as 84.8 % strength efficiency which is calculated by Eq.5 at $D/d = 15/2 = 7.5$, the bending ratio between the cylindrical block and the rope. Strength efficiency of Zylon-Dyneema become large, and the fixations under 2, 4 and 6 windings

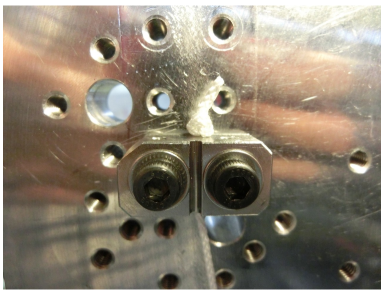


Figure 12. Making knot at the end of clamping

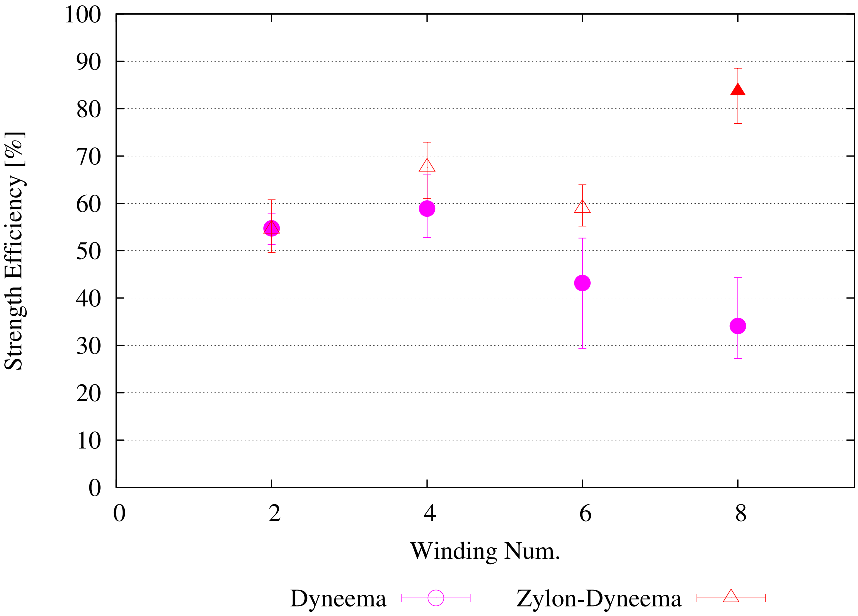


Figure 13. Relation between winding number and strength efficiency. Error bars show errors of three samples.

broke by rope slipping. This is because of a lack of frictional force by winding. Finally, under 8 windings, fixation was broken by rope breaking. Since Zylon-Dyneema consists core and sleeve fiber, a rope wasn't broken under large tension by frictional wear.

In addition, the experiment was carried out under the condition of changing terminal shape of a synthetic fiber rope. Fig.14 shows Dyneema whose terminal was disentangled. We considered that clamping this part could transmit clamping force to all fiber uniformly and strength efficiency would increase, however, the result doesn't differ from normal one very much as shown in Table6. Since strength efficiency became a little small, making terminal of rope disentangled was not effective method. Fig.15 shows Zylon-Dyneema which sleeve fiber was peeled from to expose core fiber. Since the core fiber has larger friction coefficient than the sleeve fiber, strength efficiency was much higher than normal one with small and large clamping as shown in Table7. Therefore, exposing core fiber to increase friction coefficient is effective method for fixation. However, strength efficiency became small with cylindrical clamping because the core fiber was weaker against frictional wear than the sleeve fiber.

Figure 14. Disentangled Dyneema

Table 6. Strength efficiency of fixation of disentangled Dyneema

		Dyneema	
		normal	disentangled
Diameter	[mm]	2	
Tensile strength	[kN]	2.14	
Clamping (small)	[%]	28.3	25.1
Clamping (large)	[%]	65.0	55.1

(shaded) : Slipping   (blank) : Rope breaking

All type of knot fixation can get around 50 % strength efficiency with Dyneema, and this result fits with the result under $D/d = 1$. In contrast, in the case of Zylon-Dyneema, rope was broken with only figure-eight loop and was slipped in the knot with other knots because the rope would be broken under large tension. This shows that figure-eight loop is better than the others. However, although this method can be made easily, strength efficiency is generally small.

Under enough calking, we can get high strength efficiency over 80 % with Dyneema. Although

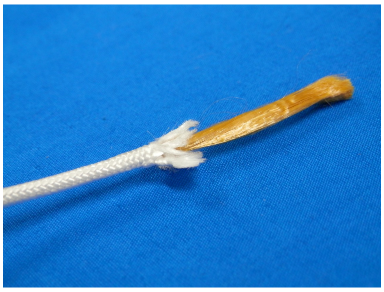


Figure 15. Peeled Zylon-Dyneema

Table 7. Strength efficiency of fixation of peeled Zylon-Dyneema

		Zylon-Dyneema	
		normal	peeled
Diameter	[mm]	2	
Tensile strength	[kN]	2.99	
Clamping (small)	[%]	18.6	58.7
Clamping (large)	[%]	72.3	83.6
Clamping (cylinder)	[%]	83.7	56.7

(shaded) : Slipping (white) : Rope breaking

3 components of calking is not enough in the case of Zylon-Dyneema, strength efficiency got large by increasing the number of calking components linearly.

Sewing also can get high strength efficiency over 80 % with Dyneema and Zylon-Dyneema. Moreover, since each the length of sewing agree with the length required each the number of calking, sewing can get higher strength efficiency than calking in the case of Zylon-Dyneema.

We show the characteristics of each fixation methods in Table 8. In conclusion, clamping fixation can get 65 % strength efficiency with Dyneema and 84 % strength efficiency with Zylon-Dyneema. Clamping fixation has the advantages that it can be performed easily and the rope can be put by unfastening clamping and drawing the rope when the rope gets elongation during drive even though strength efficiency depends on rope's friction coefficient. Knot fixation can get only 50 % strength efficiency, however, it doesn't require any components to make. Although calking and sewing fixation has disadvantage that they require special machines to make and they can not change the length of a rope, they can get large strength efficiency such 80 to 90 %. Therefore, it is important that we should take advantage of various methods and choose the optimum fixation depending on the use.

4. Conclusions and future work

In this paper, we investigated the relation between bending ratio D/d and tensile strength and the method of the terminal fixation with synthetic fiber rope. We demonstrated the following features as design guidelines of a mechanical drive system with synthetic fiber rope:

(1) The relation between bending ratio D/d and strength efficiency is almost the same as metal wire rope and small D/d causes strength reduction although required force to bend synthetic fiber rope is very small. Therefore, in regards to D/d ratio, the design guideline for metal wire rope can be applied to the mechanism with synthetic fiber rope.

(2) Since small D/d causes strength reduction, when the end point of synthetic fiber rope is fixed with knot, strength efficiency become around 50 % at knot point in all kinds of knot.

Table 8. Characteristics of each fixation methods

	Advantage	Disadvantage	Strength efficiency
Clamping	- Easy to make - Easy to change rope length	- Strength efficiency depends on rope's friction coefficient	65 % (Dyneema) 84 % (Zylon-Dyneema)
Knot	- Easy to make - Not necessary any components	- Low strength efficiency	50 %
Calking Sewing	- Large strength efficiency	- Require machines to make - Impossible to change the length of a rope	80 - 90 %

(3) Applying pressuring force to clamping can get large strength efficiency although synthetic fiber rope has low friction coefficient.
(4) Winding a rope around cylindrical clamping block can get large strength efficiency with synthetic fiber ropes which consist of core and sleeve fiber such as Zylon-Dyneema because the rope can be protected from frictional wear. However, increasing winding number might have the opposite effect in case of a synthetic fiber rope which doesn't be covered with sleeve fiber, such as Dyneema.
(5) When the length of a rope doesn't change in using, fixations of calking and sewing are effective and can get around 90 % strength efficiency.

In comparison with the metal wire rope, the synthetic fiber rope has some advantages:

- Lightweight as 1/5 to 1/8 besides high tensile strength as same
- More flexible
- Low coefficient of friction although sometimes it can be disadvantage
- It can be knotted or sewed for fixation

, disadvantages:

- Hard to make fixation by clamping
- More unevenness of strength efficiency

and same characteristic:

- Small D/d causes strength reduction.

Although synthetic fiber rope has some disadvantages, it also has great advantages. We believe that we can make a lot of profit from synthetic fiber ropes if we develop an understanding and use them for mechanical drive systems correctly.

In our future work, we will do more experiments with other types of synthetic fiber ropes and numerical analysis in order to investigate the reason why the relation between D/d and tensile strength of a synthetic fiber rope is the same as a metal wire rope. About clamping fixation, we will pursue strength efficiency under many types of shapes and surface of clamping blocks. Understanding the mechanism of a rope breaking at the point of clamping, calking or sewing, we will also investigate smaller and easier fixation than the methods we did in this paper. Finally, we plan to investigate fixation method with 100 % strength efficiency.

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