Friction knots – their strength under static load

Vladimír Michalička, Radek Telvák
Military Department of the Faculty of Physical Education and Sport, Charles University Prague

ABSTRACT
Introduction: The article is focused on description and comparison of the selected friction knots manners during static load.
Aim of Study: The main objectives of the study are to find the proper values and standard manners of five friction knots used in military climbing, rescue techniques, arboriculture and mountaineering. How strong is the system constructed from friction knot tied from reep cord and low stretch kernmantle rope? What are the processes happening in the friction system leading to its malfunction and where the breakage happens? These were the unanswered questions we were facing to.
Material and Methods: Experimental research was conducted on five selected friction knots – Blake hitch (ABoK #1693), Double prusik (variant of ABoK #1763), Triple prusik (ABoK #1763), Distel hitch (ABoK #1465) and Vánočka knot (ABoK #1758). All of them were part of friction system which was tested 10 times in laboratory conditions on certified device. Firstly, nominal static strength of used material was tested. The initial phase was followed by testing all of the selected friction systems and statistical analysis of all attempts and their comparison between each other. The one-way ANOVA and multi-comparative Tukey test in post hoc analysis were used.
Results: The nominal strength of used material is stronger than ordered by European norms. 81 % of friction system malfunctions happen in friction knot. All selected friction knots decrease the nominal strength of friction systems. The range of decrease differs between 14 % and 49 % depending on specific friction knot and its maximal nominal strength. Number of strands used for knot tying is not determining parameter of its maximal nominal strength.
Conclusion: The friction knots are commonly used in many expert fields of human activities. Their proper selection based on our results might be crucial for safety as well as using the features specific friction knots have.
Keywords: Drop of nominal static breaking strength, drop of nominal static breaking strength, first slip, military climbing, point of failure.

SOUHRN
Úvod: Článek je zaměřen na popis a porovnání vybraných samosvorných uzlů a jejich chování při statickém zatížení.
Cíl: Hlavními cíli práce je nalézt přesné hodnoty a standardy chování pěti samosvorných uzlů používaných ve vojenském lezení, záchranných technikách, arboristice či horolezectví. Jakou pevnost má systém konstruovaný ze samosvorného uzlu uvázaného na reep šňůře na statickém laně? Jaké procesy vedoucí k selhání se dějí

ve vzniklém samosvorném systému a kde k selhání dochází? To byly nezodpovězené otázky, kterým jsme čelili.
Metody: Experimentální studie byla přivedena na pěti vybraných samosvorných uzlech - Blake hitch (ABoK #1693), Double prusik (variant of ABoK #1763), Triple prusik (ABoK #1763), Distel hitch (ABoK #1465) and Vánočka knot (ABoK #1758). Všechny byly částí samosvorného systému, který byl vždy 10 testován v laboratorních podmínkách na certifikovaném trhacím zařízení. Nejprve byla testována nominální statická pevnost použitého materiálu. Po této iniciační fázi byly testovány všechny samosvorné systémy a byla provedena statistická analýza všech pokusů. Pro statistickou analýzu dat byla využita one-way ANOVA a multikomparativní Tukey test v post hoc analýze.
Výsledky: Nominální pevnost použitých materiálů je vyšší, než vyžadována Evropskými normami. 81 % samosvorných systémů selhalo v samosvorném uzlu. Všechny vybrané samosvorné uzly snižují nominální pevnost samosvorného systému. Rozsah poklesu variuje mezi 14 a 49 % a závisí na vybraném uzlu a jeho maximální nominální pevnosti. Počet pramenů použitých pro konstrukci uzlu není určujícím parametrem maximální nominální pevnosti.
Závěr: Samosvorné uzly jsou často využívány v mnoha oblastech lidské činnosti. Výběr toho správného může mít zásadní vliv na bezpečnost, stejně jako může být výhodná znalost dalších vlastností konkrétního uzlu.
Klíčová slova: Bod selhání, maximální statická pevnost, pokles nominální statické pevnosti, první prokluz, Vojenské lezení.

INTRODUCTION

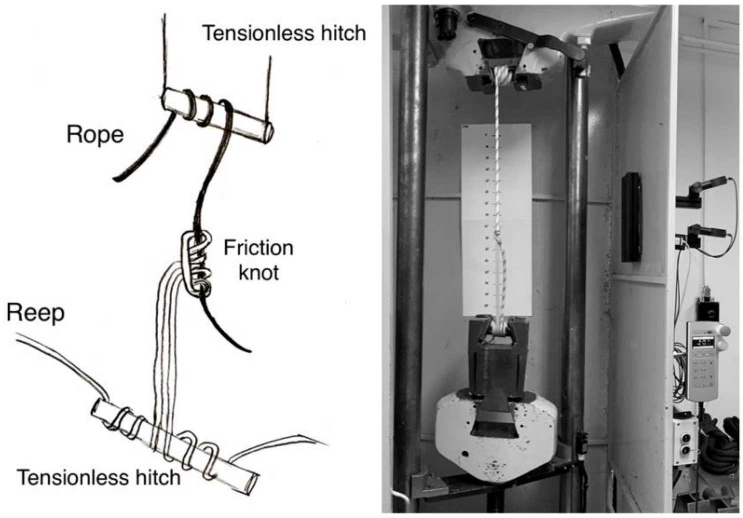
Friction knots are commonly used in wide field of human outdoor, industry and professional activities. No matter whether mountaineer, lifeguard, arborist or other specialist, everyone rely on used materials. All of them should use certified equipment (ČSN EN 564) and follow manuals. It means, the weakest points result from used approach and working techniques. Except from misuse or using improper techniques (Schubert, 2016), the safety chain is as weak as its weakest point, therefore textile materials mostly. Its connection precisely.

It has been proved (Evans, 2016) that every knot tied to connect two rope strands, to make a loop or used in some other special occasions results in weakening the strength of original material such as rope, cord or sling. According to recent study (Šimon, Dekýš & Palček, 2020), conducted on loop knots, the decrease of nominal strength might be up to 53 %. If we count normalized strength of almost every textile material as 22 kN, it means load capacity only 1,25 kN. It is always one or combination of reasons such as shear friction, heat, pressure or abrasion that lead into system failure (Frank & Kublák, 2007).

The goal of our article focuses on selected friction knots used for special techniques in mountaineering, rescue operations, military climbing or arboriculture. Their manners and thus the level of weakening the system they are part of is not well known (Frank & Kublák, 2007; Kublák, 2014). We conducted experimental research of selected knots (Telvák, 2020) to find out the maximal strength of system, its nominal strength drop and other features.

MATERIAL AND METHODS

Due to the high complexity of physical and chemical influences and changes, the conducted experiment focused only on static load performed on brand new materials, utilizing only static ropes, reep cords and steel carbines. Five friction knots used in military climbing (Michalička et al., 2019) and arboriculture (Jepson, 2000) were chosen to work as a part of friction system. Each of the systems consisted of a few components and was examined on vertical laboratory testing device (ZD 30, manufactured in 1957) under stabile laboratory conditions in Lanex company, Bolatice. Used software TIRAtest was produced by TIRA GmbH (Germany). Force measurements were performed by tensometric sensors connected to the control unit and a computer. Two opposite steel rods (diameter 50 mm) were used to fix the testing material – the friction system. The rope/reep cord was wrapped three times to make a tensionless hitch ABoK #2047 (using friction to fix both textile materials). Rod movement was conducted by a hydraulic mechanism according to standard ČSN EN 564 and range 0 – 160 cm. Complete diagram can be seen in Picture 1, as well as final attachment.



Picture 1 Diagram and final attachment of the friction system

Reference testing was conducted before experimental part to gain information about up to date features of the used material. Thus, the data were related to gained details – the real static breaking strength of utilized materials.

Whole research was designed as the laboratory experiment, where five chosen friction systems were exposed to growing tension force up to the destruction of part of the friction system. Every system was measured 10 times (Evans, 2016). Before each session, rope and reep cord were cut (2 m and variable length depending on used knot respectively) and chosen friction knot was applied and preloaded by 5 kg steel weight (Komorous, 2016).

Maximum static breaking strength, drop of nominal static breaking strength, point of failure and first slip were recorded for each session. After the session, all parts of the used friction system were stored for further examination.

For statistical analysis the one-way ANOVA and the multi-comparative Tukey test in post hoc analysis were used.

Rope and cord

Chosen diameter and type of the classic modern polyamide low stretch kernmantle rope and reep cord are commonly used in military climbing. Due to the collaboration with rope producer Tendon, brand new materials from their production were used. In total, 96 m of the rope and 117 m of the reep cord were utilized during all the experimental sessions. Features of the used materials are mentioned in Table 1 and thus might be replicable in future experiments.

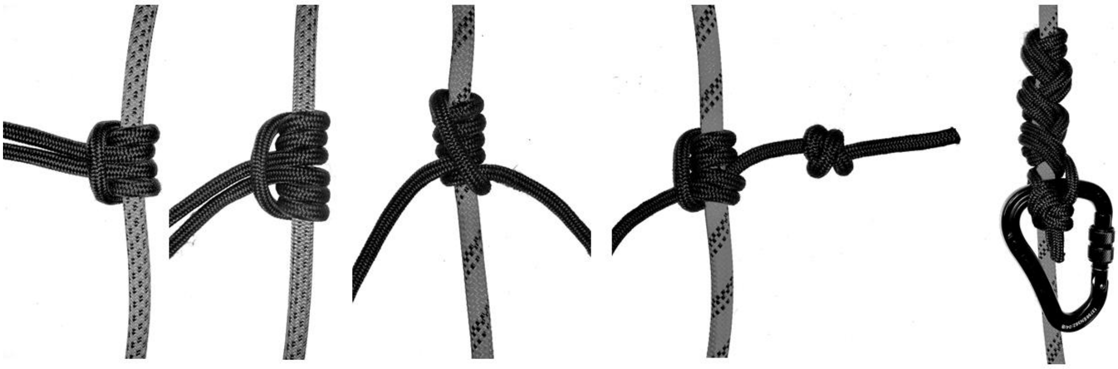
Table 1 Parameters of tested rope and reep cord by the manufacturer

Manufacturer	Tendon	Tendon
Rope trademark label	Tendon Static 10,5 mm	Tendon Reep 6 mm
EN standard Type	ČSN EN 1891:2000	ČSN EN 564: 2015
Type	A	N/A
Material	Polyamide (PA)	Polyamide (PA)
Year of manufacture	2020	2020
Diameter [mm]	10,5	6
Static breaking strength (Tenacity) [kN]	22	7,2
Static breaking strength (Tenacity) [kN] from reference testing	**32**	**10**
Weight per meter [g/m]	72	25
Number of falls due to EN 1891 (f = 1)	20	N/A
Sheath slippage [%]	0	N/A
Elongation [%]	3,4	N/A
Sheath mass [%]	35	N/A
Core mass [%]	65	N/A
Shrinkage according to EN 1891 [%]	1,9	N/A
Core structure	8S + 7Z	2S + 3Z

Chosen knots

Five friction knots commonly used in military climbing and arboriculture were chosen. All of them come from literature (Ashley, 1993) yet not often with proper name, therefore we use commonly used terms. It was precisely Double Prusik hitch (variant of ABoK #1763), Triple Prusik hitch (ABoK #1763), Distel hitch (ABoK #1465), Blake hitch (ABoK #1693) and hitch called Vánočka (ABoK #1758) in Czech, used in Military climbing or Czech mountaineering association (Kublák, 2014; Michalička et al., 2019).

Each of them was tied in the same way, according to ABOK and with all strands straightened. The view of chosen friction knots in proper way of tying can be seen in Picture 2.



Picture 2 Chosen friction knots

RESULTS

In order to gain proper results for comparison, the experimental model was designed and five friction knots were chosen. The specific friction system, together with rope end reep cord, was formed. All five systems were compared and thus, the range of decrease of maximum nominal strength, point of failure and first slip was determined.

Rope and cord without knot

According to EN 564, the static breaking strength is set to 22 kN for static ropes, type A; 7,2 kN for 6 mm reep cord respectively. Before the experimental phase, the reference measurement was conducted to give the real insight of values the utilized material itself has. Thanks to this phase, the time consumption of the experiment was better known, also the real demands for textile materials but moreover, the real static breaking strength of materials used for constructing friction systems.

Static breaking strength of Tendon Static rope 10,5 mm was measured at level of 32 kN, whereas 10 kN was the static breaking strength of 6 mm reep cord we used. Gained values were used for all the others calculations.

Point of failure

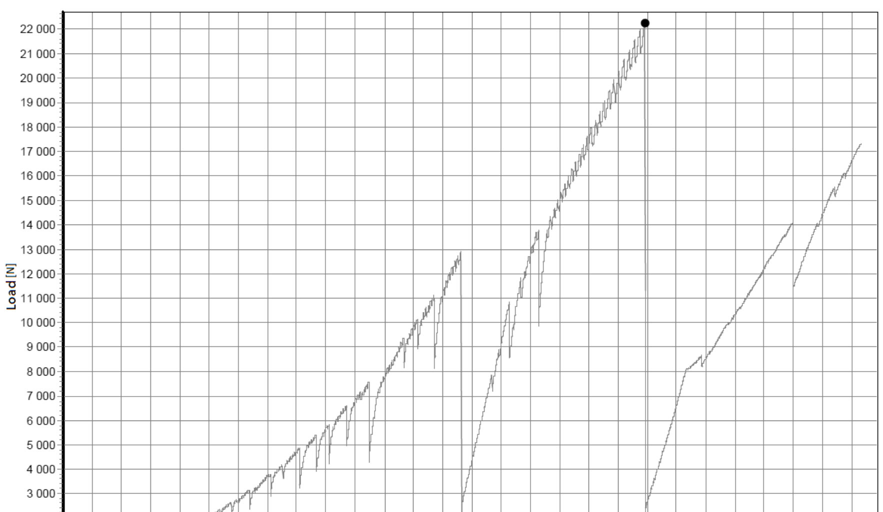
It is well known, that the knot is the weakest point in connected textile materials used in mountaineering (Frank & Kublák, 2007) but is it also true for friction knots? The temperature rising in a connective knot which is being tighten until breaking has been measured (Šimon, Dekýš & Palček, 2020) yet friction knots plays different role and due to their slippage at the static rope, not only temperature plays role in breakage of friction system. We did not use an infrared camera (Ibid) yet we thoroughly examined every sample directly after experiment.

As we supposed, the weakest point of all friction systems was the reep cord and the friction knot tighten out of it. Not only has it broken in more than 80 % of all sessions but in these occasions, it was always in friction knot. The rope breakage was in 6 % and so we suppose, the temperature out of friction during slippage played a role there. In 13 % of experimental sessions, no breakage occurred which was mostly caused by reaching the range limits of device.

First slip

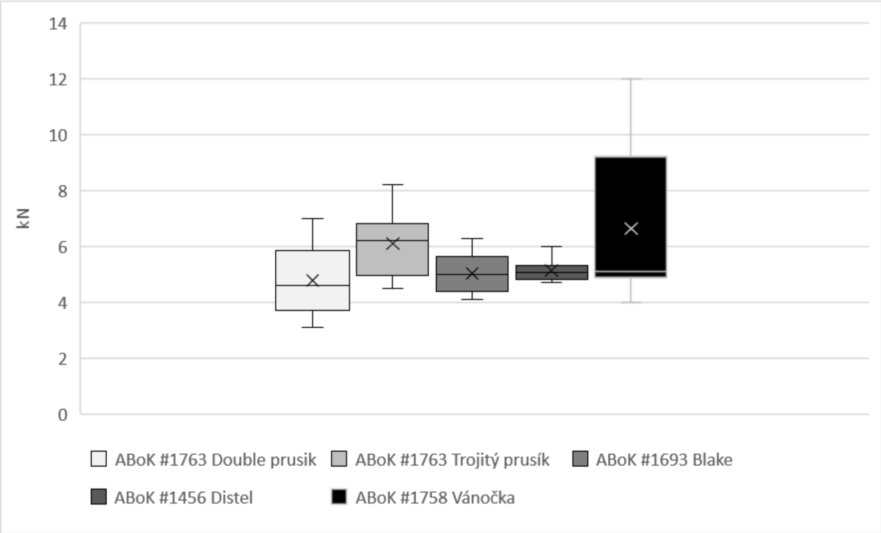
We decided to research also the first sign of friction system breakage – the first slip. This area of friction knots is yet not known and so we set the limit when system static strength firstly changes ≥ 0,8 kN. The value 0,8 kN (80 kg) was set from valid mountaineering norm and is strictly used for testing ropes and other materials (ČSN EN 892).

The course of friction system manners during static load is illustrated by Picture 3, including a drop, which means slippage of friction knot, other increase of load until maximal static strength of system and its breakage.



Picture 3 Illustration of friction system manners during static load

The comparison of first slips among chosen friction systems is illustrated on Picture 4.



Picture 4 First slip

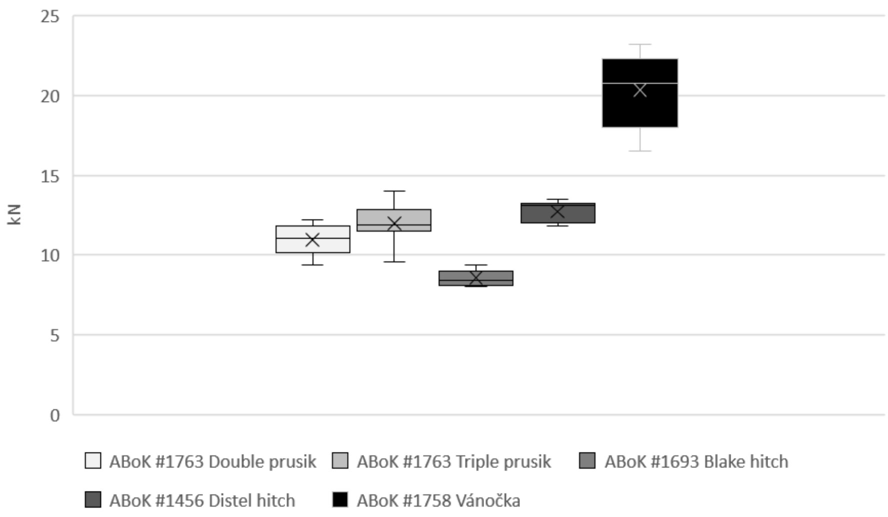
Maximal nominal strength of system

As previously mentioned, the rope system is weakest mostly in used knot. The nominal strength of commonly used connection knot is quite well known yet completely unknown in field of friction knots.

We researched our five friction systems with growing static load up to the level of breaking. As seen in Picture 3. the maximal nominal strength of friction system is illustrated by black dot.

Different results originate not only from different manners of the friction system but also from distinction of friction knot construction itself. Some used knots are tied from 1, whereas some from 2 or 4 strands. Therefore, Picture 5 illustrates the precise, yet nominal, values of each knot.

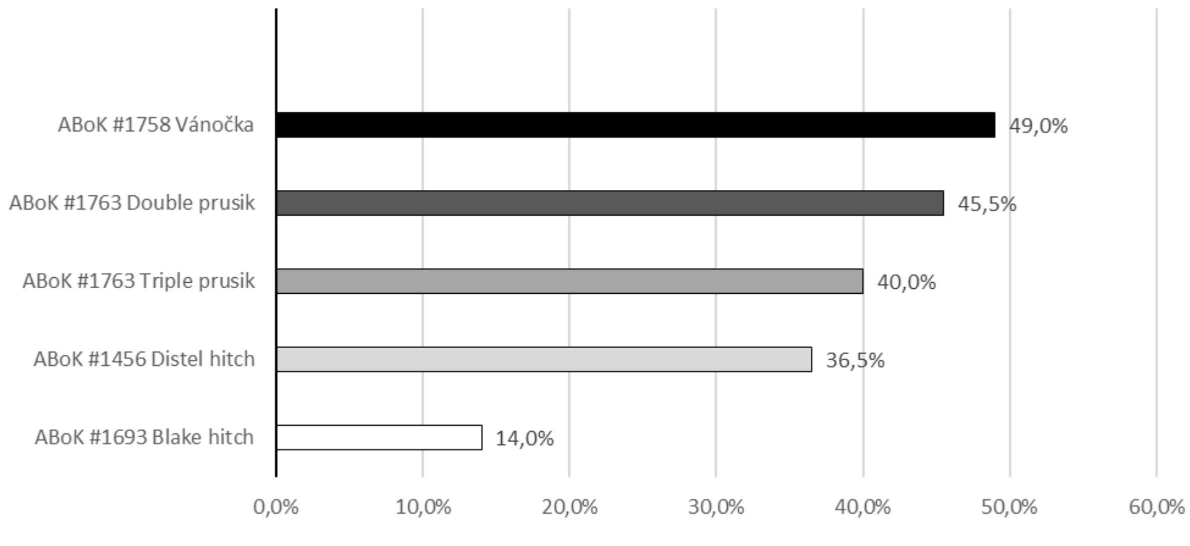
The Blake hitch (ABoK #1693) represents 1 strands knots and its average maximal strength (8,56 kN) is almost as strong as reep cord itself (10,0 kN). No big disproportions among Double prusik (variant of ABoK #1763), Triple prusik (ABoK #1763) and Distel hitch (ABoK #1465), where all are constructed from 2 strands, can be seen. The knot Vánočka (ABoK #1758), constructed from 4 strands, shows the average maximal nominal strength of 20,36 kN.



Picture 5 Maximal nominal strength of system

Drop of nominal static breaking strength

The last feature we have examined was the drop of nominal static breaking strength. As proved, figure eight knot in I geometry, as one of the most used knots, weakens the nominal static strength of rope by 35,58 % (Šimon, Dekýš & Palček, 2020). What are the values for chosen friction systems? We have calculated the drops for each of the chosen friction system and the results are displayed in Picture 6. As obvious, the minimal drop is shown by Blake hitch (ABoK #1693) with only 14 % in one side, the Vánočka hitch (ABoK #1758) with 49 % in the other.



Picture 6 Drop of nominal static breaking strength

DISCUSSION AND CONCLUSION

Our article focuses on relatively unknown topic, the strength of rope systems with friction knots. The experimental research was conducted on 5 chosen friction knots tied on low stretch kernmantle rope and reep cord. We supposed, according to similar researches (Evans, 2016; Šimon, Dekýš & Palček, 2020) that the weakest point in the friction system is the reep cord with friction knot. This fact was proved, 80 % of system points of failure were in friction knot.

We also examined first slip due to the fact that all friction knots are defined by slight slip, it is their principle. The first slip ≥ 0,8 kN was measured for its importance for climbers as a first sign of system malfunction. The load of cca 4 kN is the start point for first slips and we assume this value as quite low. A 400 kg load might be represented as a wounded person, two lifeguards and equipment – quite common in rescue techniques.

We examined maximal nominal strength of system, the most common feature in the field of "knot strength" (Komorous, 2016; Evans, 2016). Against the other authors who work with connective knots, we work with the friction system strength which was not properly examined. Our results show that the more strands used for the knot construction, the stronger system is. The function is not exponential though. The Blake hitch (ABoK #1693) made from 1 strand is not twice as weak as Double prusik (variant of ABoK #1763) or Distel hitch (ABoK #1465) and not four times as weak as Vánočka knot (ABoK #1758). This fact, linked with the last researched feature – drop of nominal static breaking strength, must be taken into account.

Drop of nominal static breaking strength shows the Blake hitch (ABoK #1693) as strongest (with lowest drop) yet tied from 1 strand. The lowest drop of nominal static breaking strength, the more reliable or legible for users.

The mountaineering, rescue techniques or arboriculture are hazardous human activities. Even when demanding for know-how and certifications, many accidents happened every year. We believe, this article might be helpful for this highly specific workers and also for all military climbers who use friction knots in their daily routine. As all other knots, also the friction knots have their specifics, their strengths and weaknesses – important features when working in risky heights.

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Contact:
mjr. Mgr. Vladimír Michalička, Ph.D.
Faculty of Physical Education and Sport, Charles University Prague
José Martího 269/31, 162 52 Praha 6, Czech Republic
e-mail: michalicka.vladimir@gmail.com